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Degree of Doctor of Philosophy

The University of Edinburgh

June 2005
Declaration

I hereby declare that the work presented in this thesis is my own unless otherwise stated by reference.
Acknowledgements

I would like to express my gratitude to the following people;

Dr Hamish McNab and Dr Andrew Mount for their help and guidance over the past 3 ½ years.

Dr David Reed, Dr Ian Sadler, Mr Juraj Bella and Mr John Millar for their training and assistance with NMR spectroscopy.

The EPSRC for funding.

The McNab and Mount research groups past and present.

Dr Steven Magennis for carrying out the fluorescence lifetime studies discussed in this thesis.

All who work in the departmental technical services (mass spectrometry, elemental analysis etc).

My Mum for her financial support over the years.
Postgraduate courses and lectures attended.

Sensors, The University of Edinburgh (5 lectures)
Mass spectrometry, The University of Edinburgh (5 lectures)
Chemical carcinogens, The University of Edinburgh (5 lectures)
Departmental postgraduate seminars (3 years attendance)
Departmental colloquia (3 years attendance)
RSC Perkin meeting, Scottish division (3 years attendance)
Postgraduate lectures in synthetic techniques, The University of Edinburgh (1/2 day)
Organon symposium on organic synthesis 2004, The University of Glasgow (1 day)
Tomorrow,s World Roadshow 2003, SECC Glasgow (1 day)
Abstract

A novel gas-phase free-radical cyclisation to carbazoles has been developed. A number of 2-nitrodiphenylamines were subjected to flash vacuum pyrolysis (FVP) to produce, after cleavage of the nitro-group, a phenyl radical that cyclises to produce carbazoles. Phenazines are formed as by-products during this FVP reaction by an electrocyclisation process involving the nitro group. Carbazole formation was favoured when electron withdrawing groups were present in the 2-nitrodiphenylamines. The cyclisation strategy was also applied to the preparation of carbolines. These were successfully obtained when the heterocyclic nitrogen was para to the amine nitrogen atom. When an ortho nitrogen atom was present, the production of carbolines required the initial radical to be generated on the heterocycle. When the radical was generated on the phenyl ring, the products were benzo-fused benzimidazoles.

The gas-phase cyclisation methodology developed for the preparation of carbazoles was applied to the synthesis of the fused indole systems indolo- and pyrrolo-[3,2,1-jk]carbazole. Both systems were prepared in good yield and the method was successfully applied to the production of substituted indolo- and pyrrolo-[3,2,1-jk]carbazoles. Novel aza-analogues of indolo-and pyrrolo-[3,2,1-jk]carbazole were prepared for the first time.

The electrochemical properties of indolo- and pyrrolo-[3,2,1-jk]carbazole were studied. It was found that when both compounds were subjected to electro-oxidation, electro-active conducting films were formed on the electrode surface. The electro-oxidised indolo[3,2,1-jk]carbazole product was analysed by NMR spectroscopy and mass spectrometry and was found to consist of three dimers. The film was highly fluorescent in the blue region of the spectrum with a lifetime of the order of 10 ns, making it a potential candidate for application in display technology such as LEDs. The structures of the components of the film were confirmed by synthesising the dimers chemically using Suzuki-coupling methodology, with comparison of their NMR spectroscopic, electrochemical and fluorescence characteristics. Electro-oxidation of substituted indolo[3,2,1-jk]carbazoles was also studied and found to have similar characteristics.
These studies were extended to 7-azaindolo[3,2,1-\(jk\)]carbazole and an electro-active conducting film was again formed. Like indolo[3,2,1-\(jk\)]carbazole, the film consisted of three dimers and was highly fluorescent in the blue region of the spectrum. The pyridine nitrogen atom in the 7-azaindolo[3,2,1-\(jk\)]carbazole system was found to be sensitive to pH between pH 1-5.5 in aqueous electrolyte. Changing the pH of the electrolyte produced a change in the electrochemical response of the film, this demonstrates the potential of this type of system as a novel electrochemical sensor.

In the case of pyrrolo[3,2,1-\(jk\)]carbazole it was found that the film was also highly fluorescent in the blue/green region of the visible spectrum. However, the film products were found to be more polymeric in nature resulting in more complex fluorescence properties. The components of the film have not been characterised due to poor solubility.
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Preamble

In this thesis, the synthesis and spectro-electrochemical characterisation of two novel conducting films will be discussed. The conducting films are based upon indolo[3,2,1-jk]carbazole (IC) and pyrrolo[3,2,1-jk]carbazole (PC), 1 and 2 respectively. Initial work on the discovery of these films was carried out by M Chapman. Initial studies have shown that 1 forms a conducting film at a platinum electrode upon electro-oxidation. Compound 2 also forms a film which is initially conducting but becomes rapidly insulating. Both film species are highly fluorescent.

This thesis is separated into 2 parts; the first is concerned with the synthesis and characterisation of 1 and 2 and related compounds. The second part is concerned with the electrochemical and spectroscopic characterisation of the films produced upon electro-oxidation of 1 and 2 and related compounds. In the first chapter of Section A, a brief introduction to the chemistry of 1 and 2 is discussed. An introduction to conducting polymers will be discussed in Section B.
SECTION A. Gas-phase radical cyclisation of phenyl type radicals.

Chapter 1. Introduction.

1.1 Indolo[3,2,1-ijk]carbazole (IC).

1.1.1 Synthesis.

Compound 1 was originally synthesised by Tucker\(^2\) in 1939. This synthesis is shown in Scheme 1 and consists of an \(N\)-arylation by Ullman condensation of carbazole 3 with 100% excess 2-chloronitrobenzene 4 to form \(N\)-(2-nitrophenyl)carbazole 5. Compound 5 was reduced to the amine 6 using \(\text{SnCl}_2\). The amine was then cyclised via the diazonium salt to produce IC 1. This work was originally carried out in attempt to form optically active tervalent nitrogen compounds. It was thought that 1 would be bowl shaped and if it could be substituted in any position other than at the 2-position then it would be asymmetric. If this was the case then it was thought that such derivatives could be resolved into optically active forms.

![Scheme 1](image-url)

Scheme 1
Tucker and co-workers have also synthesised a number of derivatives of 1 utilizing this methodology.\(^2\) Initially the strategy was used to form 5-substituted derivatives. The substituents introduced included methyl, chloro, carboxylic acid and cyano groups. The yields of the reactions are shown in table 1.

<table>
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<th>Stage in reaction</th>
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<th>H</th>
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<td>N/A</td>
<td>N/A</td>
<td>18 b</td>
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Notes: a. Yields not given. b after nitrile hydrolysis.

**Table 1. Yield of 5-substituted indolocarbazoles.**

Tucker\(^2\) has also shown that the 2- and 5-substituted indolocarbazole 7 and 8 were synthesised from N-phenyl derivative 9 in an unknown ratio (Scheme 2). It was shown by comparison of the melting points of the purified product from Scheme 2 that 2-carboxylic acid 7 was the predominant product. The melting point of the 5-carboxylic acid 8 obtained by unambiguous synthesis using the methodology shown in Scheme 1 was different. The fact that no 5-substituted derivative was isolated could be due to the main product being subjected to extensive purification by crystallisation which would result in the loss of the minor isomer. Tucker\(^2\) suggested that the 5-isomer was present as there are two sites of potential cyclisation and the melting point of the crude product was sufficiently depressed to suggest there was an impurity present.

The 2,5-disubstituted indolocarbazole carboxylic acid derivative 10 was also synthesised by this strategy from 11 (Scheme 3). The synthesis of the 2,5-dicarboxylic derivative 10 was shown to proceed to give the desired product. No isomerisation is possible in this case due to the symmetry of the starting amine 11. No yields have been reported for the target compounds.
Further work on the synthesis of 1 by Tucker\(^3\) from 9-aminocarbazole 12 has been carried out. Reaction of 12 with cyclohexanone 13 formed the hydrazone 14. This was then reacted in tetralin with dry HCl to give the tetrahydro intermediate 15 by a Fischer indole type cyclisation. The cyclised product was then dehydrogenated to give 1 (Scheme 4).
Scheme 4

It was also shown\(^3\) that \(1\) could be synthesised from 1-nitrocarbazole \(16\) by Ullman condensation with iodobenzene \(17\). The resulting nitro compound \(18\) was reduced to the amino compound \(19\) and cyclised to indolo[3,2,1-\(jk\)]carbazole \(1\) \emph{via} the diazonium salt as before (Scheme 5).
When comparing the three routes to indolocarbazole devised by Tucker et al, the method shown in Scheme 1 is obviously the most useful route to compound 3 due to the higher yields. In summary, Tucker pioneered the synthesis of 1 and derivatives of 1. However, he was without success in the attempt to optically resolve unsymmetrical derivatives.2,3,4

The above synthetic studies were carried out between the late 1930s and the early 1950s. The chemistry of this compound has otherwise been neglected until recent years when Brown and co-workers5 performed a mechanistic study into the gas phase pyrolytic generation and rearrangement reactions of N-substituted 1,2-didehydrocarbazoles. 10-Phenyl-10-furo[3,4-a]carbazole-1,3-dione 20 was synthesised from 1-phenylindole-3-carboxaldehyde 21 by Wittig reaction to form 3-ethenyl-1-phenylindole 22, which was then reacted with dimethylacetylene dicarboxylate to give diester 23. Diester 23 was then converted to the anhydride 20 (Scheme 6).

Scheme 6
The final step to form 1 was the cyclisation by flash vacuum pyrolysis (FVP, see later). The furnace temperature was set at 900 °C with a pressure of 0.03 Torr and the inlet oven temperature at 140-170 °C. The anhydride, when pyrolysed, formed an aryne intermediate 24, which, immediately cyclised to indolo[3,2,1-jk]carbazole 1. The yields of the reaction sequence are as shown in Scheme 6, with the pyrolysis stage yield being a crude yield before 1 was subjected to flash chromatography.

McNab and Crawford ⁶ have also recently synthesised 1 by pyrolytic methods. The synthesis consists of the formation of an N-aryl carbazole, which is then pyrolysed to generate the radical species 25. The radical species 25 undergoes cyclisation with the carbazole moiety to form compound 1 (Scheme 7). Two different radical generating groups have been utilised for this synthesis, these are the allyl ester precursor 26 and an aromatic nitro functionality 5. The usefulness of the allyl ester as a radical generating group for gas phase cyclisation reactions has been known for some time.⁷ The use of nitro groups for this type of reaction was demonstrated by de Mayo in the late 1970s.⁸

The allyl precursor 26 was synthesised from the Ullmann condensation of methyl 2-iodobenzoate 27 with carbazole to give 28. The allyl ester 26 was formed by the hydrolysis of the methyl ester followed by allyl ester formation. The allyl ester was pyrolysed at 950 °C, 10⁻² Torr and gave indolo[3,2,1-jk]carbazole 1 in 60% yield (Scheme 7). The requirement for the hydrolysis/allylation stages was due to a poor yielding Ullmann condensation of allyl 2-iodobenzoate with carbazole. The methyl ester proved to be more stable to the conditions used than the allyl ester.

The nitro precursor 5 was prepared by the SNAr reaction of 2-fluoronitrobenzene 29 with carbazole 3 to give N-(2-nitrophenyl)carbazole 5, which was pyrolysed at 850 °C (10⁻² Torr) and yielded 1 in 48% yield (Scheme 8). This reaction sequence has not yet been optimised for maximum yield (see later).
1.1.2 Summary of syntheses of Indolo[3,2,1-jk]carbazole.

Tucker et al has devised a useful 3-step synthesis to compound 1 as outlined in Scheme 1. This has also been utilized for the synthesis of 5-substituted derivatives and for the 2 and 2,5-dicarboxylic acid derivatives. Brown et al has utilized a gas phase methodology as outlined in Scheme 6, but requires a long multi-step strategy. McNab and co-workers
have produced a convenient gas phase radical cyclisation strategy that takes place in good yield and in two steps.\textsuperscript{6}

1.1.3 Properties of Indolo[3,2,1-jk]carbazole.

1.1.3.1 Chemical properties.

The chemical properties of 1 have not yet been fully investigated. This compound can be viewed as a fusion of indole with a carbazole. The resulting structure has the expected carbazole type reactivity due to two carbazole substructures being present. Carbazole’s reactivity to electrophiles is demonstrated by the bromination of carbazole with NBS.\textsuperscript{9} Reaction with 1 molar equivalent gives solely 3-bromocarbazole, further reaction gives 3,6-disubstituted carbazole. Further reaction still with electrophiles then substitutes in the 1 and 8 postitions.

In Tucker’s original paper,\textsuperscript{2} the bromination of 1 was carried out using bromine to give mono- and di-bromo derivatives. The structure of the mono-substituted product was thought to be the 2-substituted derivative but there is little experimental evidence to back this assignment up. Evidence of mono-bromination was presented by microanalysis. The di-bromo derivative was proposed to be the 2,5-disubstituted product. Microanalysis showed that reasonably clean di-bromo derivative was formed.

A recent German patent\textsuperscript{10} has utilised the strategy employed by Tucker \textit{et al} \textsuperscript{2} to form indolo[3,2,1-jk]carbazole which was used as starting material for the synthesis of azo derivatives of indolocarbazole. The authors claim to have produced 2,5,10-trinitroindolo[3,2,1-jk]carbazole \textbf{30} by direct nitration of 1. This was then reduced with Raney nickel and hydrazine monohydrate to give the triaminooindolo[3,2,1-jk]carbazole \textbf{31} (Scheme 9). No yields were given.
Compound 31 was then successfully diazotised and azo coupled to a wide variety of heterocyclic and aromatic couplers, which were proposed to be useful as pigments. No information was given into how the nitration proceeded and no analytical data were presented to assess whether or not any of the other possible nitro isomers were present.

1.1.3.2 Physical properties.
It has been shown by Mount and co-workers that 1 undergoes electro-oxidation at a platinum working electrode resulting in the deposition of a conducting film. The film is highly fluorescent in nature due to the high degree of conjugation. No information is available about the nature of the film. The characterisation of the film is part of the study to be discussed in this thesis.

Brown and co-workers have assigned a 200 MHz proton NMR spectrum of 1, probably by inspection (Figure 1). The numbering scheme is shown on structure 1 (page 1). A $^{13}$C NMR spectrum was also recorded and showed the correct number of methine and quaternary carbon resonances. Mass spectrometry showed the correct mass and the melting point reported by Brown corresponds with that reported by Tucker. The analytical data reported by McNab and co-workers are in strong agreement with those of Tucker and Brown.

Scheme 9
There has also been interest in 1 as a substructure of fullerene molecules. Computational studies have been carried out on N-doped azafullerene analogues of \( \text{C}_{60} \).\textsuperscript{11,12} Research is being undertaken into the possible synthesis of these fullerenes.

1.2 Pyrrolo[3,2,1-jk]carbazole.

1.2.1 Synthesis.

Pyrrolo[3,2,1-jk]carbazole 2 was first synthesised accidentally by Bailey et al.\textsuperscript{13} The reactions of hexahydropyrrolo[3,2,1-jk]carbazole 32 were being investigated. Compound 32 was dehydrogenated to form 1,2-dihydro[3,2,1-jk]carbazole 33 in 50% yield. In attempt to maximise the yield, the reaction conditions were varied. At 190 °C/16 h, 1-ethylcarbazole 34 was formed in 60% yield. At 180 °C/4 h, pyrrolo[3,2,1-jk]carbazole 2 was formed in 8% yield (Scheme 10). The synthesis of 2 was not pursued in the work carried out by Bailey and co-workers as the focus of the research was on the reactions of 32 with arenesulfonyl azides.
Compound 2 has been largely ignored until Hallberg et al.\textsuperscript{14} carried out a synthesis of this molecule in 1985. The initial aims of Hallberg's studies were the synthesis of phenothiazines 35 and dibenz\[b,f\]azepines 36 for potential use as conformationally restricted tranquilizers. A series of these compounds was prepared in an earlier study by Hallberg.\textsuperscript{15} The synthesis was carried out by a Bischler type cyclisation of heterocyclic \(N\)-acetaldehydes 37 over molecular sieves (scheme 13).

An electron impact mass spectrometry study of the fragmentation of 35 and 36 both produced a pyrrolocarbazolium structure. To test their hypothesis of the formation of this fragment a sample of pyrrolo[3,2,1-\(jk\)]carbazole 2 was required for mass spectrometry. Synthesis of pyrrolo[3,2,1-\(jk\)]carbazole 2 was attempted by the method shown in Scheme
11 using carbazole-\(N\)-acetaldehyde in place of 37. Failure of this synthesis was attributed to steric strain.

Hallberg and co-workers, however, utilised the conditions for the nickel mediated desulfurisation of phenothiazine to carbazole developed by Eisch \textit{et al} \textsuperscript{16} to promote the desulfurisation of 35. This reaction was carried out using 4 molar equivalents of a bis(1,5-cyclooctadiene)nickel(0) and 2,2'-bipyridyl complex 38 (Scheme 12). Pyrrolo[3,2,1-jk]carbazole was isolated in 72% yield by this methodology. This method, however may be of limited use due to a large stoichiometric excess of a non-commercially available nickel complex being required. The product also required repetitive purification by column chromatography to remove the nickel complex and by-products.

![Scheme 12](image)

Brown \textit{et al} \textsuperscript{5} have also synthesised 2. This was achieved in the gas phase by flash vacuum pyrolysis. 9-Ethynylcarbazole 39 was pyrolysed at 1050 °C (0.03 Torr) to produce 2 in 46% yield (Scheme 13). The 1,2-dihydro analogue 33 of 2 was also pyrolysed and gave 2 in 10% yield. Pyrolysis in this instance was carried out at 920 °C (0.01 Torr) (Scheme 13). Although both these reactions successfully produced 2, the first method involved rather harsh conditions and the latter produced a very low yield. Compound 2 in both cases was only produced in very small quantities.
McNab et al. have produced three synthetic methodologies for this molecule. Initial studies were prompted by the results of some studies on the gas phase reactions of dibenzo[b,j]azepines. 5- Allyl-5H-dibenzo[b,j]azepine 40 was pyrolysed at 950 °C (10 Torr), as a result, pyrrolo[3,2,1-jk]carbazole (Scheme 14) was produced in 46% preparative yield (0.5 g of precursor). 5H-Dibenzo[b,j]azepine 41 was also detected in the pyrolysate (Scheme 14). A mechanism for the formation of 2 was proposed and involved the homolytic cleavage of the N-allyl group to produce azapin-1-yl radical intermediate 42. Radical intermediate 42 then underwent a ring contraction to 43 followed by a ring opening reaction to form the phenyl radical intermediate 44, which then cyclised with loss of a hydrogen atom to yield 2. Dibenzo[b,j]azepine 41 was formed from 42 by hydrogen capture.

Scheme 14
The phenyl radical 44 was thought to be a key intermediate. In order to support this proposal an alternative method to generate this radical intermediate was used to show that cyclisation would produce pyrrolo[3,2,1-\textit{jk}]carbazole. This was achieved by synthesising allyl 2-(indol-1-yl)benzoate 45 and 1-(2-nitrophenyl)indole 46. These compounds were then pyrolysed to produce 2. The preparation of 45 and 46 was carried out as outlined for the carbazole analogues shown in Schemes 7 and 8. The allyl ester cyclisation produced 2 in 42% and the nitro cyclisation produced 2 in 33% yield. Precursors were formed in similar yield to their carbazole analogues. The yield of cyclisation is only moderate, however this reaction has not been optimised. It is likely that this method would provide a more general route to analogues of 2 due to ease of derivatisation using substituted indoles and benzenes. Substituted dibenzo[\textit{b,f}]azepines are not commercially available and no general synthetic method is available.

1.2.2 Properties of pyrrolo[3,2,1-\textit{jk}]carbazole.

1.2.2.1 Chemical properties.

Pyrrolo[3,2,1-\textit{jk}]carbazole 2 can be thought of as either a modified indole or a modified carbazole due to its unique structure. Therefore it is thought that this compound could react readily with electrophiles. The reaction of 2 with oxalyl chloride followed by quenching with methanol produced methyl 2-oxo-2-(pyrrolo[3,2,1-\textit{jk}]carbazole)acetate 47. Vilsmeier reaction of 2 produced 2-formylpyrrolo[3,2,1-\textit{jk}]carbazole 48. Halogenation with bromine and with iodine produced 2-bromo- and 2-iodopyrrolo[3,2,1-\textit{jk}]carbazole 49 and 50 respectively. A Suzuki coupling reaction was also successfully
carried out using 2-iodopyrrolo[3,2,1-\textit{j-}k\textit{]}carbazole 50 and phenylboronic acid to yield 2-phenylindolo[3,2,1-\textit{j-}k\textit{]}carbazole 51.

1.2.2.2 Physical properties.
As with indolo[3,2,1-\textit{j-}k\textit{]}carbazole 1, pyrrolo[3,2,1-\textit{j-}k\textit{]}carbazole 2 is a highly conjugated and strained heterocyclic system. It also forms a conducting thin film at a platinum working electrode surface when subjected to electro-oxidation.\(^1\) The film is also highly fluorescent in nature due to the high degree of conjugation. As with 1, no information is available about the nature of the film. The characterisation of the film is part of the study to be discussed in this thesis.

The \(^1\)H NMR spectrum has been reported and assigned for this compound by Hallberg\(^14\) and McNab (Figure 2).\(^6\)

![Figure 2. Proton NMR assignment for pyrrolo[3,2,1-\textit{j-}k\textit{]}carbazole.](image-url)
This compound is a highly strained system and has been identified as a substructure in N-doped fullerene analogues. A theoretical study has been done as part of research in to the possible synthesis of fullerene analogues of $\text{C}_60$.\textsuperscript{11,12}

1.3 Pyrrolo[3,2,1-hi]indole.

1.3.1 Introduction

As can be seen with the above literature review of indolo 1 and pyrrolo[3,2,1-jk]carbazole 2, very little is known about these fused cyclic hetero-aromatic systems. The parent structure from which both these systems derive is the pyrrolo[3,2,1-jk]indole moiety 52. The chemistry of this sub-unit will now be reviewed.

![52]

1.3.2 Synthesis.

The only full synthesis of pyrrolo[3,2,1-hi]indole was reported in 1969 by Paudler.\textsuperscript{17} The route involves the cyclisation of hydrazone 53 using boron trifluoride etherate to give indole derivative 54. This was then dehydrogenated to the fully aromatic system 55. Hydrolysis and subsequent decarboxylation was reported to have produced 52. The yields of the various steps are shown in Scheme 15.

![Scheme 15]
Very little is known of pyrrolo[3,2,1-hi]indole 52, as the above synthesis is the only one to be found in the literature. Analogous ring systems have been reported; Rapoport and Tretter\(^{18}\) (Scheme 16) have reported a route to 56, the 1,2-dihydro analogue of 52. This was carried out by the same type of cyclisation as Paudler carried out to prepare 54. The cyclisation of the hydrazone 53 was achieved using ethanol/10 volume % H\(_2\)SO\(_4\). The result of this synthesis was to produce hydroxyquinoline 57 as the major product with 54 as the minor product. The dihydro compound 56 was prepared by saponification of 54 to the acid followed by decarboxylation. No yields were reported by the authors.

\[\text{Et}_2\text{C}=\text{Me} \xrightarrow{\text{SO}_2\text{C}} \text{HO} \]

\[\text{N} \quad \text{Me} \]

\[\text{53} \quad \text{57} \quad \text{54} \]

1. Saponification
2. Decarboxylation

\[\text{56} \]

**Scheme 16**

Anet *et al*\(^{19}\) reported the synthesis of the 1,2,4,5-tetrahydro analogue of pyrrolo[3,2,1-hi]indole 58 and 1,2,4,5-tetramethylpyrrolo[3,2,1-hi]indole 59. The preparation of 58 was carried out by refluxing 2,6-(2-hydroxyethyl)aniline 60 with concentrated hydrobromic acid to give 61. Refluxing 61 with NaH in xylene produced the 1,2,4,5-tetrahydro analogue 58 (Scheme 17). The tetramethylpyrrolo[3,2,1-hi]indole 59 was prepared by reaction of 1-amino-2,3-dimethylindoline 62 with ethyl methyl ketone 63 to give the tetrahydro intermediate 64 followed by dehydrogenation to give 59 in 20% yield (Scheme 18).
The preparation of 1,5-diphenylpyrrolo[3,2,1-hi]indole 65 was reported by Bartsch et al. The synthesis of this compound was carried out by heating compound 66 in polyphosphoric acid at 100 °C (Scheme 19). The 1-phenyl-5-methyl derivative was also prepared by Bartsch and co-workers by a similar procedure.
1.3.3 Properties of pyrrolo[3,2,1-\textit{jk}]indole

1.3.3.1 Chemical properties.
The chemical properties of 52 have not been studied.

1.3.3.2 Physical properties.
Very little is also known about the physical properties of 52, however Paudler\textsuperscript{17} reported a $^1$H NMR spectrum of 52 the resonances were assigned by inspection (Figure 3). Paudler\textsuperscript{17} also reported a UV/vis absorption spectrum and observed a range of $\lambda_{\text{max}}$ between 250 and 320 nm.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{$^1$H NMR assignment of 52.}
\end{figure}

1.4 Aims of this study.
A main aim of this study is to investigate if the radical cyclisation methodology used for the preparation of 1 and 2 can be used to prepare heterocycles such as indoles and carbolines. Another aim is to carry out a study of the reaction mechanism of the cyclisation.

It is also a goal of this work to carry out further research into the synthesis of indolo[3,2,1-\textit{jk}]carbazoles 1 and pyrrolo[3,2,1-\textit{jk}]carbazoles 2. Our aim is to create an efficient synthesis of both 1 and 2 that can be utilised as a general method providing access to derivatives and analogues of such systems. As discussed previously, both 1 and 2 have been prepared within the McNab group by a gas phase radical cyclisation methodology. The aim of the first section of this thesis is to optimise the synthetic procedure developed by McNab and co-workers. The optimised procedure will also be used to prepare substituted derivatives of 1 and 2 and also to attempt to introduce other hetero-atoms into the ring system. Optimisation is currently required for this procedure.
as the cyclisation yields are only moderate and the products have only been prepared in small quantities.

The ultimate aim of this project is to study the electro-oxidation and fluorescence characteristics of 1 and 2 in more depth and attempt to characterise the products of electro-oxidation. The electrochemical and fluorescence studies carried out will be discussed in full in the second section of this thesis.
Chapter 2. Carbazole synthesis.

2.1 Introduction.

Carbazole synthesis is a vast area of study. Many different carbazole syntheses are known, these include the classic Graebe-Ullman cyclisation \(^{22}\) and the Fischer indole cyclisation.\(^{23}\) More recently metal mediated cyclisations have been the predominant methods of synthesis of carbazoles for use in the preparation of carbazole based natural products.\(^{24}\) The area of carbazole synthesis is too large to be able to do it justice in the form of a brief summary as presented here. This section is strictly limited to gas phase cyclisation strategies. The purpose of this section is to develop a new carbazole synthesis developed for the purpose of substituting indolo[3,2,1-jk]carbazole.

Diphenylether radicals 53 have been generated in the gas phase by McNab and co-workers.\(^{25}\) Once formed, they were found to undergo cyclisation to yield dibenzofurans 54 (Scheme 20). The radical generating group used was an allyl ester 55. Radical generation occurs through de-allylation and decarboxylation. Dibenzothiophenes 56 and fluorenes 57 have also been produced by this methodology. Carbazole was however not produced when the appropriate substituted diphenylamine 58 was subject to the same reaction conditions. Instead, acridone 59 was formed in preference to carbazole 3. Acridone formation was proposed to occur \textit{via} a ketene intermediate 60 (Scheme 21) and subsequent cyclisation. At present no gas phase radical cyclisation is known for the synthesis of carbazoles. It is thought that the use of the radical cyclisation strategy utilizing the nitro group as a radical generator may give the first known gas-phase radical cyclisation of carbazoles.

\[
\begin{align*}
\text{Scheme 20}
\end{align*}
\]
2.2 The nitro group as a radical precursor.

The aromatic nitro group has previously been demonstrated by de Mayo et al.\(^8\) to undergo homolysis to form the required phenyl radical intermediate. Scheme 22 shows the retro-synthesis of carbazole 3 to give a 2-anilinophenyl radical intermediate 61. The diphenylamine radical can be further be broken down into the respective o-fluoronitrobenzene 29 and aniline 62 starting materials which would be used for the preparation of potential carbazole precursors.
The forward synthesis (Scheme 22) consists of an SNAr type reaction of 2-nitrofluorobenzene with aniline to produce the 2-nitrodiphenylamine 63 which is then subjected to FVP in attempt to produce the carbazole derivative. A wide range of procedures is known for the SNAr synthesis of the precursors.\textsuperscript{26,27} The methods usually consist of heating the reagents in a dipolar aprotic solvent such as DMSO in the presence of a base, such as K\textsubscript{2}CO\textsubscript{3}, KF or KOBu\textsuperscript{t}.

\begin{center}
\begin{tikzpicture}
\node at (0,0) {$\text{F}$};
\node at (0.5,0) {$\text{NO}_2$};
\node at (1.5,0) {$\text{H}_2\text{N}$};
\node at (2.5,0) {$\text{H}_2\text{N}$};
\node at (3.5,0) {$\text{NO}_2$};
\node at (4.5,0) {$\text{H}$};
\node at (5.5,0) {$\text{H}$};
\node at (0,0.1) {29};
\node at (2.5,0.1) {62};
\node at (4.5,0.1) {63};
\node at (6.5,0.1) {3};
\draw[->] (0,0)--(0.5,0);
\draw[->] (0,0.1)--(0.5,0.1);
\draw[->] (0.5,0)--(1.5,0);
\draw[->] (1.5,0)--(2.5,0);
\draw[->] (2.5,0)--(3.5,0);
\draw[->] (3.5,0)--(4.5,0);
\draw[->] (4.5,0)--(5.5,0);
\draw[->] (5.5,0)--(6.5,0);
\node at (0,-0.3) {Base};
\node at (0,-0.6) {Sovent};
\node at (0,-0.9) {Heat};
\node at (2.5,-0.3) {Heat};
\node at (2.5,-0.6) {10\textsuperscript{-2} Torr};
\node at (2.5,-0.9) {N};
\node at (4.5,-0.3) {Heat};
\node at (4.5,-0.6) {10\textsuperscript{-2} Torr};
\end{tikzpicture}
\end{center}

Scheme 22

\subsection*{2.3 Fate of the nitro group.}
In the course of the following pyrolyses, there is the presence of a distinct blue colour at the liquid nitrogen level in the U-tube. This blue substance turns brown as it warms to room temperature. The blue colour is thought to be due to dinitrogen trioxide which is formally the anhydride of nitrous acid. The brown gas is thought to be NO\textsubscript{2} which can be derived from dinitrogen trioxide.\textsuperscript{28} No attempt has been made to trap and identify the gaseous by-products.

\subsection*{2.4 Flash vacuum pyrolysis.}
Flash vacuum pyrolysis (FVP) involves gaseous molecules being subjected to high temperatures for very short periods of time, usually 10\textsuperscript{-2} - 10\textsuperscript{-3} seconds. In principle, the substrate is distilled or sublimed through an electrically heated tube which is connected to a cold trap and vacuum line. Figure 4 illustrates the apparatus used in such experiments and is based on the design of W.D. Crow of the Australian National University.
The products are collected at the exit of the furnace tube in a trap surrounded by liquid nitrogen. A “U-shaped” trap is used for small-scale pyrolysis (50 mg). The entire pyrolysate is washed through with a suitable deuteriated solvent for NMR analysis by $^1$H and $^{13}$C NMR spectroscopy.

As it was stated in section 2.2 the nitro group is to be used as the radical generating group required to cyclise to carbazoles. The nitro group after homolysis produces highly reactive gases. It was shown by work carried out by L. Crawford that low yields were produced upon isolation of products. It was found that the reactive NO by-products were the cause of the low yields. It was found that by trapping the NO$_x$ gases separately from the product the yield was improved considerably.$^6$

Figure 5 shows modified FVP apparatus for the pyrolysis of nitro compounds on a preparative scale. The apparatus contains and additional new trap before the U-tube. The trap is cooled with dry-ice/acetone and is used to trap the product. The highly reactive nitrous by-products are collected in the second trap, the liquid nitrogen cooled U-tube.
2.5 Carbazole synthesis.

2.5.1 Precursor synthesis.

A series of substituted 2-nitrodiphenylamines was prepared by $S_N$Ar methodology as described in section 2.2 scheme 4. The compounds prepared are reported with their yields in Table 1. All entries in the table were prepared as stated above with the exception 13 which is commercially available, and 22 which was prepared by methylation of 13. Table 1 shows the conditions used for each preparation. The numbering scheme used for 2-nitrodiphenylamine 13 is shown below.
Table 1. Preparation of precursors for attempted carbazole synthesis.

The moderate yields reported in Table 1 are post purification by either recrystallisation or flash chromatography. It is thought that yields could be improved by optimising both reaction and workup conditions. The low yield observed for 70 is thought to be due to the ortho methyl group on the aniline causing steric hindrance to the reaction.

2.5.2 FVP of 2-substituted 2-nitrodiphenylamines.

Initially 2-nitrodiphenylamine 63 was subjected to FVP over a variety of furnace temperatures to assess if any reaction occurs and also to obtain the optimum reaction temperature. It was found that the optimum reaction temperature was 875 °C at 10^{-2} Torr. At this temperature no starting material was found to be left unreacted in the product. It was discovered, that upon the pyrolysis of 2-nitrodiphenylamine 63 that carbazole was formed in 55% preparative yield. However, it was also discovered that phenazine 73 was also produced in 13% preparative yield (Scheme 23). Following this result the other precursors were pyrolysed under the same conditions and the results presented in Table 2.
Small scale (50 mg) non-preparative FVP reactions were carried out in conjunction with preparative scale (0.5 g) pyrolyses for the purpose of the calculation of product ratios. The small scale reaction products were fully dissolved in an appropriate deuteriated solvent for the purpose of examining the ratio of products by $^1$H NMR spectroscopy by calculation of integral ratios. The formation of phenazine was also observed for all of the derivatives prepared by this method by $^1$H NMR spectroscopy. The mechanisms of carbazole and phenazine formation will be discussed in a later section in this chapter due the quantity of results obtained in elucidating these mechanisms. The results of the small scale pyrolyses are presented in Table 3. Numbering schemes for carbazole 3 and phenazine 73 are shown in scheme 23.

It has been shown that in all cases where the substituents are para and meta to the nitrogen (precursor position 4 and 3 respectively) that carbazoles are formed as the major product. The appropriately substituted phenazines are also produced as the by-products. In the case of precursor 69 where the methyl group is in the meta position it was found that two isomeric carbazoles were produced. The ratios of the products (2-methylcarbazole 84: 4-methylcarbazole 85) were calculated from the $^1$H NMR spectrum and were shown to be approximately 43:57 respectively.

When there is an ortho substituent present on the phenyl ring it was shown that carbazoles can be formed when the substituent is unreactive to the phenyl radical. However when a reactive substituent is present in the ortho position e.g. methyl functionality, reaction at the functionality occurs. In the case of a methyl group the
product formed is acridine 88. Acridine formation will be discussed in a later section. In the case of the pyrolysis of the N-methyl precursor 72 both carbazole and phenazine were formed indicating demethylation is occurring at some point in the process. Phenanthridine 93 is also found to be produced as a minor by-product.

<table>
<thead>
<tr>
<th>Precursor pyrolysed</th>
<th>Product(s) formed in order of quantity</th>
<th>Yield(s) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-OH 64</td>
<td>3-Hydroxycarbazole 74 and 2-hydroxyphenazine 75</td>
<td>33 and 20 a</td>
</tr>
<tr>
<td>4-Me 65</td>
<td>3-Methylcarbazole 76 and 2-methylphenazine 77</td>
<td>38 b</td>
</tr>
<tr>
<td>4-H a 63</td>
<td>Carbazole 3 and phenazine 73</td>
<td>56 and 13 a</td>
</tr>
<tr>
<td>4-Cl 66</td>
<td>3-Chlorocarbazole 78 and 2-chlorophenazine 79</td>
<td>39 b</td>
</tr>
<tr>
<td>4-CN 67</td>
<td>3-Cyanocarbazole 80 and 2-cyanophenazine 81</td>
<td>73 b</td>
</tr>
<tr>
<td>4-CF3 68</td>
<td>3-Trifluoromethylcarbazole 82 and 2-Trifluoromethylphenazine 83</td>
<td>65 b</td>
</tr>
<tr>
<td>3-Me 69</td>
<td>2 84 and 4-methylcarbazole 85 plus 2 86 and 3-methylphenazines 87</td>
<td>c</td>
</tr>
<tr>
<td>2-Me 70</td>
<td>Acridine 88, 1-methylcarbazole 89 and 1-methylphenazine 90</td>
<td>38 b,d</td>
</tr>
<tr>
<td>1-CN 71</td>
<td>1-Cyanocarbazole 91 and 1-Cyanophenazine 92</td>
<td>68 b</td>
</tr>
<tr>
<td>N-Me b 72</td>
<td>Carbazole 3, phenazine 63, phenanthridine 93 and trace N-methylcarbazole 94</td>
<td>23, 33, 11 a</td>
</tr>
</tbody>
</table>

Table 2 – Results of FVP of substituted 2-nitrodiphenylamines.
Notes.

a The yields presented are in the same order as the respective product in the adjacent column.

b By-products not isolated, characterisation carried out by 1H NMR spectroscopy.

c No products isolated, characterisation carried out by 1H NMR spectroscopy.

d FVP carried out at 975 °C.
In the table above it was found that acridine 88 was produced upon pyrolysis of 70. FVP at 875 °C produced a complex mixture of dihydroacridines 95 and acridine 88 as well as the carbazole 3 and phenazine 63 by-products. It was found that dihydroacridine formation was minimised at 975 °C due to dehydrogenation resulting in a much cleaner pyrolysate.

From the results presented in Table 3 it is clear that there appears to be an electronic effect occurring in the reaction. It is shown that when strong electron withdrawing groups are present, the carbazole product is favoured with only small quantities of phenazine being produced. The quantity of phenazine produced increases as the strength of the electron donating group increases.

<table>
<thead>
<tr>
<th>Substituted diphenylamine</th>
<th>Ratio of carbazole : Phenazine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carbazole</td>
</tr>
<tr>
<td>4-OH 64</td>
<td>60</td>
</tr>
<tr>
<td>4-Me 65</td>
<td>76</td>
</tr>
<tr>
<td>4-H 63</td>
<td>78</td>
</tr>
<tr>
<td>4-Cl 66</td>
<td>82</td>
</tr>
<tr>
<td>4-CN 67</td>
<td>88</td>
</tr>
<tr>
<td>4-CF 68</td>
<td>84</td>
</tr>
</tbody>
</table>

Table 3. Carbazole/phenazine ratio for para substituted 2-nitrodiphenylamines.
2.5.3 Phenanthridine formation.

It is proposed that the phenanthridine 93 produced upon pyrolysis of \( N \)-methyl-2-2-nitrophenylamine 63 is formed by the radical generated by homolysis of the nitro group abstracting a hydrogen from the \( N \)-methyl group (Scheme 24). The newly generated CH\(_2\) radical 96 can then attack the aromatic ring at the ipso position to the nitrogen. The spiro intermediate generated can then rearrange to give the phenanthridine minor product after aromatisation.

![Scheme 24](image)

2.5.4 Acridine.

2.5.4.1 Acridine synthesis.

Acridine 88 was found to be the major product upon pyrolysis of 70. The feature of this compound that allows this to occur is the ortho methyl group. The precursor 70 was pyrolysed under the conditions used for the formation of carbazole to yield a complex mixture of products. Previous work by McNab and co-workers\(^{29}\) on this type of cyclisation to give acridines required temperatures in excess of 900 °C. At lower temperatures dihydroacridines 95 were produced along with the acridine 88 product.
From analysis of the $^1$H NMR spectrum of the 875 °C pyrolysis, it was shown that there was both acridine and dihydroacridine in the mixture by comparison to literature spectra.$^{30}$

When pyrolysis was carried out at 975 °C, no dihydroacridines $^9_5$ was found to be present, however there was still found to be a mixture of products by $^1$H NMR spectroscopy. The major product recovered was acridine $^8_8$ in a 38% preparative yield after flash chromatography. The other products were shown to be 1-methylcarbazole $^8_9$ and 1-methylphenazine $^9_0$ (Scheme 25) by comparison of the $^1$H NMR spectrum of the crude pyrolysate with literature.$^{31,32}$ The side products were not isolated due to loss upon workup by flash chromatography. Product ratios were obtained from the $^1$H NMR spectrum of the crude small scale pyrolysate and the ratio of the products were found to be 65:25:8 for acridine $^8_8$, 1-methylcarbazole $^8_9$ and 1-methylphenazine $^9_0$ respectively. The low preparative yield was due to decomposition of starting material in the inlet tube upon heating.

![Scheme 25](image)

A sample of 2, 6-dimethyl-2'-nitrodiphenylamine $^9_7$ was available.$^{33}$ It was thought that because both ortho sites on the aromatic ring adjacent to the one which hosts the radical intermediate were occupied by methyl groups, the acridine product may be the sole product due to the other potentially reactive sites being blocked to direct cyclisation. The result of pyrolysis at 975 °C gave 1-methylacridine $^9_8$ in 33% preparative yield and 1-
methylphenazine 99 in 7% preparative (Scheme 26) in 77:23 ratio by $^1$H NMR spectroscopy.

Scheme 26

2.5.4.2 Mechanism of cyclisation.

It was thought that the mechanism of cyclisation of acridine was via an initial radical generation followed by a hydrogen abstraction from the ortho methyl group. The CH$_2$ radical species was then thought to either attack the adjacent aromatic ring at the ipso position to form a spiro intermediate or directly attack the ortho position. Scheme 27 shows the mechanism for the FVP of N-(4-methyl-2-nitrophenyl)-o-toluidine 100. Direct attack gives 3-methylacridine 101. The spiro intermediate formed 102 can rearrange to give a radical intermediate 103 which would then cyclise to 2-methylacridine 104. This hypothesis was put to test by preparing 100 and pyrolysing it at 975 °C. If the radical mechanism was occurring, pyrolysis of N-(4-methyl-2-nitrophenyl)-o-toluidine 100 should produce two differing products (101 and 104).
There is literature precedent for this type of mechanism. In the early 1990s McNab and co-workers carried out a study of the gas-phase cyclisation reactions of 2-benzylphenylaminyl radicals 105. It was shown that when these radicals were generated they can undergo a rearrangement to give a spiro intermediate 106. Further rearrangement gives the alkyl radical 107. Both radicals can cyclise to give isomeric acridines 101 and 104 (Scheme 28). High temperatures were also required in this case so that dihydroacridine formation was minimised due to dehydrogenation to the acridine.

In the case of McNab and co-workers' results, entry into the aminyl and alkyl radical was only achieved by initial formation of the aminyl radical by pyrolysis of the N-allyl precursor. If this was the type of mechanism occurring in the formation of acridines using the nitro precursors then a similar product ratio should be obtained. The formation of the spiro intermediate in this case would be due to formation of the alkyl radical by radical translocation. Standard routes to benzyl radicals could not be used to generate 107.
Scheme 28

\[ \text{Scheme 28} \]

\[ \text{Scheme 28} \]

\[ N-(4\text{-Methyl-2-nitrophenyl})-o\text{-toluidine 100 was prepared from 4-chloro-3-nitrotoluene 108 and } o\text{-toluidine 109 in a 14\% yield by Ullman condensation (Scheme 29). Pyrolysis at } 975 \text{ °C produced a } ^1\text{H spectrum of the acridines 101 and 104 that varied in chemical shifts slightly to that reported in the literature.}^{34} \text{ This could be a result of the well known NMR concentration effect that can occur in solutions of small flat heterocycles which can easily } \pi\text{-stack.}^{35} \text{ The pyrolysis was repeated at } 875 \text{ °C to yield two differing dihydroacridine products identified as 2-methylidihydroacridine 110 and 3-methylidihydroacridine 111 by comparison with literature } ^{13}\text{C NMR spectra.}^{30} \text{ The corresponding acridines 101 and 104 were also found to be present in the pyrolysate and are formed by the dehydrogenation of the dihydro precursors. The ratio of the two dihydroacridine products was 42:58 by } ^{13}\text{C NMR spectroscopy. This result supports the proposed hydrogen abstraction mechanism and rearrangement } \text{via spiro 102 intermediate proposed in Scheme 27.} \]
2.6 Scope and limitations of carbazole synthesis.

A novel gas phase cyclisation of an ortho diphenylamine radical to carbazoles which uses the nitro group as a radical generating species has been discovered. The use of the nitro group removes the problems that were found to occur when ester leaving groups were used. It is clear from the above discussion that the carbazole synthesis developed is an efficient method for the preparation of carbazoles substituted with electron withdrawing groups that are para to the nitrogen. Cyclisation occurs in high conversion with only minor phenazine by-product. However, the presence of electron donating groups complicates the reaction through more formation of phenazine by a competing reaction pathway.

Care must also be taken when placing substituents into the system, substituents should be para to the nitrogen in order to avoid complications. Placing substituents that are reactive to the o-radical in the ortho position can cause complications by allowing other reaction pathways to occur, such as acridine formation. As a synthetic route, the production of acridines is limited by the moderate yield and mixtures of products that were produced. It is possible to have a substituent in the ortho position if it is stable to the radical generated. The cyano group has been shown to be suitable, producing only 1-cyanocarbazole and small amounts of the phenazine by-product.
Having a substituent in the meta position can lead to the formation of isomeric carbazoles due to there being two reactive sites for cyclisation to occur. This was shown in practice by preparing and pyrolysing N-(2-nitrophenyl)-m-toluidine 69. The result was the production of both 2- and 4-methylcarbazoles 84 and 85 respectively in approximately 45:55 ratios.

2.7 Studies on mechanism of phenazine formation.

2.7.1 Proposed mechanism.

Phenazine 73 was found to be a side product in the formation of carbazole from 2-nitrodiphenylamine 63. Substituted phenazines were also formed from substituted 2-nitrodiphenylamines. It is clear that in the case of phenazine formation the nitrogen atom of the nitro group must be retained so that the phenazine can be formed. It is thought that the mechanism of formation must be an electrocyclisation process. The mechanism proposed (Scheme 30) involves a [1,5]-sigmatropic H-shift from the secondary amine to the nitro group to give 112. The intermediate 112 that is formed cyclises to intermediate 113 which then undergoes a loss of an oxygen atom and water to yield phenazine 73.

Scheme 30
The stage at which the oxygen atom is lost is currently unknown. It was thought that phenazine N-oxide 114 may be formed from intermediate 113 and deoxygenated under the thermal conditions. Phenazine N-oxide 114 was therefore prepared from phenazine 73 by heating with hydrogen peroxide to give the dioxide 115. The dioxide 115 was refluxed in toluene to give the mono-N-oxide 114 in quantitative yield (Scheme 31). The N-oxide was pyrolysed at a variety of temperatures (Figure 6) to show that de-oxygenation does occur. However, de-oxygenation is far from complete at 875 °C and incomplete even at higher temperatures. This result could imply that the oxygen may be lost at an earlier stage than the water as no evidence of N-oxide formation was shown in any of the 2-nitrodiphenylamine pyrolysies by \(^1\text{H}\) NMR spectroscopy.

![Scheme 31](image-url)
2.7.2 Control of carbazole mechanism pathway.

The results in Table 3 of section 2.5.2 were analysed by plotting the ratio of substituted product/parent product against Hammett values. If the formation of carbazole goes via direct cyclisation, then the reactive site is meta to the substituent. The ratio was plotted against the appropriate Hammett $\sigma_m$ values, however there was no correlation. As there appeared to be no correlation of the substituent effect on the carbazole formation, it was thought that there may be a Hammett correlation for the formation of the phenazine by-product.

The mechanism proposed in Scheme 30 shows cyclisation through intermediate 112 after an initial proton abstraction. Closer inspection of this intermediate shows that the presence of an electron donating group para to the nitrogen can have a stabilising effect.
on intermediate through resonance (Scheme 32). This stabilising effect is not possible when electron withdrawing groups are present.

Scheme 32

The substituent on the phenazine is para to the imine nitrogen. A Hammett plot was produced for the ratios of phenazine formation against the appropriate $\sigma^+$ value (Figure 7). The plot clearly shows a good linear relationship indicating a Hammett correlation for this experimental observation. The slope is negative; this is an indication of an electronic effect in which conjugative electron donation accelerates the rate of the reaction, thus supporting the resonance stabilisation in Scheme 32.

The extra resonance stabilisation effect of the electron donating group can allow the preceding proton abstraction to occur more favourably than when an electron withdrawing group is present. In the case of electron withdrawing groups, the default mechanism is direct cyclisation to the carbazole product via loss of the nitro group.
2.8 Carbazole mechanism of cyclisation.

2.8.1 Introduction.

The nitro group is thought to be lost by homolytic cleavage to give the aromatic $\sigma$-radical. The radical generated can cyclise by variety of possible mechanisms. The mechanisms are: 1. the radical cyclise directly with the adjacent aromatic ring to give a carbazole product or it can translocate to the adjacent ring and then undergo direct cyclisation (Scheme 33). 2. the radical generated can abstract a hydrogen from the amine nitrogen to give diphenylamino radical 116 and cyclise through the aromatic ring (Scheme 34). 3. the nitro group and the amine hydrogen could be lost as HNO$_2$ to give a carbene intermediate which can then insert into an aromatic CH bond of the adjacent ring (Scheme 35).

Figure 7. Hammett plot of phenazine formation.
The direct cyclisation/phenyl radical translocation mechanism method of cyclisation has been observed in similar cyclisations. \textsuperscript{25} Dibenzofurans \textsuperscript{57} and dibenzothiophenes \textsuperscript{58} have been prepared by a radical cyclisation as above using allyl esters as the radical generating group to give diphenyl ether radical intermediates. Scheme 36 shows the result of a methyl labelling experiment in the dibenzofurans carried out by McNab \textit{et al.} \textsuperscript{25} After initial radical generation \textsuperscript{117} it was shown that products \textsuperscript{118} and \textsuperscript{119} were produced. This result indicated that the mechanism was a radical mechanism.

However, it was incorrectly explained by McNab \textit{et al} \textsuperscript{25} that the radical generated \textsuperscript{117} (Scheme 36) abstracted a hydrogen from the opposite aromatic ring to give the isomeric radical \textsuperscript{72} and both of these were under complete equilibrium to give \textsuperscript{118} and \textsuperscript{119} in a statistical ratio of 75:25 respectively. It was explained that radical species \textsuperscript{117} can cyclise to either of the two identical \textit{ortho} sites of the adjacent phenyl ring to give only \textsuperscript{118} as the product. Radical species \textsuperscript{120} can cyclise at two different \textit{ortho} sites on the adjacent phenyl ring to give products \textsuperscript{118} and \textsuperscript{119}. The statistical ratio of the products of the reaction if radical species were in complete equilibrium would be 75:25 (84:85 respectively).

What the explanation failed to take into consideration was the possibility of radical translocation to give \textsuperscript{121}. If radical species \textsuperscript{117}, \textsuperscript{120} and \textsuperscript{121} were in complete equilibrium then the statistical ratio would be 50:50. The result of the original experiment would indicate that the diphenylether radical equilibrium is not complete and that there is a kinetic factor that controls the cyclisation. It is thought possible that the mechanism of carbazole cyclisation from nitro group precursors is similar to that observed for the dibenzofurans.

\begin{center}
\begin{tikzpicture}
\node[anchor=center] at (0,0) {\textbf{56}};
\node[anchor=center] at (1,0) {\textbf{57}};
\end{tikzpicture}
\end{center}
In order to elucidate the mechanism of cyclisation that is occurring during the pyrolysis of the 2-nitrodiphenylamines a few simple experiments were devised. The first of these is a methyl labelling experiment similar to that carried out McNab and co-workers for the dibenzofuran series (Scheme 36). If a radical translocation mechanism was to take place, two possible carbazole products could be formed. The compound prepared for pyrolysis was 5-methyl-2-nitrodiphenylamine 122. Once the nitro group is lost, a hydrogen abstraction can occur, transferring the radical to the adjacent aromatic ring, therefore giving two different possible sites of cyclisation. This would be the case only for a radical mechanism. The second experiment is a deuterium exchange of the exchangeable hydrogen. Pyrolysis of deuterium exchanged 2-nitrodiphenylamine should have some $^2$D incorporated into the aromatic structure if the N-centred radical process (Scheme 34) took place. This process will be studied using $^2$H NMR spectroscopy. The third experiment is the deliberate generation of diphenylamino radical 116 to find if cyclisation to carbazole occurs.
2.8.2 Methyl labelling.

The precursor, 5-methyl-2-nitrodiphenylamine 74 was synthesised as before by standard methods (Scheme 37). It is observed that upon FVP at 875 °C/10² Torr, 2-methylcarbazole 84 and 4-methylcarbazole 85 are formed respectively in 57:43 ratios (Scheme 37). This result supports the proposed radical formation, however, the ratio of the products is different to that found in the dibenzofuran series. The result shows that in the case of the 2-nitrodiphenylamine series that the equilibrium of the radical species is different. The result however, does not confirm a mechanism as detailed in Scheme 33 as the amine H-atom abstraction mechanism (Scheme 34) can still occur and would also account for the methyl scrambling (Scheme 38). What the result confirms is that the mechanism is a radical mechanism as the only other mechanism that is proposed is the carbene mechanism in Scheme 35. The carbene mechanism cannot explain the formation of the two isomeric methylcarbazoles 84 and 85 as the carbene that would be formed 123 could only cyclise to give one product (2-methylcarbazole 84). The carbene mechanism is therefore ruled out.

Pyrolysis of 69 and 122 both give the same the same two products (84 and 85). However the ratio of the two products is exactly complementary. Substrate 69 gives products 84 and 85 in 43:57 ratios by ¹H NMR spectroscopy. Substrate 69 gives 84 and 85 in 57:43 ratios by ¹H NMR spectroscopy. The radical generated by pyrolysis of 69 and 122 are common to the same equilibrium as can be seen in the radical equilibrium shown in Scheme 37. The fact that the ratios of the products are different shows that the species, like the benzofuran case are not in complete equilibrium. There is a kinetic factor occurring in the cyclisation that influences when the cyclisation occurs and prevents full equilibrium being achieved.
Scheme 37
2.8.3 Deuterium exchange.

Deuterium exchange studies were carried out in order to probe the reaction mechanism further. If a deuterium exchange with the NH of 2-nitrodiphenylamine was carried out and then reacted under FVP conditions as described previously and the mechanism shown in Scheme 33 is the mechanism of cyclisation, the deuterium would remain on the nitrogen. If the N-centred radical mechanism predominates, the deuterium would be incorporated into the aromatic ring 124 if radical attack occurred at the ortho proton site (Scheme 39). It should be noted that attack at the other site will result in both loss of deuterium or transfer back to the nitrogen, though either of these should be disadvantaged by the kinetic isotope effect.
Scheme 39

A deuterium exchange and subsequent pyrolysis was carried out on diphenylamine 125 and carbazole 3 at first. These control reactions were carried out to assure no other process occurs upon pyrolysis such as [1,5]-sigmatropic shifts of the deuterium atom to aromatic positions without radical generation/transfer. Deuterium exchange was carried out by dissolving the substrate in CH$_3$OD with heating within the inlet tube of the FVP system (Scheme 40). After removal of solvent under vacuum, the substrate was subject to FVP immediately.

The analysis of the deuteriated diphenylamine pyrolysate by $^2$D NMR spectroscopy at 55 MHz (Figure 8) and comparison with the $^1$H NMR spectrum of diphenylamine (Figure 9) showed that the deuterium remained on the nitrogen atom. In the case of the deuteriated carbazole, comparison of the $^2$H NMR (Figure 10) with the $^1$H NMR spectrum of carbazole (Figure 11) shows that the deuterium remains predominantly on the nitrogen.
Close inspection of the carbazole $^2$H spectrum, shows that traces of the label have transferred into all the aromatic sites, however in comparison with the quantity that remains on the nitrogen the amount that rearranges is insignificant. All $^1$H NMR spectra were recorded in acetone-$d_6$ and $^2$H NMR spectra were recorded in acetone.

![Scheme 40](image)

Figure 8. 55 MHz $^2$D NMR spectrum of deuteriated diphenylamine after FVP.
Figure 9. 360 MHz $^1$H NMR spectrum of diphenylamine.

Figure 10. 55 MHz $^2$D NMR spectrum of deuteriated carbazole after FVP.

Figure 11. 360 MHz $^1$H NMR spectrum of carbazole.
The deuterium exchange was repeated with 2-nitrodiphenylamine and the N-deuteriated substrate subjected to the FVP conditions used for the synthesis of carbazole as described in the previous chapter. The pyrolysate was analysed directly by $^2\text{H}$ NMR spectroscopy (Fig 12) and compared with the $^1\text{H}$ NMR spectrum of carbazole (Fig 11). Comparison of the two spectra clearly shows deuterium incorporation in the aromatic ring at 7.54 ppm. This is the 1-position 126 of the carbazole. This result would indicate that the N-centred radical mechanism outlined in Scheme 39 is a process that is occurring during the FVP of 2-nitrodiphenylamine 63. It can also be observed that there is still some deuterium present on the nitrogen atom. This indicates that the deuterium has either not been abstracted or that it has been transferred back to the nitrogen atom as shown in Scheme 39.

![Figure 12. 55 MHz NMR spectrum of deuteriated 2-nitrodiphenylamine pyrolysate.](image)

2.8.4 N-radical generation.

In the consideration of the N-centred radical mechanism discussed above, the deliberate generation of diphenylamino radical was carried out under the gas phase cyclisation conditions. This was carried out by pyrolysis of N-allyl, benzyl and amino diphenylamines. The N-allyl 127 and benzyl derivatives 128 were prepared from diphenylamine 129 and allyl bromide or benzyl bromide respectively (Scheme 41). N-aminodiphenylamine 130 is commercially available as the hydrochloride salt. The free base was liberated by washing an ether solution of the salt with base.
1. NaH
2. Allyl or benzyl bromide

Scheme 41

\[ \text{N-Allyldiphenylamine 127 was pyrolysed over a range of temperatures and the ratio of the products was calculated from the } ^{1}H \text{ NMR spectrum integrals (Figure 13). The results show that carbazole is produced along with diphenylamine. Hence the } N \text{-radical can undergo cyclisation through radical delocalisation through the aromatic ring system. It can be noted that at } 875 \, ^\circ C \text{ only } 35\% \text{ carbazole is produced by } ^{1}H \text{ NMR ratio. The remaining } 65\% \text{ of the reaction mixture is diphenylamine which will have been produced by hydrogen capture (Scheme 42). The quantity of carbazole is shown to increase with temperature. This will be due to the radical being given more energy by the higher temperature which induces the cyclisation.} \]

Scheme 42
Figure 13. *N*-Allyldiphenylamine pyrolysis temperature profile.

Hydrogen capture is highly dependent upon reaction conditions such as the hydrogen flux thorough the furnace. The hydrogen flux is controlled by the pressure at which the reaction is occurring. Higher pressure would clearly lead to conditions at which hydrogen capture may be increased due to a larger proportion of molecules coming into contact. The optimum conditions of 975 °C were used for the preparative scale pyrolysis. The problem of hydrogen capture was increased when the reaction was scaled up to preparative scale and only 23% carbazole was recovered the remainder (75%) was diphenylamine. This problem was reduced when the pressure was lowered to $10^{-5}$ Torr using a diffusion pump rather than $10^{-2}$ Torr and a 42% preparative yield of carbazole was produced. The allyl leaving group was thought to add to the problems of the hydrogen flux due to liberation of hydrogen (Scheme 43) to give allene 131.
The use of a benzyl leaving group improved the scale yield of carbazole so that it was possible to recover a 55% preparative yield at 975 °C/10^2 Torr. The ratio of carbazole to diphenylamine by \(^1H\) NMR spectroscopy after pyrolysis at 875 °C was only marginally improved by using the benzyl leaving group at the small scale, the main effect of using the alternative leaving group is witnessed upon scale up to preparative scale. The improvement in the preparative yield was thought to be due to lower hydrogen flux when the benzyl group is used over the allyl leaving group due to the fact that the benzyl group cannot liberate hydrogen in the same way as the allyl group (Scheme 43). The pyrolysis of \(N\)-aminodiphenylamine 130 gave a similar result to that of the \(N\)-benzyl pyrolysis.

![Scheme 43](image)

The resulting formation of carbazole demonstrates the ability of the aminyl radical to undergo cyclisation as shown in Scheme 42. The lack of complete conversion to product may not be taken to mean that the \(N\)-centred radical mechanism is merely a side mechanism. The reaction conditions of the \(N\)-allyl/benzyl vary significantly between the \(N\)-substituted diphenylamine pyrolyses and the 2-nitrodiphenylamine process. In the case of the \(N\)-substituted diphenylamines there is clearly a greater potential for hydrogen capture due to the greater quantity of hydrogen atoms available in the reaction than compared with the 2-nitrodiphenylamine case. It has been clearly demonstrated that hydrogen capture is a process that occurs during the pyrolysis of \(N\)-substituted diphenylamines.

3.1.6 Discussion of results.
The direct cyclisation/aromatic hydrogen abstraction mechanism for carbazole is supported by the methyl scrambling shown in Scheme 37 as two differing carbazole products are formed. The formation of these products can however also be explained by the mechanism shown in Scheme 38 which shows translocation of the radical to the
nitrogen atom. Cyclisation can occur through both aromatic rings to yield the same methyl scrambled products as in Scheme 37.

Deuterium exchange of the amine NH followed by subsequent pyrolysis of 2-nitrodiphenylamine shows deuterium incorporation into the aromatic ring in the carbazole product at the position adjacent to the NH position. This mechanistic feature can only be explained by the aminyl mechanism shown in Scheme 42 where the NH hydrogen is abstracted. However, when the aminyl radical was generated by an authentic strategy only about 40% of the product mixture was carbazole, leaving 60% of hydrogen captured diphenylamine. There was no presence of diphenylamine in the crude pyrolysate of 2-nitrodiphenylamine.

The results of the methyl labelling and the deuterium exchange support the formation of the radical and subsequent cyclisation. The $N$-radical generation results demonstrate that the $N$-radical can undergo cyclisation. The lack of full conversion of the $N$-radical to product can be taken to mean that the $N$-centred radical is a process that is occurring during the reaction. Taking into account the lack of diphenylamine in the crude pyrolysate of 2-nitrodiphenylamine it can be assumed that however the $N$-centred radical mechanism is only a minor mechanism. The main mechanism can be taken to be the phenyl radical abstraction and cyclisation.

In comparison with the cyclisation of the 2-phenoxyphenyl radical (Scheme 36), the 2-phenoxyphenyl radical cyclisation is much simpler. A methyl labelling experiment in the carbazole case demonstrated that a mechanism similar to that shown in Scheme 36 was occurring. However in the 2-phenoxyphenyl radical case there is no hydrogen to abstract from the bridging heteroatom. It is shown in the studies on the diphenylamine radicals that the reaction mechanism is more complex, but still arrives at the analogous cyclised products.
In the diphenylether radical case, the ratio of the two methyl labelled products was 75:25. In the case of the diphenylamine radical the ratio is comparable to the diphenylether at 60:40. The slight deviation could be due to a number of factors, such as the bond length and angle differences between the two due to the carbon-nitrogen bond-length being different to that of carbon-oxygen bond length. There has also been shown to be two differing mechanisms of cyclisation occurring during the pyrolysis reaction, this may be having an effect on the ratio of the products.
Chapter 3. Carboline synthesis.

3.1 Introduction.

3.1.1 Preamble.
Carbolines were thought to be a suitable target for synthesis using the gas phase cyclisation developed in the previous section. Carbolines are carbazoles in which one or both of the benzene rings are replaced by pyridine type rings. The presence of the ring nitrogen has the same effect as an electron withdrawing group on a benzene ring in the respect that it makes the ring electron deficient. It is due to this feature that carbolines were thought of as an attractive target. Carboline compounds could in the long term be used in the synthesis of novel aza analogues of indolo[3,2,1-jk]carbazoles and pyrrolo[3,2,1-jk]carbazoles.

3.1.2 Literature synthesis of carbolines.
Because the synthesis of the parent carboline ring system is not as widely studied as that of carbazoles, a brief review of the current literature syntheses of carbolines is relevant here. The review is not comprehensive, only the most efficient of the current methods to prepare the carbolines are included. The targets selected for carboline synthesis were α-carboline 132 γ-carboline 133 γ, γ'-carboline 134 and α, δ-carboline 135.

3.1.2.1 α-Carboline.
Few α-carboline 132 syntheses are known in the literature. The majority of the early studies on the synthesis of 132 are concerned with photolysis or thermolysis chemistry. α-Carboline 132 has been prepared by the photolysis of 2-anilinopyridine 136 (Scheme 44) in 80% yield via an oxidative cyclisation mechanism. The main drawback with this procedure is that it requires to be done in very dilute solutions (100 mg per 300 cm³ solvent). This potentially limits scale up possibilities.
A study of the photolysis and thermolysis of N-(2-pyridyl)benzotriazole 137 has been undertaken. Polyphosphoric acid (PPA) or zinc chloride has been used to prepare α-carboline 132 by acid catalysis in 70% yield (Scheme 45) by Graebe-Ullmann type cyclisation. The main drawback of this reaction is the fierce reaction conditions which may be problematical with some functionality. In contrast photolysis of 137 (Scheme 46) resulted in the formation of the fused benzimidazole 138 in 70% yield with only 5-10% of the carboline. It is suggested that in this case the benzotriazole loses nitrogen to form a carbene that then reacts with the lone pair of electrons on the nitrogen to give the fused benzimidazole.
A Graebe-Ullmann type synthesis has been carried out by Warburton and co-workers \(^{40}\) (Scheme 47). \(N\)-\(o\)-Anilino-2-pyridylamine 139 was treated with sodium nitrite and polyphosphoric acid to yield the carboline. The reaction was shown only to proceed under forcing conditions to give a moderate cyclisation yield (35%).

![Scheme 47](image-url)

Further studies on the photolysis of benzotriazoles produced \(\alpha\)-carboline 132 synthesis.\(^{41}\) \(N\)-Phenyl-7-azabenzotriazole 140 was irradiated to give 132 in 61% yield (Scheme 48). In comparison with the previous benzotriazole photolysis (Scheme 46) the carbene generated is on the same ring as the nitrogen and can only insert into an aromatic CH bond on the adjacent phenyl ring. As with the previous photolysis reaction, the preparation was only carried out under very dilute conditions.

![Scheme 48](image-url)

The Fischer indole synthesis has been applied to the preparation of \(\alpha\)-carboline 1 (Scheme 49).\(^{42}\) The hydrazone 141 was first prepared and treated with polyphosphoric acid to give the tetrahydrocarboline 142 which was then dehydrogenated to give \(\alpha\)-carboline 132 in 53% yield.
The most recent method is the palladium catalysed coupling strategy devised by Sakamoto and co-workers\textsuperscript{43} which was based on Buchwald methodology. Firstly, 2-anilino-3-bromopyridine 143 was prepared by Buchwald-Hartwig amination (Scheme 50). Palladium catalysed cross coupling using palladium acetate resulted in the formation of α-carboline 132 in only moderate yield (31\%) after 67 h reaction time.

3.1.2.2 γ-Carboline.
Very little work has been reported on the synthesis of the parent heterocycle, γ-carboline 133. One of the methods that has been reported is the palladium catalysed coupling strategy reported by Sakamoto and co-workers\textsuperscript{43} which was based on Buchwald methodology\textsuperscript{44} that was used to prepare α-carboline 132. As in Scheme 50, a Buchwald-
Hartwig amination was carried followed by subsequent palladium catalysed cyclisation to give γ-carboline 133 in 47% yield after an extensive period of heating (Scheme 51).

\[
\text{Pd}_2(\text{dba})_3 \quad \text{dppf} \\
\text{NaOBut} \\
\text{PhMe} \\
\text{Pd(OAc)}_2 \\
\text{NaOAc} \\
\text{DMF}
\]

Scheme 51

The oxidative photolysis shown in Scheme 44 was utilised by the same authors to prepare γ-carboline from 4-anilinopyridine (Scheme 52).\(^{38}\) The photolysis yielded 70% γ-carboline 133. However, this preparation suffered from the same restrictions as the α-carboline 132 case, the reaction was carried out under very dilute conditions.

\[
\text{hv} \\
\text{N\textsuperscript{\textprime}O} \\
\text{N} \\
\text{N} \\
\text{N} \\
\text{N} \\
\text{N}
\]

Scheme 52

The only other preparation of γ-carboline 135 to be considered was carried out in the gas phase by FVP.\(^{45}\) The precursor \(N\)-(2-nitro-4-pyridyl)benzotriazole 144 (Scheme 53) was subjected to a mass spectrometry study of the species formed upon treatment by FVP. The FVP apparatus was connected directly to an electron impact mass spectrometer. The result of the pyrolysis was a mixture of γ-carboline 135, 1-hydroxy-γ-carboline 145 and 1-nitro-γ-carboline 146. Yields were not reported for any of the species formed.
3.1.2.3 γ, γ'-Carboline.

One of the main methods of the synthesis of 134 is the Graebe-Ullmann cyclisation of azabenzotriazole 147 (Scheme 54).\textsuperscript{46} γ, γ'-Carboline 134 was isolated in 23% yield along with 4-(4-pyridylamino)-3-hydroxypyridine 148 in 38% yield.

The other main method involves the ZnCl\(_2\) mediated condensation of 4,4'-diamino-3,3'-bipyridine 149 (Scheme 55) to give dicarboline 134.\textsuperscript{47} Bipyridine 149 was prepared from the Ullmann reaction of 3-bromo-4-nitropyridine \textit{N}-oxide 150. Compound 151 was then reduced to give 149 (Scheme 55).
3.1.2.4 \(\alpha,\delta\)-Carboline.

\(\alpha,\delta\)-Carboline 135 has been prepared by Parrick and co-workers \(^4\) in the literature by a thermal cyclisation of pyrazinylhydrazones (\textit{i.e.} a Fischer indole synthesis without an acid catalyst) followed by dehydrogenation (Scheme 56). \(^4\) The product carboline was obtained in 40\% yield.

\(\alpha,\delta\)-Carboline 135 has also been prepared by the reaction of 2-piperidinoindol-3-one 152 with ethylenediamine (Scheme 57). \(^4\) 2-Piperidinoindol-3-one 152 was prepared by the catalytic oxidation of indole 153 in the presence of CuCl, 3 Å sieves and piperidine (Scheme 57).
3.1.2.5 Summary.

In general, with a few exceptions, the literature methods for the majority of the carbolines which were reviewed involves either reaction conditions that are extremely forcing or produce only moderate yields. Photolysis reaction conditions usually require very dilute conditions that would make scale up difficult to obtain sufficient quantity for further reaction in multi-step syntheses. Some of the syntheses to date already use multi-step strategies. It is hoped that the two-step strategy developed for carbazoles will produce a useful and efficient gas-phase alternative.

3.2 Carboline synthesis.

3.2.1 Precursors.

The initial targets for carboline synthesis were α-carboline 132, γ-carboline 133, γ, γ′-carboline 134 and α, δ-carboline 135. The precursors for 132, 133 and 135 (154, 155 and 156 respectively) were formed by standard SNAr reaction (Scheme 58). Precursors 154 and 155 were prepared from 2-chloro-3-nitropyridine 157 and 4-chloro-3-nitropyridine 158 with aniline 159 in good yield. Precursor 156 was prepared from chloropyrazine 161 and o-nitroaniline 160 (Scheme 58). 4-Chloro-3-nitropyridine 158 was prepared from 4-hydroxy-3-nitropyridine 162 by a literature procedure using phosphoryl chloride.⁵⁰ (Scheme 59).

\[
\begin{align*}
\text{NO}_2 & + \text{Cl} \quad \text{H}_2\text{N} \quad \text{K}_2\text{CO}_3 \quad 140^\circ\text{C} \quad \text{NO}_2 \\
\text{Cl} & \quad \text{H}_2\text{N} \quad \text{K}_2\text{CO}_3 \quad 140^\circ\text{C} \quad \text{NO}_2 \\
\text{NO}_2 & + \text{NH}_2 \quad \text{Cl} \quad \text{KOBu}^+ \quad \text{DMSO} \quad 125^\circ\text{C} \quad \text{NO}_2
\end{align*}
\]
Scheme 59

The precursor for γ, γ′-carboline 134 was prepared by using different methodology. The method employed is that of Koenigs\textsuperscript{51} and involves the reaction of pyridine 163 with 4-pyridylamine 164 in the presence of PCl\textsubscript{3}. The resulting 4,4′-dipyridylamine 165 was nitrated to yield the γ, γ′-carboline precursor 166 (Scheme 60).\textsuperscript{51}

\[ \text{Scheme 60} \]

3.2.2 Cyclisation of carboline precursors.

The carboline precursors 154, 155, 156 and 166 were subjected to the FVP gas phase cyclisation conditions (875 °C/10\textsuperscript{-2} Torr) used for the preparation of the carbazole analogues (Scheme 61). The results of the pyrolysis of the precursors show that loss of the nitro group and subsequent cyclisation has occurred for all the precursors. α-Carboline 132, γ-carboline 133 and γ, γ′-carboline 134 were all successfully made in good yield by pyrolysis of their respective precursors (154, 155 and 166 respectively) in good yield. In the case of the pyrolysis of 154, benz[4,5]imidazo[1,2-α]pyridine 138 was produced as a minor by-product. The ratio of the α-carboline 132 and benz[4,5]imidazo[1,2-α]pyridine 138 was 85:15, favouring the carboline. Preparative yields after chromatography are shown in Scheme 61.
However, when precursor 156 was pyrolysed, α, δ-carboline 135 was not the major product, but instead pyrido[3,4-b]benzimidazole 167 was found to be the major product (Scheme 62). α, δ-Carboline 135 was present as a minor product. The ratio of the two products 167:135 was 80:20 respectively at 875 °C by 1H NMR spectroscopy.

This unexpected cyclisation was further studied by means of recording the 1H NMR product ratios from FVP at a range of temperatures to produce a temperature profile of the reaction (Figure 14). The profile shows that as the temperature increases, the ratio of the products changes. Increasing the temperature increases the quantity of the carboline 135 produced and lowers the quantity of the fused benzimidazole 167. The temperature at which the preparative yield of the fused benzimidazole 167 yield is maximised is 825 °C.
°C and is 60% on a preparative scale after flash chromatography. At temperatures below 825 °C, an appreciable amount of starting material is left unchanged after pyrolysis. It was not possible to isolate the carboline at any temperature due to difficulty in separation by chromatography. Analysis was carried out on crude $^1$H NMR spectra and by comparison with literature spectra.$^{52,53}$

One of the entries in the plot has a silica wool additive. When the temperature rises to around 1000 °C the vacuum grease at the joints of the furnace tube decomposes gradually during the course of the reaction making it difficult to maintain the vacuum. Silica wool, when packed lightly at the exit end of the furnace tube is known to have an effect equivalent of a rise in temperature by around 100 °C.$^{54}$ The effect is thought to be due to restricting the gas flow through the furnace tube, thereby keeping the substrate in the hot zone for longer than normal. The use of silica in this way makes it possible to reach molecular reactivities that would only be possible at temperatures at which rapid decomposition of grease occurs.

The conversion to the carboline was maximised at 975 °C with silica additive. It can clearly be seen in the temperature profile in Figure 1 that there is a clear and distinct effect of carrying the reaction out at 975 °C with and without the silica additive. The carboline yield was maximised at 45% by $^1$H NMR spectroscopy. A preparative yield was not measured as the reaction was not deemed synthetically useful due to the poor conversion.
During the course of the above pyrolysis there were only two products formed. The carboline was formed in greater quantities at higher temperatures with a subsequent reduction of the quantity of the benzimidazole. The additional formation of the carboline is thought to occur either through homolysis of the carbon-nitrogen bond that is formed to produce the benzimidazole to give a di-radical species which then recyclises to form the carboline (Scheme 63). The alternative mechanism is a carbene mechanism as shown in Scheme 64. The driving force is to form a $2 \times 6\pi$ ring system which is more thermodynamically stable.
3.2.3.3 Scale up of cyclisation.

Due to the success of the cyclisation reaction in the production of carbolines the reaction was attempted on a much larger scale. Previous pyrolyses are usually carried out on a test scale of 20-50 mg of precursor. Preparative scale reactions are often carried out on a 500 mg of precursor. The cyclisation of precursor 154 to α-carboline 132 was carried out on a 3.5 g precursor scale. After column chromatography the yield of the cyclised product is 62%.

This demonstrates the synthetic utility and of this reaction; the yield is good and the reaction is easily scaled up. The reaction was not carried out above this scale and it is not known what the scale limit is for this reaction using the apparatus available. It is anticipated that this and the other carboline syntheses could easily be scaled up to produce large scale preparative reactions.
3.2.2.4 Comparison of carboline synthesis with literature methods.
The gas phase cyclisation used to generate the carbolines has been found to produce carbolines efficiently and reliably. With respect to the current literature on the synthesis of carbolines, the gas phase method developed and reported in this thesis has shown to be comparable, if not giving better cyclisation yields in only two steps. The conditions used avoid the problems of dilution associated with the photolysis reactions. The cyclisation is in the gas phase and does not require acidic reagents such as in the Graebe-Ullmann cyclisation and Fischer indole synthesis methods therefore acid sensitive functionality could be tolerated. The high furnace temperature used may affect some functionality however the short contact time experienced by the molecule allows a range of functionality to remain intact as demonstrated in the carbazole synthesis section. Further evidence of the survival of functionality, such as halogens, amino and nitrile is demonstrated in the later chapter dedicated to indolo- and pyrrolo[3,2,1-jk]carbazole synthesis.

3.3 Carbon-nitrogen bond formation.
The formation of the carbon-nitrogen bond observed in the case of the cyclisation of the pyrazine precursor 156 was further investigated by the preparation of the pyrimidine analogue 168 and an alternative precursor 169 for α-carboline. Precursor 168 was prepared in order to investigate if only one product is formed upon pyrolysis due to both cyclisation sites being nitrogen atoms. In the case of the cyclisation to α-carboline, the nitro group is on the same ring as the pyridine whereas in the case of the pyrazine precursor 156 it is on the opposite ring to the ring nitrogen atoms. Precursor 169 was prepared to investigate the effect of changing the position of the radical generating group on the synthesis of α-carboline.

Precursors 168 and 169 were prepared by the same methodology used for 154, 155 and 156 which involves SNAr reaction of o-nitroaniline 160 with 2-chloropyrimidine 170 to give 168 and 2-pyridylamine 171 with o-fluoronitrobenzene 29 to give 169 (Scheme 65). The products were formed in moderate to good yield. The pyrolyses were carried out at 825 °C/10^{-2} Torr and 875 °C/10^{-2} Torr respectively. Pyrolysis resulted in the formation.
of the carbon-nitrogen bond as previously observed (Scheme 62) to give fused benzimidazoles 172 and 138 in good yield, 72% and 65% respectively (Scheme 66).

From the results of the pyrolysis of 168 and 169 it was found that the fused benzimidazoles were not the only products of the reactions. In the case of the pyrimidine precursor 168 it was found that pyrrolo[2,3-b]quinoxaline 173 was formed as a by-product. This side reaction is to be discussed briefly in a following sub section and in depth in a following full section dedicated to this mechanism. The pyrolysis of the alternative α-carboline precursor 169 resulted in the formation of both of the same products produced in the similar pyrolysis of 154. The product ratios were reversed from 85:15 (carboline 132:benzimidazole 138) to 15:85 as calculated from the \(^1\)H NMR spectra.

![Scheme 65](image)

![Scheme 66](image)
3.4 Pyrrolo[2,3-b]quinoxaline formation.

The formation of pyrrolo[2,3-b]quinoxaline 173 during the pyrolysis of 168 was studied over a variety of furnace temperatures. The ratio of the two products was calculated from the $^1$H NMR spectra and plotted as a temperature profile (Figure 15). The reaction was found to favour benzimidazole formation at the lower end of the scale. Temperatures lower than 825 °C resulted in recovery of starting material. Increasing the furnace temperature resulted in the increased formation of the quinoxaline product. Maximum conversion was found to occur at 975 °C in the presence of silica wool in the furnace. Pyrrolo[2,3-b]quinoxaline 173 was isolated in 50% preparative yield under these conditions. The loss in quantity could be accounted for by decomposition on the silica wool surface; the wool was observed to blacken during the pyrolysis. The yield could possibly be improved by careful packing of the wool in the furnace or by use of differing type of insert such as small silica tubes.

![Graph](image-url)

**Figure 15.** Temperature profile of the pyrolysis of 168.
A proposed mechanism for this transformation is shown in Scheme 67. The mechanism involves initial formation of the intermediate benzimidazole. The quinoxaline is proposed to be formed by an electrocyclic ring expansion/contraction process. The benzimidazole undergoes an electrocyclic ring opening to form the carbodiimide intermediate 174. The diimide then undergoes an electrocyclic ring closure to form the pyrroloquinoxaline type structure 175. The final product is produced by a [1, 3]-H shift. Pyrido[2,3-b]benzimidazole 173 isolated from pyrolysis at 825 °C was pyrolysed at 975 °C with silica wool in the furnace tube to confirm it was this species that was rearranging. The result was formation of pyrrolo[2,3-b]quinoxaline as in previous pyrolysis of nitro precursor. The mechanism of formation will be discussed in more depth in a following section.

Scheme 67

3.5 Carboline/fused benzimidazole cyclisation mechanism.

3.5.1 Introduction.

In the cases where the nitrogen heteroatom is not ortho to the amine, cyclisation is thought to proceed via the mechanisms discussed in the carbazole section. However when there is the presence of a nitrogen heteroatom ortho to the amine, cyclisation predominantly occurs onto the nitrogen in most cases. The exception is in the case where N-phenyl-3-nitropyridin-2-amine 154 was pyrolysed where α-carboline 132 is produced as the major product. However, FVP of 169 produced benzimidazole 138 upon pyrolysis with only minor quantities of the carboline. The main difference between the FVP of 154 and 169 is that the initial radical is generated on the heterocycle in the case of 154 and on
the phenyl ring in the case of 169. The ratio of products is reversed for each case. The FVP reactions of 154 and 169 are summarised in Scheme 68.

![Scheme 68](image)

### 3.5.2 Potential mechanisms of cyclisation.

The first mechanism under consideration for the pyrolysis of 154 and 169 is the phenyl hydrogen translocation mechanism (Scheme 69). When 154 and 169 are subjected to FVP, radicals 176 and 177 are produced respectively. These radicals can interconvert to give both products. This mechanism can account for the formation of both the products in each of the cases however it does not explain the reversing ratio in each case. This may be explained using the analogous carbazole scenario when isomeric methyl labelled carbazole precursors 69 and 124 were subjected to the FVP. Both precursors yield the same two carbazole isomers. It was found that there were slightly different ratios of each of the products when both precursors were pyrolysed. This was accounted for by proposing that the equilibration similar to that shown in Scheme 69 was not complete and the cyclisation occurred faster than the hydrogen transfer. This argument could also be used to explain the differing ratios of products in the cases presented in this chapter.
The nature of the cyclisation onto the nitrogen could be thought of being able to occur through one of two ways, direct attack on the nitrogen (Scheme 70) or attack at the carbon-nitrogen bond (Scheme 71). The type of attack shown in Scheme 70 can be ruled out immediately because there is no orbital on the N atom to accommodate the single electron. The type of attack shown in Scheme 71 is the most likely however it is unclear why this attack is favoured over attack at the ortho CH position.
Another mechanism that requires to be considered is the aminyl type mechanism (Scheme 72). The N-centred radical 178 that is formed is common to both 176 and 177. If this was the predominant mechanism occurring during the cyclisation then the ratio of products formed in each case should be the same, however this is not the case. Again this could be explained by the rate of cyclisation being faster than the rate of hydrogen transfer meaning that the hydrogen transfer is not under complete equilibrium.

\[ \text{Scheme 72} \]

3.5.3 Mechanistic studies.

As in the carbazole mechanism section, the mechanism was investigated by methyl labelling, deuterium exchange and N-radical generation.

3.5.3.1 Methyl labelling.

Methyl labelling was carried out in order to find if hydrogen abstractions leading to translocation were occurring during the pyrolysis. The mechanistic study in this case was carried out on a pyrazine example. \( N \)-(5-Methyl-2-nitrophenyl)pyrazin-2-amine 179 was prepared from 3-fluoro-4-nitrotoluene 180 and aminopyrazine 181 (Scheme 73). The product was subject to FVP and the crude pyrolysate was analysed by \( ^1 \)H NMR spectroscopy. The result of the pyrolysis was the formation of two differing methyl isomers 182 and 183 (Scheme 74).
The proposed structures of the products were supported by COSY and NOESY NMR spectroscopy. Key features of each structure, such as the 1,2,4-trisubstituted aromatic substructure of 182 and the 1,2,3-trisubstituted aromatic substructure of 183 were identified from the COSY NMR spectrum and also by using the NOE correlations from the methyl group into these substructures. Two other 1,2,4-trisubstituted coupling patterns were identified from the COSY spectrum and were attributed to each fused pyrazine ring in 182 and 183. This was supported by the correlation of the methyl group of 183 to the adjacent pyrazine doublet and a doublet of the 1,2,4-trisubstituted aromatic substructure in 182 to a doublet in the pyrazine 1,2,4-trisubstituted aromatic substructure. The ratio of the two products was 60:40 for 182:183. This is the same as that found for the carbazole case indicating that the mechanisms of the cyclisations may be similar.

![Scheme 73](image)

Scheme 73

![Scheme 74](image)

Scheme 74

The results of this pyrolysis can be explained by both the phenyl radical and the aminyl radical mechanisms. Phenyl hydrogen abstraction can transfer the radical to the pyrazine ring and a further abstraction can transfer the radical back to the phenyl ring to either of two different positions (Scheme 75). Cyclisation of these radical intermediates results in the production of both of the products formed in Scheme 74. In the case of the N-centered radical mechanism, the radical will delocalise to the ortho nitrogen on the pyrazine and cyclise to produce the two observed products (Scheme 76).
3.5.3.2 Deuterium labeling studies.

Deuterium labelling was carried out in order to assess whether or not that an aminyl radical was being produced. If it was being produced then deuterium should be incorporated into the phenyl ring at the position adjacent to the nitrogen. The deuterium exchange was carried out on N-(2-nitrophenyl)aminopyrazine 156 with MeOD. After exchange the precursor was then subject to immediate pyrolysis and analysed by $^2$H NMR spectroscopy at 55 MHz in DMSO (Figure 16). The spectrum was compared with that of the fused benzimidazole 167 (Figure 17) in DMSO-$d_6$. The result showed deuterium incorporation at the position predicted in structure 185. The $^1$H NMR spectroscopy assignment of the fused benzimidazole was supported by a NOESY experiment using the correlation of the proton adjacent to the fused nitrogen of the pyrazine into a doublet of the phenyl ring. This key correlation was used as the basis of the assignment of the $^1$H NMR spectrum of 167. This result supports the proposal that an aminyl radical is produced to some extent and is involved in the subsequent cyclisation to yield fused benzimidazole 185.
Figure 16. 55 MHz $^2$H NMR spectrum of deuterated pyrolysate of 156.

Figure 17. 360 MHz $^1$H NMR spectrum of fused benzimidazole 156.

3.5.3.3 $N$-Centered radical generation.

In order to assess whether or not the aminyl radical mechanism is important in the formation of the carbolines and fused benzimidazoles the generation of this type of radical was carried out in a similar manner to the diphenylamine case. The compounds that were prepared were $N$-benzyl-$N$-phenylpyridin-4-amine 186, $N$-benzyldipyridin-4-amine 187 and $N$-benzyl-$N$-phenylpyridin-2-amine 188. The preparation of each is shown in Schemes 77, 78 and 79 respectively. Compound 186 was prepared by the benzylation of amine 189. Amine 189 was prepared from 4-chloropyridine hydrochloride.
190 and aniline 191. Compound 187 was prepared from the benzylation of amine 165. Compound 188 was prepared by the Ullmann reaction of 192 with iodobenzene 193. Compound 192 was prepared by benzylation of 2-aminopyridine 171.

Scheme 77

Scheme 78

Scheme 79

Each of the substrates, 186, 187 and 188 was pyrolysed at 875 °C/10⁻² torr. The results of the FVP of 186 produced $N$-phenylpyridin-4-amine 191, $\gamma$-carboline 133 and isonicotinonitrile 194 (Scheme 80) in a 76:16:8 ratio respectively. The pyrolysis of 190 produced a similar result in that the products formed were dipyridin-4-amine 165, isonicotinonitrile 194 and $\gamma$, $\gamma'$-carboline 134 (Scheme 81) in a 79:14:7 ratio respectively. Bibenzyl 195 was also produced in each case by coupling of the benzyl radical leaving group. The secondary amine is produced by hydrogen capture. The formation of isonicotinonitrile will be discussed in a later section. In each case only a very small
quantity of the cyclised product was detected. The low level of cyclisation could indicate that there is not enough energy at 875 °C to induce complete radical rearrangement and cyclisation. This may indicate that hydrogen abstraction from the amine to give the aminyl, followed by cyclisation is a possible process occurring during the formation of the carbolines. However, as only very little cyclised product was detected it may be unlikely that this is the predominant mechanism. The predominant mechanism is likely to be the phenyl radical mechanism as with the carbazole series.

Scheme 80

The FVP of 187 and 188 was repeated at 975 °C in attempt to maximise the formation of the cyclised product. The FVP of 187 at the elevated temperature led to the formation of the same three products 191:133:194 in the ratio 45:33:22. The FVP of 38 at the elevated temperature led to the formation of the same three products 165:134:194 in the ratio 33:17:50. In both cases the quantity of H-capture is reduced and there is an increase in the quantity of the cyclised product. There is also an increase in the quantity of isonicotinonitrile 194.

Scheme 81
In the case of pyrolysis of substrate 188 at 875 °C/10⁻² torr, the product formed was the fused benzimidazole 138 (Scheme 82). No carboline, isonicotinonitrile or hydrogen capture products were detected however a minor unknown impurity was visible in very small quantity by ¹H NMR spectroscopy. This result, in contrast to the pyrolysis of 186 and 187 showed almost exclusively cyclisation to the pyridine nitrogen. Once the radical is generated it is thought to delocalise onto the pyridine nitrogen and to subsequently cyclise (Scheme 82). This result suggests that the abstraction of the amine hydrogen by the phenyl radical formed by FVP of the nitro precursors to give N-centred radicals may be occurring in the cyclisation reaction to form the fused benzimidazoles.

Scheme 82

In the case of the pyrolysis of the nitro precursors 154 and 169 differing products are formed. The pyrolysis of 169 yields the fused benzimidazole 138 and the pyrolysis of 154 gives the carboline 132. Both give the other product as a minor by-product. If both were to react via the nitrogen centred radical it would be sensible to expect the same ratio of products, however this is not the case. The result in Scheme 82 demonstrates that the aminyl radical cyclisation is possible. The reason that the product ratio for the FVP of 154 and 169 are not the same is that the hydrogen transfer/radical translocation mechanism is not in complete equilibrium.
Deuterium exchange was carried out on \(N\)-(3-nitropyrid-2-yl)aniline 154 (the precursor to radical species 179) and was then pyrolysed as in previous cases of deuterium exchange. The crude pyrolysate was dissolved in acetone and analysed by \(^2\)H NMR spectroscopy. The \(^2\)H NMR spectrum (Figure 18) was compared with the \(^1\)H NMR spectra of \(\alpha\)-carboline 132 (Figure 19) and the fused benzimidazole 138 (Figure 20). Peaks at \(\delta_H 7.6\) and 7.9 clearly show that there has been deuterium incorporation into the carboline and fused benzimidazole respectively, in both cases at the position adjacent to the non-pyridine nitrogen atom.

Upon pyrolysis of \(^2\)H enriched 154 the initial pyridyl radical 196 can cyclise to give \(N\)-deuteriated carboline 197. This deuterium incorporation into the aromatic structure is due radical translocation to give the aminyl radical 198 (Scheme 84). The aminyl radical can then cyclise through the rings to give fused benzimidazole 199 with deuterium incorporated or it can cyclise to give \(\alpha\)-carboline 132. This result demonstrates and supports the formation and cyclisation of the aminyl radical.

Fig 18. 55 MHz \(^2\)H NMR spectrum of deuteriated 154 crude pyrolysate.
Figure 19. 250 MHz $^1$H NMR spectrum of crude $\alpha$-carboline 132.

Fig 20. 250 MHz $^1$H spectrum of fused benzimidazole 138.
3.5.3.4 Summary of mechanistic results of carbazole and carboline cyclisation.

From the results generated it was shown that both direct cyclisation and aminyl radical cyclisation is occurring in both the case of the formation of carbazoles and carbolines. In carbazoles and in carbolines where the pyridine type nitrogen is not in the ortho position direct cyclisation is likely to be the predominant mechanism of cyclisation. The aminyl radical mechanism is occurring however it is only a minor side mechanism. This proposal can be concluded from the results of the methyl labelling, deuterium labelling and aminyl radical generation.

In the case where there is a nitrogen atom present at the 2-position on the pyridine/pyrazine/pyrimidine type rings, the predominant mechanism of cyclisation is likely to be via the aminyl radical mechanism. This is only the case when the radical is initially generated on the phenyl ring. This is proposed due to the result shown in Scheme 82 demonstrating the cyclisation of an aminyl radical by an authentic method. When the radical is initially generated on the pyridine ring then cyclisation occurs predominantly by the direct method.
3.6 Isonicotinonitrile formation.

When N-benzyl compounds 186 and 187 were pyrolysed it was found that the predominant product was the secondary amine. This is formed by hydrogen capture of the N-centred radical. Two minor products were observed to be formed and were found to be isonicotinonitrile and the carboline. The carboline was the species formed in the smallest quantity. Isonicotinonitrile was a curious and unexpected by-product formed during the course of the reaction. It was found that when the furnace temperature was increased from 875 °C to 975 °C the ratio of the products changed to give more isonicotinonitrile. Some mechanisms are proposed to describe the formation of this by-product.

Using the pyrolysis of 187 as an example, the first mechanism to be considered is one in which a pyridyl unit is lost to give an aminyl radical 200. The aminyl radical then loses a hydrogen atom to give imine 201. The imine can the either lose a phenyl radical or a hydrogen atom to give an imidoyl radical species 202 or 203 respectively. Either radical can then rearrange via a spiro intermediate 204 to give isonicotinonitrile 194 (Scheme 85). An alternate pathway for the aminyl radical 200 is to lose a phenyl radical to give N-methylenepyridin-4-amine 205 which can lose a hydrogen atom and rearrange through a spiro intermediate to give isonicotinonitrile 194 (Scheme 86).
Scheme 85

Scheme 86

An alternative mechanism would be to lose a hydrogen atom by homolysis at the benzyl \( \text{CH}_2 \) to generate radical species 206. This could rearrange \( \text{via} \) spiro intermediate 207 to give an intermediate aminyl radical 208. Loss of a phenyl radical would give imine 209 (Scheme 87). Imine 209 could then react as proposed in Scheme 85 for imine 201.

Scheme 87

A final alternative is a mechanism in which the \( N \)-centred radical 210 is generated. This is the radical that, when generated, cyclises to give the carboline by-product. An alternative reaction for this species might be to ring open to give 211. Species 211 can then recyclise to give five membered ring radical species 212. A hydrogen shift followed
by a loss of pyrrole would give carbene intermediate 213 which would then rearrange to give isonicotinonitrile 194 (Scheme 88).

Initially it was thought that the mechanisms in Scheme 87 and 88 were unlikely as there is no precedent for these in gas phase chemistry. It was thought that the mechanisms in Schemes 85 and 86 were more likely. Imine 201 was therefore prepared by reflux of 4-aminopyridine 214 with benzaldehyde 215 in toluene under Dean-Stark conditions and pyrolysed under the conditions used for the FVP of the N-benzyl precursors (Scheme 89). No isonicotinonitrile 194 was observed in the crude pyrolysate, only unreacted starting material was recovered. This result indicates that mechanism in Scheme 38 is unlikely to be the method of formation of the isonicotinonitrile 194. Imine 209 was prepared by the same method as imine 201 and was pyrolysed under the same conditions (Scheme 90). Again, no isonicotinonitrile was produced, only unreacted starting material was recovered. This result can be taken to suggest that the mechanism in Scheme 87 is also not the method of formation of the isonicotinonitrile.
Currently the mechanism of formation of the isonicotinonitrile is unclear, however it may be possible to elucidate it by pyrolysis of \( N\)-amino-4,4\+'</\prime>-dipyridylamine 216. The object of this experiment would be to generate the aminyl radical by an alternative route and to find out if isonicotinonitrile is produced. If it were then this would show that the benzyl group does not take part in the formation of this by-product and therefore rule out the mechanism in Schemes 85, 86 and 87. This would leave only the mechanism in Scheme 88 as the default proposed mechanism. If no isonicotinonitrile was produced it could be taken that by default that the mechanism of formation may be that shown in Scheme 86 as the mechanisms in Schemes 85 and 87 have already been ruled out by pyrolysing imines 201 and 209 and only recovering starting material.

3.7 Pyrido[2,3-\(b\)]benzimidazole rearrangement.

3.7.1 Introduction.

It was shown previously in Scheme 67 that pyrrolo[2,3-\(b\)]quinoxaline 173 is produced by a thermal rearrangement of fused benzimidazole 172 and an electrocyclic ring opening and ring closure mechanism was suggested. The rearrangement proceeds through a 9-membered carbodiimide intermediate 175. There has been a large interest in this type of intermediate.\(^{55, 56}\) At present in the literature only ring sizes up to the 7-membered analogues 217 are known (Scheme 91).
Currently the strategy used to produce the 7-membered analogues is from thermolysis of 2-pyridylnitrenes 218 (Scheme 92). Nitrene 218 then undergoes a ring expansion-contraction processes through carbodiimide 217 to give 2-cyanopyrrole 219. Intermediates of type 217 have been characterised by matrix isolation and subsequent IR spectroscopic analysis. Analogous examples of the 7-membered intermediates have been produced from phenylnitrene 220 and phenylcarbene 221 (Schemes 93 and 94 respectively). The equivalent 9-membered carbodiimide 222 has not yet been observed, due to the unavailability of the 8-membered precursors such as 223 that are required to make them by the traditional (Scheme 95). In the course of our studies it has been shown that a novel route into the analogous 9-membered ring 224 has been found in the form of 175.

Scheme 92

Scheme 93
The rearrangement of pyrido[2,3-b]benzimidazole 172 may be a general route to carbodiimide intermediates which does not require a nitrene ring expansion. The key structural feature in the rearrangement of pyrido[2,3-b]benzimidazole 172 to pyrrolo[2,3-b]quinoxaline 173 is the three nitrogen arrangement in the imidazo[1,2-a]pyrimidine 225. If this were to undergo the same rearrangement then the parent 9-membered intermediate 226 would be formed followed by pyrrolo[2,3-b]pyrazine 227 (Scheme 96).
It is the purpose of this chapter to investigate further the nature of this rearrangement in order to assess its potential synthetic utility and to find if reactions via analogous 9-membered intermediates can be formed. In addition to compound 225, precursors 228, 138, 229 and 230 were chosen for this study (Scheme 97). Precursors 228 and 138 were chosen to investigate the rearrangement when the carbodiimide intermediate was changed to a ketenimine, e.g. 231 and 232. The other key change with precursors 228 and 138 are that the final products contain indene rings rather than the indole type ring associated with the rearrangement of pyrido[2,3-b]benzimidazole to pyrrolo[2,3-b]quinoxaline. The driving force of the reaction may be the thermodynamic driving force of the production of an aromatic product. In the case of precursors 228 and 138 the products (233 and 234) are not fully aromatic, this may effect the outcome of the reaction.

Precursor 229 also would go through a ketenimine intermediate 235, however the product is the same as the rearrangement of pyrido[2,3-b]benzimidazole 172 to give the fully aromatic pyrrolo[2,3-b]quinoxaline 173. For precursor 230 an H-shift is required for the first step (Scheme 98) to get to carbodiimide 236 before it can undergo the rearrangement to 237. Compound 230 is commercially available and was subjected to FVP to investigate the potential of the H-shift to occur prior to the rearrangement.
3.7.2 Preparation of precursors for study.

Imidazo[1,2-a]pyrimidine 225 was prepared by literature procedure\textsuperscript{57} involving the condensation of 1,1,3,3-tetramethoxypropane 238 with 2-aminoimidazole sulfate 239 (Scheme 99). Imidazo[1,2-a]pyridine 228 was also formed by a literature condensation\textsuperscript{58}
between 2-aminopyridine 171 and chloroacetaldehyde 240 (Scheme 100). Benzo[4,5]imidazo[1,2-a]pyridine 229 was prepared by a method devised by Prager which involved the nucleophilic substitution of 2-bromopyridine 241 with benzotriazole 242 followed by FVP of the product 243 to give benzo[4,5]imidazo[1,2-a]pyridine 138 via a carbene mechanism (Scheme 101). This analogue was prepared by this method rather than the method used to generate it in the previous chapter due to higher overall yield and the use of milder conditions.

The final analogue to be prepared was pyrido[4,5-b]benzimidazole 229. This was carried out using the methodology discovered in this chapter for the synthesis of fused benzimidazoles. Firstly 4-aminopyrimidine 244 was prepared from pyrimidine 245 using a modified literature procedure. Van der Plaas reported the Chichibabin synthesis of 244 by using potassium metal rather than sodium. The actual method of preparation was not well explained and was developed in this work to give 244 in a 65% yield. The reaction was also carried out with sodium metal and it was found that the yield was lower. The 4-aminopyrimidine 244 was used in a nucleophilic substitution with o-fluoronitrobenzene 29. The product 246 was then reacted under FVP conditions to produce 229 (Scheme 102). 7-Azabenzimidazole 230 was also required for this investigation; however his was a commercially available starting material.

![Scheme 99](image)

Scheme 99

![Scheme 100](image)

Scheme 100
3.7.3 FVP of rearrangement precursors.

All of the above compounds prepared were pyrolysed at 975 °C/10⁻² Torr, the same conditions used for the preparation of pyrrolo[2,3-b]quinoxaline 173. The results of all the pyrolyses are shown in Scheme 103. Pyrolysis of 225 was shown to undergo the electrocyclic rearrangement to give the pyrrolo[2,3-b]pyrazine 227 in 60% yield. Pyrolysis of 228 and 138 gave only unreacted starting material. The furnace temperature
was increased to 1150 °C. The result of FVP of 228 and 138 at 1150 °C was that only decomposition of the starting material occurred, no product was detected by ¹H NMR spectroscopy.

Pyrolysis of 229 resulted in some rearrangement to give pyrrolo[2,3-b]quinoxaline 173, unreacted starting material and α,γ-carboline 247. The yields reported for the products reported for the pyrolysis of 229 were calculated from the crude ¹H NMR spectrum of the reaction. The production of 247 was tentatively deduced from the crude ¹H NMR spectrum in conjunction with COSY and NOESY spectra by the identification of two meta coupled doublets which correlated to one another in the COSY spectrum. One of the meta coupled doublets showed a correlation to a doublet of coupling of about 8 Hz which would be expected between the two six-membered rings in 247.

The pyrolysis of 230 produced a complex mixture of products under the above conditions as well as leaving some unreacted starting material. The pyrolysis temperature was increased until no starting material was left. After work up by flash chromatography only mixtures were obtained, however the fractions recovered were significantly improved to allow characterisation by ¹H and ¹³C NMR spectroscopy and mass spectrometry. The products were shown to be isomeric pyridines 248 and 249 along with the isomeric pyrroles 250 and 251. An explanation of this result will be discussed in the following section.
The results of the pyrolyses shown in Scheme 103 show that when the carbodiimide functionality of the intermediate is replaced with a ketenimine function using precursors 228, 138 and 229 that the rearrangement does not take place as readily. It is found in the
case of 228 and 138 that no rearrangement takes place at all. This result could suggest that either the ketenimine is higher in energy than the respective carbodiimide and thus is a barrier to the rearrangement taking place. It has been suggested in the literature by Wentrup\textsuperscript{55} and co-workers that the ketenimine intermediates are higher in energy to the respective carbodiimides by DFT calculations. The products of rearrangement are also not fully aromatic unlike the case of pyrrolo[2,3-b]quinoxaline 173. This may also remove the driving force for the rearrangement from taking place.

In the case of precursor 229 a ketenime a the intermediate would also formed, however the product is pyrrolo[2,3-b]quinoxaline 173 as in the case with the rearrangement of pyrido[2,3-b]benzimidazole 172 thus giving a fully aromatic product. The result of this pyrolysis showed that the major compound in the pyrolysate was the precursor 229, however some rearrangement did take place to give pyrrolo[2,3-b]quinoxaline 173. This result shows that the ketenime intermediate is likely to be higher in energy than the corresponding carbodiimide. It is also shown that an additional important driving force is present. This driving force is the production of a fully aromatic product. Both the carbodiimide and the driving force to give an aromatic product have been shown to essential for the rearrangement to proceed efficiently. The results show that the key structural feature required for the key carbodiimide to be present and for the rearrangement to occur is the presence of sub-structure 252 in the precursors.

\[ \text{252} \]

It was also shown that some of the carboline 247 was produced. This was also shown to occur in the case of the pyrolysis of 156 in section 3.2.2 and is thought to occur by a similar mechanism as to that shown in Schemes 63 and 64.
3.8 Pyrolysis of 7-azabenzimidazole.

The pyrolysis of 230 was carried out at much higher furnace temperatures in order to react all of the starting material. The furnace temperature required for complete reaction was found to be 1150 °C. However, at this temperature very little material was recovered due to decomposition in the furnace tube on the silica wool which would be aided by the excessively high temperature involved. Four products were isolated after multiple treatments by flash chromatography. No yields are reported due to poor recovery form the FVP and loss on work up. The products were characterised by $^1$H and $^{13}$C NMR spectroscopy as well as high resolution mass spectrometry. The products were deduced to be 2-amino-3-cyanopyridine 248, 2-cyano-3-aminopyridine 249, 2-cyanopyrrole 250 and 3-cyanopyrrole 251. For the rearrangement to take place a hydrogen shift is required to take place before the ring opening could occur. For the rearrangement to occur the hydrogen would have to remain in the appropriate position (Scheme 98) long enough for the rearrangement to take place. A reason that the rearrangement does not take place may be that the hydrogen shift occurs very fast and does not remain in position long enough for the rearrangement to take place.

Mechanisms for the formation of these compounds are proposed in Schemes 104 (pyridines) and 105 (pyrroles). The mechanism in Scheme 104 shows a homolytic cleavage in the imidazole ring to form a diradical 253 followed by subsequent rearrangement to give 2-cyano-3-aminopyridine 248. There is precedent for this type of ring opening of a benzimidazole to form a cyan group from work carried out by L. Crawford. FVP of N-(2-nitrophenyl)benzimidazole 254 was found to produce 1-cyanocarbazole 255 Scheme 106 by a similar mechanism to that shown in Scheme 104.

The mechanism shown in Scheme 105 shows the same homolytic cleavage as shown in Scheme 104, however HCN is lost to give diradical 256. The radicals then combine and species 257 undergoes a ring contraction via carbene intermediate 258 to give 2-cyanopyrrole 250. There is literature precedent for this type of mechanism from work carried out by Wentrup and co-workers on the rearrangement of nitrene 218 (Scheme 92). The isomeric pyridine 249 and pyrrole 251 will be formed formed from the
tautomeric benzimidazole 259 (Scheme 107) by similar mechanisms to that shown in Schemes 104 and 105.

Scheme 104

Scheme 105

Scheme 106

Scheme 107

4.1 Introduction.

The nitro group has been shown to be of use as a radical generating group in the synthesis of carbazoles/carbolines and benzo fused benzimidazoles (chapters 2 and 3). Indolo[3,2,1-jk]carbazole 1 and pyrrolo[3,2,1-jk]carbazole 2 (IC and PC respectively) have been synthesised by McNab et al using the nitro group strategy. The syntheses have been carried out as shown in Scheme 108. The reaction is believed to involve the homolysis of the aromatic nitro group bond in N-(2-nitrophenyl)carbazole 25 or N-(2-phenyl)indole 44 under the gas phase conditions of flash vacuum pyrolysis (FVP) to produce a radical intermediate 5 and 46 respectively. This was sufficient yield for further investigation. Therefore, the radical undergoes cyclisation to yield 1 and 2 with loss of a hydrogen atom in 48% and 33% yields respectively. The synthesis of both 1 and 2 has not yet been optimized further to establish if it is of use in the preparation of substituted analogues or other heterocyclic analogues.

Scheme 108
The preliminary work was carried out by L. Crawford. N-(2-Nitrophenyl)carbazole 25 and N-(2-nitrophenyl)indole 44 were synthesised by the SNAr reaction of carbazole 3 and indole 155 respectively with 2-fluoronitrobenzene 29 in the presence of potassium carbonate in dimethylformamide at 125 °C (Scheme 109). The cyclisation procedure was carried out at 875 °C and 10⁻² Torr.

\[
\begin{align*}
\text{N} & \quad \text{O}_2
\end{align*}
\]

The purpose of the work discussed in this chapter is to optimise the reaction conditions used for both the synthesis of the precursors and the cyclised products. The synthesis has also be an extended to the attempted production of substituted derivatives of 1 and 2 and also novel heterocyclic analogues.

4.2 Optimisation and of synthesis of 1 and 2.

4.2.1 Indolo[3,2,1-\(jk\)]carbazole precursors and cyclisation.

Cesium carbonate is known to promote SNAr reaction better than other bases when DMSO or DMF are used as solvents. Conditions were varied by changing base, solvent and reaction temperature. DMSO and cesium carbonate were found to be the most suitable solvent and base respectively for the SNAr reaction. Standard conditions usually involve heating at above 100 °C in DMSO with potassium carbonate as shown in Scheme 109. These conditions may prove to be too forcing if sensitive functionality is present.
Precursors 25 and 44 have been prepared using the Cs₂CO₃ conditions and these have been isolated in marginally better yields of 95%. Derivatives of 25 and 44 have been successfully prepared using the same conditions, however they still required to be optimised. In all cases the appropriate substituted o-fluoronitrobenzene was used with the exception of the cyano derivative 362 where 5-cyano-2-chloronitrobenzene was used due to its commercial availability. Conditions for this precursor were not optimised further due to the reasonable yield obtained. The precursors were then converted to their appropriate cyclised products by FVP as discussed before (Scheme 110).

\[
\begin{align*}
\text{NO}_2 & \quad 260 \ R = \text{H} \\
263 & \quad R = \text{NH}_2 \\
261 & \quad R = \text{Br} \\
262 & \quad R = \text{CN}
\end{align*}
\]

Scheme 110

<table>
<thead>
<tr>
<th>Indolocarbazole precursor</th>
<th>SNAr conditions</th>
<th>Yield (%)</th>
<th>FVP conditions</th>
<th>Product</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>260</td>
<td>Cs₂CO₃/DMSO/140 °C</td>
<td>80</td>
<td>875 °C/10⁻² Torr</td>
<td>263</td>
<td>57</td>
</tr>
<tr>
<td>25</td>
<td>Cs₂CO₃/DMSO/140 °C</td>
<td>95</td>
<td>875 °C/10⁻² Torr</td>
<td>1</td>
<td>71</td>
</tr>
<tr>
<td>261</td>
<td>Cs₂CO₃/DMSO/125 °C</td>
<td>90</td>
<td>875 °C/10⁻² Torr</td>
<td>264</td>
<td>62</td>
</tr>
<tr>
<td>262</td>
<td>K₂CO₃/PhNO₂/180 °C*</td>
<td>65</td>
<td>875 °C/10⁻² Torr</td>
<td>265</td>
<td>74</td>
</tr>
</tbody>
</table>

* Not optimised


4.2.2 Stability of functional groups.

The results in 4.2.1 show that a range of functionality can be tolerated under the reaction conditions employed. In the case of the bromo analogue 264, some de-bromination of the parent molecule was found to occur. Loss of halogens under FVP conditions has been
reported in the literature.\(^{62}\) Due to the observation of debromination, it is thought that this methodology would not be suitable if iodo functionality was present. If iodo functionality was required, diazotisation of the amine analogue 263 followed by treatment of the diazonium salt with potassium iodide should give the iodo substituted indolo[3,2,1-\(jk\)]carbazole.

Other functionalities that would not be suitable under the conditions used are carboxylic acids and nitro groups. Carboxylic acids have been found to decarboxylate under the reaction conditions used.\(^{63}\) Introduction of carboxylic acid functionality could be carried out by hydrolysis of the cyano analogue 264.

**4.2.3 Scale up of FVP cyclisation reaction.**
The maximum scale of the FVP reaction is dependent upon a number of factors; these include the size of the FVP equipment and the volatility of the precursors under the required reaction conditions. The best results are obtained when the pyrolysis is carried out so that the pressure does not rise too rapidly within the system during pyrolysis. Minimisation of decomposition at the outlet of the furnace tube also is an important factor in maintaining good yield. Minimisation of decomposition is carried out by thermally insulating the outlet so that the majority of the product condenses on the cold finger. The FVP reaction of precursor 25 has been carried out on a preparative scale of between 0.5 g and 5.0 g and gives consistently good yields of indolo[3,2,1-\(jk\)]carbazole 1 (65-70%).

**4.3.1 Pyrrolo[3,2,1-\(jk\)]carbazole synthesis.**
The methodology discussed previously for indolo[3,2,1-\(jk\)]carbazole 1 was directly applied to pyrrolo[3,2,1-\(jk\)]carbazole 2. The precursor 44 was formed in 90% yield and the cyclisation proceeded in 60% yield. The yield is significantly improved from the previously reported 33% for pyrrolo[3,2,1-\(jk\)]carbazole (see section 4.1). The improvement is thought to be due to the reaction conditions being further optimised. Best results are obtained by having the cold-finger trap as close to the furnace as possible.
without causing damage to the joints from the furnace heat. For the FVP apparatus used the desired throughput is in the region of 1 g per hour.

The 4-cyano substituted derivative 266 (Scheme 111) has also been prepared. The 4-cyanopyrrolo[3,2,1-jk]carbazole precursor 267 was prepared by the cesium carbonate DMSO method in 90% yield from 3-cyanoindole 268 and 2-fluoronitrobenzene 29. 3-Cyanoindole 268 was prepared by literature methodology from indole-3-carboxaldehyde 269 and nitroethane. The cyclisation product 266 which was prepared from the FVP of 267 was obtained in 70% preparative yield.

\[
\begin{align*}
\text{CHO} & \quad \text{EtNO}_2 \\
\text{N} & \quad \text{NaOEt} \\
\text{AcOH} & \quad \text{reflux} \\
\text{H} & \quad 875 \degree \text{C} \\
10^{-2} \text{Torr} & \quad 70 \%
\end{align*}
\]

Scheme 111

4.4 Comparison with literature synthesis of indolo and pyrrolo[3,2,1-jk]carbazole.
Both indolo and pyrrolo[3,2,1-jk]carbazole have been reported previously in the literature. In the above section it was demonstrated that a new and efficient short synthesis has been developed for the preparation of these substituted in which the key stage is a gas phase cyclisation by flash vacuum pyrolysis which proceeds in good yield in all cases. This will now be compared to previous syntheses.
4.4.1 Indolo[3,2,1-\textit{jk}]carbazole.

Indolo[3,2,1-\textit{jk}]carbazole has been prepared by two differing strategies as discussed in Chapter 1. The first preparation of this compound was carried out by Tucker\textsuperscript{2} and co-workers. The strategy was a three stage strategy; the first stage was the formation of N-2-nitrophenylcarbazoles by Ullmann condensation. The second stage was to reduce the nitro group to an amine so that cyclisation could be carried out in the third and final stage by diazotisation. The key diazotisation stage for the parent molecule proceeded in good yield; however, no yields were reported for any of the substituted variants.

One drawback of Tucker's methodology is that the reaction will not tolerate the presence of amine groups due to the diazotisation stage. In the gas phase method reported in this thesis it was shown that this group is tolerated and that pyrolysis proceeds in good yield. The gas phase methodology does have some limitations to functionality such as iodo, nitro and carboxylic acid groups.

The method developed by Brown\textsuperscript{5} and co-workers was not carried out in order to provide a novel preparative route to this compound. This synthesis was carried out as part of a mechanistic study on the gas phase cyclisations of aryne intermediates. This was is a five step synthesis whereas the method developed in this thesis is a two step strategy. The new method discovered by L. Crawford\textsuperscript{6} and optimised in this thesis therefore provides a shorter and more efficient route to indolo[3,2,1-\textit{jk}]carbazoles than these current literature procedures.

4.4.2 Pyrrolo[3,2,1-\textit{jk}]carbazole.

The synthesis of pyrrolo[3,2,1-\textit{jk}]carbazole has also been reported in the literature. Pyrrolo[3,2,1-\textit{jk}]carbazole was prepared during the mechanistic study carried out by Brown\textsuperscript{5} as previously discussed in section 4.4 for 1 which is a multi-stage procedure. The only other preparative procedure reported is that of Hallberg\textsuperscript{15} and co-workers. The method consists of a Bischler type cyclisation of phenothiazine N-acetaldehydes followed by a transition metal mediated desulfurisation. The procedure is three synthetic stages; this is one more than the FVP method developed in this thesis. The main drawback of
this procedure is that the desulfurisation stage utilises a nickel complex in stoichiometric quantities that is not commercially available. The gas phase method developed in this thesis uses a much cheaper starting materials and is a short two step procedure that is clean, efficient and good yields.

4.5 Mechanism of cyclisation.
It is believed that the nitro group undergoes homolytic cleavage to generate a σ-radical. This highly reactive σ-radical then undergoes cyclisation with the carbazole/indole followed by resultant loss of a hydrogen atom (Scheme 112).

![Scheme 112](image)

This theory has now been supported experimentally by “labelling” the N-(2-nitrophenyl) moiety of the radical precursor with a methyl group in the 5 position 270. If radical formation occurs, the radical 271 can undergo translocation to give 272. This radical species can also undergo a translocation to give radical species 273. This type of transfer has been observed in the formation of dibenzofurans 25 and also with carbazoles (Chapter 2). The isomeric radical system would then have two possible sites of cyclisation and hence the possible formation of two methyl isomers 274 and 275 (Scheme 113). The indole cyclisation will proceed via a similar mechanism. Compound 270 was prepared by the reaction of carbazole 3 with 3-fluoro-4-nitrotoluene 180 in DMSO in the presence of Cs2CO3 at 125 °C (Scheme 114).
Scheme 113

Scheme 114

125 °C
90%

K₂CO₃
DMF
Compound 270 was subjected to FVP and the experimental result showed the presence of two methyl peaks in the $^1$H NMR spectrum of the crude pyrolysate in 48:52 ratios. The methyl peaks were attributed to the presence of 274 and 275 (48:52). Evidence of the presence for the presence of the appropriate substituted indolo[3,2,1-\(jk\)]carbazole has been provided by analysis of the 360 MHz $^1$H NMR spectrum of the crude pyrolysate by COSY, NOESY and HSQC NMR experiments. These spectra showed the presence of a 1,2,4-trisubstituted aromatic substructure which is present on the methyl substituted ring on compound 274. The 1,2,3-trisubstituted substructure of 275 on the ring with the methyl functionality was also present from NMR analysis. High resolution mass spectrometry data was also obtained which gave a mass of 255.1049, which is consistent with the molecular formula $C_{18}H_{12}N_2$ which is representative of 274 and 275.

The above experimental result clearly supports the proposed radical mechanism as described in Scheme 113 as the isomers could not be formed by any other way. Radical species 271 has two identical carbazole sites to cyclise on and can only give compound 274. Radical species 272 has two different phenyl sites to cyclise on and can give compound 274 and 275. Radical species 272 has two identical carbazole sites on which to cyclise and can only give compound 275. If the radical translocation is in complete equilibrium the statistical ratio of the products is 50:50. The experimental ratio measured by NMR proton integrals of the products shows complete equilibration of the three radical intermediates 270, 271 and 272. This result is similar to that observed in the preparation of carbazoles using the same strategy. However, in the case of the carbazole synthesis (Chapter 2) there is a slight deviation in the ratios from the statistical prediction. In the case of the carbazole the failure to equilibrate fully was attributed to cyclisation occurring faster than the translocation of the radical. In the case of indolo[3,2,1-\(jk\)]carbazole the presence of two fused 5-membered rings will introduce a large amount of strain into the system. Due to the increased steric stress it is thought that it will be harder for the radical to cyclise and hence give it more time to equilibrate. This could account for the full equilibration observed in the indolo[3,2,1-\(jk\)]carbazole case and its failure in the carboline (Chapter 3) and carbazole case (Chapter 2).

As described in the Introduction (Chapter 1), 1 was first prepared from the diazonium salt of N-(2-aminophenyl)carbazole 6. This compound is prepared by the reduction of N-(2-nitrophenyl)carbazole 25. Tucker\(^2\) achieved this by reduction with stannous chloride/HCl in good yield. However, the catalytic hydrogenation of nitro groups is well known and removes the problem of using and removing stoichiometric quantities of tin salts.\(^6\) \(^6\) N-(2-Nitrophenyl)carbazole, 25 was reduced by catalytic hydrogenation in 90% yield (Scheme 115) and diazotised as described by Tucker to produce 1 in 67% yield.

![Chemical Structures](image)

Scheme 115

In Tucker’s original publication no indication was given as to the mechanism of cyclisation. It was thought that the mechanism of cyclisation could be one of two different types. The first could involve an electrophilic aromatic substitution reaction. An electrophilic substitution can occur either as a diazonium coupling to the carbazole followed by loss of nitrogen or by loss of nitrogen to give a phenyl cation which can then cyclise with the carbazole moiety. The other mechanism may involve a radical mechanism (electron transfer), however from the reaction conditions used, it is hard to see a likely electron transfer route. It is for this reason that this potential mechanism is ruled out. In the course of this study it was noted that after diazotisation, there was a presence of an intense red colour prior to reflux. The intermediate diazonium salt could not account for this colour. The possibility of a triazepine intermediate 276 was therefore investigated (Scheme 116).
All attempts at isolation of this intermediate 276 failed due to decomposition or conversion to 1 upon work up by DCM extraction/ aqueous washing techniques. After extraction into DCM, the solvent was immediately removed under high vacuum (10⁻² Torr) and dissolved in various deuteriated solvents. Acetone-\(d_6\) was found to be the solvent in which the intermediate was most stable. Analysis of this intermediate by \(^1\)H NMR spectroscopy and electrospray mass spectrometry is consistent with the species being a diazonium salt 277. The diazonium salt was found to cyclise slowly at room temperature with time. The intense red colour is unlikely to come from this species, however there were other minor signals present in the \(^1\)H NMR spectrum which may or may not have been from a diazo- coupled species. Unfortunately it was not possible to analyse the signals of the minor component any further due to overlapping signals. It is assumed therefore that the major mechanism is electrophilic substitution after loss of nitrogen (Scheme 117).

\[
\text{NaNO}_2, \text{AcOH} \quad \to
\]
\[
\text{H}_2\text{SO}_4, 0^\circ\text{C} \quad \to
\]
\[
\text{Reflux, 30 min} \quad \to
\]

Scheme 116
4.7 Structural characterisation of indolo[3,2,1-\textit{jk}]carbazole.

4.7.1 X-ray crystal structure of indolo[3,2,1-\textit{jk}]carbazole 278.

When 1 was first prepared in the late 1930s by Tucker \textit{et al} it was originally thought that the molecule would be bowl-shaped due to the strain in the central three ring system. It was thought the nitrogen bonds would prefer to take a more trigonal pyramidal form. Tucker \textit{et al} assumed that if the molecule was made unsymmetrical by substitution, it would then be chiral due to the bowl shape. Many unsuccessful attempts were made to resolve such molecules.

In the studies carried out in this work an X-ray crystal structure was obtained of the picrate of 1 (278). Figure 21 shows the indolo[3,2,1-\textit{jk}]cabazole portion. The crystal structure clearly shows that the molecule is in fact planar. Bond lengths and angle data are shown in Appendix 1. The indolocarbazole units form co-crystals with picric acid and alternate in planes (Figure 22). The central nitrogen atom is too non-basic in nature to form the picrate salt due to the delocalisation of the nitrogen lone pair of electrons into the conjugated \(\pi\)-system.

The considerable strain imposed by the three ring pyrrolo[3,2,1-\textit{hi}]indole sub-structure 52 is accommodated almost entirely by bond length and angular distortion of the central benzene ring and around the central nitrogen. The driving force for the system to be a planar aromatic molecule must outweigh the need to relieve the serious distortion in bond lengths and angles. The bond length N8-C8B [1.363 Å (4)] is considerably shorter than N8-C8A [1.399 Å (5)] and N8-C9A [1.407 Å (5)] (see Appendix 1). The bond angle
C1A C3B C3A [132.9 (3)] is significantly larger than that expected for a benzene ring [120°]. The shorter bond length suggests that the nitrogen lone pair of electrons interact more favourably with the central benzene ring associated with the pyrrolo[3,2,1-hi]indole substructure 52. This would imply that the central benzene ring is the more electron rich ring.

Figure 21. Indolo[3,2,1-jk]carbazole crystal structure.
Bromination of IC was originally carried out by Tucker et al² by treating IC with Br₂. The result of this experiment was ambiguous and no conclusive result could be drawn about the substitution pattern. The authors did however show evidence for mono-bromination in the form of an elemental analysis. The bromination was repeated by L. Crawford and produced a similar result. ¹H and ¹³C NMR spectroscopic data was very complex and the product proved difficult to purify. Mass spectroscopy showed masses of 319/321 and 399/401, as required for mono and di-brominated species respectively. It was thought that a mixture of mono-bromo isomers was produced along with some di-bromo compounds. The NMR data was too complex to be able to give an unambiguous analysis.
It was thought that a milder brominating reagent may help prevent di-bromination and provide a more selective mono-bromination procedure. N-Bromosuccinamide (NBS) was chosen as it has been successfully used for the selective bromination of carbazole to give 3-bromocarbazole and 3,6-dibromocarbazole. The result of bromination of IC with 1 equivalent of NBS was a mixture of compounds but in this case there was clearly one major isomer and what looked to be one minor isomer by $^1$H NMR spectroscopy. The crude compound was purified by recrystallisation from glacial acetic acid to give a clean isomer by $^1$H NMR spectroscopy (Figure 23) in 55% yield. Only a symmetrically substituted IC 279 can give the $^1$H NMR spectrum presented. The singlet present could only be produced if substitution occurs in the position specified in compound 279. The other features of the $^1$H NMR spectrum are also consistent with this structure (2 × td and 2 × dd). The structure was also supported by NOESY and COSY NMR spectra. The singlet shows an NOE cross peak associated with the doublet adjacent to it in the $^1$H NMR spectrum. Each of the other signals is linked by NOE signals. The COSY spectrum then correlates the other signals to represent a 1,2-disubstituted aromatic substructure. Coupled with mass spectrometry data, compound 279 represents the only viable structure that can fit.

Fig 23. 250 MHz $^1$H NMR spectrum of major isomer of IC bromination.
The impurity in the crude $^1$H NMR spectrum from the bromination reaction is of the 5-bromo isomer 264 synthesised previously by FVP. The spectroscopic data were shown to be identical. The ratio of the products was calculated from the $^1$H NMR spectrum and was shown to be 75:25 of 279:264 (Scheme 118). The larger quantity of 279 can be explained by examining the X-ray crystal structure data of IC. As discussed in Section 4.7, the bond length N8-C8B is considerably shorter than N8-C8A and N8-C9A. This suggests that the nitrogen lone pair of electrons interact more favourably with the benzene ring associated with the pyrrolo[3,2,1-hi]indole substructure than the others. This would imply that this is the more electron rich benzene ring, thus explaining the preference for the bromination of this ring.

\[
\begin{align*}
\text{Br} & \\
\text{NBS} & \\
\text{silica} & \\
\text{DCM, RT} & \\
\end{align*}
\]

\[
\begin{align*}
\text{1} & \rightarrow \text{Br} \\
\text{279} & \text{N-Br} \\
\text{264} & \text{25% by NMR} \\
\end{align*}
\]

Scheme 118


The X-ray crystal structure of 2 has also been elucidated as a picrate 280 (Figure 23). This structure also shows 2 to form a co-crystal with picric acid rather than a picrate salt. This is presumably also due to the poor basicity of the fused pyrrole-type nitrogen atom. The structure contains large disorder due to two different occupancies of the co-crystal being in a 70/30 ratio. Figure 23 shows the representations of the pyrrolocarbazole structure with an numbering. Figure 24 shows how the PC molecule is orientated with the picric acid molecule. Bond lengths and angles are shown in Appendix 2.

The structure of 2 is shown to be almost planar with only the slightest distortion. This planar structure would be expected by analogy with IC as the only difference in structure is lack of one fused benzene ring. In comparison to IC, the PC structure also shows bond
length and angular distortion around the benzene ring of the pyrrolo[3,2,1-\textit{hi}]indole substructure 52. The fusion of the pyrrole nitrogen N5 to the benzene rings is also comparable to the respective IC bond length; N8-C8B [1.363 Å (4)]. The N5A'-C11" bond [1.370 Å (8)] is considerably shorter than the similar bond in IC, N5'-C5B' [1.436 Å (12)]. This is again indicative of greater electron interaction with this ring.

Figure 23. Crystal structure of pyrrolo[3,2,1-\textit{jk}]carbazole
Figure 24. Picric acid co-crystal of PC.
4.10  Aza analogues of indolo and pyrrolo[3,2,1-\textit{jk}]carbazoles.

The synthetic strategy to substituted analogues of 1 and 2 that has been developed was utilised in the preparation of a novel class of heterocycles, the aza derivatives. A variety of aza analogues of indolo and pyrrolo[3,2,1-\textit{jk}]carbazole have been prepared.

4.10.1  Azaindolo[3,2,1-\textit{jk}]carbazole precursors.

4.10.1.1  SNAr methodology.

The precursors to the azaindolocarbazoles were prepared as described for IC in Section 4.1. However, the \textit{N}-(nitropyridyl)carbazole precursors were found to be remarkably difficult to prepare. The preparation of \textit{N}-(3-pyrid-2-yl)carbazole 281 from carbazole 3 and 2-chloro-3-nitropyridine 157 (Scheme 119) was used as a model reaction. It was assumed that the chlorine in the pyridine would be similarly active to nucleophilic displacement as the fluorine in 2-fluoronitrobenzene due to the electron withdrawing ring heteroatom and the nitro group both being ortho to the chlorine atom. However, when carbazole was stirred with the pyridine in the presence of cesium carbonate very little reaction took place. The poor conversion could be attributed to the poor reactivity of the carbazole and the over reactivity of the pyridine 157.

\[
\text{Cl} \quad \text{Cs}_2\text{CO}_3 \\
\text{DMSO, DMF or MeCN} \\
\text{Varying temp} \\
\text{(119)} \\
\]

Scheme 119

The reaction was carried out at a variety of temperatures (60 °C, then 80 °C, 100 °C and finally 125 °C). The reaction proceeded more efficiently with increasing temperature up to 100 °C. Some of the pyridine was found to decompose upon heating in all cases. Above 100 °C, the extent of the decomposition resulted in the product becoming
unworkable. Changing solvent to DMF resulted in poorer conversion to product at all temperatures and also resulted in increased decomposition.

At 100 °C in DMSO, the preparative yield was 60%. It was attempted to improve the yield by using an excess of reagents. When carbazole was used in excess it was shown to be difficult to remove by both chromatography and aqueous washing techniques. When the more expensive pyridine was used in 50% excess the yield only improved by 15% to 75% but the purification was made more difficult due to the worsening of decomposition. The use of excess reagents was therefore not effective in optimizing the reaction conditions.

The use of acetonitrile as the solvent improved the problems of decomposition of starting material however, the rate of reaction was low in comparison with the DMSO solution. It was found that the yield could be maximised by keeping the reaction conditions as anhydrous as possible, however this is difficult due to the hygroscopic nature of DMSO and DMF. When the base was changed to potassium carbonate, sodium hydroxide or potassium fluoride the conversion to product was found to worsen with significant tarring of the product.

A possible reason for the difficulty incurred during the above preparation is the poor nucleophilicity of carbazole due to the delocalisation of the nitrogen lone pair of electrons into the aromatic system. As well as this, the pyridine is very reactive at the chlorine site due to the electron withdrawing effects of the pyridine nitrogen and the nitro group. When both of these problems are combined it may explain the poor results observed. Purification by flash column chromatography is required for purification of product at all temperatures.

The best method for the nucleophilic substitution of 2-chloro-3-nitropyridine with carbazole is when the reaction is carried out in DMSO at 100 °C. The base of choice is cesium carbonate. Use of other bases results in a lowering of the yield. It is crucial that fresh DMSO is used as the reaction should be kept as water free as possible and DMSO is very hygroscopic in nature. The reaction should also be carried out under an inert
atmosphere to prevent lowering of the yield. When these conditions were used, yields of 50 – 60% were regularly achieved.

It was decided to attempt to apply this methodology to other N-substituted carbazole and indole compounds in order to test its general synthetic utility. Carbol ine 282 and indole analogues 283 were synthesized by this procedure in 35% and 70% yields respectively. The low yield of the carbazole analogue 282 was likely due to poor nucleophilicity of the α-carbol ine 132. In comparison with carbazole, α-carbol ine 132 has a pyridine-type nitrogen that is able to stabilise the negative charge of the deprotonated species, thus making the nucleophilicity of this compound worse than carbazole. The synthesis of α-carbol ine 132 was carried out as discussed in the previous chapter. The N-(3-nitropyridin-4-yl)carbazole 284 and indole analogues 285 were also prepared using 4-chloro-3-nitropyridine 158 (Scheme 119).

![Chemical structures](image)

The procedure for the preparation of N-(3-nitropyridin-4-yl) analogues required further optimization. 4-Chloro-3-nitropyridine is more reactive than its 2-chloro-3-nitropyridine isomer and hence, more sensitive to moisture, therefore making substitution of the chloro group more difficult. The reaction was attempted over the range of temperatures 25 – 100 °C. The reaction however, failed to proceed satisfactorily at any temperature. It was decided that a less hygroscopic dipolar aprotic solvent may be of use and the reaction was carried out successfully in refluxing anhydrous acetonitrile. Product 284 was obtained in 60% yield. An excess of 50% pyridine 158 gave 80% yield of desired product. The use of the excess pyridine made purification much easier due to the reaction proceeding further to completion. In this case, the improvement outweighed the problems of tarring as the starting materials were found to be difficult to separate. Product 285 was isolated in 70% yield using a 10% excess of 158.
4.10.1.2 Buchwald-Hartwig amination.

In the last decade, both Buchwald \textsuperscript{67} and Hartwig \textsuperscript{68} independently discovered a novel procedure for the palladium catalysed amination of halogenated aromatic systems. Since this discovery, this procedure has been studied on a wide variety of model systems.\textsuperscript{69,70,71} Many different palladium catalysts/ligand systems, bases and solvents have been used. A model system as close to what is being attempted in this work was utilised.\textsuperscript{72} The Buchwald-Hartwig amination was only used for the synthesis of compound 281 at this stage, and was prepared in 80\% yield (Scheme 120).

Scheme 120.
It is appreciated that in the above synthesis, a very large excess of base is used. The reaction was carried without catalyst to rule out nucleophilic aromatic substitution as the mode of reaction. Without the catalyst and co-catalyst no reaction takes place, confirming the catalytic nature of the reaction. This procedure was used as described by the author and has not been optimised. It is envisaged that optimization of this process would reduce the quantity of base used and possibly the quantity of catalyst. The results of this preparation suggest that this methodology could be used in place of the SNAr method for many of the examples prepared.


The precursors prepared in Section 4.10.1 were subjected to the FVP gas phase cyclisation conditions described for the preparation of indolo[3,2,1-jk]carbazole. All successfully underwent cyclisation to produce the desired products, 7-azaindolo[3,2,1-jk]carbazole 286, 7,9-diazaindolo[3,2,1-jk]carbazole 287, 5-azaindolo[3,2,1-jk]carbazole 288, 6-azapyrrolo[3,2,1-jk]carbazole 289 and 8-azapyrrolo[3,2,1-jk]carbazole 290. The preparative yields were 80%, 60%, 58%, 55% and 50% respectively. All of these compounds represent members of novel classes of aza heterocycles.

The X-ray crystal structure of 286 has been elucidated (Figure 25). Bond lengths and angles are shown in Appendix 3. The structure of this compound has been shown to be very similar to that of indolo[3,2,1-jk]carbazole 1. The structure is almost completely planar as is the case with indolo[3,2,1-jk]carbazole.

The structure deviates from planarity slightly around the position of the pyridine nitrogen and is only noticeable upon close inspection using a crystal imaging package. This deviation would be expected as the carbon-nitrogen bond is shorter than the carbon-carbon bond.\(^73\) Apart from the effect of the presence of the pyridine ring, the structures bond lengths and angles show similarities to indolo[3,2,1-jk]carbazole 1. As in 1, the bond length N8-C8B [1.362 Å (4)] is significantly shorter than N8-C8A [1.399 Å (5)] and N8-C9A [1.410 Å (5)], indicating greater lone pair interaction with the benzene ring associated with the pyrrolo[3,2,1-hi]indole 52 substructure. The bond lengths and angles in the pyrrolo[3,2,1-hi]indole 52 are again distorted to accommodate planarity. The bond angle in the central benzene is 131.4° which is significantly larger than would be expected of a benzene ring.
Figure 25. X-ray structure of 7-azaindolo[3,2,1-jk]carbazole.

4.12 Quaternisation of pyridine nitrogen.

Pyridine-type nitrogen atoms can undergo reactions, such as quaternisation, due to the lone pair lying in a $\sigma$-orbital.\textsuperscript{74} It was found that 5-azaindolo[3,2,1-jk]carbazole 288 could undergo quaternisation easily in quantitative yield when treated with dimethyl sulfate to provide the quaternary ammonium salt 291 (Scheme 121). 7-Azaindolo[3,2,1-jk]carbazole 286 however, did not undergo quaternisation when treated with dimethyl sulfate, methyl iodide, or methyl tosylate (Scheme 121). It is thought that in this compound the basic pyridine nitrogen is too sterically hindered to undergo reaction.
Scheme 121

4.13 Scope and limitations of FVP synthesis.

The radical cyclisation strategy employed for the preparation of indolo[3,2,1-\textit{jk}]carbazoles and pyrrolo[3,2,1-\textit{jk}]carbazoles and their aza analogues has been successfully used to produce the required products in good preparative yield. The method has also been used to introduce additional functionality through the use of substituted ortho-fluoro(chloro)nitrobenzenes. The synthesis has also been successfully scaled up to 3-5 g precursor to give product in good quality and yield demonstrating the synthetic utility of this reaction. In addition the strategy has been utilised in the preparation of aza analogues of indolo and pyrrolo[3,2,1-\textit{jk}]carbazole. These aza analogues are the first of their kind to be synthesised and represent the first of novel classes of heterocycle.

The synthesis is limited for IC as demonstrated in Scheme 6. Due to the nature of the mechanism of cyclisation, the substituent on the phenyl ring should be \textit{para} to the carbazole nitrogen to avoid formation of isomers due to radical translocation. As shown previously, substitution at the \textit{meta} site results in isomer formation. Substitution at the \textit{ortho} site may prove to be too sterically hindered to allow cyclisation (with the exception of pyridine based systems). However, this aspect has not been investigated. The carbazole moiety must also be symmetrically substituted to prevent cyclisation potentially occurring at two different carbazole sites. PC is a simpler system and would
not present as many problems due to the presence only one site of cyclisation. However, *meta* substitution on the *N*-phenyl moiety would still produce problems.

The methodology developed in this section is a short 2-step (in most cases) synthesis of these fused indole type systems. In comparison with the literature procedure already known, this new gas-phase method is shorter in steps than all of the previous examples. The reaction is easily scaleable and is tolerant of a wide range of functionality. Using this method, it was possible to generate some novel aza analogues which have not been prepared before. These aza analogues represent a new class of heterocycles and nothing is known of their chemistry.
Further research into the conductivity of poly(acetylene) $^{292}$ revealed that when doped with iodine, the conductivity of the polymer increased to around $10^4$ S cm$^{-1}$.\textsuperscript{82} Poly(phenylenevinylene) (PPV) $^{293}$ has also generated much interest and has been subject to a great deal of work due to its electroluminescence properties.\textsuperscript{83} It is thought that PPV may have applications in LEDs due to this property.

$^{292}$

$^{293}$

Due to their rigid backbones, polymers based upon poly(acetylene) and PPV have been found to have some drawbacks, such as poor solubility and high melting points. Air sensitivity of polymeric material can also be problematic. Some of these properties are desirable for device structure, but can hamper processing. Processing methods have been developed to deal with this problem, for example the addition of side groups into the polymer were used to improve solubility. Solution-soluble precursors that can be converted into the desired polymer during processing was also been used.\textsuperscript{84,85}

In addition to the above polymers, other aromatic polymers have been studied for their electrical conductivity such as, polypyrrole,\textsuperscript{86} polyaniline,\textsuperscript{87} polyindole,\textsuperscript{88,89} polycarbazole\textsuperscript{90} and polythiophene\textsuperscript{91} have all been studied. Indole based conducting polymers are particularly relevant to the work reported in this thesis as both indolo[3,2,1-\textit{jk}]carbazole 1 and pyrrolo[3,2,1-\textit{jk}]carbazoles 2 can be viewed as condensed indole type systems. A review of the relevant literature work on indole polymers is presented later in this chapter along with a brief review of other aromatic conducting polymer systems.
5.3 *Synthesis of polymers.*

The synthesis of conducting polymers can be divided into two main areas, chemical and electrochemical. Both methods are discussed in the following sections.

5.3.1 **Chemical synthesis.**

Poly(acetylene) can be synthesised by a variety of chemical methods. The methods that are usually employed are the chemical oxidation by transition metal salts such as FeCl₃ and CuCl₂. The introduction of charge carriers into the polymer is accomplished by redox reactions, often referred to as "doping". This involves the removal of an electron which leads to the generation of a radical cation. This removal of an electron creates a charged paramagnetic defect in the polymer lattice. The charge of these sites must be compensated for and this happens during the "doping" process. Anions penetrate into the polymer lattice and counter the charge generated. Poly(acetylene) polymers have been synthesised by use of catalysts but generally poor control of the morphology of the final product results.

5.3.2 **Electrochemical synthesis.**

Electrochemical synthesis is generally carried out by the electro-deposition of the polymer onto a working electrode from a solution of the monomer in background electrolyte. A suitable solvent/electrolyte system is selected where the oxidation potential is accessible and where the generation of reactive radical cations sustains the reaction.

Electro-polymerisation offers several advantages over chemical synthesis, for example, the absence of catalyst, direct adherence to the electrode surface in a more controllable manner. Polymer that is attached to an electrode surface lends itself to being easily analysed for its electrochemical properties.

A typical electrochemical synthesis of a conducting polymer generally starts with a solution of the monomer dissolved in electrolyte. The electrochemical set up involves the standard three electrode system, consisting of a working electrode, counter electrode and...
a reference electrode. The monomer is oxidised in solution to form radical cations which can then couple to form polymer. If the radical species is unstable and highly reactive, coupling can occur to form linked species, e.g. dimer, trimer etc. The coupled species precipitates out and adsorbs onto the electrode surface. The oxidised film on the electrode surface incorporates anions from the solution which act as dopant ions. The film is conducting in its oxidised form and insulating in its reduced form. If the radical cation is stable, the species can diffuse away into the bulk solution to form lower molecular weight oligomers.

Radical-radical coupling is similar to the ECE (electron transfer, chemical reaction, electron transfer) mechanism used to describe reactions of many irreversible systems in which a monomer dimerises to form a product, but can be extended to be thought of as an E(CE)\textsubscript{n} mechanism. The oligomer can continue to grow by reaction with other radicals and finally result in the deposition of an insoluble film on the working electrode surface.

5.4 Mechanism of conduction.

The mechanism of conduction in conducting polymers has been fiercely debated and several models have been proposed. These include the delocalised band model and a redox hopping model which emphasises the redox chemistry between localised species in the polymer chain.

5.4.1 Delocalised band model.

Polymers are generally thought to have an electronic band structure in which the energy gap is greater than 1.5 eV. An energy gap of this size effectively makes polymers insulating materials. Conductive polymers have band gaps which are lower in energy. In the delocalised band model, the charge carriers are thought to be radical cations and dications. Radical cations and dications can be referred to as polarons or bipolarons respectively.
Polyheteroaromatic conducting polymers such as polypyrrole 294 can be oxidised to the quinonoid form 295 by removal of a single electron which results in the formation of a radical cation (polaron). The polaron can be further oxidised to give the respective bipolaron 296. The formation of polarons and bipolarons is shown in Scheme 122.

Scheme 122.

The polaron species is a radical cation and as such, contains an unpaired electron. The bipolaron species is doubly charged and has no unpaired electrons. EPR spectroscopy has shown the presence of polarons and bipolarons. EPR measurements have also shown that the conductivity increases as the number of spins increases, suggesting that the charge carriers are polarons.
If oxidation is increased further, the EPR signal is observed to saturate then decrease. This is consistent with the theory that polarons can combine to give bipolarons. In the fully conducting state, no EPR signal is observed, this may be taken to suggest that the charge carriers are bipolarons.

The above model is a general theory for conduction in a polymer chain. The theory only describes conduction for very short well orientated strands. In a real polymer system there is usually a range of finite chain lengths. The chains will be randomly orientated and may not be fully conjugated, this can lead to some charge transfer between chains and segments within chains. This has led to the development of the localised redox chemical model.

5.4.2 Localised redox chemical model.
Albery et al.⁹⁹ have proposed a two electron redox model and is represented as in Scheme 122. The model is based on polypyrrole and describes a two state A (294), B (295), C (296) system which takes into consideration two forms, termed α and β. It was proposed that a polymer can exist in either form, α being stable at reducing potentials and β being stable under conducting conditions. In the conducting state the polymer contains a large amount of charge. It has been suggested that the polymer accommodates this charge by adopting a helical arrangement with a pore of counterions surrounded by a helix polymer.¹⁰⁰ In the insulating α form, the polymer is thought to be tightly packed. Electrons would be removed upon oxidation via the electrode interface and counterions supplied from the electrolyte. The reaction of A to B to C would therefore be accompanied by a phase change from α to β.

5.5 Heterocycle based conducting polymers.
5.5.1 Preamble.
As described in section 5.2, conducting polymers based on heterocycles such as pyrrole, thiophene and indole have been widely studied. The heterocycles under investigation in this thesis have strong structural similarities to indole. Due to this similarity a review of
the current literature on indole conducting polymers will be presented in the following section.

5.5.2 Electropolymerisation of indole.

Indole was first electropolymerised by Tourillon and Garnier\textsuperscript{102} and has since been subject to a wide study by other research groups.\textsuperscript{103} A range of applications has been proposed for indole conducting polymers, such as poly(indole-5-carboxylic acid) as a fast-response pH sensor.\textsuperscript{104} Tourillon and Garnier believed that indole formed a linear N-N bonded structure based upon the fact that N-methylindole does not form a conducting film upon electro-oxidation. Waltman \textit{et al}\textsuperscript{103} proposed that indole actually polymerised through a 1-3 linkage\textsuperscript{296}. This was based on the observation that indoles substituted at the 1, 2 or 3 positions do not polymerise.

\begin{center}
\includegraphics[width=0.1\textwidth]{296.png}
\end{center}

5.5.3 Structural characterisation polyindole films.

More recently, much work has been carried out by Mount and co-workers into the electropolymerisation of substituted indoles. Initial work was carried out on the polymerisation of indole-5-carboxylic acid\textsuperscript{88, 105, 106} and 5-cyanoindole,\textsuperscript{89} both of which were found to form electro-active conducting films upon oxidation. It was reported that the electro-active film consisted of differing fractions with differential solubility, one fraction was DMF soluble and the other was only DMSO soluble. The DMF fraction was analysed by \textsuperscript{1}H NMR spectroscopy and two-step laser desorption laser photo-ionization time-of-flight mass spectrometry (L\textsuperscript{2}TOFMS). The structure was found to be consistent with an asymmetric trimer\textsuperscript{297}. The DMSO soluble fraction was analysed by \textsuperscript{1}H NMR spectroscopy and was consistent with the presence of polymeric species.
Further analysis of the DMF soluble and DMSO soluble fractions by UV/vis spectroscopy, fluorescence spectroscopy and L²TOFMS showed that both fractions emit and absorb via the same chromophore. It should be noted that the structure proposed by Mount and co-workers accounts for Waltmans observations that indole does not polymerise when substituted at the 1, 2 and 3 positions. Mount and co-workers have also studied the electro-oxidation of N-methylindole and have confirmed that it does not form a conducting film. However, analysis using a ring rotating disc showed the presence of a soluble product. This soluble product was isolated and shown to be an N-methylated trimer species. This result was consistent with Tourillon and Garnier’s observation. No evidence of polymer formation was found for N-methylindole. Upon consideration of the above evidence Mount and co-workers have proposed that the DMSO soluble fraction consists of polymeric indole based trimers linked through the nitrogen atoms.

5.5.4 Mechanism of electropolymerisation of indole.
The mechanisms of polymerisation of indole-5-carboxylic acid and 5-cyanoindole were investigated using electrochemical techniques. Both of these indoles were found to polymerise via the same mechanism, which is shown in Figure 26. Initially, monomer is oxidised to form radical cations, these then link to form an asymmetric trimer in the diffusion layer near the electrode surface. The trimer is insoluble in acetonitrile and therefore precipitates out and adsorbs onto the electrode surface to form a film. The material adsorbed on the surface facilitates the adsorption and coupling of monomer radical cations. The reaction proceeds via adsorption and oxidation of monomer followed by linkage to form the trimer. The trimer can then go on to link further on the electrode surface.
5.5.5 Effects of substitution.

The electropolymerisation of a range of 5-substituted indoles as well as indole was studied by Mount and co-workers. Indole was shown to polymerise and form a film on the electrode surface as were indoles substituted in the 5-position with an electron withdrawing group. Indoles substituted with electron donating groups, such as hydroxy and amino were found not to form films on the electrode surface upon electro-oxidation. Oxidation of 5-amino and 5-hydroxyindole was found to occur at the substituent, which then adsorbed to the electrode and prevented film formation. This problem was avoided by using a preformed indole film as a template. The 5-amino- and 5-hydroxyindoles were then subjected to electro-oxidation at the modified electrode surface. Conducting films were found to form using the polymer modified electrode surface. Electropolymerisation on the indole template proceeded similarly to the other indole systems studied.

5.5.6 Fluorescence of substituted polyindoles.

The steady-state fluorescence spectroscopy of the indole monomers, trimers and the polymers formed from various 5-substituted indoles were also studied. All three species were found to be fluorescent. The 5-cyanoindole trimer was found to have a fluorescence quantum yield 1.3 times that of indole (in ethanol). The emission spectra of the trimer and polymer species are very different to that of the monomer, showing a shift to longer wavelengths which is characteristic of larger conjugated aromatic systems. The fluorescence emission spectra were found to have little dependence on the polarity of the solvent or the nature of the 5-substituent. The polymer emission occurs at longer...
wavelengths than the trimer emission and is lower in intensity. It is also broad, which suggests that a range of different emitting species are present.

5.6 Applications of conducting polymers.
5.6.1 Opto-electronic displays.
Conducting polymers have been proposed to have application as materials for light emitting diodes (LEDs) due to their good conduction and electroluminescence characteristics. These phenomena are rapidly being utilised in an ever expanding area of research. Conducting polymers display electroluminescence that ranges from red through to blue. An example of such a system is derivatised polythiophenes. Electroluminescent devices have been produced with colours ranging from blue to near infrared. The blending of different polymers has led to the possibility of simultaneous emission to give a secondary colour.

5.6.2 LED technology.
In LED technology, the mechanism of light emission is electroluminescence. The method of study of the luminescence properties of most conducting polymers is photoluminescence.

In photoluminescence, emission is stimulated by excitation of an electron from the highest occupied molecular orbital to the lowest unoccupied orbital. This results in the formation of a singlet excited state. The singlet excited state can then decay to the ground state by the emission of a photon. The wavelength of the emitted photon is always longer than the absorbed photon. This difference in wavelength is known as the Stokes shift.

In electroluminescence the singlet excited state is generated through a different mechanism from that of photoluminescence (Fig 27). An electron is injected into the material at the cathode and produces a negatively charged polaron. A hole is injected at
the anode, producing a positively charged polaron. These two species migrate through the polymer material under the influence of an electric field. These species may combine to form a singlet exciton. This exciton is indistinguishable from that obtained by photoexcitation and, as in photoluminescence, can decay to the ground state by the emission of a photon.

Figure 27. Electroluminescence mechanism (reproduced from reference 111).

A simple LED, such as the one shown in Figure 28 is usually made up of four layers. The substrate layer is an optically transparent material such as glass. On this substrate layer there is a layer of an optically transparent, electrical conductor such as indium-tin-oxide. The indium-tin-oxide serves as the anode or positive contact. The next layer is a light emitting layer followed finally by a layer of metal such as Ca or Al, which serves as the cathode. An electrical potential is created between the two electrodes. This forces electrons in through the cathode and holes in through the anode.
5.6.3 Battery applications.

Conducting polymers are known to possess a high level of electrical conductivity and a high level of redox sites. Due to the efficient storage and discharge of currents by conducting polymers, such as polythiophene and polyazulene, interest has stemmed in battery applications. A typical battery cell consists of a layer of polymer deposited on a platinum electrode surface of an anode and a cathode. During the discharge phase, an anion is incorporated into the cathode film from the background electrolyte in order to maintain electroneutrality. A corresponding loss of an anion occurs at the cathode. Such cells have been reported to yield a maximum circuit voltage of around 2.3 V and 4 mA.

5.6.4 Photovoltaic cells.

Photovoltaics is the direct conversion of light into electricity at the atomic level. When a conducting polymer is irradiated, an electron can be excited to the conducting band from the valence band. This creates a hole in the valence band. The hole and electron then separate and flow to an outer circuit through conducting electrodes. This phenomenon results in the production of electricity. This is the opposite phenomenon associated with LED technology. Conducting polymers have been investigated for use in photovoltaic cells due to their high conductivity and stability.
5.7 Indolo[3,2,1-\textit{jk}]carbazole 1 and pyrrolo[3,2,1-\textit{jk}]carbazole 2.

Preliminary studies on 1 have demonstrated that it undergoes an electo-oxidation to form a conducting film at a platinum electrode surface.\textsuperscript{1} It has been shown that the reaction proceeds under first order kinetics by Koutecky-Levich analysis. Both 1 and the species formed upon electro-oxidation were shown to be highly fluorescent by steady state fluorescence studies. The film species emission is red-shifted with respect to the monomer and is in the blue visible region. The fluorescence studies were carried out in both the solution phase and the solid phase and produced similar results. Time correlated single photon counting experiments have shown that the species produced has a fluorescence lifetime of around 10 ns (major) and 5 ns (minor). Further work on the fluorescence lifetimes of the film species is to be discussed in a later section in this thesis.

Little is known about how long the potential polymer chain in this species is or where the linkage occurs. DFT calculations were carried out on the radical cation intermediate to determine the sites of high electron density, as represented in Figure 4 by the marked sites. The sites of high electron density are thought to be likely positions of linkage due the reaction of two radicals to form a covalent bond. As can be appreciated from Figure 29, there are a lot of potential coupling sites which may lead potentially to complex products. It was proposed that this material, due to its conductive and fluorescence properties may have potential applications in LED technology.

\begin{center}
\includegraphics[width=0.2\textwidth]{figure29.png}
\end{center}

\textbf{Figure 29. Sites of high electron density as predicted by DFT calculations.}
Pyrrolo[3,2,1-\textit{jk}]carbazole was also shown to form a polymeric film on the electrode surface.\textsuperscript{1} The film produced upon electro-oxidation was shown not to give steady state currents, indicating that the film quickly becomes non-conducting. Both the monomer and the film were shown to be highly fluorescent in solution. The film species was red-shifted with respect to the monomer, indicating larger conjugated species being formed. It is currently unknown why this system has poorer conducting properties, but it has been postulated that it may be due to minor impurities in the monomer.

5.8 Aims of project.

The aim of the second half of this project is to further investigate the electrochemical and fluorescence properties of both indolo[3,2,1-\textit{jk}]carbazole 1 and pyrolo[3,2,1-\textit{jk}]carbazoles 2. The structure of the species formed upon electro-oxidation of 1 will be elucidated and that the mechanism of polymerisation will be explained. An investigation of the electrochemistry and luminescence properties of analogues of 1 will also be carried out to assess the effects of substituents and other functionality such as heteroatoms upon the electropolymerisation.

A brief investigation into the electrochemical properties of 2 will also be carried out in order to find if it will form a conducting film. Further purification of the monomer will be carried out in hope that a conducting species can be formed and investigated for conducting properties.
Chapter 6. Theory.

6.1 Introduction
This chapter presents a summary of the relevant theory behind the electrochemical and fluorescence methods used.

6.2 Electrochemistry
6.2.1 Preamble.
All of the electrochemical experiments used in this work were carried out using a three electrode system. This comprised a working electrode, reference electrode and a counter electrode. Potential sweep voltammetry was used to measure the oxidation potentials of the monomers and study their polymer films. Potential step voltammetry was used to produce and investigate IC and PC films.

6.2.2 Basic electrochemical experimental considerations.
Linear sweep voltammetry and cyclic voltammetry are two of the most commonly used electrochemical techniques. Both techniques are forms of potential sweep voltammetry and yield information about the redox processes occurring in the system of interest. Linear and cyclic voltammetry are usually the techniques of choice for initial analysis of new systems as they rapidly provide information about new redox process. Potential sweep voltammetry will be discussed in more depth in a later section.  

6.2.3 Three electrode system.
The working electrode is the electrode where the reaction of interest occurs, the reference electrode maintains a constant potential drop across the interface of the solution and the third electrode, the counter electrode is used to circumvent the problem of iR drop (i is the current passed and R is the electrical resistance) that occurs in the solution due to passage of current between the working electrode and the counter electrode.
If a voltage \( E \) is applied between a working electrode and a reference electrode and assuming a finite current is flowing between them, then

\[
E = (\Phi_m - \Phi_s) + iR + (\Phi_s - \Phi_{REF}) \quad \text{Eq" 1}
\]

Where \((\Phi_m - \Phi_s)\) is the electrochemical driving force for electrolysis at the working electrode/solution interface, \(iR\) is the voltage drop described above and \((\Phi_s - \Phi_{REF})\) is the potential drop at the reference electrode/solution interface and is fixed by the chemical composition of the electrode. The aim of any voltammetry experiment is to measure \(i\) as a function of changes in \((\Phi_m - \Phi_s)\). For microelectrode experiments, \(iR\) can be neglected and consequently changes in the applied potential are directly reflected in \((\Phi_m - \Phi_s)\). However, with large electrodes, as is the case with the work presented in this thesis, \(iR\) is no longer negligible and therefore changes in the applied potential are no longer confined to changes in \((\Phi_m - \Phi_s)\). The passage of large currents can change the reference electrode’s chemical composition and therefore \((\Phi_s - \Phi_{REF})\) may no longer be constant. The use of a counter electrode ensures that no current is passed through the reference electrode so that it can maintain a constant potential.

6.2.3 Potential sweep voltammetry

There are two types of potential sweep voltammetry; linear-sweep voltammetry (LSV) and cyclic voltammetry (CV), both of which are performed on a stagnant solution. This is so that material is only transported to the working electrode surface by diffusion and natural convection. In LSV the potential is swept from a starting value of \(E_1\) to an end value \(E_2\) at a constant sweep rate. In CV, the LSV experiment described above is performed but upon reaching \(E_2\) the potential sweep is reversed back to \(E_1\) (Figure 30). The current passed, \(i\) is then plotted against the potential giving a typical CV as shown in Figure 31 where \(i_p^c\) is the peak cathodic current, \(i_p^a\) is the peak anodic current, \(E_p^c\) is the cathodic potential and \(E_p^a\) is the anodic potential.
The shape of a typical linear-sweep or cyclic voltammogram can be easily explained as follows. As the voltage is swept, initially the potential is not sufficient to induce reaction. As the electrode becomes more reactive then oxidation or reduction can occur. The electrochemical rate constant becomes greater and rises almost exponentially in accordance with Equation 2 where $\alpha$ is the electron transfer co-efficient.

$$ k = k^0 \exp[\alpha F(E-E^0)/RT] \quad \text{Eq}^n 2 $$
At this point the voltammogram is under electrochemical control. As $E$ increases further the concentration of $R$ at the electrode surface becomes depleted and eventually the value of $i$ reaches a maximum ($i_p$). The peak current represents a balance between the increasing electrochemical rate constant and the decreasing surface concentration of the reactant. As $E$ is increased beyond $E_p$, the current starts to fall as the diffusion layer at the electrode surface becomes thicker and mass transport to the electrode becomes less efficient. At this point the voltammogram is said to be under mass-transport control under these conditions.

The shape of a linear-sweep or cyclic voltammogram can give useful qualitative information on whether a redox reaction is electrochemically reversible or irreversible. A reversible Nernstian reaction is characterised by fast electrode kinetics. As a consequence of this, $[R]$ and $[O]$ at the electrode surface will be equal to the concentrations predicted from the Nernst relationship (Equation 3). This will be true for any particular working electrode potential and is the case even when the system is not at equilibrium. A simple diagnostic for a one electron reversible reaction is that the peak separation between the peak current and the peak half-width is $56.5/n$ mV at 25 °C. $E_p$ is independent of sweep rate used.

$$E = E^\circ + \frac{RT}{nF} \ln \frac{[O]}{[R]} \quad \text{Eq}^n 3$$

An irreversible reaction has slow electrode kinetics and therefore requires a large overpotential for current to flow. Due to this, the increase in current for an irreversible reaction with potential is slower than for a reversible reaction. $E_p$ will be shifted to a more positive potential for an oxidation than for a reversible reaction at the same $v$. As $v$ is increased $E_p$ will be pushed to increasingly positive potential.
For both reversible and irreversible systems where the redox active species is in solution, \( i_p \) is proportional to \( v^{1/2} \). This relationship demonstrates diffusion control of the experiment. In the case where the redox active species forms a product which is adsorbed onto the electrode surface, this relation be the case as long as the whole film is not reduced/oxidised on each sweep. If the product film is completely reduced and oxidised on each sweep, \( i_p \) will be proportional to \( v \).

6.2.4 Potential step voltammetry

At the start of a potential step voltammetry experiment, the potential of the working electrode is held a potential, \( V_1 \), where no reaction occurs. During the experiment the potential is instantaneously stepped directly to \( V_2 \) and is held constant. The change in current is recorded against time. The mass transport to the working electrode is controlled by use of a hydrodynamic electrode such as a rotating disc electrode (RDE). The RDE is rotated at a constant speed so that the rate of mass transport of material to the electrode surface is constant. A schematic of a potential step and a typical current-time transient for such an experiment is shown in Figure 35.

![Figure 35. A typical potential step voltammogram.](image)

On stepping the potential from \( V_1 \) to \( V_2 \), when \( V_2 \) is a potential that is in the mass transport region of the CV of the species under investigation, all the species at the surface of the RDE will immediately undergo electro-oxidation. At this point the current increases sharply to form an initial ‘spike’. The oxidised monomer can then react to form
the initial layer of product that if insoluble in solution can form a film on the surface of
the RDE. If the solution were stagnant, this drop in current would steadily continue to
zero. When using a RDE, the diffusion layer is constantly replenished with species from
the bulk solution. A steady state current eventually arises due to the concentration of the
species of interest at the electrode surface becoming constant. Therefore, in order for the
steady-state current to be maintained, the product film must be conducting in nature.
Where the film is non-conducting i will decrease with time until no current is passed.

6.2.5 Rotating disc electrode.
CVs generally yield qualitative information about reaction kinetics. Quantitative kinetic
information can be obtained by control of the rate of mass transport of a reactant to the
electrode surface. In order to control diffusion and convection processes, a hydrodynamic
electrode, such as the rotating disc electrode (RDE), is used. A hydrodynamic electrode
uses controlled forced convection to determine the mass transfer of reactant to the
electrode surface, therefore the need to consider the effects of natural convection is
removed. However, diffusion and forced convection must still be considered.

A typical RDE, such as that shown in Figure 32, has the form of a Pt disc embedded in an
insulating mantle, such as epoxy resin. The Pt disc should be polished smooth and lie
flush with the plastic housing.

Figure 32. Schematic of a rotating disc electrode (RDE) showing solution flow.
The RDE is placed in the solution so that the Pt disc is horizontal and the disc can then be rotated at a constant speed, $W$. Control of $W$, allows the control of the rate of mass transfer. Rotation in a solution gives a well defined flow pattern which was first described by Cochran.\textsuperscript{116} As the RDE rotates the solution at the surface is dragged along with it and then thrown out radially with fresh solution being constantly drawn up from the bulk. The concentration profile of a solution species at the RDE is shown in Figure 33.

![Figure 33. The concentration profile of a species in solution at a RDE.](image)

Rotation of the RDE causes the formation of a diffusion layer at the electrode surface. Within this layer, the species in solution has zero velocity towards the electrode, therefore mass transport can only occur by diffusion only. At distances, $X$, that are greater than the diffusion layer thickness ($X_D$), the solution is well stirred and mass transport can occur by diffusion and convection. For distances smaller than $X_D$, transport by diffusion is the main method of mass transport and distances within this region are in the diffusion layer. The diffusion layer thickness, $X_D$, for a particular species at a RDE is given by Equation 4:

$$X_D = 0.6435v^{1/6}W^{1/2}D^{1/3}$$

\textit{Eq. 4}
where \( v \) is the kinematic viscosity of the solution (cm\(^2\) s\(^{-1}\)), \( W \) is the rotation speed of the RDE (Hz) and \( D \) is the diffusion coefficient of the species (cm\(^2\) s\(^{-1}\)). The thickness of the diffusion layer can be controlled by the rotation speed of the RDE.

Under conditions where the rate of the reaction occurring at the RDE is limited only by the rate of mass transfer of the reactant to the electrode and the concentration of reactant at the electrode surface is so small that it may be assumed to be zero, the RDE mass transport limited current, \( i_L \), for a reaction is predicted by the Levich equation (Equation 5):

\[
i_L = 1.554nFAD^{2/3}W^{-1/2}v^{-1/6}W^{1/2}
\]

**Eq. 5**

By measuring \( i_L \) at different rotation speeds a plot of \( i_L \) versus \( W^{1/2} \) should give a straight line. The Levich relationship describes a simple electron transfer at the electrode surface. However, many electrochemical processes may involve a process that is independent of the potential prior to the electron transfer (Scheme 34).

\[
O \xrightarrow{k_1} O^* \xrightarrow{k_2} R
\]

**Scheme 34**

The observed rate constant is given by

\[
1/k = 1/k_1 + 1/k_2
\]

where \( k_1 \) is the rate constant of the transport independent step and the smaller of the two constants is the rate limiting step. In this case, the equation for the mass transport limiting current is given by equation 6 and can be rearranged to equation 7. This is the Koutecky-Levich equation.
nFAC_\infty - i_L = 0.6435D^{2/3} \nu^{1/6}/W^{1/2} + 1/k_l

Eqn 6

1/i_L = [0.6435\nu^{1/6}/nFAD^{2/3}W^{1/2}] + 1/k_l

Eqn 7

In equations 6 and 7, n, is the number of electrons needed to reduce or oxidise one molecule of reactant, F is Faraday constant, A is the area of the Pt disc, D is the diffusion coefficient of the reactant (cm^2 s^-1), c_\infty is the bulk concentration of reactant, X_D is the thickness of the diffusion layer, W is the rotation speed of the RDE (Hz) and \nu is the kinematic viscosity of the solution (cm^2 s^-1). A plot of 1/i_L vs 1/W^{1/2} will give a straight line, the gradient of which may be used to calculate n, if the diffusion coefficient is known. Such a straight line plot indicates first order reaction kinetics, as this is an assumption in the derivation of the relationship. The intercept of the plot gives a measure of the rate of the electrode reaction when the concentration of reactant at the electrode surface is equal to the bulk concentration, and therefore there are no mass transport effects.

6.3 Fluorescence spectroscopy.

6.3.1 Steady state fluorescence spectroscopy.

Most molecules occupy the lowest vibrational level of the ground electronic state. Upon absorption of radiation the molecules are elevated to an excited state. Fluorescence spectroscopy measures the emission of radiation that results from the relaxation of an excited state. This is unlike ultra-violet and infrared spectroscopy which, arise from absorption due to excitation of the molecule. Figure 36 shows the transitions that lead to fluorescence emission.
A = photon absorption  
F = fluorescence (emission)  
P = phosphorescence  
S = singlet state  
T = triplet state  
IC = internal conversion  
ISC = intersystem crossing

Figure 36. Jablonksdiagram.

The molecule on excitation can reach any of the sub levels associated with each electronic state. As the energy is absorbed as discrete quanta, this should result in a series of distinct absorption bands. Figure 36 neglects the rotational levels associated with each vibrational level which would increase the number of possible energy bands. The increase in the number of energy bands can make it impossible to resolve the transitions, therefore most compounds have broad spectra. Some exceptions are flat aromatic compounds where the rotational energy levels are restricted.

On absorption of radiation it is possible to induce the promotion of an electron to an unoccupied orbital. Thus, the molecule is excited to the its next highest electronic state (S1) from its ground state (S0). Upon having absorbed energy and reaching a vibrational level of the S1 electronic state the molecule rapidly loses vibrational energy by collision and it falls to the lowest vibrational level of the state. From this state there are several ways to proceed.
The molecule can return to the ground state by vibrational relaxation, undergo chemical reaction or it can pass to the triplet state by spin inversion of the excited electron. The molecule can return to any of the vibrational levels of the ground state, emitting its energy in the form of a photon (fluorescence).

The transition from the lowest vibrational energy level of the ground state \((S_0)\) to the lowest vibrational level of the exited \((S_1)\) is common to both absorption and emission phenomena, whereas all other absorption transitions require more energy than transition in the fluorescence emission. Therefore the emission spectrum is coincident with the absorption spectrum corresponding to the 0-0 transition. The rest of the emission spectrum is at lower energy, or longer wavelength.

The absorption of energy to produce the first excited state does not perturb the shape of the molecule greatly. This means that the distribution of the vibrational energy levels is very similar in both the \(S_0\) state and the \(S_1\) state. The energy differences between the bands in the emission spectrum will be approximately the mirror image of the absorption spectrum. Figure 37 shows typical fluorescence emission and excitation spectra (steady state fluorescence).

![Figure 37. Typical emission and excitation spectra and the transitions whose intensities are measured.](image)
6.4 Fluorescence lifetime measurements

The measurement of fluorescence lifetimes is far more complex than the measurement of steady-state fluorescence spectra. Fluorescence lifetime measurements can show the presence of more than one molecular conformer in a sample where different conformers have different lifetimes. In this project such lifetime measurements were used to analyse the type and weighting of different components in indolo[3,2,1-jk]carbazole films.

In this project fluorescence lifetimes were measured using the technique of time-correlated single photon counting (TCSPC) and was carried out by Dr Steven Magennis of The University of Edinburgh. In a TCSPC experiment a laser pulse is directed at the sample. This pulse excites the sample and simultaneously starts a 'clock'. When the first photon to be emitted from the sample is detected, the 'clock' is stopped. Typically this process is repeated around 10,000 to 20,000 times and a histogram (decay curve) of the number of counts vs time is built up. A schematic of a single exponential decay curve from a TCSPC experiment is shown in Figure 38 (a).

![Figure 38. Schematic of (a) single exponential decay curve (b) decay curve in (a) plotted with ln(counts).](image)

When a single exponential decay curve is plotted as ln(counts) vs t, the lifetime of the fluorophore, τ, is the inverse of the gradient of the line. Such a plot is shown in Figure 38 (b). Where there is more than one fluorescence lifetime contributing to the data, ie the decay curve is multiexponential, the extraction of lifetimes is more complicated.

7.1 Introduction.

There has been much interest in the formation of indole-based redox active conducting polymers.\textsuperscript{101-107} The film structures formed, apart from being highly conducting, have also been shown to be highly fluorescent with lifetimes in the order of 5 ns.\textsuperscript{89} It is because of these properties that there could be potential applications in light emitting diodes (LEDs). Studies of substituted indole monomers have also shown the oxidation potentials to be tuneable by variation of substituents, however the fluorescence properties are not affected by substitution.\textsuperscript{89} There is therefore a need to investigate indole analogues which may have different fluorescent properties.

It is the aim of this study to identify novel organic conducting systems that have the basic properties that are required for potential application in LEDs. In this thesis indolo[3,2,1-jk]carbazole 1 and pyrrolo[3,2,1-jk]carbazole 2 and their analogues have been studied. The two compounds under study are fused indole type systems with more extensive conjugation. It was hoped that electro-oxidation of these compounds may result in the formation of conducting films which retain the desirable electrochemical features of indole whilst having differing photoluminescence properties to indole. This chapter concentrates on the electrochemistry of indolo[3,2,1-jk]carbazole based monomers. Other systems will be discussed in later chapters.

Preliminary studies have been carried out on the electro-oxidation of indolo[3,2,1-jk]carbazole.\textsuperscript{1} The study was carried out on a platinum working electrode using cyclic voltammetry and rotating disc electrode methods. The results of the studies show that upon electro-oxidation of a solution of indolo[3,2,1-jk]carbazole in LiClO\textsubscript{4}/MeCN a conducting film is formed. Initial rotating disc studies and Koutecky-Levich analysis have shown the reaction to proceed by first order kinetics.\textsuperscript{1} The steady-state fluorescence properties of the film species have been studied, showing the film to be highly fluorescent in the blue region in both solution and as a solid phase. The fluorescence lifetimes of the films were studied. The decay was found to be bi-exponential, yielding lifetimes of \(\sim 10\) ns and \(\sim 5\) ns.
Currently no information is known about which species are formed upon electro-oxidation. The aim of this work was to conduct a more in depth electrochemical and spectroscopic study of the reaction in order to gain an insight into the processes that are occurring at the electrode surface. Further fluorescence analysis is also carried out to confirm that the products formed upon electro-oxidation are consistent with those found in the previous study by M. A. Chapman.¹

### 7.2 Electro-oxidation of indolo[3,2,1-\textit{jk}]carbazole

All electrochemistry was carried out with a solution of the monomer in a background electrolyte of 0.1 M LiClO₄ in acetonitrile. A standard three electrode system was used consisting of a platinum disc working electrode, platinum gauze counter electrode and a Ag/Ag⁺ reference electrode, using AgClO₄ at 0.01 M in background electrolyte. Unless otherwise stated, potentials were recorded and are reported with respect to this electrode. They can also be quoted against the standard ferrocene/ferrocinium couple (Fc/Fc⁺) in the same electrolyte (measured as E⁰ = E₁/₂ = 0.07 V with respect to Ag/Ag⁺ (0.01M)).

The peak oxidation potentials, Eₚ, of the monomers 1 were measured using cyclic voltammetry (CV). In similar studies on indoles it was found that indole monomers are oxidised to form radical cations which then couple to form a redox active “polymer” film.¹⁰¹-¹⁰⁶ The rate of such a coupling is given by equation 8:

\[
\text{rate} = k[m^{++}]^2
\]

(Eq 8)

where k is the rate constant and [m^{++}] is the concentration of the radical cation, m^{++} in solution. At high concentrations the rate is large and hence the coupling of monomer to form polymer can affect the shape of the CV of the monomer. In order to minimise any such effects and obtain the monomer oxidation potential (ideally independent of coupling), low concentration solutions (typically 1 mM) of monomer in electrolyte were typically used to measure the Eₚ.⁸⁹

Figure 39 shows a CV of a 1 mM solution of 1. Cycle 1 oxidation occurs with a peak potential at 1.10 V vs Ag/Ag⁺ (1.03 V vs Fc/Fc⁺) resulting in the deposition of a green
film. On the reverse sweep a small back peak is present at around 1.0 V vs Ag/Ag⁺ followed by a much larger redox peak at 0.60 V vs Ag/Ag⁺. Continued cycling results in the growth of an oxidation peak at 0.75 V vs Ag/Ag⁺ and also the growth of the reduction peak at 0.60 V. The peaks can therefore be attributed to the redox reaction of the film formed by oxidation at 1.10 V, which shows there is appreciable monomer coupling, and that the film is electro-active. The electrode was removed from the solution and washed with acetonitrile and a CV was recorded in background electrolyte (Figure 40). The redox peaks centered around 0.6V in this CV were almost identical to those in the same position in Figure 39, thus confirming that these redox peaks are associated with a redox active surface bound electroactive film.

Figure 39. CV of 1 mM indolo[3,2,1-jk]carbazole solution. In these and subsequent figures the sweep rate \( v = 50 \text{ mV s}^{-1} \) and the initial direction of sweep is to more positive potentials unless otherwise stated.
Figure 40. CV of the resulting film in background electrolyte.

The charge associated with the oxidation peak at +1.10 V in Figure 39 is much larger than the corresponding reduction peak at +1.0V. As with indole at higher concentrations this is consistent with the oxidation being irreversible and the radical cations formed undergoing coupling to form product. Thus, even at this low concentration the coupling of the radical cations is efficient enough to form a film. This coupling is more efficient than for indole (k in eqn. (8) is larger), for which no product redox peaks are observed at this concentration. The radical cations are however stable enough that a small amount remain and cause the appearance of a small back reduction peak near 1.0 V.
Figure 41 shows CVs of a 1 mM solution of the monomer at different sweep rates. As discussed in Chapter 6.2.3, for both reversible and irreversible electrochemical systems where the redox active species are in solution, $i_p$ should be proportional to $v^{1/2}$, which demonstrates diffusion control. The CVs that are shown in Figure 41 are observed to hold true to this relationship (Figure 42). It is also observed that as $v$ increases, relatively larger and more distinct back peaks at 1.0 V are observed; this is consistent with less coupling taking place. This is due to the faster sweep rate allowing insufficient time for the radical cations to couple before they are reduced to the indole monomer.

Figure 41. CVs of 1 with varying sweep rate.
7.3 Rotating disc electrode studies (RDE) of electro-oxidation of indolo[3,2,1-\(jk\)]carbazole.

7.3.1 Preamble.

Cyclic voltammetry is a useful technique to give qualitative information about novel systems of interest. However, the technique gives little quantitative information about the electrode kinetics of the reaction. In cyclic voltammetry, the analysis is carried out in an essentially stagnant solution where material can only be brought to the electrode surface by diffusion and relatively inefficient natural convection. When using a rotating disc electrode (RDE) the mass transport to the electrode surface can be controlled through forced convection. This allows quantitative information on the electrode kinetics.
to be obtained. An account of the basics of electrochemical theory is presented in Chapter 6.

7.3.2 Electro-oxidation of indolo[3,2,1-jk]carbazole by potential step voltammetry.

The electro-oxidation of indolo[3,2,1-jk]carbazole was studied by potential step voltammetry (section 6.2) for the purpose of gaining some quantitative data about the electrochemical processes occurring. The technique involves initially holding the system at a potential at which no reaction occurs and then changing the potential to that required for mass transport limited reaction. Mass transport to the working electrode was controlled by use of an RDE, which was rotated at a constant speed. This ensured that the rate of mass transport of material to the electrode surface remained constant, giving steady-state currents.

The peak oxidation potential was determined to be +1.10 V from the CV of the monomer in section 7.2 (Figure 39). The electropolymerisation potential selected was therefore 1.19 V vs Ag/Ag⁺, 0.09 V above that of the the peak oxidation potential of the monomer. As the film grows oxidation of the oligomers can occur as well as oxidation of the monomer on the redox active film. These oxidation potentials are likely to be lower than the oxidation potential of the monomer. Therefore an oxidation potential of +1.19 V should be sufficient to ensure that electrochemical oxidation is not the rate determining step of film formation and steady state currents should be observed at the RDE.

The electro-oxidation of indolo[3,2,1-jk]carbazole at a rotating platinum disc working electrode by potential step voltammetry was carried out on a range of concentrations, c₀, between 1 and 20 mM. The electro-oxidation was studied at different rotation speeds, W, between 1 and 16 Hz for each concentration. A typical current/time transient for the reaction is shown in Figure 43, for the electro-oxidation of a 10 mM solution at W = 1 Hz.
Figure 43. Current/time transient for the electro-oxidation of a 10 mM solution of indolo[3,2,1-jk]carbazole at $W = 1$ Hz.

The above transient shows an electro-oxidation that was carried out over a period of approximately 10 seconds. During this period of time a green/black insoluble film was deposited onto the electrode surface. The transient shows a sharp rise after an initial spike which reaches a peak before subsiding into a steady-state current. The time for establishment of this steady-state current is of the order of that required to establish steady-state hydrodynamics. This steady-state current continues for minutes, which is indicative of steady state growth of a conducting species on the electrode surface. The film continues to grow in thickness as time progresses.
The film produced from the rotating disc electrode was analysed by cyclic voltammetry in a stagnant solution of background electrolyte and was observed to give stable peaks upon repeated cycling (Figure 44). This indicates that the film remains on the electrode surface. The film was washed with acetonitrile prior to analysis to ensure no residual monomer was trapped. The CV was then recorded at varying sweep rates (Figure 45) and the peak redox potentials were plotted against the sweep rate (Figure 46).

Figure 44. Repeat cycling of an indolo[3,2,1-jk]carbazole film formed in Fig. 43.
Figure 45. CV sweep rate variation of the IC film formed in Fig. 43.

Where the film redox kinetics are fast with respect to \( v \), the whole film is reduced/oxidised on each sweep. As a consequence, the peak current, \( i_p \), will be proportional to \( v \), whereas when film kinetics are slow with respect to \( v \), the whole film is not reduced/oxidised on each sweep and \( i_p \) becomes smaller, approaching \( i_p \propto v^{1/2} \) for diffusion limited reaction of the redox centres in the film. Figure 46 shows a linear relationship \((i_p \propto v)\) between the peak currents and the sweep rate at all the sweep rates employed. This is indication of complete oxidation and reduction of a surface bound species, with the whole film being oxidised and reduced on each sweep. As a consequence of these fast redox kinetics, the area under each peak (proportional to the integral of current with respect to time) gives the charge required to fully oxidise or reduce the film. Films above a certain thickness fail to follow this relationship. The
failure to comply with this relationship occurs mainly at the faster sweep rates due to the sweep rate being too fast for a thick film to be completely oxidised or reduced.

Figure 46. A plot of the peak oxidation and reduction currents, $|i_p|$, from Fig. 45.

For fast kinetics such as these, the area under the redox peaks gives the total redox charge. This charge can then be compared to the charge passed during film formation (Figure 43). Comparison shows that the redox charge is 33\% of the polymerisation charge. This ratio was found to be constant for film formation at rotation speeds between 1 and 16 Hz and for a variety of concentrations between 1 and 20 mM. These experiments were repeated to ensure consistent results. This calculation was also supported by a similar calculation from the $v = 50$ mV s$^{-1}$ CV recorded of the monomer at 1 mM (Fig. 39). The charge ratio was calculated for the charge passed in the oxidation of the monomer (peak at +1.10 V) and the charge passed in the reduction of the resulting
film (peak at +0.6V). The ratio was also shown to be 3:1 and supports the calculation described in the previous paragraph. This also suggests that a similar polymerisation efficiency is obtained in both experiments.

A FAB mass spectrum was obtained for the film resulting from electrooxidation of a 20 mM indolo[3,2,1-jk]carbazole solution. The sample for FAB mass spectrometry was prepared by electro-oxidising the IC solution at W = 2 Hz for 2-3 minutes until the steady-state current began to drop, at which point the reaction was ceased by stepping the potential back to 0 V. The potential was held for 30 seconds to ensure the film was fully reduced. The sample was then removed from the electrode by gentle scraping. The only significant mass peak was found at \(m/z\) 481. This mass corresponds to that of an M+1 peak of a dimer of indolo[3,2,1-\(jk\)]carbazole coupled with a single C-C bond (as the monomer mass is 241). High resolution FAB mass spectrometry confirmed that the accurate mass (M+1) was 481.1628 which corresponds within experimental error to this dimer (M+1, 481.1660), with its molecular formula of C_{36}H_{20}N_{2}. Full spectral characterisation of the film will be detailed in Chapter 8.

The simplest explanation of these observations is that the film consists entirely of dimers and the redox reaction involves 1 e\(^{-}\) for the dimer species. Given the 33% ratio, this would suggest that three electrons are involved in the electro-oxidation of the monomer and formation of the dimer. It can be thought that two of the three electrons are from the initial oxidation of two indolo[3,2,1-\(jk\)]carbazole molecules to form radical cation species. These radical cations can then couple with loss of two protons and the formation of the required single C-C bond. As the oxidation is carried out at 1.19 V vs Ag/Ag\(^+\) and the redox peaks for the film are centred around 0.6 V vs Ag/Ag\(^+\), the film will be found in its oxidised state and this will account for the third of the electrons involved in film formation. This is therefore consistent with the film being a dimer species. The proposed mechanism of dimer formation is shown in Scheme 123 where IC represents one indolo[3,2,1-\(jk\)]carbazole monomer.

7.3.3 Koutecky-Levich analysis of IC film formation.

The indolo[3,2,1-jk]carbazole film formation was investigated at different rotation speeds of 1, 2, 4, 9 and 16 Hz for solutions of varying concentration between 1 and 20 mM. Typically, to minimise systematic errors, the rotation was set to 1 Hz and the potential was stepped from 0 V to 1.19 V vs Ag/Ag⁺. Once a steady state current was obtained, the rotation speed was increased to 2 Hz. After a steady state was reached the rotation speed was increased to 4 Hz. This process was repeated up to 16 Hz before being decreased through the same rotation speeds until back at 1 Hz again (Figure 46). This experiment was carried out on 1, 2.5, 5, 10, 15 and 20 mM solutions and each experiment was repeated to ensure consistent results. The results were then subjected to Koutecky-Levich analysis to give a Koutecky-Levich plot (Figure 47). Typical results shown in Figure 46 show a rise in the current for each rotation speed on the reverse run. This can be explained by the film growing in area during formation. The result of this is would be a slight increase in the current obtained upon reaction at each particular rotation speed. Therefore the initial “step-up” data was used, as the effective area could be best approximated to the initial electrode area, A.
Figure 46. Current-time transient for the electropolymerisation of 5 mM IC in electrolyte at 1.19 V vs Ag/Ag⁺ at rotation speeds 1, 2, 4, 9 and 16 Hz.

Koutecky-Levich analysis involves plotting the experimental data for each concentration against the parameters of the Koutecky-Levich equation (Eq 9). The parameter $1/i_{\text{obs}}$ is plotted against $W^{-1/2}$. If the results follow this relationship then a straight line plot should be produced with a gradient of $0.6435v^{1/6}/nFAC_{o,w}DW^{1/2}$ and an intercept equal to $1/i_{\infty}$ (see section 6.2).

$$\frac{1}{i_{\text{obs}}} = \left( \frac{0.6435v_{\text{MeCN}}^{1/6}}{nFAC_{o,k}D_{k}^{2/3}W^{1/2}} \right) + \frac{1}{i_{\infty}}$$

(Eq 9)
In the Koutecky-Levich equation, \( i_{\text{obs}} \) is the observed steady-state current (A), \( n \) is the number of electrons needed to reduce or oxidise one molecule of reactant, \( F \) is the Faraday constant (C mol\(^{-1}\)), \( A \) is the area of the Pt disc (0.387 cm\(^2\) in his case), \( D_{IC} \) is the diffusion coefficient of the reactant IC (cm\(^2\) s\(^{-1}\)), \( W \) is the rotation speed of the RDE (Hz), \( \nu_{\text{MeCN}} \) is the kinematic viscosity of acetonitrile (cm\(^2\) s\(^{-1}\)), \( c_{\infty,IC} \) is the bulk concentration of reactant (mol cm\(^{-3}\)) and \( i_0 \) is the current observed as \( W \) tends to infinity, when the current is independent of mass transport.

Figure 47. Koutecky-Levich plots for 1, 2.5, 5, 10, 15 and 20 mM solutions of indolo[3,2,1-ijk]carbazole. The lines shown are lines of theoretical gradient calculated using \( D_{IC} = 3.0 \times 10^{-5} \) cm\(^2\) s\(^{-1}\).
It has already been shown that the species formed on the electrode is likely to be a dimer species and that three electrons are required to be removed from two monomers to form the oxidised dimers in the film. With three electrons over two monomer units, the value of $n$ is therefore taken to be 1.5. From the Koutecky-Levich analysis and the knowledge of the $n$ value, the diffusion co-efficient, which is a constant of the monomer in solution can be calculated using the Koutecky-Levich relationship.

The results from the Koutecky-Levich analysis show that straight line plots are produced for all of the concentrations analysed. This indicates that the oxidation of the monomer proceeds with 1st order kinetics as this is an assumption of the Koutecky-Levich relationship. The data was analysed by fitting the best line to all data. This gave a monomer diffusion coefficient of $D_{IC} = 3.0 \pm 0.5 \times 10^{-5}$ cm$^2$ s$^{-1}$. This result is consistent with that expected for an organic molecule of this size.$^{89}$

The intercepts in the Koutecky-Levich plot (Figure 47) are $1/i_{\infty}$ (eqn. 9), which give the mass transport independent current ($i_{\infty}$, Table 5). This is the current when $W \rightarrow \infty$, mass transport is fast and the concentration of IC at the electrode surface is equal to the bulk concentration of IC. From Figure 47 each straight lines converge at the same intercept at and above 10 mM, giving the impression that the oxidation rate of IC is insensitive to the concentration of the monomer at these concentrations. This is confirmed by the $i_{\infty}$ values, which are the same within experimental error. This shows that the rate of oxidation of IC is insensitive to the concentration of the monomer. At concentrations lower than 10 mM the intercepts do not converge, this suggests that the rate determining step of the monomer oxidation involves an adsorbed intermediate which gradually increases cover of the electrode area with concentration until it is fully covered. This result is similar to that observed for 5-substituted indoles.$^{89}$
<table>
<thead>
<tr>
<th>Monomer concentration (mM)</th>
<th>$i_\infty$/mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.2 ± 0.2</td>
</tr>
<tr>
<td>2.5</td>
<td>3.3 ± 0.2</td>
</tr>
<tr>
<td>5.0</td>
<td>4.3 ± 0.2</td>
</tr>
<tr>
<td>10.0</td>
<td>5.9 ± 0.7</td>
</tr>
<tr>
<td>15.0</td>
<td>4.8 ± 0.5</td>
</tr>
<tr>
<td>20.0</td>
<td>5.9 ± 0.7</td>
</tr>
</tbody>
</table>

Table 5. Mass transport independent currents ($i_\infty$) for IC electro-oxidation.

7.4 Second oxidation potential of film.

It has been found in section 7.3.2 that the product of the electro-oxidation of IC produces a dimeric species. One possible reason for the coupling process halting at the dimer stage is that the dimer radical cation is sufficiently stable that it does not form at the disc potential and therefore cannot couple. If this is the case, unlike indole, it would be expected that there would be a second oxidation potential of the dimers in the film at a markedly higher potential than that of monomer oxidation. If this oxidation potential were reached then a dimer radical cation would be produced which may undergo further coupling.

To test this, an IC film was produced from electro-oxidation of a 20 mM solution of the monomer. This film was cycled in background electrolyte until a constant CV was produced as before. The potential was then swept to potentials above the potential used for film formation (1.19 V wrt Ag/Ag⁺). The CV produced is shown in Figure 48. The CV shows a further oxidation above 1.1 V. On the return sweep a new relatively large reduction peak is also observed at 0.95 V. It is most likely that this is the back reduction peak associated with this second dimer oxidation peak. Therefore, if this oxidation leads to irreversible dimer coupling in the film, this oxidation must be relatively slow and little coupling occurs with each cycle. Furthermore, the fraction of oxidation at 1.19 V is small. This supports the suggestion of insignificant dimer coupling at the potential used
for electrooxidation and film formation. Upon repeated cycling it can be seen that the shape of the CV does change slightly. This could be taken to be an indication of the nature of the film changing. A reason for this change may be that the second oxidation of the film causes the film to undergo some further coupling. If this were the case the film would become more cross linked in nature; this would be expected to affect film kinetics and hence the shape of the CV would change. It must be remembered that film formation occurs in the presence of monomer, which will be oxidised at these dimer oxidation potentials, further reducing the dimer radical cation concentration in the film compared to these experiments and reducing the amount of dimer coupling even further. These results are therefore consistent with little dimer coupling due to the relative stability of the dimer radical cation.

![Graph showing 2nd Oxidation potential of IC film](image)

**Figure 48. 2nd Oxidation potential of IC film.** The oxidation potential used for film formation and each cycle is labeled.
7.5 Fluorescence spectroscopy of IC monomer and IC film.

7.5.1 Steady state fluorescence spectroscopy.

It was reported by M A Chapman\(^1\) that the both the IC monomer and the IC film were highly fluorescent. The IC monomer was reported to fluoresce at around 375 nm and the film was reported to fluoresce at around 405 nm. The red-shifting of the fluorescence spectrum is a good indication that the monomer has undergone linkage to form a larger conjugated system.

For the purpose of comparison to M A Chapman’s film, the fluorescence spectra of the monomer and the film products were recorded in DMF at \(10^{-6}\) M concentration. Emission spectra for the monomer were recorded at differing excitation wavelengths and are shown in Figure 49. It can be seen that there is a major emission with a peak at 374 nm with a minor emission with a peak at 340 nm. The minor emission was assigned to be due to minor impurities in the monomer left over from its synthesis. It was found that the shapes of the emission spectra at 374 nm are independent of the excitation wavelength which suggests that Kasha’s rule is obeyed. This means that the emission in each case is always from the lowest vibrational level of the first singlet excited state \(S_1\). It also means that there are unlikely to be any other emitting species present that are excited and emit in the same region as the monomer, such as impurities or aggregates.
Figure 49. Steady state emission spectra of $10^{-6}$ M IC monomer in DMF at fixed excitation wavelengths of 300, 320, 340, 360, 380, and 400 nm. The spectra are all normalised to the peak emission intensity to enable comparison.

The emission spectra of the IC film in solution in DMF were recorded at different excitation wavelengths and the data are presented in Figures 50 and 51. Figure 50 shows emission at their true intensities where Figure 51 shows the emission after normalisation to the same Y-axis limits. The results show similar emission spectra to that of produced by M A Chapman with a peak emission at 405 nm. This longer emission wavelength is characteristic of more conjugated species such as dimers. Emission with a peak at 405 nm is found independent of the excitation wavelength indicating that there is unlikely to be another emitting species in this region. Two other emissions are observed at longer excitation wavelengths; the first is at 456 nm and the second is at 507 nm. It is shown in Figure 50 that these emissions are much less intense than the major emission at 405 nm, although the major emission at 405 nm shows a slight broadening of the peak (Figure 51). This may be an indication that there may be a relatively small amount of more conjugated longer chain products which emit in this region. The fluorescence samples were diluted
and the shapes of the spectra were constant showing that there was no presence of excimers, which should be concentration dependent.

![Figure 50. Steady state fluorescence spectra of IC film at the excitation wavelengths 300, 320, 340, 360, 420 and 460 nm (shown above) in nm as true intensities.](image)

![Figure 51. Steady state fluorescence spectra of IC film at excitation frequencies of 300, 320, 340, 360, 420 and 460 nm at normalised intensities.](image)
The results presented here are essentially identical to those produced by M A Chapman. This indicates that the film formation process is robust and reproducible and that the same fluorophore species are being formed in both sets of experiments.

### 7.5.2 Time resolved fluorescence spectroscopy.

Time resolved fluorescence spectra were recorded by M A Chapman and showed that the film produced a bi-exponential decay yielding fluorescence lifetimes of ~10 ns and ~5 ns for excitation at 360 nm. The purpose of this section is to record the lifetimes of the film and the monomer and to compare the results to that obtained by M A Chapman. The data in this section was recorded and analysed by Dr Steven Magennis of The University of Edinburgh. The sample was prepared by Mr S Wharton and was dissolved in DMF at 10⁻⁶ M concentration. The experimental conditions were as follows; The excitation wavelength used was 360 nm and the lifetimes were recorded at 6 different emission wavelengths (390 nm, 410 nm, 440 nm, 470 nm, 500 nm and 530 nm).

These experiments were carried out under the same conditions as were carried out by M. A. Chapman. The results of the time resolved studies in this work with the film species also showed a bi-exponential decay. Decay plots for IC film are shown in Figure 52 and the lifetime data corresponding to Figure 52 for an emission of 410 nm is shown in Table 6. The decay plot for the IC monomer is shown in Figure 53 and the corresponding lifetime data is also shown in Table 6 for monomer emission at 410 nm.
Figure 52. Fluorescence decays for IC film at an excitation wavelength of 360 nm.

<table>
<thead>
<tr>
<th>Compound</th>
<th>$\tau_1$ / ns</th>
<th>$A_1$/%</th>
<th>$%_1$</th>
<th>$\tau_2$ / ns</th>
<th>$A_2$/%</th>
<th>$%_2$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film</td>
<td>9.47</td>
<td>85.0</td>
<td>92.3</td>
<td>4.47</td>
<td>15.0</td>
<td>7.7</td>
<td>1.023</td>
</tr>
<tr>
<td>Monomer</td>
<td>12.90</td>
<td>85.3</td>
<td>92.5</td>
<td>5.70</td>
<td>14.7</td>
<td>7.5</td>
<td>1.054</td>
</tr>
</tbody>
</table>

Table 6. Fluorescence decay parameters for the decay measured for the IC film formed at 1 Hz at an emission of 410 nm and for the IC monomer also at 410 nm. The excitations were carried out at a wavelength of 360 nm. $\tau_n$ is the lifetime of component n, $A_n$ is the A factor for component n (which gives the percentage amount of component n) and $\%_n$ the %-contribution to the steady-state emission intensity of component n.
From Table 6, it can be seen that lifetimes of 9.5 ns and 4.5 ns were obtained for the film, with the 4.5 ns contribution being the minor one (contributing 7.7% of the total steady-state emission). The film shows variations in the fluorescence decay with emission wavelength. However, these variations are small at wavelengths where the polymer emission is strong (e.g. 410 and 440 nm). In other words, impurities may contribute more at longer wavelengths. Global analysis may clarify this. At the peak of the polymer emission, the decay of each sample is well described by biexponential kinetics.

Clearly, the bulk of the monomer emission arises from a ca. 12-13 ns component. There also appears to be a second component of ca. 5 ns, which accounts for ca. 5% of the emission. The second component in the dimer lifetimes was around 4.5 ns, so the same "impurity" could be present in monomer and dimer samples. Global analysis of the monomer and dimer data may provide more information.
Analysis of the monomer by other techniques such as $^1$H NMR spectroscopy do not usually easily show up impurities lower than 1% due to the sensitivity of most instruments. The analysis of low level impurities can be made possible by use of a high field instrument such as a 600 MHz spectrometer. If the $^{13}$C satellite peaks of the other signals can be made visible then $^1$H NMR active impurities can be observed to around 0.5%. This is due to $^{13}$C being 1.1% in natural abundance and each single peak having an outlying satellite of 0.55% on each side of the $^1$H signal. Analysis of the IC sample used for dimerisation by $^1$H NMR spectroscopy at 600 MHz shows low level impurities of the order of 1%.
Chapter 8. IC Film Characterisation.

8.1 Preamble.
Previous work (Chapter 7) has shown that indolo[3,2,1-\textit{jk}]carbazole forms an electrically conducting film on a platinum working electrode surface upon electro-oxidation. The film produced is also shown to be highly fluorescent in the blue region of the visible spectrum in solution and in the solid phase. Spectroelectrochemical characterisation has indicated that the species formed at the electrode may be dimeric in nature. The purpose of this section is to fully characterise the structure of the species formed.

8.2 Spectroscopic, mass spectrometry and computational characterisation.

8.2.1 FAB mass spectrometry
The FAB mass spectrum was reported in section 7.2 and showed the species to consist of IC dimers ($m/z$ 481, MH$^+$).

8.2.2 HPLC analysis.
As the mixture appears to consist of dimers it is thought that it would be possible to separate the dimers by chromatography. HPLC conditions were varied in order to investigate the separation of the components. The best HPLC conditions were found to be:
Column – Spherisorb S5-ODS1
Flow rate – 1 cm$^3$ min$^{-1}$
Injection volume – 20 µL
Detection wavelength – 254 nm
Eluant gradient – A = 9:1 water/MeCN, 1% NH$_4$Ac and B = MeCN
The gradient used is shown in Table 7. The HPLC chromatogram is shown in Figure 54.
Table 7. Solvent gradient for HPLC analysis.

<table>
<thead>
<tr>
<th>Time/min</th>
<th>%B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>30</td>
<td>95</td>
</tr>
<tr>
<td>55</td>
<td>95</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 54. HPLC chromatogram of IC film mixture.

It is shown in Figure 54 that the film consists of three major components in approximately 1:2:1 ratio by integration of the peak areas. Several minor impurities are also observed for the film species. These impurities may account for the minor fluorescence lifetime associated with the film species as described in the previous
The possibility of any overlapping peaks in any of the three major signals was investigated by changing the eluant gradient and also by using various isocratic solvent systems. In some cases poor separation was observed, however in all cases where good separation was observed the peaks observed were all Gaussian in shape indicating that they were likely to consist of one species. The presence of another species with a similar retention time would still likely result in the distortion of the peak shape.

8.2.3 Density functional theory.
Density functional theory (DFT) calculations were carried out by M.A. Chapman on the spin density of the IC monomer radical cation formed upon electro-oxidation. The result (Figure 55) of these calculations gives information about the radical cation distribution around the system. The sites of high electron density are marked by asterisks in Figure 55. The result of the DFT calculations allows the identification of potential sites of linkage. The radical cations that are formed can then couple to give products. The sites next to the cavity are likely to be too hindered for coupling to occur and are neglected.

Figure 55. DFT spin density calculation results. Potential coupling sites are shown by * hindered sites, where coupling is unlikely to occur, are shown by **.

8.2.4 NMR characterisation.
A sample for NMR spectroscopy characterisation was generated at 4Hz rotation speed from a 20mM solution of IC in 0.1M LiClO₄/MeCN as described in section 7.2; this process was repeated until sufficient quantity was produced for NMR analysis. The sample was found to be soluble in DMSO and THF. DMSO-d₆ was used for the analysis due to availability and cost. It was observed that there was a significant difference in the quality of spectra acquired at different field strengths. A ¹H NMR spectrum was recorded at 200 MHz and it was found that the spectrum was highly structured in nature.
which is not a feature that would be associated with polymers. A polymer usually yields a very broad spectrum due to its relatively slow molecular tumbling characteristics. This spectrum contained a large amount of overlapping signals therefore a $^1$H spectrum was recorded at 600 MHz in order to attain the best possible dispersion. The spectrum was found to broaden at high field strength.

The sample was diluted with acetone-$d_6$ and a $^1$H NMR spectrum was recorded (Figure 56). It was found that the spectrum was significantly improved in structure which was thought to be due to making the sample less viscous. The sample was analysed on a Bruker Avance 600 MHz spectrometer. The spectra that were obtained were a $^1$H spectrum, a COSY, an HSQC and a NOESY (Figures 54, 55, 56 and 57 respectively). All figures contain the appropriate expansions for the following analysis.

![Figure 56](image)

**Figure 56.** 600 MHz $^1$H NMR spectrum of IC film in acetone-$d_6$/DMSO-$d_6$.

It is clear from the HSQC (Figure 58), (which was run in order to separate out the overlapping $^1$H signals using the $^{13}$C dimension) that the signals at 8.05 ppm are two
different sets of doublet of doublets, the signals at 8.56 ppm are 2 separate singlets and the signals at 8.69 ppm are 2 different doublets. It can be clearly seen from the COSY spectrum (Figure 57) that there are two distinct different 1,2,4-trisubstituted aromatic substructures 1. These are marked by black lines in Figure 55. The COSY confirms the signals at 8.56 ppm are singlets as there is no coupling associated with these signals.

The signals visible which are not part of overlapping signal patterns (8.05 ppm and 8.69 ppm show typical structure of substructure 298 i.e. a meta coupled singlet with a coupling constant of around 1.5 Hz (8.69 ppm) and a doublet of doublets with couplings of around 8.0 Hz and 1.5 Hz (8.05 ppm). One of the signals is not apparent due to its coincidence with an overlapping multiplet at around 8.3 ppm, however it is shown by the presence of the COSY correlation. It was found that the HSQC (Figure 58) separated these signals in the $^{13}$C dimension. The 1D data for these signals were extracted from the 2D data (Figure 60) and shows two doublets with coupling constants around 8.0 Hz.

![Structure 298](image)
Figure 57. 600 MHz 2D COSY spectrum of IC film in acetone-$d_6$/DMSO-$d_6$. 
Figure 58. 600 MHz 2D $^1$H/$^{13}$C HSQC spectrum of IC film in acetone-$d_6$/DMSO-$d_6$.

Taking into account the analysis performed so far, if the structure is an IC dimer the only sub-structure that can give an uncoupled singlet is an IC molecule that is substituted in the 2-position 299. The protons either side of the substituent are identical in nature and would give a singlet. It is observed in the spectrum that there are at least two of these types of molecule that are visible in the $^1$H spectrum. It was proposed that there were two differing 1,2,4-trisubstituted aromatic substructures that were visible in the $^1$H spectrum by inspection of the COSY (Figure 57) and HSQC (Figure 58) spectra. Structures 300 and 301 represent the only possible IC sub-structures that can have 1,2,4-trisubstituted benzene units.
Structures 302 to 306 show all dimer possible structures from the NMR analysis discussed above. A 2D NOESY was obtained at 360 MHz (Figure 59) in order to establish the connectivity of the dimers present in the mixture. It is clear from the NOESY spectrum that dimer 304 or 306 is present in the mixture. It is possible to say this due to the presence of an NOE correlation between one of the meta coupled doublets from the 1,2,4-trisubstituted aromatic substructures to a doublet of doublets from the same 1,2,4-trisubstituted substructure. This correlation is marked by the black line in Figure 59. This correlation is only possible from the symmetrically coupled dimers 304 and 306. Dimer 306 was ruled out as a possibility, due to the result of the DFT calculation on the IC radical cation species showing the sites of high electron spin density. The coupling site in dimer 306 is not one of high electron density predicted by the DFT calculation results. It is therefore proposed that dimer 304 is present in the dimer mixture.
One of the singlets shows an NOE correlation to the other meta coupled doublet and doublet of doublets that is associated with the second 1,2,4-trisubstitued aromatic substructure indicating it is either due to dimer 302 or 303 (green line in Figure 59). It was not possible to analyse the $^1$H spectrum further due to the overlapping of the peaks. Distinguishing between 302 and 303 can be done based on chemical shifts. It is shown that the meta coupled doublet in 304 is at 8.7 ppm. This doublet is adjacent to the benzene ring and is meta to the central nitrogen and would not be subject to the resonance effects of the nitrogen lone pair of electrons. The meta coupled doublet (resulting from a proton only coupled to a meta proton) in dimer 302 is in a similar chemical environment as 304. It would be reasonable to expect a similar chemical shift in each case. In the case of dimer 303 the meta coupled doublet is not adjacent to a benzene ring and is meta
to the central ring nitrogen. As a consequence it will experience the resonance effect of the lone pair of electrons from the nitrogen. It would be reasonable to expect it to have significantly larger shielding effect than that of the corresponding signal in dimer 302. This would result in a lower chemical shift. It can be seen from the $^1$H NMR spectrum that the second meta coupled doublet is next to the one that is accounted for by dimer 304. This would imply that the second 1,2,4-trisubstituted aromatic substructure is due to the presence of dimer 302. The results of the DFT calculations support the proposal that the dimer is structure 302 as the coupling in 303 does not follow the pattern predicted by the DFT calculations. The above chemical shift argument can also be used to justify the assignment of 304 over 306.

No significant correlation is shown for the other singlet at 8.56 ppm. This is likely to indicate that it is due to the other symmetrically coupled dimer 305. It is proposed that the film mixture consists of dimers 302, 304 and 305 in a 2:1:1 ratio calculated from the $^1$H NMR spectrum integrals.

Figure 59. 360 MHz NOESY spectrum of IC film.
8.3 Total synthesis of dimers.

Further confirmation of dimer structures was obtained by synthesising authentic specimens of the proposed structures and analysing them by NMR and HPLC. The fluorescence characteristics and CVs of the dimers were also recorded and compared to those of the electrochemical products.

8.3.1 Retrosynthesis.

Schemes 124, 125 and 126 show a retrosynthesis for each of the dimers. Each of the retrosyntheses consists of an initial disconnection at the biaryl linkage. This bond could potentially be formed by Suzuki coupling reaction, which is the Pd (0) catalysed coupling of a boronic acid with an aryl halide or triflate.118 Standard syntheses of aryl boronic acids consist of lithium-halogen exchange of an aryl bromide and reaction with a trialkylborate ester or reaction of the aryl Grignard reagent with the same borate ester.119,120

Scheme 124
The three retrosyntheses shown in Schemes 124, 125 and 126 show disconnections to two distinct substructures (307 and 308). The bromo substituted 264 and 279 have been previously reported in this thesis and both could potentially be used in a Suzuki coupling reaction. In order to attempt the Suzuki biaryl coupling, IC boronic acids substituted in positions shown in 307 and 308 are also required. The boronic acids can be prepared from the aryl bromides.

Both the Kumada \(^1\) (Grignard) and Negishi \(^2\) (organozinc) coupling could also be attempted to form the required carbon-carbon bond. These types of coupling are also Pd catalysed reactions involving the coupling of an aryl halide with a Grignard reagent of organozinc compound respectively. Both aryl bromides have been synthesised by Tucker \textit{et al.} \(^2\) who also attempted to form Grignard reagent without success. The use of magnesium powder also did not prove successful even with heating and addition of
iodine. Decomposition of the starting material was all that was reported to occur. Grignard synthesis was also unsuccessful in this work. It was due to this problem that it is anticipated that the arylzinc compound may also be problematical in formation. It was therefore decided to attempt a Suzuki coupling and prepare the required boronic acids.

8.3.2 Boronic acid synthesis.

8.3.2.1 Introduction.

Indolo[3,2,1-ijk]carbazole-2-boronic acid 309 can be synthesised via the Grignard or aryl lithium. Due to the difficulty of preparing Grignard reagents with IC the butyl lithium methodology was chosen for this study. Significant advances have been made in Grignard chemistry since the 1930's, such as the discovery by Reike\textsuperscript{123} of the generation of highly active, finely divided magnesium powder. The magnesium powder in question is generated \textit{in situ} by reduction of MgCl\textsubscript{2} with molten potassium in refluxing THF or molten Na in diglyme. This type of magnesium is known to enhance the rate of formation of Grignard reagents to such an extent that it is now possible to prepare reagents, such as phenylmagnesium fluoride which was not possible before.\textsuperscript{124} Due to safety issues concerning the use of potassium metal in refluxing THF, the aryl lithium methodology was used rather than Grignard chemistry.

\[ \text{B(OH)}_2 \]

8.3.2.2 Indolo[3,2,1-ijk]carbazole-2-boronic acid.

The starting point for this synthesis was to attempt to utilise known methodology such as that for the synthesis of 1-naphthylboronic acid 310 (Scheme 127).\textsuperscript{125} This is the reaction of 1-bromonaphthalene 311 with \textsuperscript{9}butyl lithium at -78 °C followed by addition of trimethyl borate, warming to room temperature and subsequent acid hydrolysis.
This strategy was directly applied to the synthesis of indolo[3,2,1-jk]carbazole-2-boronic acid 309 (Scheme 128). Unfortunately, no product was formed, only indolo[3,2,1-jk]carbazole was produced. The synthesis was repeated with 10 equivalents of trimethyl borate and still no product was formed. The aryl bromide was clearly undergoing the lithium-halogen exchange due to the observation of a colour change of the clear solution of arylbromide to a yellow/green colour upon addition of $^n$butyl lithium.

It was thought that the reason for failure to produce the desired product was due to an unusual lack of reactivity of the aryl lithium species. The aryl lithium species formed was allowed to stir for longer at room temperature in the presence of the borate ester. However, no product was formed. The species retained its yellow/green colour even after stirring at room temperature for a period of 3 hours; this is unlike other aryl systems such as lithiated naphthalenes which react when warmed to room temperature.$^{125}$

The next stage of the development was to heat the reaction mixture to 40 °C after 2 equivalents of borate ester was added. After work up, the required mass of the boronic acid was detected by electrospray mass spectrometry. However by $^1$H NMR spectroscopy, the crude material recovered was almost entirely indolo[3,2,1-jk]carbazole with some unidentifiable impurity. The reaction was repeated at 60 °C and it was observed that there was an increase in the intensity of the impurity signals that were present in the 40 °C product. The reaction was repeated with 10 equivalents of trimethyl borate and yet another increase in the impurity proton signals was observed. It became clear that these signals were potentially associated with product. The sample was also analysed by $^{11}$B NMR spectroscopy and it was found that a boron signal was observed at ~35 ppm relative to boron trifluoride etherate as an external reference. This is the
position (30 to 40 ppm) at which arylboronic acids and esters are expected to appear.\textsuperscript{126} \textsuperscript{11}B NMR spectra were also run for trimethyl borate and boric acid and it was found that the signal at 35 ppm was not due to the either of these compounds. The triisopropyl borate and acid \textsuperscript{11}B resonances were present at around 20 ppm.

It has been reported that boronic acid formation is improved by the use of a bulkier borate ester.\textsuperscript{125} The reaction at 60 °C was repeated with 2 equivalents of triisopropyl borate and the resulting \textsuperscript{1}H NMR spectrum proved to be very complicated with the unknown signals observed in the previous attempts increasing in size to account for around 50% of the total spectrum. The quantity of triisopropyl borate was increased to 10 equivalents and it was found that the \textsuperscript{1}H NMR spectrum had become much cleaner and showed very little indolo[3,2,1-\textit{jk}]carbazole 1. The spectrum showed a large singlet at 8.68 ppm (DMSO-\textit{d}_6) which would be expected if the molecule was substituted as shown by 309. This signal was shifted in comparison with that of the bromo precursor (8.44 ppm). All NMR work was carried out in DMSO-\textit{d}_6 due to the solubility of the boronated species. The bromo precursor and indolo[3,2,1-	extit{jk}]carbazole are soluble in CDC\textsubscript{13}, thus providing further evidence that it was not starting material. The poor solubility of the product provided an effective purification method to remove any IC or unreacted starting material.

Based on the singlet giving an intensity of 2 protons the total integral count of the \textsuperscript{1}H NMR spectrum did not match what was required. The \textsuperscript{13}C NMR spectrum however, showed the presence of twice as many carbon signals as should be expected. Further characterisation by FAB mass spectrometry indicated a presence of an M+1 peak at 370, this would correspond to the mass of the aryl borate ester. The proton NMR spectrum did not, however, show any distinct isopropyl group even after boron NMR decoupling experiments were carried out. This may indicate that any ester may be at levels that cannot be detected by NMR spectroscopy but can still be detected by mass spectrometry. Boronic acids are known to form dehydrated trimers known as boroxines \textsuperscript{312} when heated \textsuperscript{127} and it is thought that this might be what was occurring to produce multiple peaks. However, no mass peak was found for this species by FAB, EI or electrospray
mass spectrometry. Analysis by LC-MS using the conditions used for the analysis of the IC dimers showed a major peak at 80% by area in the HPLC chromatogram but had no mass associated with it. This suggests it was not that of the boronic acid as it would be expected to be ionisable by electrospray ionisation techniques. This peak could be that of the boroxine trimer 312 which may not be ionisable by electrospray mass spectrometry and may be broken down by the harder techniques of electron impact or FAB mass spectrometry.

Characterisation of the boronated species was carried out by $^1$H, NOESY, COSY, HSQC and $^{11}$B NMR spectroscopy. The $^1$H NMR spectrum at first glance showed what looked to be the expected substitution pattern, however the integral count was in error and there were additional signals that could not be accounted for. The HSQC confirmed that the signal that was thought to be a singlet was indeed a singlet. The NOESY correlated this signal to a doublet which would be expected from an IC substituted in the position shown by 309. The $^{11}$B NMR spectrum confirmed the presence of the appropriate boron type species at 35 ppm, however there was a slight broadening of this peak which may have represented an overlapping resonance. A second minor resonance at 23 ppm confirmed that there was more than one boron species in the mixture. It was not possible to assess what the actual components were by NMR spectroscopy, however, electrospray mass spectrometry provided evidence that there was some boronic acid present. IR spectroscopy also provided evidence for the presence of the B-O bond (1340 cm$^{-1}$).

The reaction is shown in Scheme 127 and shows the boronated (boronic acid, borate ester or boroxine) species was recovered in an 80% crude yield by mass. Final characterisation of the species was carried out by Suzuki coupling to form dimer species 305. If it is a mixture of boronic acid, ester and boroxine, Suzuki coupling should produce only dimer 305 as the ester and boroxine will be hydrolysed under the basic Suzuki coupling conditions. This will be discussed more fully in section 8.3.3.
8.3.2.3 Indolo[3,2,1-\(jk\)]carbazole-5-boronic acid.

The methodology described above was applied directly to the synthesis of isomeric aryl boronic acid 313. As with the previous synthesis, species with the appropriate boron substitution were produced in 75% yield, though species characterisation was ambiguous. Most of the \(^1\)H spectrum was overlapping at 360 MHz and the \(^{13}\)C spectrum showed more carbon signals than expected. Analysis by \(^{11}\)B NMR spectroscopy showed the presence of two boron signals, one at 35 ppm and a minor one at 25 ppm. The chemical shift of boronic species with the general formula RB(OR')\(^2\) is known be \(-35\) ppm.\(^{125}\) Electrospray mass spectrometry shows a molecular mass peaks at \(m/z\) 284 and 285; these are representative of the \(^{10}\)B and \(^{11}\)B isotopes of the IC boronic acid 313. IR spectroscopy showed the presence of a B-O bond (1340 cm\(^{-1}\)).\(^{128}\) No further characterisation of the product was possible. Experimental support for the synthesis of the required boronic species was provided by homo-coupling under Suzuki conditions to provide dimer 304. This will be discussed in a later section.
8.3.3 Suzuki coupling.

8.3.3.1 Homo-coupling

8.3.3.1.1 2,2'-bisindolo[3,2,1-jk]carbazole.

Suzuki coupling conditions were employed to produce dimer 305 from 274 and 309 (Scheme 129) using Pd(PPh3)4 and K2CO3 in dioxane/water (3:1).129 Dimer 305 precipitated and was filtered and washed with dioxin/water to give 305 in a 80% preparative yield after 4 hours. The product was characterised by 1H (Appendix 4), 13C/DEPT 90, COSY, NOESY and HSQC NMR spectroscopy at 360MHz (1H) and 91 MHz (13C) and by high resolution FAB mass spectrometry. The dimer was sparingly soluble in DMSO-d6, however it was more soluble in THF-d8. Full NMR characterisation was carried out in THF-d8. However, 1H NMR spectroscopy was also carried out in DMSO-d6/acetone-d6 (30:70) for comparison with the NMR spectroscopic data of the electrochemically produced mixture.

Scheme 129
8.3.3.1.2 5,5'-bisindolo[3,2,1-jk]carbazole.

The conditions used for the 2,2'-dimer 305 were used for the 5,5'-dimer (Scheme 130). The dimer was formed in 65% yield. The lower yield was likely due to problems with the reaction and work up conditions. Even though the reaction was left for exactly the same time as the previous dimer synthesis (section 8.3.3.1.1) the product precipitated out as a thick white slurry after about 30 minutes. After this time with stirring, the product quantity appeared to reduce and the mixture became light brown. This suggests that some degradation of product may have occurred. The product was also purified by column chromatography on silica, during which some product may have been lost. The yield may therefore be improved by filtration after 30 min. The product was characterised by \(^1\)H (Appendix 5), COSY, NOESY, HSQC and HMBC NMR spectroscopy at 360/600 MHz and also by high resolution FAB mass spectrometry. The \(^1\)H, COSY and NOESY NMR spectra were recorded at 360 MHz in THF-\(d_8\). Solubility problems prevented 1D \(^13\)C data from being acquired, however the acquisition of an HMBC spectrum allows quaternary carbon data to be extrapolated by comparison with an HSQC spectrum at 600 MHz (\(^1\)H) and 150 (\(^13\)C) in DMSO-\(d_6\). The \(^1\)H NMR spectrum was also recorded in acetone-\(d_6\)/DMSO-\(d_6\) for comparison with the electrochemically produced dimer mixtures.

\[
\begin{align*}
\text{N} & \quad \text{Br} \\
\end{align*}
\]

\[
\begin{align*}
\text{RO} & \quad \text{B} & \quad \text{RO} \\
\end{align*}
\]

\[
\begin{align*}
\text{4\% Pd(PPh}_3)_4 & \\
5\text{eq K}_2\text{CO}_3 & \\
dioxane/water(3:1) & \text{reflux, 12 h} \\
\end{align*}
\]

65%

\[
\begin{align*}
\text{304} \\
\end{align*}
\]

Scheme 130
8.3.3.1.3 Heterocoupling - 2,5'-bisindolo[3,2,1-jk]carbazole.
The conditions used for the 2,2'-dimer were used for the synthesis of the 2,5'-heterodimer 5 (Scheme 131). The hetero-dimer was produced in 60% yield after column chromatography and was characterised by \(^1\)H (Appendix 6), \(^1^3\)C/DEPT 90, COSY, NOESY and HSQC NMR spectroscopy at 360/600 MHz and by high resolution mass spectrometry. This isomeric dimer proved to be the most soluble of the three dimers (in dioxane, DMSO and THF), however the sensitivity of a Bruker Avance 600 NMR spectrometer was required to acquire the \(^{13}\)C NMR data due to the maximum concentration of the dimer in DMSO/acetone being relatively low.

![Scheme 131](image)

8.4 HPLC analysis of the synthetic dimers.
HPLC analysis of the dimers was carried out to ensure purity and to compare the retention times with those of the electrochemistry mixture. The same experimental method as used in section 1.1.2 was used. Dimers 302 (Appendix 7), 304 (Appendix 8) and 305 (Appendix 9) were run individually and were also run as individual spikes in the electrochemistry sample. The HPLC chromatograms of authentic samples of 302, 304 and 305 show peaks with similar retention times to the peaks in the electrochemical mixture. When each dimer was individually spiked into the mixture the appropriate peak increased in intensity whilst retaining it shape, indicating the species is likely to be the
same and confirming the assignment of the individual dimers formed during electrochemical film formation. The results of the spiking are represented in Figure 61.

Figure 61. HPLC chromatogram showing dimer peaks.

8.5 Comparison of electro-synthetic and synthetic dimers by NMR spectroscopy. The NMR data recorded for characterisation purposes was carried out in a range of solvents in order to minimise solubility problems. However for comparison with the electro-oxidation dimer mixture the same solvent mixture was used (acetone-$d_6$/DMSO-$d_6$ 70:30). Samples were prepared by first dissolving in DMSO-$d_6$, then diluting with acetone-$d_6$ and finally filtering to remove insoluble material.

Although the NMR spectra of the synthetic dimers are comparable upon visual inspection to those obtained for the electro-synthetic mixture, further analysis by spiking was be carried out to confirm their presence in the electrochemical mixture. The results
of such an experiment would back up the HPLC analysis described in the previous section and support the proposal of the formation of dimers 302, 304 and 305 by electro-oxidation. A sample of each dimer was individually spiked into a sample of the electrochemical mixture and the $^1$H spectrum was recorded. Each spike in turn increased the intensity of the appropriate peaks in the $^1$H spectrum of the electrochemical mixture. The $^1$H NMR spectra of the dimer authentic specimens are shown in Appendices 4, 5 and 6. The $^1$H NMR spectra for the spiked samples are in Appendices 10, 11 and 12. The results of the spiking are represented in Figure 62 and show which signals are due to which dimer. The results are consistent with the analysis of the electrochemical dimer mixture NMR spectra. The ratio of dimer 302:dimer 304:dimer 305 was calculated to be 2:1:1 from the $^1$H NMR spectrum integrals and is consistent with the HPLC analysis ratio.

Figure 62. Representation of $^1$H NMR spiking results.
8.6 Chemical oxidation of IC.
Chemical oxidation of IC was carried out by use of an oxidising agent. IC was oxidised with exactly one molar equivalent of FeCl₃ in anhydrous MeCN. The clear solution became purple in colour as soon as the oxidant was added. A similar observation was recorded during the electrochemical oxidation of IC. A precipitate was formed and was filtered and washed with MeCN and resulted in the formation of the same IC dimer mixture in 35% yield. The product was analysed by ^1^H NMR spectroscopy and high resolution mass spectrometry and gave almost similar product ratios as in the electro-oxidation.

8.7 Cyclic voltammetry of synthetic IC dimers.
The CVs of dimers 302, 304 and 305 are shown in Figures 63, 64 and 65. The samples were drop coated onto a platinum disc electrode from a solution in THF and allowed to evaporate to produce the film. The CVs were recorded in 0.1 M LiClO₄/MeCN.
Figure 63. CV of drop coated dimer 302 in 0.1M LiClO$_4$/MeCN at 50 mVs$^{-1}$. 
The results of the CVs show similar characteristics to that of the film species with the redox peaks being in similar positions (*i.e.* being centred around 0.7 V). The results show that they have similar redox characteristics to each other and to the film formed through monomer electro-oxidation. There are some slight differences in the shape of the CVs however it should be noted that the samples of authentic specimen dimers were drop coated from THF and not deposited by a controlled process such as electro-oxidation at a rotating disc electrode. Also, pure dimers were deposited rather than mixtures. The surface morphology will therefore likely differ in nature. It should also be remembered that the film is a mixture of all three species and due to this the shape of the CV of the electrochemical mixture must consist of a combination of the CVs of all three species.
Figure 65. CV of drop coated dimer 305 in 0.1 M LiClO$_4$ in MeCN at 50 mVs$^{-1}$.

8.8 Fluorescence spectroscopy.

8.8.1 Steady state fluorescence spectroscopy.

Steady state fluorescence spectra were recorded for each of the synthetic dimers. Figure 66 shows a spectrum of each of the synthetic dimers and also one for the film species at an excitation wavelength of 360 nm. All four spectra are scaled to the same Y intensity and it can be clearly seen all three emit at 410 nm. The shapes of the spectra are all similar with the only noted feature of a little broadening in some in the tail at the more red-shifted wavelengths. The results indicate that all four spectra are produced from similar fluorophores and would confirm that the synthetic dimers represent similar species to that produced by electrochemistry.
Figure 66. Normalised fluorescence emission spectra at a fixed excitation wavelength of 360 nm of IC dimers and film.

8.8.2 Time resolved fluorescence spectroscopy.

The fluorescence lifetimes of each synthetic dimer was characterised by time resolved fluorescence spectroscopy by Dr. Steven Magennis for comparison to the film species reported in section 7.5.2. The experimental conditions were as follows; The excitation wavelength used was 360 nm and the lifetimes were recorded at 6 different emission wavelengths (390 nm, 410 nm, 440 nm, 470 nm, 500 nm and 530 nm). Figure 67 shows an example decay plot at an emission wavelength of 410 nm for each dimer. Table 7 shows the results for each dimer at an emission wavelength of 410 nm. All three dimers produced bi-exponential decays. The heterodimer 302 gave a major lifetime of 9.03 ns, the homodimer 304 gave a major lifetime of 10.27 ns and the homodimer 305 gave a major lifetime of 7.64 ns. The minor lifetime of 4.5 ns was also found to be present in the electrochemically produced dimer mixture.
A possible explanation for the presence of the 4.5 ns lifetime is that it is the resultant of an impurity from the synthesis of indolo[3,2,1-jk]carbazole (IC) 1. IC is the only material that is common to all four samples. IC is the monomer from which the dimers are electrochemically prepared. IC is also common to each of the synthetic dimers as a stating material in their synthesis. It is thought that there could have been a low level impurity present in the IC used in each of the preparations which was not visible in the analysis carried out on the monomer. The lifetime of the monomer was also recorded at emission wavelength of 410 nm after excitation at 360 nm (Figure 68). The result of this experiment is also detailed in Table 8. Clearly, the bulk of the monomer emission arises from a ca. 12-13 ns component. There also appears to be a second component of ca. 5 ns, which accounts for ca. 5% of the emission. The second component in the dimer lifetimes was around 4.5 ns, so the same "impurity" could be present in monomer and dimer samples. The third short component is probably from the DMF. Global analysis of the monomer and dimer data may provide more information.

![Fluorescence decay plots recorded at an emission wavelength of 410 nm for IC dimers excited at 360 nm in DMF.](image)

Figure 67. Fluorescence decay plots recorded at an emission wavelength of 410 nm for IC dimers excited at 360 nm in DMF.
Table 8. Dimer lifetimes recorded at an emission wavelength of 410 nm after excitation of 360 nm in DMF. Data were fitted to biexponentials.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\tau_1$/ns</th>
<th>$A_1$/%</th>
<th>$%_1$</th>
<th>$\tau_2$/ns</th>
<th>$A_2$/%</th>
<th>$%_2$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>302</td>
<td>9.03</td>
<td>94.8</td>
<td>97.4</td>
<td>4.33</td>
<td>5.2</td>
<td>2.6</td>
<td>1.046</td>
</tr>
<tr>
<td>304</td>
<td>10.27</td>
<td>87.5</td>
<td>94.1</td>
<td>4.54</td>
<td>12.5</td>
<td>5.9</td>
<td>1.020</td>
</tr>
<tr>
<td>305</td>
<td>7.64</td>
<td>79.5</td>
<td>87.0</td>
<td>4.44</td>
<td>20.5</td>
<td>13.0</td>
<td>1.056</td>
</tr>
<tr>
<td>Electro</td>
<td>9.47</td>
<td>85.0</td>
<td>92.3</td>
<td>4.47</td>
<td>15.0</td>
<td>7.7</td>
<td>1.023</td>
</tr>
<tr>
<td>Monomer</td>
<td>12.7</td>
<td>86.0</td>
<td>95.4</td>
<td>3.85</td>
<td>14.0</td>
<td>4.6</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Figure 68. Fluorescence decay plots recorded at various emission wavelengths for the IC monomer when excited at 360 nm in DMF.

9.1 Introduction.
Due to the ability of IC to undergo electro-oxidation to form a conducting film and the availability of derivatised IC monomers, the effect of varying the substituent on the electrochemical properties was investigated. A variety of substituted IC compounds was reported in Chapter 4 of this thesis. The derivatives to be studied in this section are 5-aminoIC 263, 5-bromoIC 264 and 5-cyanoIC 265.

\[
\begin{array}{c}
263 \quad R = NH_2 \\
264 \quad R = Br \\
265 \quad R = CN \\
\end{array}
\]

9.2 Cyclic Voltammetry.
Each monomer was analysed by cyclic voltammetry in order to find out the effect of the substituent on the system. The series under investigation covers both electron donating and electron withdrawing groups, all of which showed similar CVs to that of IC and showed an irreversible oxidation peak. The results of the cyclic voltammetry are presented in Table 9. The oxidation potentials reported were measured relative to the ferrocene/ferrocinium couple.

<table>
<thead>
<tr>
<th>Substituent</th>
<th>Peak oxidation potential (vs Fe/Fe\textsuperscript{+}) / V</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-NH\textsubscript{2}</td>
<td>0.36</td>
</tr>
<tr>
<td>5-H</td>
<td>1.01</td>
</tr>
<tr>
<td>5-Br</td>
<td>1.12</td>
</tr>
<tr>
<td>5-CN</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Table 9. Oxidation potential of various IC monomers at 1 mM concentration.
The results of the cyclic voltammetry of the substituted monomers show that as the substituent becomes more electron withdrawing, the oxidation potential increases. As electrons are pulled towards the electron withdrawing substituent, the monomer becomes more difficult to oxidise due to less electron density being present in the ring structure. Electron donating groups will on the other hand increase the electron density of the system, thus making it easier to oxidise giving a lower oxidation potential. The results in Table 8 follow this pattern. As previously for indoles, the results were analysed by plotting the potential against the $\sigma^+$ Hammett parameter to give a Hammett plot (Figure 69). As expected, the positive slope of the Hammett plot indicates that the oxidation is less facile when electron withdrawing groups are present. This is a similar result to that of the electro-oxidation of 5-substituted indoles, where an essentially linear relationship was observed\textsuperscript{105}; although not enough substituents have been synthesised to test whether there is a linear relationship, it is interesting that a similar gradient is observed compared to indole in this case.
9.3 Film formation.
As in the case of the film formation with IC (section 7.2), a potential was selected, typically 90-100 mV above that of the peak oxidation current to ensure that electrochemical oxidation is not the rate determining step of film formation, ensuring that steady state currents should be observed at the RDE. Each was then subject to electro-oxidation by potential step voltammetry at a rotating disc electrode. It was noted that for each derivative there were solubility problems in acetonitrile, both the amino and the bromo derivatives were only soluble to around 2-3 mM whereas the cyano derivative was soluble to 5 mM. Both 5-amino 263 and 5-cyanoindolo[3,2,1-jk]carbazole 265 were studied further using the rotating disc electrode to cover both electron donating and withdrawing groups. 5-Bromoindolo[3,2,1-jk]carbazole 2 was not studied any further.

9.3.1 5-Aminoidolo[3,2,1-jk]carbazole.
5-Amin indo[3,2,1-\textit{jk}]carbazole 1 (3-5 mM) did not form a film upon electro-oxidation by potential step voltammetry. This effect has been observed for 5-amino and 5-hydroxyindole.\textsuperscript{89} The failure to form a film could be due to one of two reasons, the first being that electro-oxidation could occur at the amino group substituent, perhaps promoted by adsorption via this substituent onto the platinum surface and this may lead to a different mechanism of oxidation, preventing film formation\textsuperscript{89}. An alternative is that the solution may not be concentrated enough to allow coupling and initial film formation in the diffusion layer near the electrode, due to the electron donating amino group reducing the reactivity of the monomer\textsuperscript{89}.

In either case, this failure to form a film was overcome for 5-amino and 5-hydroxyindole by use of a template synthesis.\textsuperscript{89} In this case a template of a known conducting film was formed first, such as polyindole. This polymer modified electrode was then used as a surface on which to oxidise amino- and hydroxyl-indoles. The layer both prevents surface adsorption via platinum and allows electrooxidation and coupling of 5-amino and 5-hydroxyl indoles via an adsorptive mechanism on the film surface. The template methodology was therefore used in attempt to form an aminoIC film, using a preformed film of polyindole as the template. Unfortunately film formation was still unsuccessful.

The reason that no film is being formed on the template may because the solution is not being concentrated enough; however, this is limited by the solubility of the monomer in acetonitrile. One way to test this hypothesis is to find a more suitable solvent. For comparison to IC to be possible all studies would have to be repeated in the new solvent/electrolyte system, it is for this reason that further analysis of this compound has not been carried out.

### 9.3.2 5-Cyanoindolo[3,2,1-\textit{jk}]carbazole.

An initial test to check if film formation occurs upon electro-oxidation of the cyano derivative was carried out. This proved to be successful so a detailed electro-chemical analysis was performed.
9.3.2.1 Cyclic Voltammetry.
A cyclic voltammogram with repeated cycling was recorded of a 1 mM solution of 5-cyanoindolo[3,2,1-\textit{jk}]carbazole in 0.1 M LiClO$_4$/MeCN (Figure 70). As with IC, cycle 1 showed little occurring until the appearance of an irreversible oxidation peak at 1.3 V vs Ag/Ag$^+$. The deposition of a green film was noticed during the oxidation of the monomer. When repeated cycling was allowed to occur, close inspection showed a very small back reduction peak but this is less intense than in the case of IC. A set of redox peaks was observed centred on 0.90 V vs Ag/Ag$^+$ upon repeated cycling. This is a similar response to that of IC, however due to the electron withdrawing nature of the cyano group both the film and the monomer are more difficult to oxidize and therefore more positive potentials are observed.

![Cyclic voltammogram](image)

**Figure 70.** Repeated cyclic voltammetry of 5-cyanoindolo[3,2,1-\textit{jk}]carbazole.
Cyclic voltammetry at differing scan rates (Figure 71) shows a similar response to IC. As discussed in Chapter 6.2.3, for both reversible and irreversible electrochemical systems where the redox active species is in solution, $i_p$ should be proportional to $v^{1/2}$, which demonstrates diffusion control. The CVs that are shown in Figure 71 are observed to hold true to this relationship (Figure 72). The back reduction peak observed in the case of IC is less distinctive in the case of the cyano substituted IC. This would be consistent with more radical cations undergoing coupling when compared to IC. This indicates that the electron withdrawing nature of the substituent increases the reactivity of the radical cation species.

![Cyclic voltammetry of 5-cyanoIC with varying sweep rate.](image)

Figure 71. Cyclic voltammetry of 5-cyanoIC with varying sweep rate.
Figure 72. $i_p$ vs $v^{1/2}$ for the electro-oxidation of indolo[3,2,1-$jk$]carbazole.

9.3.2.2 Film formation.

As in the case of the analysis of IC, the oxidation of 5-cyanoIC was studied at a rotating disc electrode. The potential for the oxidation by potential step voltammetry was selected to be $+1.40$ V vs Ag/Ag⁺, in the mass transport region of the CV to ensure that electrochemical oxidation is not the rate determining step of film formation and that steady state currents should be observed at the RDE. Electro-oxidation of 5-cyanoIC was indeed shown to proceed with a steady state current (Figure 73). The steady state current was maintained for minutes before there was a significant drop in current, which indicates that the film is conducting in nature and is growing with time.
Figure 73. Steady state current produced upon electro-oxidation of a 5mM solution of 5-cyanocIC at 1Hz. The potential was applied at approximately 2.4 s.

A CV was obtained (Figure 74) of a film synthesised at the rotating disc electrode after washing with background electrolyte to remove any residual monomer. It is interesting that the CV of the film looks slightly different in appearance than that of the redox peaks formed at a lower concentration during the oxidation of the monomer as shown in Figure 70. This most likely reflects a change in film structure.
Figure 74. CV of 5-cyanoIC film formed from a 5 mM solution at $W = 1\text{Hz, } v = 20 \text{ m V s}^{-1}$.

When the film was subjected to repeated cycling (Figure 75), after an initial small decrease in area of the peaks a steady state CV was eventually found. This is identical to the case in which an IC film is subject to repeated cycling.
Figure 75. Cycling of a 5-cyanoIC film at 20mVs\(^{-1}\). Successive sweeps show a gradual decrease in peak currents.

After a steady state CV was attained, CVs were recorded at varying sweep rates and the peak redox potentials, \(|i_p|\) plotted against the sweep rate, \(v\) (Figure 76). When the redox-active species forms a film which is adsorbed onto the electrode surface, \(i_p\) should be proportional to \(v\) if film kinetics are fast, as the whole film is reduced/oxidised on each sweep. When film kinetics are slow with respect to \(v\), the whole film is not reduced/oxidised on each sweep. The result of the analysis displayed in Figure 76 show a linear relationship (\(i_p \propto v\)) between the peak currents and the sweep rate. This is indication of complete oxidation and reduction of a surface bound species, with the whole film being oxidised and reduced on each sweep. As a consequence of fast redox kinetics, the area under each peak gives the charge required to fully oxidise or reduce the film.
Figure 76. A plot of the peak oxidation and reduction currents from the CV of a film formed from 5 mM 5-cyanoindolo[3,2,1-jk]carbazole at \( w = 1 \) Hz.

A comparable charge ratio calculation to that for IC was therefore carried out, comparing the charge passed during electrooxidation (from the current/time transient in Figure 73) with the charge under each redox CV peak (in Figure 74). The result of this was a 3:1 (actually 32%) ratio of the electrooxidation to film redox charge. This is similar to IC and thus supports the proposal of a similar film formation mechanism, with the film most likely being dimeric in nature. A FAB mass spectrum was recorded which gave a parent ion \( M+1 \) \( m/z \) of 531 (consistent with the protonated form of the expected singly coupled dimer, mass 530). The proposed mechanism of dimer formation is therefore as shown in Scheme 123 in section 7.3. The % charges were calculated for films produced at different rotation speeds for a range of concentrations (1-5 mM). This charge showed to
be a consistent 32-34% indicating the presence of dimer species at all rotation speeds irrespective of the monomer concentration. This is a similar result to that found for IC.

9.3.2.3 Koutecky-Levich analysis.

The film synthesis was also studied by Koutecky-Levich analysis as described in section 7.3.3 (Figure 77). The result from this analysis shows that straight line plots are produced for all of the concentrations studied. This indicates that the oxidation of the monomer proceeds with 1\textsuperscript{st} order kinetics as this is an assumption of the Koutecky-Levich relationship. This is similar to results observed for IC.

Fig 77. Koutecky-Levich plots for 1, 2.5 and 5 mM solutions of 5-cyanoundolo[3,2,1-\textit{jk}]carbazole. Fitted data with $D = 2.2 \times 10^{-5}$ cm\textsuperscript{2} s\textsuperscript{-1}.
It has already been shown that the species formed on the electrode are likely to be dimers (section 9.3.2.1). As a result three electrons are required to be removed to form an oxidised dimer. With three electrons required for two monomer units, the value of $n$ is therefore taken to be 1.5. From the Koutecky-Levich analysis and the knowledge of the $n$ value, the diffusion co-efficient, which is constant of the monomer in solution can be calculated using the Koutecky-Levich relationship.

The results from the Koutecky-Levich analysis show that straight line plots are produced for all of the concentrations analysed. This indicates that the oxidation of the monomer at all concentrations proceeds with first order kinetics. The data was analysed by fitting the best line to the data using a variety of diffusion coefficients based on the diffusion coefficient of indoles ($3.0 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$).

The diffusion coefficient was altered and the diffusion coefficient for the data set with the best fit was taken to be the diffusion co-efficient for the compound. The diffusion co-efficient was found to be $2.2 \times 10^{-5} \pm 0.5 \times 10^{-5}$ cm$^2$ s$^{-1}$ and is comparable to that found for IC ($3.0 \times 10^{-5} \pm 0.5 \times 10^{-5}$ cm$^2$ s$^{-1}$). This result in the correct order of magnitude for the diffusion coefficient of an organic molecule of this size.\textsuperscript{89}

The intercepts in the Koutecky-Levich plot (Figure 77) give the mass transport independent current ($i_\infty$). This gives the current where the concentration of 5-cyanoIC at the electrode surface is equal to the bulk concentration of 5-cyanoIC. This value for each concentration is presented in Table 10.

<table>
<thead>
<tr>
<th>Monomer concentration/ mM</th>
<th>$i_\infty$/mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.4 ± 0.2</td>
</tr>
<tr>
<td>2.5</td>
<td>4.0 ± 0.6</td>
</tr>
<tr>
<td>5.0</td>
<td>5.6 ± 1.2</td>
</tr>
</tbody>
</table>

Table 10. Mass transport independent currents ($i_\infty$) for 5-cyanoIC electro-oxidation.
The intercepts in the Koutecky-Levich plot (Figure 77) are $1/i_\infty$ (eqn. 9, chapter 7), which give the mass transport independent current ($i_\infty$, Table 10, chapter 7). This is the current when $W \to \infty$, mass transport is fast and the concentration of IC at the electrode surface is equal to the bulk concentration of IC. It is interesting that the values of $i_\infty$ are the same within experimental error at the higher monomer concentrations of 2.5 and 5.0 mM. This indicates that the rate of oxidation of IC is insensitive to the concentration of the monomer at these relatively high concentrations. This suggest that the rate determining step of film formation is the rate of coupling of a monolayer of adsorbed intermediate on the electrode surface. This was also shown to be the case with 5-substituted indoles.\textsuperscript{89}

However, at 1 mM $i_\infty$ is lower; as observed previously for indoles,\textsuperscript{89} this suggests that at these monomer concentrations, the rate determining step of film formation is dependent on monomer concentration and that the monomer oxidation involves an adsorbed intermediate which is not covering the electrode surface, but increases coverage with concentration. It is unfortunate that the decreased solubility of 5-cyanoIC with respect to IC (chapter 7) precludes measurements at higher monomer concentrations. It is interesting that the mass transport independent current for both IC (chapter 7) and 5-cyanoIC at concentrations between 1 and 5 mM lie within the same range (Table 11) indicating equivalent coupling rates within experimental error. This is consistent with little effect of the substituent on coupling.

<table>
<thead>
<tr>
<th>Concentration/mM</th>
<th>$i_\infty$/mM (5-cyanoIC)</th>
<th>$i_\infty$/mM (IC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.4 ± 0.2</td>
<td>2.2 ± 0.2</td>
</tr>
<tr>
<td>2.5</td>
<td>4.0 ± 0.6</td>
<td>3.3 ± 0.2</td>
</tr>
<tr>
<td>5.0</td>
<td>5.6 ± 1.2</td>
<td>4.3 ± 0.2</td>
</tr>
</tbody>
</table>

Table 11. Comparison of IC and 5-cyanoIC reciprocal mass transport independent currents.
9.4 HPLC analysis.

When IC was electro-oxidised to form the dimeric film it was shown by electrochemical means, $^1$H NMR spectroscopy and HPLC that the film consisted of three isomeric dimers. In section 8.3 it was shown by both electrochemical means and mass spectrometry that the 5-cyanolC film also consisted of dimers. HPLC analysis of the cyano derivative was carried out (Figure 78) using the same method as was used for IC. Although the chromatogram shows extensive tailing of the peaks, the result of the analysis showed the presence of three distinct major peaks indicating the presence of three different species in the mixture. The tailing of the peaks is likely to be caused by the long retention time and could probably be improved by some method development if required. This tailing makes accurate quantification of the proportion of dimeric products extremely difficult.

From the electrochemistry, mass spectrometry, HPLC analysis and the information known about the electron density on the parent IC radical cation, it would be reasonable to predict that the electro-oxidation of 5-cyanoIC also produces three isomeric dimers. The structures proposed are based upon the structures elucidated for the parent IC molecule. It is predicted that the dimers would couple through the head and side positions as with IC to give dimers \(314, 315\) and \(316\). Coupling would not occur on the ring bearing the cyano group due to blocking of the reactive site.
Figure 78. HPLC chromatogram of 5-cyanoIC film.
9.5 Steady state fluorescence spectroscopy.

The steady state fluorescence emission spectra were recorded for both the monomer and the film in DMF. Selected representative spectra are shown in Figure 79 for the dimeric species. The film shows significant red shifting when compared with the monomer, with similar peak emission wavelengths of 369 nm and 408 nm for both monomer and film compared to the parent IC wavelengths of 374 nm and 405 nm respectively. This red shifting is again indicative of the presence of a more conjugated chromophore than the monomer.

![Representative emission spectra for 5-cyanoIC (red) and film (blue) at excitation wavelengths of 320 nm and 370 nm respectively.](image)

For 5-cyanoIC it was found that the shape of the emission spectrum is independent of the excitation wavelength, in other words Kasha's rule is obeyed. This means that the emission in each case is always from the same state, the lowest vibrational level of the first singlet excited state $S_1$. It also means that there are unlikely to be any other emitting species present that are excited and emit in the same region as the monomer, such as impurities or aggregates. This is also the case with the parent IC molecule. There are
however, other light emitting species present in the film at longer wavelength indicating the presence of longer chain length emitting species with a emission wavelength near 453 nm (Figure 80). This scale is normalised to the same y-intensity due to the emission at 453 nm being very weak.

![Graph showing fluorescence emission spectra](image)

**Figure 80. Normalised fluorescence emission spectra for 5-cyanoIC monomer at excitation wavelengths 370 nm (blue) and 400 nm (red).**

These spectra show that the dimer emission, which peaks at 408 nm, is much more intense than the longer wavelength emission peaking 453 nm, suggesting that there is substantially more dimer present than longer chain length species. However, it should be remembered that the difference in intensity does not necessarily reflect a difference in the relative amounts of the emitting species in solution. This is because the different species may have different quantum yields. In fact long chain length polymers often have lower quantum yields than short chain length polymers, as they have more competing non-radiative de-excitation pathways. Therefore there may be more of the longer wavelength
emitting species present in solution relative to dimer than is suggested in the emission spectra. Lifetime measurements would be required to establish this.

The results are comparable to that of IC where there was a large emission species at around 410 nm, a weak emission at 455 nm and also a further emission at 505 nm. It is likely that a similar reaction pathway has occurred for the cyano species when compared to the unsubstituted IC. The most intense peak most likely due to the presence of dimers which are the major product as this was shown to be the case with IC. The presence of dimers is supported by mass spectrometry and % charge calculations. Absolute confirmation of the exact structures of the dimers by $^1$H, COSY and NOESY NMR spectroscopy was not carried out in this case, however full structural characterisation of the electrochemically similar 7-azaIC is reported in the following chapter.
Chapter 10 7-Azaindolo[3,2,1-jk]carbazole.

10.1 Introduction.

It has been demonstrated in chapters 7 and 9 that indolo[3,2,1-jk]carbazole and substituted indolo[3,2,1-jk]carbazoles can undergo an irreversible electro-oxidation to produce an electrically conducting film at a platinum working electrode surface. The films have been shown to be composed of a mixture of dimer species which are shown to be highly fluorescent in the blue region of the visible light spectrum.

In this chapter the effects of the introduction of a pyridine type nitrogen on the electrochemistry of the system will be investigated. It is anticipated that 7-azaindolo[3,2,1-jk]carbazole (7-azaIC) could follow a similar reactivity pattern, however the pyridine nitrogen may influence the system to undergo different chemistry, and in particular allow complexation.

The inclusion of the ring nitrogen could lead to other potential applications of this class of ring system such as in sensor technology. It is well known that pyridine-type rings can chelate metals such as nickel and copper \(^{131}\) and it is anticipated that this may also be possible with 7-azaindolo[3,2,1-jk]carbazole. If chelation to metals occurs, the film species would then be expected to undergo a corresponding change in ring electron density. This should lead to a measureable change in the electrochemical characteristics of the film. Pyridines can also undergo protonation to the nitrogen lone pair of electrons as they are located in the \(\sigma\)-orbital in the plane of the ring rather than delocalised into the ring. Protonation of the film should also lead to an electrochemical response and hence a potential application of this system as a pH sensor. The synthesis of 7-azaindolo[3,2,1-jk]carbazole (7-azaIC) is described in chapter 4.


A 5 mM solution of 7-azaindolo[3,2,1-jk]carbazole in 0.1 M LiClO\(_4\)/MeCN was subjected to analysis by cyclic voltammetry. A CV for the electro-oxidation of a 1.0 mM solution of 7-azaIC is shown in Figure 81. The CV shows an irreversible oxidation peak at +1.27 V. The oxidation potential is higher than found with IC; this is most likely due
to the presence of the electron deficient pyridine nitrogen, which reduces the electron density in the ring system. The result of this would be to make the oxidation more difficult. There is also a presence of a reduction peak at +0.67 V wrt Ag/Ag⁺ electrode. This is similar to IC and can be attributed to the presence of an oxidised film being deposited on the electrode surface as for IC (section 7.3).

![Graph of CV of 1.0 mM 7-azaIC at 50 mVs⁻¹](image)

**Figure 81. CV of 1.0 mM 7-azaIC at 50 mVs⁻¹.**

There is one significant difference in the CV of 7-azaIC compared with those of IC and 5-cyanoIC (Figs. 39 and 70) at a comparable concentration. This is that there is a lack of the small reduction peak associated with the irreversible oxidation peak. In IC, the back reduction peak is consistent with the radical cation species formed being relatively unreactive so that not all of the radical cations formed undergo irreversible coupling on the timescale of the CV experiment. When the potential is cycled repeatedly (Figure 82), an oxidation peak at +0.83 V appears. This peak is due to the film oxidation, associated
with the reduction peak at +0.67 V. The magnitude of the peak increases with each cycle and subsequent formation of a green film on the electrode surface confirms the formation of an electro-active surface film. The film redox peaks occur at a higher potential than that of IC product indicating the presence of a product that is harder to oxidise than the IC film. This is consistent with the presence of the electron deficient pyridine in the film.

Figure 82. Repeated cycling of potential of 1.0 mM 7-azaIC at 50 mVs⁻¹.

7-AzaIC film formation was analysed by cyclic voltammetry at a variety of sweep rates (Figure 83). The results of this analysis are shown in Figure 84 as a plot of $i$ versus $v^{1/2}$. As discussed in Chapter 6.2.3, for both reversible and irreversible electrochemical systems where the redox active species is in solution, $i_p$ should be proportional to $v^{1/2}$, which demonstrates diffusion control. The plot shown in Figure 84 shows an essentially linear relationship demonstrating that $i \propto v^{1/2}$. At low concentrations, the values of $i_p$ are slightly larger than expected. This is consistent with Fig. 83, which shows a change in
peak shape at low \( v \) due to an additional further oxidation above 1.3 V which would add to the observed current. In the case of IC (Fig. 39), it is observed that as \( v \) increases, larger back peaks at 1.0 V are observed, this is consistent with relatively slow coupling, and less coupling taking place as the sweep rate is increased. This is not the case with 7-azaIC, which again indicates faster monomer coupling than IC in solution.

![Graph showing CVs of 7-azaIC with varying sweep rate.](image)

**Figure 83.** CVs of 7-azaIC with varying sweep rate.
10.3 Electro-oxidation of 7-azaIC by potential step voltammetry.

As with IC, 7-azaIC was electro-oxidised at a platinum rotating disc electrode by potential step voltammetry. The electropolymerisation potential selected was 1.38 V, 0.09 V above that of the peak oxidation potential of the monomer. As the film grows, oxidation of the oligomers can also occur as well as oxidation of the monomer on the redox active film. These oxidation potentials are likely to be lower than the oxidation potential of the monomer. Therefore an oxidation potential of +1.38 V should be sufficient to ensure that electrochemical oxidation is not the rate determining step of film formation and steady state currents should be observed at the RDE. The film species formed upon electro-oxidation was found to be electrically conducting, due to the observation of a steady-state current during chronoamperometric studies. The initial
spike shown in Figure 85 is caused by the electro-oxidation and adsorption of the first layer of product on the film and the establishment of steady-state conditions. The current then decreases and proceeds towards a steady state. This is indicative of the formation of a conducting film that is growing. A CV of the film prepared is shown in Figure 86 and shows the presence of a redox active conducting film.

![Current vs Time Graph](image)

**Figure 85.** Current time transient for the electro-oxidation of a 10 mM solution of 7-azaIC at +1.38 V/1 Hz rotation. A potential step from 0.00V to +1.38 V was performed at 1.4 secs.
Figure 86. A typical first CV of the 7-azaIC film in background electrolyte.

As with IC, the electrochemical characteristics of the resulting film were studied further by cyclic voltammetry in background electrolyte. The films were first subjected to repeated cycling by cyclic voltammetry (Figure 87). This repeated cycling shows an initial decrease in the redox peaks for film oxidation and reduction. This can be attributed to loose film being removed from the electrode. A steady state CV is then rapidly produced indicating the film is a stable electro-active film. Cyclic voltammetry at different sweep rates (Figure 88) was then carried out and the peak currents, $i_p$, of the scans at different sweep rates plotted against the sweep rate (Figure 89).
Figure 87. Repeated cycling of 7-azaIC dimer. The cycle numbers are indicated above.

Where film kinetics are fast, the whole film is reduced/oxidised on each sweep. As a consequence, $i_p$ will be proportional to $v$. Figure 89 shows this linear relationship ($i_p \propto v$) between the peak currents and the sweep rate. This is indicative of fast redox kinetics, with complete oxidation and reduction of the surface bound species and the whole film being oxidised and reduced on each sweep. As a consequence of this, the area under each peak gives the charge required to fully oxidise or reduce the film.
Figure 88. CVs of 7-azaIC film at different sweep rates.
A sample of film was analysed by FAB mass spectrometry by H Armstrong\textsuperscript{132} and gave a nominal mass M+1 molecular ion of \( m/z \) 483. The mass of a dimeric species with a single C-C covalent linkage is 482. The FAB mass spectrometry result is therefore consistent with such a dimeric species. The presence of these dimer species was also confirmed by high resolution FAB mass spectrometry, which gives an accurate mass of \( m/z \) 483.1707 for the sample. The molecular formula C\textsubscript{34}H\textsubscript{19}N\textsubscript{4} requires \( m/z \) 483.1710. The deviation of this experimental result is therefore 0.61 ppm, which confirms the molecular formula of the dimer species.

Figure 89. Plot of peak oxidation and reduction currents vs sweep rate for 7-azaIC film.
The ratio of the charge passed during redox oxidation and reduction of the film was calculated with respect to the charge passed in film formation. Assuming that the redox chemistry of the film is a one electron process, then the number of electrons passed in the formation of the film can be calculated. The ratio was again found to be $34 \pm 2\%$ (CV:film) for films synthesised from monomer concentrations of 10 and 20 mM and between $W = 1$ and 16 Hz. This implies that, as with IC and substituted IC (sections 7.3 and 9.3), there are three electrons involved in the monomer oxidation and formation of the film. This would again indicate that the product consists of dimeric species and that the redox reaction involves one electron for each dimer species (Scheme 123 in section 7.3).

Two electrons are accounted for in the oxidation of two monomer units which can then irreversibly couple to form a dimer with the elimination of two protons. The potential that the oxidation is carried out is greater than the redox potential of the resulting film species therefore if the redox oxidation is a one electron process, the third and final electron is accounted for by the redox oxidation of the dimer.

10.4 Koutecky-Levich analysis.

The steady-state electro-oxidation and film formation reaction was studied further by varying the rate of rotation. This experiment was repeated at different concentrations and the results were plotted as a Koutecky-Levich plot (Figure 90). The result of this analysis shows there is a linear relationship for all the concentrations studied. This shows that the reaction proceeds with 1st order kinetics with respect to the oxidation of the monomer as this is an assumption of the relationship.
It is already known that the species formed on the electrode is likely to be a dimer species due to the FAB mass spectrum showing an M+1 peak of 483 (dimer mass is 482). The proposal that the species is a dimer is supported by % redox charge in the CV being ~33%. As a result three electrons are required to be removed to form the oxidised dimers. With three electrons over two monomer units, the value of n is therefore taken to be 1.5. From the Koutecky-Levich analysis and the knowledge of the n value, the diffusion co-efficient, which is constant of the monomer in solution can be calculated using the Koutecky-Levich relationship (eqn. 9, chapter 7).
The data was analysed by fitting the best lines to all the data by adjusting the value of D. D$_{7$-azalC} was found to be $1.0 \times 10^{-5} \pm 0.1 \times 10^{-5}$ cm$^2$ s$^{-1}$. This result is comparable in magnitude to that of IC ($3.0 \pm 0.5 \times 10^{-5}$ cm$^2$ s$^{-1}$, chapter 7), 5-cyanoIC ($2.2 \pm 0.5 \times 10^{-5}$ cm$^2$ s$^{-1}$, chapter 9) and indole$^{89}$ ($1.0 \times 10^{-5}$ cm$^2$ s$^{-1}$). This result is therefore the correct order of magnitude for the diffusion coefficient of an organic molecule of this size.$^{89}$

The intercepts in the Koutecky-Levich plot (Figure 90) give the mass transport independent current ($i_\infty$). This gives the current where the concentration of 7-azaIC at the electrode surface is equal to the bulk concentration of 7-azaIC. This value for each concentration is presented in Table 12.

<table>
<thead>
<tr>
<th>Monomer concentration (mM)</th>
<th>$i_\infty$/mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>$2.9 \pm 0.3$</td>
</tr>
<tr>
<td>10</td>
<td>$5.0 \pm 0.3$</td>
</tr>
<tr>
<td>20</td>
<td>$5.9 \pm 0.3$</td>
</tr>
</tbody>
</table>

Table 12. Mass transport independent currents ($i_\infty$) for 7-azaIC electro-oxidation.

The intercepts in the Koutecky-Levich plot (Figure 90) are $1/i_\infty$ (eqn. 9), which give the mass transport independent current ($i_\infty$, Table 12). This is the current when $W \to \infty$, mass transport is fast and the concentration of IC at the electrode surface is equal to the bulk concentration of IC. These values indicate that the rate of electro-oxidation is dependent upon the bulk concentration. This suggests that the rate determining step of the monomer oxidation involves an adsorbed intermediate which gradually increases coverage with monomer concentration. These values of $i_\infty$ are comparable to those obtained for IC (Table 10) and 5-cyanoIC (Table 11), indicating similar coupling rates.
10.5 Characterisation of film.

10.5.1 Preamble.

In this section on the characterisation of the film produced upon electro-oxidation of 7-azaIC is discussed. A range of data is presented from the work carried out in collaboration with Miss Helen Armstrong on the characterisation of this film, which formed part of her undergraduate research project.

10.5.2 Fluorescence spectroscopy.

The fluorescence spectra of the monomer and the film products were recorded in DMF solution at $10^{-6}$ M concentration for comparison with IC (section 7.5). Emission spectra for the monomer were recorded at differing excitation wavelengths and are shown in Figure 91. These spectra are normalised to the same peak intensities to enable comparison. It can be seen that there are peak emissions at 365 nm, 409 nm and 454 nm for these spectra. The latter two are vastly reduced in intensity from the emission at 365 nm. Excitation spectra at these peak emission wavelengths are different to that of the emission wavelength of 365 nm which shows that these emissions occur from impurity species in the monomer. The corresponding excitation spectra are different. This is consistent with the peaks to longer wavelength being due to impurities in the monomer left over from the synthesis. It was found that the shape of the emission spectrum at 365 nm, which we attribute to 7-azaIC, is independent of the excitation wavelength (300-400 nm) or in other words that Kasha's rule is obeyed. This means that the emission in each case is always from the same state (the lowest vibrational level of the first singlet excited state $S_1$). It also means that there are unlikely to be any other emitting species such as impurities or aggregates present that are excited and emit in the same region as the monomer.
The emission spectra of the films formed from 7-azaIC were then recorded at different excitation wavelengths and the data are presented in Figures 92 and 93. Figure 94 shows each emission as true intensity whereas Figure 93 shows each emission after normalisation to the same peak intensity. The results show similar emission spectra to those of IC films (section 7.5.1), with peak emission at 406 nm. This suggests similar fluorophores and is further evidence of dimeric structures. However the spectra are broader which could indicate that there are other overlapping emitting species. The emission at 406 nm is not independent of the excitation wavelength indicating that there may be a contribution from a small amount of another emitting species in this region. As the most intense emission occurs at a similar wavelength to that of IC dimers it is proposed that this emission is due to a dimeric 7-azaIC species. There is also another emission peak at 455 nm seen at long excitation wavelengths. It is thought this may be either from a further conjugated 7-azaIC based species, or the incorporation of the monomer impurity into the film.
Figure 92. Fluorescence spectra for 7-azaIC dimer mixture at differing excitation wavelengths at true intensity.

Figure 93. Fluorescence spectra for 7-azaIC dimer mixture at excitation wavelengths of 300, 320, 340, 360, 380 and 400 nm at normalised intensity (shown above).
10.5.3 HPLC chromatography.

HPLC analysis of the film product was carried out using the same methodology as was used for the characterisation of the IC dimer mix. It was found that under the same chromatography conditions the sample was retained on the column for much longer than the IC dimers.

HPLC chromatograms were run on a Gilson HPLC as follows;

- Column – Spherisorb S5-ODS1
- Flow rate – 1 ml min⁻¹
- Injection volume – 20 µL
- Detection wavelength – 254 nm
- Eluant gradient – A = 9:1 water/MeCN, 1% NH₄Ac and B = MeCN

The gradient used is shown in Table 13.

<table>
<thead>
<tr>
<th>Time/min</th>
<th>%B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>30</td>
<td>95</td>
</tr>
<tr>
<td>55</td>
<td>95</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 13. Initial solvent gradient for HPLC analysis.

HPLC method development was carried out by Miss H Armstrong. The procedure used was gradually to increase the % of B (acetonitrile). This was carried out until % B was 95%. At this point it was noted that the chromatogram contained three distinct fractions, however the mixture still had long retention times associated with each peak. The system was switched to an isocratic system which gave the best quality of chromatogram, i.e. one in which the peaks were not broad and there was no significant tailing of the peaks. The isocratic solvent system used was 5:95 (A:B). The resulting chromatogram is shown in Figure 94. The chromatogram shows three distinct species, indicating the likely
presence of three 7-azaIC dimers. This is similar to the case of the dimerisation of IC (section 8.2).

Figure 94. HPLC chromatogram of 7-azaIC dimers  (Note that the large peak just after 0 min is the solvent front. The relatively noisy nature of the chromatogram is due to poor solubility of the material.)

10.5.4 NMR analysis.
A 20 mM solution of 7-azaIC was used to produce film product as in section 7.3 at $W = 2$ Hz. Electro-oxidation was repeatedly carried out and product removed from the electrode surface.
In the case of the IC electro-oxidation products it was possible to assign the structures of the products in the mixture from the $^1$H NMR spectrum using 2D NOESY, COSY and HSQC techniques. Due to the products of the electro-oxidation of 7-azaIC being dimeric in nature it was thought that NMR spectroscopy would also be of use in the structural assignment of the products. The spectra that were recorded were $^1$H (Figure 95), HSQC (Figure 96), COSY (Figure 97), TOCSY (Appendix 13), NOESY (Figure 98). All spectra were recorded of a sample fully dissolved in DMSO-$d_6$ on a Bruker Avance 600 MHz spectrometer. The NOESY spectrum had to be recorded at elevated temperature to counteract problems associated with the molecular tumbling which caused the experiment to give zero NOE at ambient temperature. Due to this all NMR spectra were recorded at 60 °C.

![Figure 95. 600 MHz $^1$H NMR spectrum of 7azaIC film in DMSO-$d_6$ at 60 °C.](image)

The $^1$H NMR spectrum shown in Figure 95 is highly structured indicating that the film material is not polymeric in nature. It can be clearly seen that the spectrum is very complex. This would be expected if the product was a mixture of three different isomeric dimers. All possible 7-azaIC dimers based on IC type dimerisation are shown 317, 318,
319, 320, 321 and 322. The most appropriate strategy to attack this problem was by analogy with IC. There will of course be differences in the chemistry of this compound due to the presence of the pyridine nitrogen atom, however coupling was shown to occur at the most electron rich sites on IC. Pyridine rings are more electron deficient in nature in comparison with benzene rings and therefore it can be expected that coupling will not occur on these rings. The presence of dimers 320, 321 and 322 may be ruled out due to coupling to the pyridine ring.

![Figure 96. 600 MHz HSQC spectrum of 7-azaIC film.](image)

The HSQC spectrum shown in Figure 96 was used to assist in the separation of the proton signals. This is required due to the complex nature of the spectrum with large amounts of signal overlap and signals lying very close to each other. The carbon dimension was used to separate the proton signals with similar proton chemical shifts but different carbon chemical shifts. The level of coupling detail seen in the proton dimension is dependent
upon how many data points are recorded. In most cases coupling of around 4 Hz and above can be resolved and therefore ortho coupling constants in aromatic substructures can be deduced. Smaller couplings such as meta couplings tend not to be resolved. It can be seen that the HSQC has helped in separating a large amount of proton signals.

A key feature of the spectra that was important in the assignment of the IC film species is the 1,2,4-trisubstituted aromatic substructure. It can be seen that this feature is also present in three of the proposed dimer structures (317, 319 and 322). 1,2,4-Trisubstituted aromatic substructures are visible in the spectra of the 7-azaIC mixture and are represented on the COSY spectrum in Figure 96 by the black correlation lines. This was confirmed by comparison with the TOCSY spectrum (Appendix 13) which showed no extra correlations other than those present in the COSY. This can be used as confirmation that there were no other protons in the coupling systems shown in the COSY. In simpler terms the signals arising in the COSY spectrum show each complete spin system. This is not usually the case with COSY spectra as they show only protons that are coupled. Usually TOCSY spectra are required to show complete spin systems.
However, in this type of system where the bonding is highly conjugated and there are no more than four protons in each spin system, the COSY shows the same information that the TOCSY.

Figure 97. 600 MHz COSY spectrum of 7-azaIC film mixture.

Using the HSQC in conjunction with the COSY spectrum, the HSQC confirms the signals at 8.80 ppm are two different signals with coupling constants of around 1.5 Hz. The signal at 8.15 ppm in the $^1$H spectrum that is part of a 1,2,4-trisubstituted aromatic substructure is indeed two doublets with coupling constants of around 8 Hz. This is also shown through splitting of the signals in both dimensions in the COSY and in the HSQC. The final signals that are part of the suspected 1,2,4-trisubstituted aromatic substructure are located at around 8.35-8.40 ppm and are shown to be doublets with coupling constants of around 8 Hz by extrapolation from the HSQC.
Another key feature in dimers 318-322 is the coupling that would be seen for coupling through the central ("head") benzene ring and also the coupling through the pyridine ring. If coupling were in these positions the substructure would be a 1,2,3,5-tetrasubstituted aromatic substructure and as a result the coupling would only be around 1.5 Hz as it is meta coupling. The HSQC shows four distinct singlets between 8.67 and 8.70 ppm. These could easily be doublets with 1.5 Hz coupling. Some coupling is evident on close inspection using an NMR processing package such as MestRe-C or XWIN-NMR, however overlap with a doublet (HSQC analysis) makes analysis difficult. This coupling is shown by the light green lines shown in Figure 96. Further analysis of this mixture to assign the structures must be carried out by NOESY analysis (Figure 98).

![Figure 98. 600 MHz NOESY spectrum of 7-azaIC film at 60 °C.](image)
In Figure 98 there is evidence for one of the 1,2,4-trisubstituted aromatic substructures showing an NOE from the meta coupled doublet to one of the other doublets from the same substructure as represented by the black correlation line. This feature is only possible if dimer 317 is present in the mixture. Further analysis of the spectra is complicated by overlap of the signals, however analysis is still possible by close examination of the spectra by an NMR processing package such as MestRe-C or XWIN-NMR and comparing the HSQC spectrum (Figure 96) and the NOESY spectrum (Figure 98). For a homo-coupled dimer (dimer 318) with the coupling being “head” to “head”, NOE correlations would be required between both of the protons adjacent to the aryl bond. Both of these protons would also require an NOE correlation to an additional doublet. These correlations are evident and are shown by the green correlation lines.

The final component of the mixture must have a 1,2,4-trisubstituted aromatic substructure which rules out dimers 320 and 321 leaving dimers 319 and 322. Both of these dimers require an NOE correlation from the 1,2,4-trisubstitued aromatic substructure to two different meta coupled doublets. These correlations are present and are shown by the grey correlation lines therefore it is proposed that the final product is dimer 319. If the reasonable assumption is made that coupling does not take place in the pyridine rings, then all the data are consistent with the dimer structures being 317, 318 and 319. The key NOE features used to identify the structure in conjunction with the other spectra are shown in Figure 99.
10.5 Application of 7-azaIC film as a sensor.

10.5.1 Preamble.

It was thought that a 7-azaIC based film may have potential use as a simple electrochemical sensor (such as pH or metal sensing) due to the well known fact that pyridine can co-ordinate metals such as copper or can be protonated. It was therefore decided to investigate if this was the case with 7-azaIC based conducting films.

10.5.2 pH sensing.

Previous work has been carried out on the pH sensitivity of indole based conducting films. The method used for this study was a potentiometric method in which the potential difference was measured between a working electrode and a reference electrode at different pHs. Firstly a film was produced from a 20 mM solution of 7-azaIC in 0.1 M LiClO$_4$/MeCN. The film was then transferred to aqueous electrolyte (0.1 M KCl) by slowly dropping the aqueous electrolyte in to the non-aqueous electrolyte to avoid film detachment by rapid solvent ingress due to sudden changes in osmotic pressure. The film was then transferred to a pure sample of aqueous electrolyte. The potential difference between the 7-azaIC modified platinum working electrode and a saturated calomel electrode was measured for solutions of electrolyte at differing pH.
The reaction that is expected to be occurring at the electrode surface is given by Equation 10. This shows the redox cycling of the protonated and non-protonated forms of the film species. If the general electrochemical reaction of the film is as given in Eqn. 10

\[ [\text{dimer}]_{\text{red}} \leftrightarrow [\text{dimer}]_{\text{ox}} + mH^+ + ne^- \]  

Eqn 10

then the half cell Nernst equation for this electrode is

\[ E = E^0_{\text{dimer}} + \frac{RT}{nF} \ln \left( \frac{a_{\text{dimer,ox}}^{m}a_{\text{H}^+}^{\text{red}}}{a_{\text{dimer,red}}^{m}} \right) \]  

Eqn 11

where \( a_i \) is the activity of the species \( i \) and \( E^0_{\text{dimer}} \) is the standard reduction potential of the dimer species in the film. Since \( 2.303\log_{10}x = \ln x \) and \( \text{pH} = -\log_{10}a_{\text{H}^+} \), this can be rearranged, in the potentiometric case, where the ratio \([\text{dimer}]_{\text{ox}}/[\text{dimer}]_{\text{red}}\) and hence \( \{a_{\text{dimer,ox}}/a_{\text{dimer,red}}\} \) is fixed, to give

\[ E = E'_{\text{dimer}} - \frac{2.303mRT}{nF} \text{pH} \]  

Eqn 12

where the constant, \( E'_{\text{dimer}} = E^0_{\text{dimer}} + \frac{RT}{nF} \ln \left( \frac{a_{\text{dimer,ox}}^{m}}{a_{\text{dimer,red}}^{m}} \right) \). In this case, since the potential of the calomel reference electrode is independent of pH, the measured potential difference between the 7-aza1C coated electrode and this reference electrode, potential \( E_{\text{cell}} \), would also be expected to change with pH according to Eqn. 13, as from Eqn. 12

\[ E_{\text{cell}} = E - E_{\text{cal}} = \text{const} - \frac{2.303mRT}{nF} \text{pH} \]  

Eqn 13

where \( \text{const} = E'_{\text{dimer}} - E_{\text{cal}} \).
Therefore, if the behaviour of the film is Nernstian in nature then a plot of $E_{\text{cell}}$ versus pH should give a straight line of gradient $2.303 mRT/nF$. In fact, for films, sub-Nernstian slopes are often seen, due to the inhomogeneity of the film and/or electrostatic interactions between neighbouring redox centres. This leads to a dispersion in $E^0_{\text{dimer}}$ and a sub-Nernstian slope; the degree of departure from Nernstian behaviour therefore probes these effects.\textsuperscript{133a} If such film effects are minor, where only one electron is involved in the redox reaction (as is the case for 7azaIC, see section 10.3), the theoretical Nernst slope will be of the order of 58 mV at 20 °C, which allows the number of protons involved in the reaction to be determined. Figure 100 shows this plot. It can be clearly seen that there are two distinct regions of pH with different slopes in the plot. The first is between pH 1 and pH 5.5. In this region the slope is $53 \pm 1$ mV, which gives $m = 0.91 \pm 0.02$, consistent with $m = 1$ with little film inhomogeneity. The second is above pH 5.5, where the slope is $0.61 \pm 0.07$ mV, which indicates that $m = 0.03 \pm 0.01$, consistent with $m = 0$. This is clear indication that the film is pH sensitive between the ranges of pH 1 to around pH 5.5.

This result can be easily explained by the fact that pyridine systems are known to be easily protonated\textsuperscript{133}; in fact the $pK_a$ of pyridine is 5.2\textsuperscript{134}. These results are consistent with the reduced form of the dimer in the film having a similar $pK_a$, so that when the pH is less than this value, it is protonated. In this case, for this response, Eqn. 10 would suggest that the oxidised form of the dimer is deprotonated, due to the net positive charge on the dimer on oxidation. Above the $pK_a$ of the reduced form of the dimer, the reduced form would not be protonated and no protons would be produced during the redox reaction; hence would be expected to be $m = 0$ in this region, which is essentially what is observed. In order to confirm the response was due to the pyridine nitrogen, the experiment was repeated with an IC film (Figure 100). As expected, at high pH the response of both 7-azaIC and IC films are similar, consistent with the redox reactions in both films involving unprotonated film dimers in both redox states. However, at low pH, where IC cannot protonate, no break in slope (no appreciable pH response) was found. This confirms that the pH response is due to protonation of the pyridine ring nitrogen.

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Figure 100. Potential response of a 7-azaIC and an IC film versus pH.

10.6 Summary

It has been found that when 7-azaIC is electro-oxidised, it undergoes dimer formation to give similar film coats to IC. The films consist of a mixture of three dimers in both cases. Both the 7-azaIC and the IC film species have similar steady-state fluorescence properties with major emissions at approximately 405 nm. The main difference between the two systems is that in the case of 7-azaIC there is a basic pyridine nitrogen present in the system. It was found that this pyridine nitrogen could undergo protonation and produce changes in redox response. This response was not found with IC when subjected to similar pH experiments, indicating the central nitrogen is too non-basic to be protonated. The pH response of 7-azaIC has demonstrated its ability to act as a simple electrochemical sensor.
Chapter 11. Pyrrolo[3,2,1-\textit{jk}]carbazole (PC).

11.1 Introduction.

In previous work carried out by M A Chapman on the fluorescence properties of PC\textsuperscript{1} it was found that PC 2 underwent an irreversible electro-oxidation to form an electro-active film at the surface of a platinum working electrode.\textsuperscript{1} Like IC, the film was found to be highly fluorescent in solution. However, unlike IC, when carrying out potential step voltammetry, long term steady-state currents were not achieved, as the currents were found to drop after the potential was applied and a film was formed. This indicated that the films were not as conducting as IC. The monomer used in this study was brown in colour, and although it was found to be essentially pure by \textsuperscript{1}H NMR spectroscopy it is still possible that there may be some impurity present. An impurity in the monomer may also undergo electro-oxidation or react with the radical cations formed. This may affect the film structure and composition, affecting film properties. It is therefore the purpose of this chapter to investigate the electro-oxidation of purified PC to find if a conducting film can be produced or if the film is by nature less conducting than IC.

11.2 Electro-oxidation of PC.

11.2.1 Oxidation potential of PC

PC was prepared as described in Chapter 4 and subjected to flash chromatography, giving a creamy white powder. This is clearly purer than the brown product used previously. A stock solution of 20 mM PC was made in background electrolyte (0.1 M LiClO\textsubscript{4} in MeCN) for electro-oxidation studies. A CV was then recorded from a 1 mM PC solution (Figure 102). The CV shows an irreversible oxidation peak at +1.00 V wrt Ag/Ag\textsuperscript{+}. This result is in agreement with the work carried out by M A Chapman.
Figure 102. CV of a 1 mM solution of PC in background electrolyte.

In contrast to IC and 7-azaIC (chapters 7 and 11) no appreciable redox peaks, due to the formation of a redox active film, were observed at this concentration. CVs of the PC monomer were recorded a different sweep rates, \( u \). Figure 103 shows a plot of the peak oxidation potentials of PC versus \( v^{1/2} \). As discussed in Chapter 6.2.3, for both reversible and irreversible electrochemical systems where the redox active species is in solution, \( i_p \) should be proportional to \( v^{1/2} \), which demonstrates diffusion control. The plot in Figure 98 shows that this relationship holds true.
11.2.2 Potential step voltammetry.

As with the electro-oxidation of IC and its analogues, PC was subjected to electro-oxidation by potential step voltammetry at a rotating disc working electrode. The current time transient observed is shown in Figure 104 which, shows an initial spike consistent with oxidation and coupling in solution followed by deposition on the electrode and subsequent adsorption on to the newly formed film. This behaviour is similar to the electro-oxidation of IC (Chapter 7) and indoles. This is then followed by a drop in the current before a steady-state current is achieved. This is unlike previous work; as with IC and 7-azaIC, this is indication of the formation and growth of a conducting film and
suggests that the formation of a less conducting film in the previous PC study\textsuperscript{1} was due to the presence of an impurity in the monomer.

![Figure 105. Current-time transient observed from electro-oxidation at 1.10 V wrt Ag/Ag\textsuperscript{+} from a 5 mM solution of PC.](image)

During the electro-oxidation of PC a dark green film was found to be deposited on the electrode surface. The film appeared black after a few seconds of electro-oxidation. Unlike IC, after prolonged oxidation over 2-3 minutes, the current typically dropped from its steady-state value.
11.2.3 Cyclic voltammetry of the resulting PC films.

A film was produced from a 5 mM solution of PC and was studied by cyclic voltammetry in LiClO$_4$/MeCN background electrolyte. These reveal a set of redox peaks centred around +0.75 V wrt Ag/Ag$^+$ (Figure 106). A steady-state CV was obtained, showing that the film was stable to redox cycling. The film was studied at different sweep rates and the peak oxidation and reduction potentials were plotted against the sweep rate (Figure 107). The plot in Figure 107 shows a linear correlation ($i_p \propto v$) of both the peak currents with the potential sweep rate. This is indication of fast coat redox kinetics, with complete oxidation and reduction of a surface bound species i.e. the whole film being oxidised and reduced on each sweep. As a consequence of this the area under each peak gives the charge required to fully oxidise or reduce the polymer.

![Cyclic voltammetry of PC film](image)

Figure 106. Cyclic voltammetry of PC film produced from a 5 mM solution of monomer.

260
Figure 107. A plot of the peak oxidation and reduction current of a PC film formed from the electro-oxidation of monomer from a 5 mM solution at 1 Hz.

In this case, the charge in the CV can be used to determine the quantity of electrons passed in the redox reaction of the film. If the oxidation/reduction of the film is assumed to be a one electron process, then the number of electrons used to make the film can be calculated. This is obtained from the current-time transient obtained from film formation and the CV of the film.

A percentage charge calculation was carried out with films made from a 5 mM solution of monomer using the current-time transient produced by the electro-oxidation and the CV produced of the film prepared. The calculation was carried out for films made at a range of rotation speeds between 1 and 16 Hz. Each calculation at a set rotation speed was carried out more than once to ensure consistent results. The result of the calculation showed that the % charge was found to be between 8% for the slower rotation speeds and
up to 4% for the faster rotation speeds. This is much lower than in the case with IC which was found to be around 33%. The lower charge ratio indicates that more electrons may be involved in the film formation process and hence may be used as an indication that the film species consists of higher weight oligomers.

In the case of IC the % charge found indicates that 3 electrons are used in the film formation thus indicating that the film consists of a dimer species. The % found in the PC case is closer to that found in the indole 323 electropolymerisation case which was found to be between 11% and 14%. In the case of indole the 14% charge was found to account for 7 electrons being used in the formation of a trimer species 324 which could undergo further linking through the indole nitrogen atoms to give rise to the 11% charge (Scheme 132).

![Scheme 132](image)

PC is essentially a fused indole and it may be possible that a similar trimer species 297 could be formed. The structure that could be formed may be based on three fused IC structures centred on a central benzene ring. It might be expected that this molecule could undergo further linkage through the IC like reactive sites to form a more conjugated species. However, it has not been possible to provide evidence for this proposal by NMR spectroscopy or LC-MS due to the poor solubility of the film. No mass peak based upon oligomerisation of the PC monomer was found by FAB mass spectrometry.
The most reactive position on indole 323 is the 3-position. The 3-position on indole is where that indole initially couples upon electro-oxidation. The radical cation formed upon electro-oxidation is predominantly situated at the three position. Two indole radical cations then couple with loss of two protons. Further coupling must occur at the 2-position to enable trimer formation. Support for coupling at the 2- and 3-positions of indole was provided by introducing substituents at these sites and studying the effects upon electro-oxidation. Substitution at these sites was found to block film formation. If a PC trimer was formed in this way with IC, then substitution at the reactive indole site may prevent coupling. 4-Cyanopyrrrolo[3,2,1-ijk]carbazole was studied by cyclic voltammetry and potential step voltammetry. The CV (Fig 108) of a 1 mM solution shows an irreversible oxidation peak at +1.5 V. Electro-oxidation at +1.59 V by potential step voltammetry (Fig. 109) shows a current time transient that shows an immediate drop in current after the potential step. No film is produced on the electrode surface. This result may indicate that coupling occurs through the reactive indole site in PC.
Figure 108. CV of a 1 mM solution of 4-cyanopyrrolo[3,2,1-\textit{jk}]carbazole.
11.2.4 Koutecky-Levich analysis of the electro-oxidation of PC.

The electro-oxidation of PC by potential step voltammetry was carried out at different rotation speeds for a series of concentrations. The results were analysed by Koutecky-Levich analysis in the same way as IC (Chapter 7). It was not possible to perform this analysis above 5 mM due to the film becoming non-conducting too quickly to complete the analysis. The result of the Koutecky-Levich analysis is shown in Figure 110 and shows a linear relationship with 1, 2 and 5 mM monomer concentrations. This indicates that the film formation proceeds with first order kinetics with respect to the monomer as this is an assumption in the derivation of the Koutecky-Levich equation. This is also
shown to be the case with IC (Chapter 7), 5-cyanoIC (Chapter 9) and 7-azaIC (Chapter 10) as well as indole systems.\textsuperscript{89}

It was not possible to obtain a mass spectrum by FAB or EI mass spectrometry therefore the conjugation length is not known. The diffusion coefficient for IC was calculated to be $3.0 \times 10$ cm$^2$ s$^{-1}$ in Chapter 7. Due to the similarity of structures between IC and PC it is assumed that the diffusion coefficient for PC would be similar and therefore it the diffusion co-efficient for PC is assumed to be $3.0 \times 10$ cm$^2$ s$^{-1}$. From the Koutecky-Levich equation (Equation 9) it is possible to calculate the number of electrons per monomer if the diffusion co-efficient is known. This value of diffusion co-efficient was used for the calculation of the number of electrons per monomer unit, \( n \). The number of electrons in the reaction was calculated for each concentration and the data is presented in Table 14 along with the mass transport independent currents.

\[
\frac{1}{i_{o_{2}}} = \left( \frac{0.6435 \mu M \, \text{cm} \, \text{s}^{1/6}}{nFAC_{\text{e}}ICD_{IC}^{2/3}W^{1/3}} \right) + \frac{1}{i_{o}}
\]

Equation 9.
Table 14. Data from Koutecky-Levich analysis of PC.

<table>
<thead>
<tr>
<th>Concentration/mM</th>
<th>Slope gradient</th>
<th>Intercept/ mA</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.10 ± 0.03</td>
<td>3.6 ± 0.3</td>
<td>3.44 ± 0.05</td>
</tr>
<tr>
<td>2</td>
<td>1.01 ± 0.06</td>
<td>3.2 ± 0.4</td>
<td>3.58 ± 0.30</td>
</tr>
<tr>
<td>5</td>
<td>0.21 ± 0.02</td>
<td>3.4 ± 0.1</td>
<td>6.87 ± 0.30</td>
</tr>
</tbody>
</table>

The intercepts in the Koutecky-Levich plot (Figure 110) are $1/i_\infty$ (eqn. 9, chapter 7), which give the mass transport independent current. This is the current when $W \to \infty$, mass transport is fast and the concentration of IC at the electrode surface is equal to the bulk concentration of IC. The three concentrations studied converge at the same intercept within experimental error. This shows that the rate of coupling is independent of the

Figure 110. Koutecky-Levich plot of the electro-oxidation of PC.
monomer concentration. In the case of IC this is only the case at concentrations above 10 mM. In the case of 5-cyanoIC it was shown that this was the case at concentrations above 2.5 mM. Finally, in the case of 7-azaIC this was found to be the case at concentrations above 10 mM.

The n value is the number of electrons per monomer unit. In the case of indole this value was found to be 2.33. This can be accounted for as follows; it requires 6 electrons to form the trimer and a further one electron to oxidise the monomer, if there are 7 electrons used and 3 monomer units then the n value has to be 2.33 (7/3). It can be seen for PCI that the values of n are much larger, indicating that the species formed by electro-oxidation of PC is unlikely to be trimer. This result suggests that if a similar reaction pathway occurs in the case of PC, then the resulting species formed might be more polymeric in nature and therefore have a larger chain length.

11.3 Fluorescence spectroscopy.

The PC monomer and film were studied by steady state fluorescence spectroscopy. The fluorescence spectra of the monomer and the film products were recorded in DMF solution for comparison with the results of IC. Emission spectra for the monomer were recorded at differing excitation wavelengths (260, 280, 300, 320, 340 and 360 nm) and are shown in Figure 111. The spectra are normalised to the same Y intensities. It can be seen that there is a major emission at 390 nm. It was found that the shape of the emission spectrum at 390 nm is independent of the excitation wavelength, in other words Kasha’s rule is obeyed. This means that the emission in each case is always from the same state (the lowest vibrational level of the first singlet excited state S1). It also means that there are unlikely to be any other emitting species present that are excited and emit in the same region as the monomer, such as impurities or aggregates.
Figure 111. Fluorescence emission spectrum of PC recorded at excitation wavelengths of 260, 280, 300, 320, 340 and 360 nm (shown above).

A film was prepared at 1 Hz and at 16 Hz and fully dissolved in DMF and then analysed by steady state fluorescence spectroscopy (Figures 112 and 113 respectively. The emission spectra were recorded at a range of excitation wavelengths between 260 nm and 500 nm. The spectra produced are not independent of the wavelength therefore indicating the presence of more than one species. The major emissions are 390 nm, 464 nm, 480 nm, 500 nm, and 520 nm. The spectra show sharp Raman bands in some cases at shorter wavelengths to the main emissions.
Figure 112. Steady state fluorescence spectra for PC film prepared at 1 Hz at excitation wavelengths between 260 and 500 nm increasing in 20 nm increments. Solvent Raman bands are indicated by *.

Figure 113. Steady state fluorescence spectra for PC film prepared at 16 Hz at excitation wavelengths between 260 and 500 nm increasing in 20 nm increments. Solvent Raman bands are indicated by *.
The spectra for the films prepared at 1 Hz and 16 Hz show similar emission characteristics. The emission at 390 nm may be monomer that is trapped in the film. The 464 nm, 480 nm, 500 nm and 520 nm emissions are likely to occur due to the presence of linked PC monomers. The longer the wavelength of the emission the more extensive the conjugation is likely to be. The relative intensities of the emissions at 464 nm, 480, nm, 500 nm and 520 nm are different for each case, particularly the emissions at 500 nm and 520 nm. At 16 Hz the 500 nm and the 520 nm emissions are less intense relative to the other emissions when compared with the spectra of the 1 Hz species.

The results differ slightly from those reported by M A Chapman. It was reported previously that the emission wavelengths change as the rotation speed is increased. At 1 Hz the main species was reported to emit at around 400 nm with a minor emission at 470 nm. At 2 Hz the main emission species was reported to emit at around 460 nm. The results produced in this study show that the product appears to be a more complex mixture than that produced by M A Chapman. The results in this case also are dependent on the rotation speed at which the film is produced, however not to the extent shown by M A Chapman where the emission at 400 nm is not present in the 2 Hz film. In the original work carried out by M A Chapman it was found that although PC formed a film it was shown to be insulating. It was thought that the conductivity of the film could be affected by the presence of impurities in the monomer. In the work carried out in this thesis the PC monomer was subjected to more rigorous purification. Subsequent electropolymerisation produced a conducting film in the case of this work.

11.2.4 Concluding remarks.

Despite their similar structures, PC and IC behave very differently when subjected to electro-oxidation. IC was shown to produce chemically well defined dimeric species, PC was shown to produce a film which consists of higher molecular mass oligomers which do not give clearly defined mass spectra under FAB conditions. The percentage charge in the redox peaks in the case of the PC film was found to be 8-14% whereas with IC it was found to be 33%. In the case of IC three electrons were involve in the formation of
the film species. The lower charge ratio is indicative of more electron being involved in the formation of the film and hence may suggest that the film is more oligomeric in nature when compared to IC. The film species was also shown to consist of a range of different fluorophore species leading to a complex steady-state emission spectrum.

Further structural analysis of the products of PC was hampered by the poor solubility of the film. From experience of IC and its aza analogues it is thought that it may be possible to use the aza analogues of PC to further elucidate the nature of the conjugation in PC type film products as it was found that 7azaIC film was more soluble than the corresponding IC film.
Section C. Experimental.

Organic synthesis (Section A).

Instrumentation and general techniques.

(a) Nuclear Magnetic Resonance Spectroscopy.

$^1$H NMR spectra were recorded on Bruker AVA600 (600 MHz), Bruker DPX360 (360 MHz), Bruker ARX250 (250 MHz) and Varian Gemini 200 (200 MHz) spectrometers. $^{13}$C spectra were recorded on Bruker DPX360 (91 MHz) and Bruker ARX250 (63 MHz) spectrometers.

$^{11}$B NMR spectra were recorded on a Bruker DPX360 at 115 MHz. Chemical shifts ($\delta_B$) are quoted in ppm relative to boron trifluoride etherate.

$^2$D NMR spectra were recorded on a Bruker DPX360 55 MHz. Chemical shifts ($\delta_D$) are quoted in ppm.

The Bruker AVA600 was operated by Dr. I.H. Sadler and Mr S.I. Wharton, the DPX360 was operated by Dr. D. Reed, Mr S.I. Wharton and Mr. J.R.A. Millar, the Bruker ARX250 by Mr. J.R.A. Millar and the Varian Gemini 200 by Mr. S.I. Wharton.

Deuteriated solvents used are quoted individually in each experimental. Chemical shifts ($\delta_H$ and $\delta_C$) are quoted in ppm relative to tetramethylsilane, and all coupling constants are given in Hertz (Hz).

(b) Mass spectrometry.

Low resolution electron impact mass spectra were recorded on a Kratos profile instrument. High resolution spectra were recorded on a Kratos MS50 TC instrument. Both instruments were operated by Mr. A.T. Taylor. All spectra were obtained by electron impact unless otherwise stated.

(c) Elemental analysis.

Microanalyses were carried out on an Elemental Analyzer Model CE 440 CHN by Mrs Smilja Djurdjevic.
(d) Infrared spectroscopy.
Infrared spectroscopy was carried out on a Jasco FT/IR-460 plus instrument. IR spectra were run as films, nujol mulls or solutions.

(e) Chromatography.
Thin-layer chromatography was carried out on pre-coated aluminium sheets (0.2mm silica gel, Merck, Grade 60) impregnated with an ultra violet indicator. Dry flash chromatography was carried out on silica gel (Merck, grade 60, 230-400 mesh, 60 Å). The crude materials were generally pre-adsorbed onto silica gel and then loaded onto the column. The solvent systems varied, but all employed increasing increments of the polar component.

(f) Melting points.
All melting points were recorded on a Gallenkamp melting point apparatus. Samples of known compounds that were pure by $^1$H NMR spectroscopy were not routinely recrystallised before melting point determination.

(g) Commercial chemicals.
All commercial starting materials were obtained from Aldrich, Acros or Lancaster. Fluorinated starting materials were obtained from Fluorochem. Palladium catalysts were obtained from Strem.

(h) Solvents.
All solvents were obtained from Aldrich, Fisher or Rathburn and were used without further purification unless otherwise stated.
FLASH VACUUM PYROLYSIS.

Flash vacuum pyrolysis involves gaseous molecules being subjected to high temperatures for very short periods of time, usually $10^{-2} - 10^{-3}$ seconds. In principle, the substrate is distilled or sublimed through an electrically heated tube which is connected to a cold trap and vacuum line. Figure 103 illustrates the apparatus used in such experiments and is based on the design of W.D. Crow of the Australian National University.

A glass Büchi oven was used to volatilise the substrate at temperatures lower than 300 °C and the substrate is then drawn through a silica tube (30 × 2.5 cm) heated by a Carbolite electronically controlled laboratory tube furnace (model No MTF 12/38/250). The products are collected at the exit of the furnace tube in a trap surrounded by liquid nitrogen. A “U-shaped” trap was used for small-scale pyrolysis. The system was evacuated and the vacuum maintained by an Edwards (Model ED100) high capacity oil pump.

After pyrolysis the trap was washed through with a suitable solvent. For small-scale pyrolysates (50 – 100 mg) the solvent of choice was frequently CDCl$_3$ which enabled immediate examination by $^1$H and $^{13}$C NMR spectroscopy. DMSO-$d_6$ was used for pyrolysates that were insoluble in CDCl$_3$. 

Figure 103. FVP apparatus as designed by W.D. Crow.
Standard pyrolysis parameters used throughout this section are furnace temperature $T_f$, inlet temperature $T_i$, pressure $p$, sublimation/distillation time $t_m$ and mass of substrate $m_a$.

In some cases, alternative trapping methods were employed, such as a cold finger trap (using dry ice/acetone as the cooling system) when the product was unstable to reactive waste gases and these methods are described as follows.

All FVP reactions with nitro group containing precursors on a scale greater than 100 mg were carried out using modified apparatus (Figure 104). The nitro radical leaving group forms gaseous by-products which can react with product and lower the yield of the desired compound. A modified experimental set-up is used to moderate this problem by the addition of a dry-ice acetone trap between the furnace and the U-tube trap. The dry-ice trap condenses only the product and the reactive gases pass through and collect in the U-tube trap, thereby separating the unwanted gaseous products. Reactions have been carried out on 0.1 – 5 g scale with this modification.

Figure 104. The modified apparatus used in large scale FVP of nitro group containing compounds.
12.2 Organic syntheses
Carbazole Precursors.

4-Hydroxy-2'-nitrodiphenylamine 64.

2-Fluoronitrobenzene (2.00 g, 14 mmol) and p-aminophenol (1.53 g, 14 mmol) were dissolved in DMSO (30 cm$^3$) in the presence of sodium acetate (2.76 g, 14 mmol) and stirred at 120 °C for 18 h. The suspension was diluted with water (50 cm$^3$) and extracted with DCM (3 × 100 cm$^3$). The organic extracts were combined and washed with water (3 × 100 cm$^3$), dried over MgSO$_4$ and the solvent removed under reduced pressure. The resulting mixture was separated using dry flash chromatography on silica (hexane/ethyl acetate) to give 4-hydroxy-2'-nitrodiphenylamine (2.12 g, 65 %) mp 146-149 °C [lit. 131 147-149 °C]

$\delta_H$ (250 MHz, DMSO-$d_6$) 9.58 (1H, br, s), 9.35 (1H, br, s), 8.10 (1H, dd, $^3J$ 8.6, $^4J$ 1.6), 7.43 (1H, td, $^3J$ 7.0, $^4J$ 1.5), 7.23 (2H, d, $^3J$ 8.6), 6.92 (1H, dd, $^3J$ 8.7, $^4J$ 1.0) 6.88 – 6.82 (2H, m) and 6.77 (1H, td, $^3J$ 7.1, $^4J$ 0.8); $\delta_C$ (63 MHz, DMSO-$d_6$) 155.41 (quat), 143.95 (quat), 135.90 (CH), 131.59 (quat), 129.42 (quat), 127.02 (2 × CH), 125.87 (CH), 116.43 (CH), 115.88 (2 × CH) and 115.67 (CH); m/z 230 (M$^+$, 100%), 213 (12), 184 (48), 154 (62), 121 (36), 93 (64) and 77 (34).

4-Methyl- 2'-nitrodiphenylamine 65.

2-Fluoronitrobenzene (2.00 g, 14 mmol) and p-toluidine (1.52 g, 14 mmol) were dissolved in DMSO (30 cm$^3$) in the presence of potassium carbonate (2.76 g, 14 mmol) and stirred at 180 °C for 18 h. The suspension was diluted in water (200 cm$^3$) and extracted with DCM (3 ×100 cm$^3$). The organic extracts were combined and washed with water (3 ×100 cm$^3$), dried MgSO$_4$ and the solvent removed under reduced pressure. The resulting mixture was separated using dry flash chromatography on silica (hexane/ethyl acetate) to give 4-methyl- 2'-nitrodiphenylamine (1.36 g, 42%) mp 68-70 °C [lit. 136 69 – 70 °C]

$\delta_H$ (250 MHz, CDCl$_3$) 9.38 (1H, br, s), 8.15 (1H, dd, $^3J$ 8.6, $^4J$ 1.3), 7.26 – 7.04 (7H, m) and 2.30 (3H, s); $\delta_C$ (63 MHz, CDCl$_3$) 144.15 (quat), 136.32 (quat), 136.17 (CH), 136.14 (quat), 133.23 (quat), 130.76 (2 × CH), 127.07 (CH) 125.26 (2 × CH), 117.52 (CH), 116.37 (CH) and
2-Nitro-4'-chlorodiphenylamine 16.

*p-Chloroaniline (3.85 g, 30.2 mmol) and 2-fluoronitrobenzene (4.26 cm³, 30.2 mmol) were dissolved in DMSO (40 cm³) and stirred at 170 – 180 °C for 20 h in the presence of potassium carbonate (5.00 g, 36.3 mmol). The reaction mixture was then cooled and diluted with water (150 cm³) and extracted with DCM (4 × 50 cm³). The organic layers were combined and washed with water (3 × 50 cm³) and then dried over MgSO₄ before being concentrated under reduced pressure. The crude product was recrystallised from ethanol to give 2-nitro-4'-chlorodiphenylamine (3.36 g, 45%) mp 145 - 146 °C (ethanol) [lit., 137 145.5 °C]; δH (250 MHz, CDCl₃) 9.14 (1H, br, s), 8.12 (1H, dd, 3J 8.6, 4J 1.5), 7.31 – 7.29 (3H, m), 7.15 – 7.08 (3H, m) and 6.75 (1H, td, 3J 7.1, 4J 1.3); δC (63 MHz, CDCl₃) 142.69 (quat), 137.49 (quat), 135.91 (CH), 133.60 (quat), 130.93 (quat), 129.97 (2 × CH), 126.85 (CH), 125.63 (2 × CH), 118.08 (CH), and 116.03 (CH).

4-Cyano-2'-nitrodiphenylamine 67.

4-Aminobenzonitrile (1.00 g, 8.10 mmol) and 2-fluoronitrobenzene (1.20 g 8.50 mmol) were stirred at room temperature in DMSO (20 cm³) with potassium t-butoxide (1.90 g, 16.90 mmol) for 24 h. The solution was diluted with water (200 cm³) and filtered. The orange precipitate was washed with HCl (2M) and crystallised from glacial acetic acid to give 4-cyano-2'-nitrodiphenylamine (1.12 g, 55%) mp 178 – 179 °C (glacial acetic acid) [lit., 26 179 -180 °C]; δH (250 MHz, CDCl₃) 9.64 (1H, br, s), 8.35 (1H, d, 3J 8.6), 7.78 (2H, d, 3J 8.7), 7.70 – 7.62 (2H, m), 7.48 (2H, d, 3J 8.7) and 7.12 – 7.05 (1H, m); δC 144.38 (quat), 140.12 (quat), 136.31 (CH), 136.23 (quat), 134.47 (2 × CH), 127.54 (CH), 121.81 (2 × CH), 120.84 (CH), 119.40 (CH), 117.94 (CH) and 107.47 (quat); m/z 239 (M⁺, 100%), 192 (88), 91 (11) and 77 (9).
2-Nitro-4'-trifluoromethyldiphenylamine 68.

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\text{NO}_2 \quad \text{CF}_3 \quad 4\text{-Aminobenzotrifluoride (1.00 g, 9.9 mmol), and 2-fluoronitrobenzene (1.41 g 12 mmol) were stirred at room temperature in DMSO (30 cm}\textsuperscript{3}) \text{ in the presence of potassium } t\text{-butoxide (1.0 g, 17 mmol) for 24 h. The solution was diluted with water (50 cm}\textsuperscript{3}) \text{ and extracted with DCM (3 x  100 cm}\textsuperscript{3}) \text{ The organic layers were combined and washed with water (3 x  100 cm}\textsuperscript{3}) \text{ before being dried over MgSO}_4. The mixture was pre-adsorbed onto silica for dry flash chromatography (hexane/toluene) to give 2-nitro-4'-trifluoromethyldiphenylamine (1.40 g, 50 %). mp 95 - 96 °C; (Found: C, 54.5; H 3.2; N 9.7, C\textsubscript{13}H\textsubscript{9}F\textsubscript{3}N\textsubscript{2}O\textsubscript{2}. 0.3 H\textsubscript{2}O requires C, 54.3; H, 3.1; N, 9.7%); } \delta (250 \text{ MHz, CDCl}_3) 9.65 (1H, br, s), 8.55 (1H, dd, 3J 8.6, 4J 1.5), 7.64 (2H, d, 3J 8.7), 7.49 - 7.35 (4H, m) and 6.90 (1H, d, 3J 7.2); \& (63 \text{ MHz, CDCl}_3) 142.31 (quat), 140.85 (quat), 135.60 (CH), 134.46 (quat), 126.83 (2 x CH), 126.70 (CH), 126.65 (quat), 122.21 (2 \times CH), 121.72 (quat) 118.97 (CH) and 116.43 (CH); m/z 282 (M\textsuperscript{+}, 100%), 265 (14), 235 (52), 216 (14), 167 (8), 145 (12 ) and 75 (9).

1-Cyano-2'-nitrodiphenylamine 71.

\[
\text{N} \quad \text{CN} \quad \text{Anthranilonitrile (0.50 g, 4.0 mmol) and potassium } t\text{-butoxide (0.5 g, 4.5 mmol) were stirred at room temperature in DMSO (30 cm}\textsuperscript{3}) \text{ for 30 min. 2-Fluoronitrobenzene (0.56 g, 4.1 mmol) was added and left to stir for 24 h. The purple mixture was diluted with water (50 cm}\textsuperscript{3}) \text{ and a precipitate formed. The suspension was then extracted with DCM (3 x  100 cm}\textsuperscript{3}). The organic layers were combined, washed with water (3 x  100 cm}\textsuperscript{3}) \text{ and dried over MgSO}_4. The solvent was removed under reduced pressure to give 1-cyano-2'-nitrodiphenylamine (0.67 g, 70%). mp 141-142 °C [lit.,\textsuperscript{26} 140-141 °C]; } \delta (250 \text{ MHz, CDCl}_3) 9.58 (1H, br, s), 8.23 (1H, dd, 3J 8.5, 4J 1.6), 7.69 (1H, dd, 3J 7.8, 4J 1.2), 7.58 (1H, td, 3J 7.2, 4J 1.6), 7.48 (2H, m), 7.27 (2H, m) and 6.97 (1H, dd, 3J 8.5, 4J 1.3); \& (63 \text{ MHz, CDCl}_3) 142.33 (quat), 14.01 (quat), 135.49 (CH), 135.12 (quat), 133.77 (2 x CH), 126.66 (CH), 124.66 (CH) 122.49 (CH), 119.83 (CH), 116.80 (CH), 116.80 (quat) and 107.00 (quat); m/z 239 (M\textsuperscript{+}, 100%), 192 (90), 164 (47), 139 (27), 102 (47), 63 (56) and 39 (57).


5-Methyl-2-nitrodiphenylamine 124.

3-Fluoro-4-nitrotoluene (0.55 g, 3.55 mmol), aniline (0.33 g, 3.55 mmol) and potassium carbonate (0.55 g, 3.91 mmol) were stirred at 180 °C in nitrobenzene under nitrogen for 18 h. The nitrobenzene was removed by bulb-to-bulb distillation and the resulting dark brown oil was purified by dry flash chromatography (toluene/hexane) to give 5-methyl-2-nitrodiphenylamine (0.34 g, 42%) mp 110 - 111 °C [lit., 118 °C]; $\delta$ (250 MHz, CDCl$_3$) 9.47 (1H, br, s), 8.03 (1H, d, $^3J$ 8.8), 7.36 - 7.17 (5H, m), 6.92 (1H, d, $^3J$ 0.8), 6.52 (1H, dd, $^3J$ 8.7, $^4J$ 1.5) and 2.20 (3H, s); $\delta$ (63 MHz, CDCl$_3$), 147.51 (quat), 143.28 (quat), 138.90 (quat), 132.00 (quat), 129.85 (2 × CH), 126.78 (CH), 125.72 (CH), 124.64 (2 × CH), 119.28 (CH), 115.54 (CH) and 22.13 (CH$_3$); m/z 228 ($M^+$, 100%), 181 (37), 167 (97) and 90 (10).

3-Methyl-2′-nitrodiphenylamine 69.

2-Fluoronitrotoluene (2.00 g, 14 mmol), m-toluidine (1.52 g, 14 mmol) and potassium carbonate (2.76 g, 20 mmol) were stirred at 180 °C in DMSO under nitrogen for 18 h. The reaction mixture was diluted with water (50 cm$^3$) after cooling and extracted with DCM (3 × 100 cm$^3$). The combined DCM fractions were washed with water (3 × 100 cm$^3$) and dried over MgSO$_4$ to give 3-methyl-2-nitrodiphenylamine (1.60 g, 50%) mp 75 - 77 °C [lit., 77 - 78 °C]; $\delta$ (250 MHz, CDCl$_3$) 9.48 (1H, br, s), 8.20 (1H, d, $^3J$ 8.6, $^4J$ 1.6), 7.37 - 7.25 (3H, m), 7.11 - 7.05 (3H, m) 6.77 (1H, ddd, $^3J$ 8.5, $^3J$ 6.8, $^4J$ 1.6) and 2.39 (3H, s); $\delta$ (63 MHz, CDCl$_3$) 143.47 (quat), 139.63 (quat), 138.41 (quat), 135.51 (CH), 132.90 (quat), 129.33 (CH), 126.47 (CH), 126.32 (CH), 124.88 (CH), 121.20 (CH), 117.18 (CH), 116.00 (CH) and 21.24 (CH$_3$); m/z 228 ($M^+$, 100%), 181 (41), 167 (34), 135 (10), 107 (25) and 65 (18).
FVP of substituted 2-nitrodiphenylamines.

2-Nitrodiphenylamine was initially subjected to FVP over a variety of furnace temperature to optimise the reaction temperature. This was carried out on a 20-50 mg scale so that each pyrolysate could be fully dissolved in CDCl\(_3\) for \(^1\)H NMR analysis. Once the furnace temperature was optimised the reaction was carried out on a preparative scale (~0.50 g) so that a yield could be calculated.

The appropriate 2-nitrodiphenylamine derivatives were sublimed or distilled under vacuum through the furnace tube and the product(s) were collected in a trap cooled by liquid nitrogen (20-100 mg scale). The trap was allowed to warm to room temperature under a nitrogen atmosphere. The entire pyrolysate was dissolved in an appropriate deuteriated solvent to enable removal from the trap for NMR analysis. Each derivative was also pyrolysed on a preparative scale (~0.50 g).

All preparative pyrolyses were carried out with an additional dry ice-acetone trap as described in the general experimental. The products were collected by dissolution in DCM followed by pre-adsorption onto silica for purification by dry flash chromatography using hexane/ethyl acetate unless otherwise stated. The following derivatives were pyrolysed, with the pyrolysis parameters given in brackets.

FVP of 2-Nitrodiphenylamine 63.

Small scale.

This pyrolysis was carried out under the following conditions.

\[T_f \text{ 825 - 925 °C, } T_i \text{ 110-130 °C, } P \text{ 2.6 x 10}^2 \text{ Torr, } t_m \text{ 30 min, } m_a \text{ 0.04 - 0.06 g}.\]

The characteristic doublet at \(\delta_i \text{ 8.10 for carbazole and the characteristic multiplet at } \delta_i \text{ 8.30 for phenazine from the } ^1\text{H NMR spectra (250 MHz, CDCl}_3\text{) were used to calculate the product ratio for the pyrolyses. The ratio is presented as carbazole : phenazine for each respective } T_f.\]

\(T_f \text{ 800 °C, 70 : 30. } T_f \text{ 825 °C, 71 : 29. } T_f \text{ 850 °C, 70 : 30. } T_f \text{ 875 °C, 71 : 29. } T_f \text{ 900 °C, 75 : 25. } T_f \text{ 925 °C, 72 : 28.}\)
Preparative scale pyrolysis of 2-nitrodiphenylamine.

Pyrolysis produced carbazole 3 (0.228 g, 56%) mp 247 - 248°C [lit.,\textsuperscript{140} 248 - 249 °C]; \( \delta_H \) (250 MHz, CDCl\textsubscript{3}), 8.10 (2H, d, \( ^3J \ 8.5 \)), 7.53 - 7.21 (4H, m) and 7.30 - 7.15 (2H, m). N-H masked by doublet at 8.10; \( \delta_C \) (63 MHz, CDCl\textsubscript{3}) 139.34 (2 \times \text{quat}), 125.71 (2 \times \text{CH}), 123.21 (2 \times \text{quat}), 120.21 (2 \times \text{CH}) and 119.31 (2 \times \text{CH}) and 110.45 (2 \times \text{CH}); \( m/z \) 167 (M\textsuperscript{+}, 100%), 153 (82), 63 (32), and 51 (48); Phenazine 73 (0.057 g, 13%) mp 175 - 176 °C [lit.,\textsuperscript{141} 177 - 178 °C]; \( \delta_H \) (250 MHz, CDCl\textsubscript{3}) 8.26 - 8.18 (4H, m), 7.84 - 7.77 (4H, m); \( \delta_C \) (63 MHz, CDCl\textsubscript{3}) 143.34 (4 \times \text{quat}), 130.34 (4 \times \text{CH}), 129.51 (4 \times \text{CH}); \( m/z \) 180 (M\textsuperscript{+}, 100%), 153 (20), 90 (17), 76 (32), 63 (13).

FVP of 4-Hydroxy-2'-nitrodiphenylamine 64.

Small scale.

Pyrolysis produced 3-hydroxycarbazole 74 (0.125 g, 32%) mp 255-256 °C [lit.,\textsuperscript{142} 259-260 °C]; \( \delta_H \) (250 MHz, DMSO-\textsubscript{d6}), 10.88 and 10.97 for the carbazole and phenazine respectively. The ratio was 62 : 38.

Preparative scale

Pyrolysis produced 3-hydroxycarbazole 74 (0.125 g, 32%) mp 255-256 °C [lit.,\textsuperscript{142} 259-260 °C]; \( \delta_H \) (250 MHz, DMSO-\textsubscript{d6}), 10.88 (1H, br s), 8.94 (1H, br s), 7.97 (1H, d, \( ^3J \ 7.74 \)), 7.43 - 7.27 (4H, m), 7.06 (1H, td, \( ^3J \ 7.8, ^4J \ 0.9 \)) and 6.90 (1H, dd, \( ^3J \ 7.8, ^4J \ 0.9 \)); \( \delta_C \) (63 MHz, CDCl\textsubscript{3}) 150.19 (quat), 140.20 (quat), 133.56 (quat), 125.00 (CH), 122.85 (quat), 122.08 (quat) 119.89 (CH), 117.53 (CH), 114.81 (CH), 111.11 (CH), 110.62 (CH) and 104.66 (CH); \( m/z \) 183 (M\textsuperscript{+}, 49%), 154 (8), 110 (74), 78 (100) and 63 (87).
2-Hydroxyphenazine 77 (0.075 g, 18%) mp 248-251 °C [lit.,\textsuperscript{143} 253-254 °C]; $\delta_H$ (250 MHz, CDCl$_3$) 10.97 (1H, br s), 8.21-8.12 (2H, m), 7.91-7.78 (3H, m), 7.61 (1H, dd, $^3J$ 9.4, $^4J$ 2.6) and 7.37 (1H, d, $^3J$ 2.6); $\delta_C$ (63 MHz, CDCl$_3$) 144.51 (quat), 142.70 (quat), 140.72 (quat), 139.29 (quat) 130.59 (CH), 130.47 (CH), 129.13 (CH), 128.73 (CH), 128.33 (CH), 126.31 (CH), 115.44 (quat) and 106.81.

**FVP of 4-Methyl -2'-nitro diphen ylamine 65.**

Small scale.

$[T_f$ 875 °C, $T_1$ 100-120 °C, $P$ 3.0 x 10$^{-2}$ Torr, $t_m$ 15 min, $m_a$ 0.065 g].

The ratio of 3-methylcarbazole : 2-methylphenazine was obtained from the $^1H$ NMR spectrum at 250 MHz (CDCl$_3$) from the characteristic methyl peaks, $\delta_H$ 2.41 and 2.6 for the carbazole and phenazine respectively. The ratio was 77 : 23.

Preparative scale.

$[T_f$ 875 °C, $T_1$ 100-120 °C, $P$ 2.8 x 10$^{-2}$ Torr, $t_m$ 20 min, $m_a$ 0.47 g].

Pyrolysis yielded 3-methylcarbazole 76 (0.141 g, 38%) mp 204-205 °C [lit.,\textsuperscript{144} 207 °C]; $\delta_H$ (250 MHz, DMSO-$d_6$) 11.13 (1H, br, s), 8.07 (1H, d, $^3J$ 7.4), 7.91 (1H, s), 7.46 (1H, d, $^3J$ 8.2), 7.41 – 7.33 (2H, m), 7.22 (1H, d, $^3J$ 8.3), 7.13 (1H, t, $^3J$ 7.1) and 2.41 (3H, s); $m/z$ 181 (M$^+$, 100%), 90 (19) and 77 (17).

**FVP of 4-chloro -2'-nitro diphen ylam ine 66.**

Small scale.

$[T_f$ 875 °C, $T_1$ 150 °C, $P$ 3.0 x 10$^{-2}$ Torr, $t_m$ 15 min, $m_a$ 0.05 g].

Ratio of 3-chlorocarbazole : 2-chlorophenazine was obtained from the $^1H$ NMR, (250 MHz, DMSO-$d_6$) from the characteristic peaks at $\delta_H$ 8.26 and 8.28 for the carbazole and phenazine respectively. The ratio was 86 : 14.
Pyrolysis yielded 3-chlorocarbazole 78 (0.150 g, 39%) mp 197 – 198 °C [lit.,\(^{145}\) 198 – 200 °C]; \(\delta_t\) (250 MHz, DMSO-\(d_6\)) 11.48 (1H, br, s), 8.26 (1H, d, \(^3J\ 2.0\)), 8.20 (1H, d, \(^3J\ 5.9\)), 7.52 – 7.41 (4H, m), 7.20 (1H, t, \(^3J\ 6.8\)); \(\delta_c\) (63 MHz, DMSO-\(d_6\)) 141.36 (quat), 139.16 (quat), 127.61 (quat), 126.51 (CH), 124.87 (quat), 124.03 (quat), 122.67 (CH), 121.83 (CH), 121.01 (CH), 119.90 (CH), 113.30 (CH) and 112.48 (CH); \(m/z\) 201 (M\(^+\), 100%), 166 (51), 140 (19), 101 (16) and 63 (16).

2-Chlorophenazine 79 (0.021 g, 5 %) mp 133-137 °C [lit.,\(^{146}\) 136-140 °C]; \(\delta_t\) (250 MHz, DMSO-\(d_6\)) 8.28 – 8.24 (3H, m), 7.92 – 7.87 (3H, m) and 7.20 (1H, m); \(m/z\) 214 (M\(^+\), 100%) and 179 (34).

FVP of 2-Nitro-4'-cyanodiphenylamine 67.

Small scale.

2-Cyanophenazine has had no literature \(^1\)H NMR spectrum reported and none of the product was isolated from large scale reaction. There is a singlet at \(\delta_t\) 8.75 in 3-cyanocarbazole. In the crude pyrolysate of 67 there is a small singlet at \(\delta_t\) 8.91. This is assumed to be from 2-cyanophenazine. On this basis the ratio of the carbazole to the phenazine was calculated to be 85:15.

Preparative scale.

Pyrolysis produced 3-cyanocarbazole 80 (0.174 g, 73%) mp 183 – 184 °C [lit.,\(^{147}\) 184 – 185 °C]; \(\delta_t\) (250 MHz, DMSO-\(d_6\)) 11.93 (1H, br,s) 8.75 (1H, s), 8.30 (1H, d, \(^3J\ 7.9\)), 7.82 (1H, d, \(^3J\ 8.1\) ), 7.71 (1H, d, \(^3J\ 7.9\) ), 7.62 (1H, dd, \(^3J\ 8.7\) \(^4J\ 1.6\)), 7.62 (1H, td, \(^3J\ 7.0\) \(^4J\ 1.2\) ), and 7.32 (1H, td \(^3J\ 8.6\) \(^4J\ 1.5\) ); \(\delta_c\) (63 MHz, DMSO-\(d_6\)) 139.22 (quat), 137.79 (quat), 126.14 (CH), 124.53 (CH), 123.11 (CH), 120.17 (quat), 119.13 (quat), 118.48 (CH), 118.13 (quat), 117.42 (CH), 109.57 (CH), 109.11 (CH) and 97.74 (quat); \(m/z\) 192 (M\(^+\), 100%), 164 (58) and 96 (55).
FVP of 2-Nitro-4'-trifluoromethyl diphenylamine 68.

\[ T_f \] 875 °C, \( T_i \) 130 °C, \( P \) 2.4 \times 10^{-2} \text{Torr}, \( t_m \) 30 min, \( m_a \) 0.177 g. 

Pyrolysis produced 3-trifluoromethylcarbazole 82 (68%) mp 166-167 °C [lit., 148 166-167 °C]; \( \delta_H \) (250 MHz, DMSO-\( d_6 \)) 12.46 (1H, br,s) 8.75 (1H, d, \( ^3J \) 0.7), 8.30 (1H, d, \( ^3J \) 7.8), 7.82 (2H, m), 7.71 (1H, dd, \( ^3J \) 7.3, \( ^4J \) 1.5), 7.62 (1H, td, \( ^3J \) 7.0 \( ^4J \) 1.2), and 7.62 (1H, td, \( ^3J \) 7.2, \( ^4J \) 1.1), and ); 7.32 – 7.19 (1H, m); \( \delta_C \) (63 MHz, DMSO-\( d_6 \)) 141.18 (quat), 140.14 (quat), 127.48 (quat), 126.40 (CH), 123.17 (quat), 121.87 (CH), 120.65 (CH), 119.20 (CH), 118.61 (quat), 117.68 (CH), 119.21 (CH) and 119.93 (CH). 1 \times \text{quat not apparent}; \text{m/z} 235 (M^+, 100%), 216 (17), 166 (9), 117 (10) and 69 (7).

FVP of 1-Cyano-2'-nitro diphenylamine 71.

\[ T_f \] 875 °C, \( T_i \) 135-145 °C, \( P \) 2.4 \times 10^{-2} \text{Torr}, \( t_m \) 25 min, \( m_a \) 0.49 g. 

Pyrolysis produced 1-cyanocarbazole 91 (0.264 g, 67 %) mp 198-200 °C [lit., 149 200-201 °C]; \( \delta_H \) (250 MHz, DMSO-\( d_6 \)) 8.62 (1H, dd, \( ^3J \) 7.9 \( ^4J \) 1.1), 7.62 (1H, dd, \( ^3J \) 8.7 \( ^4J \) 1.6), 7.99 (1H, dd, \( ^3J \) 7.6 \( ^4J \) 1.1), 7.69 (1H, dd, \( ^3J \) 7.1 \( ^4J \) 0.8), 7.63 (1H, td, \( ^3J \) 7.02 \( ^4J \) 1.2), 7.47 (1H, t, \( ^3J \) 7.8) and 7.43 (1H, td, \( ^3J \) 7.7 \( ^4J \) 0.9). N-H not apparent; \( \delta_C \) (63 MHz, DMSO-\( d_6 \)) 139.96 (quat), 139.91 (quat), 129.42 (CH), 126.75 (CH), 125.40 (CH), 123.59 (quat), 121.55 (quat), 120.53 (CH), 119.72 (CH), 118.57 (CH) 117.22 (quat), 111.51 (CH) and 92.65 (quat); \text{m/z} 192 (M^+, 100%), 164 (16), 94 (25), 67 (11) and 39 (14);

FVP of 5-methyl-2-nitro diphenylamine 124.

\[ T_f \] 875 °C, \( T_i \) 100 °C, \( P \) 3.0 \times 10^{-2} \text{Torr}, \( t_m \) 15 min, \( m_a \) 0.05 g.

The ratio of the two possible isomers, 2-methylcarbazole 84 and 4-methylcarbazole 85 was calculated from the \( ^1 \text{H} \) NMR spectrum (250 MHz, acetone-\( d_6 \)) using the integrals of their respective methyl signals. The methyl shifts were \( \delta_H \) 2.45 and \( \delta_H \) 2.84 respectively. The ratio of 2-methylcarbazole 84 : 4-methylcarbazole 85 was calculated to be 60 : 40.
FVP of 3-methyl-2'-nitrodiphenylamine 69.

\[ T_f \ 875 \degree C, \ T_i \ 120 - 140 \degree C, \ P \ 3.0 \times 10^{-2} \ \text{Torr}, \ t_m \ 20 \ \text{min}, \ m_a \ 0.05 \ \text{g}. \]

The ratio of the two possible isomers, 2-methylcarbazole 84 and 4-methylcarbazole 85 was calculated from the \(^1\text{H} \ \text{NMR} \) spectrum (250 MHz, acetone-\(d_6\)) using the integrals of their respective methyl signals. The methyl shifts were \( \delta_H \ 2.47 \) and \( \delta_H \ 2.85 \) respectively.\(^{150}\) The ratio of 2-methylcarbazole 84 : 4-methylcarbazole 85 was calculated to be 54 : 46.

Deuterium exchange

2-Nitrodiphenylamine 63, diphenylamine 127 and carbazole 3.

The precursors were heated in solution a flame-dried FVP inlet tube with anhydrous MeOD. The solvent was removed under vacuum. The precursors were then subjected to FVP under identical conditions. The pyrolysate was dissolved in DMSO for analysis by \(^2\text{D} \ \text{NMR} \) spectroscopy. \( [T_f \ 875 \degree C, \ T_i \ 150-170 \degree C, \ P \ 3.0 \times 10^{-2} \ \text{Torr}, \ t_m \ 15 \ \text{min}, \ m_a \ 0.05 \ \text{g}] \).

FVP of deuterium enriched 2-Nitrodiphenylamine 63.

\( \delta_D (55 \ \text{Mz, DMSO}) \ 10.37 \ (1 \times ^2\text{H}, \ \text{br s}) \) and 7.53 \ (1 \times ^2\text{H}, \ \text{br s}).

FVP of deuterium enriched diphenylamine 127.

\( \delta_D (55 \ \text{Mz, DMSO}) \ 5.60 \ (1 \times ^2\text{H}, \ \text{br s}). \)

FVP of deuterium enriched carbazole 3.

\( \delta_D (55 \ \text{Mz, DMSO}) \ 10.30 \ (1 \times ^2\text{H}, \ \text{br s}). \)

Phenazine N-oxide synthesis and pyrolysis.

Phenazine N-oxide 114.

Phenazine \( (0.5 \ \text{g}, \ 2.8 \ \text{mmol}) \) and hydrogen peroxide, 30\% (0.35 cm\(^3\)) were heated at 80 \degree C in glacial acetic acid (20 cm\(^3\)) for 3 h. Hydrogen peroxide, 30\%w/v (0.25 cm\(^3\)) was then added and heated at 80 \degree C for a further 18 h. The mixture was then allowed to cool to room temperature at which point
an orange precipitate of di-N-oxide formed. The precipitate was filtered and heated under reflux in toluene (20 cm³) for 7 h. The solvent was evaporated under reduced pressure to yield the N-oxide (0.512 g, 94%). mp 225 – 226 °C [lit.,¹⁵¹ 225 °C]; δH (250 Mz, CDCl₃) 8.59 (2H, d, 3J 8.6, 4J 1.8), 8.10 (2H, d, 3J 8.4, 4J 1.6) and 7.75 – 7.66 (4H, m); δC (63 MHz, CDCl₃) 145.59 (2 x quat), 134.94 (2 xquat), 131.39 (2 x CH), 130.50 (2 x CH), 130.21 (2 x CH) and 119.21 (2 x CH); m/z 196 (M⁺, 100%), 180 (40), 76 (14) and 57 (41).

Phenazine N-oxide 114 pyrolysis temperature profile.
Phenazine N-oxide was subjected to FVP over a range of temperatures to assess the extent of de-oxygenation. The phenazine 73 signal at δH 8.22 and the phenazine N-oxide 114 signal at δH 8.59 were used to calculate the ratio of the two compounds.

\[ T_f = 825 - 925 °C, \ T_i = 160-170 °C, \ P = 10^{-2} \text{ Torr}, \ t_m = 10 \text{ min}, \ m_a = 0.015 - 0.025 \text{ g}. \]

Tf 825 °C. Ratio of Phenazine 114 N-oxide : Phenazine 73 85 : 15.
Tf 900 °C. Ratio of Phenazine 114 N-oxide : Phenazine 73 40 : 60.
Tf 925 °C. Ratio of Phenazine 114 N-oxide : Phenazine 73 27 : 73.

N-Methyl-2-nitrodiphenylamine 72.

A solution of 2-nitrodiphenylamine (0.50 g, 2.33 mmol) in DMF (10 cm³) was added to a stirred suspension of sodium hydride (0.112 g, 4.66 mmol) in DMF (5 cm³) and stirred at room temperature for 1 h. Methyl iodide (0.144 cm³, 2.33 mmol) was then added and stirred for 1.5 h. The solution was then dissolved in water (100 cm³) and extracted with ether (4 x 50 cm³). The organic layers were combined and washed with water (3 x 100 cm³) and then dried over anhydrous magnesium sulfate. The solvent was then removed under reduced pressure. N-Methyl-2-nitrodiphenylamine was produced as a red oil (0.522 g, 98 %) bp 144 °C (0.02 Torr) [lit.,¹⁵² 145 °C, 0.02 Torr]; δH (250 MHz, CDCl₃) 7.84 (1H, dd, 3J 8.1, 4J 1.4), 7.58 (1H, td, 3J 7.5, 4J 1.6), 7.37 (1H, dd, 3J 8.1, 4J 1.4), 7.31 – 7.17 (4H, m), 6.85 (1H,
t, $^{3}J 7.3$), 6.74 (1H, dd, $^{3}J 8.8$, $^{4}J 1.1$ ) and 3.32 (3H, s); $\delta$ (63 MHz, CDCl$_3$) 147.72 (quat), 146.26 (quat), 142.18 (quat), 133.76 (quat), 129.15 (2 × CH), 128.99 (CH), 125.56 (CH), 124.95 (2 × CH), 119.83 (CH), 115.51 (CH) and 40.19 (CH$_3$); m/z 228 (M$^+$, 90%), 211 (33), 181 (100), 167 (45), 152 (12), 91 (13) and 77 (41).

FVP of $N$-Methyl -2-nitrodiphenylamifle.

$[T_f 875^\circ C, T_i 150-160^\circ C, P 2.2 \times 10^{-2} \text{Torr, } t_m 30 \text { min, } m_a 0.3 \text { g}].$

Pyrolysis yielded carbazole 3 (0.051 g, 23%) mp 246–247 $^\circ C$ [lit.,$^{140}$ 248-249 $^\circ C$]; $\delta_H$ (250 MHz, CDCl$_3$), 8.08 (2H, d, $^{3}J 7.9$), 7.53 – 7.34 (4H, m) and 7.30–7.15 (2H, m). N-H masked by doublet at 8.08; m/z 167 (M$^+$, 100%), 139 (61), 113 (23), 83 (67) and 67 (41).

$N$-Phenazine 73 (0.078 g, 33%) mp 175–176 $^\circ C$ [lit.,$^{141}$174–175 $^\circ C$]; $\delta_H$ (250 MHz, CDCl$_3$), 8.28–8.20 (4H, m), 7.85–7.78 (4H, m); m/z 180 (M$^+$, 100%), 153 (20), 90 (17), 76 (32), 63 (13).

$N$-Phenanthridine 93 (0.026 g, 11%) mp 104–105 $^\circ C$ [lit.,$^{153}$ 108 $^\circ C$]; $\delta_H$ (250 MHz, CDCl$_3$) 9.28 (1H, s), 8.62 – 8.55 (3H, m) and 8.27–7.64 (5H, m); m/z 179 (M$^+$, 100%), 76 (69) and 50 (63).

**N-Alkylation of diphenylamine.**

A solution of diphenylamine (0.500 g, 2.96 mmol) in DMF (10 cm$^3$) was added to a stirred suspension of sodium hydride (0.142g, 5.92 mmol) in DMF (5 cm$^3$) and stirred at room temperature for 1 h. The appropriate alkyl halide (2.96 mmol) was then added and stirred for 1.5 h. The solution was then dissolved in water (100 cm$^3$) and extracted with ether (4 x 50 cm$^3$). The organic layers were combined and washed with water (3 x 100 cm$^3$) and then dried over anhydrous magnesium sulfate. The solvent was then removed under reduced pressure. Purification is shown for each below if applicable.
**N-Allyldiphenylamine 129.**

Allyl bromide was used as the alkyl halide. The crude product was pre-adsorbed onto silica for purification by dry flash chromatography (hexane) to give N-allyldiphenylamine as a clear oil (81%) bp 115 (0.6 mmHg) °C [lit.,\(^{154}\) 320 –325 °C 1 atm]; \(\delta_t\) (250 MHz, CDCl\(_3\)) 7.18 (2H, t, \(3J7.3\)), 6.95 (4H, d, \(3J7.6\)), 7.87 (4H, t, \(3J7.3\)), 5.87 – 5.80 (1H, m), 5.18 (1H, dd, \(3J17.2, 4J1.7\)), 5.10 (1H, dd, \(3J10.4, 4J1.6\)) and 4.28 (2H, d, \(3J4.8\)); \(\delta_C\) (63MHz, CDCl\(_3\)) 148.28 (2 \(\times\) quat), 134.71 (CH), 129.65 (4 \(\times\) CH), 121.70 (2 \(\times\) CH), 121.16 (4 \(\times\) CH), 116.85 (CH\(_2\)), and 55.20 (CH\(_2\)); \(m/z\) 209 (M\(^+\), 100%), 168 (78), 91 (34) and 77 (57).

**N-Benzylidiphenylamine 130.**

Benzyl bromide was used as the alkyl halide. The crude product was pre-adsorbed onto silica for purification by dry flash chromatography (hexane) to give N-benzyldiphenylamine (0.498 g, 65%) mp 88 - 89 °C (from ethanol) [lit.,\(^{155}\) 88 –90 °C]; \(\delta_t\) (250 MHz, CDCl\(_3\)) 7.82 – 7.48 (9H, m), 7.36 (4H, d, \(3J7.6\)), 7.23 (2H, dd, \(3J7.3\)) and 5.28 (2H, s); \(\delta_C\) (63MHz, CDCl\(_3\)) 148.48 (2 \(\times\) quat), 139.63 (quat), 129.71 (4 \(\times\) CH), 129.01 (2 \(\times\) CH), 127.23 (2 \(\times\) CH), 126.95 (CH), 121.81 (2 \(\times\) CH), 121.11 (4 \(\times\) CH), and 57.74 (CH\(_2\)); \(m/z\) 259 (M\(^+\), 91%), 167 (97), 91 (100) and 77 (72).

**FVP of N-alkylidiphenylamines.**

**FVP of N-allyldiphenylamine 129 temperature profile.**

\[T_f\] 550 - 975 °C, \(T_i\) 140 °C, \(P\) 4.0 \(\times\) \(10^{-2}\) Torr, \(t_m\) 10 - 15 min, \(m_a\) 0.04 – 0.06 g]. Pyrolysis was carried out at a variety of temperatures to assess the ratio of products (diphenylamine, carbazole) to any unreacted starting material. At 975 °C silica tubes were packed into the exit end of the hot tube of the FVP apparatus. This is known to cause an effect equivalent to raising the furnace temperature by 50 - 100 °C as discussed in Chapters 2 and 3. The ratios were calculated from the integrals of the characteristic \(^1\)H NMR peaks for protons (200 MHz, CDCl\(_3\)) at 5.6, 8.1 and 4.3 for diphenylamine 127, carbazole 3 and N-allyldiphenylamine 129 respectively. The ratios are quoted as, carbazole 3 : diphenylamine 127 : N-allyldiphenylamine 129.
$T_f$ 550 °C, 0 : 12 : 88. $T_f$ 700 °C, 0 : 33 : 67. $T_f$ 875 °C, 35 : 65 : 0

$T_f$ 925 °C, 50 : 50 : 0 $T_f$ 975 °C, 60 : 40 : 0 and

$T_f$ 975 °C (silica tubes), 55 : 45 : 0.

Preparative scale FVP over 20 min.

$[T_f$ 975 °C, $T_i$ 80 °C, $P$ 5.0 x 10$^{-2}$ Torr, $t_m$ 17 min, $m_a$ 0.496 g].

Analysis of the crude $^1$H NMR spectrum (200MHz, CDCl$_3$), gave diphenylamine 127 : carbazole 3 in a 70 : 30 ratio.

Preparative scale FVP over 60 min

Pyrolysis produced carbazole 3 (42%) mp 245 – 246 °C [lit. 140 246-247 °C]; $\delta_H$ (250 MHz, CDCl$_3$), 8.10 (2H, d, $^3J$ 8.5), 7.53 – 7.21 (4H, m) and 7.30 – 7.15 (2H, m). N-H masked by doublet at 8.10.

$N$-Benzyldiphenylamine.

Small scale FVP.

$[T_f$ 975 °C, $T_i$ 60 - 70°C, $P$ 1.9 x 10$^{-2}$ Torr, $t_m$ 30 min, $m_a$ 0.055 g].


Preparative scale FVP.

After purification by dry flash chromatography (hexane/ethyl acetate), pyrolysis produced carbazole 3 (55%) mp 245-246 °C [lit. 140 246-247 °C]; $\delta_H$ (250 MHz, DMSO-d$_6$) 11.05 (1H, br, s), 7.87 (2H, d, $^3J$ 7.2), 7.26 (4H, d $^3J$ 8.2), 7.17 (2H, t, $^3J$ 7.4) and 6.94 (2H, t, $^3J$ 7.1).
**FVP of N-aminodiphenylamine 132.**

N-Aminodiphenylamine was liberated as a free base from the commercial hydrochloride salt by dissolution in ether and extraction of the ether solution with aqueous NaOH (1 M). The ether solution was dried over MgSO₄ and the solvent was removed under reduced pressure to give N-aminodiphenylamine mp 35-36 °C [lit., 156 37 °C].

Small scale FVP

\[ T_f \ 700-900 \, ^\circ C, \ T_l \ 100-120 \, ^\circ C, \ P \ 10^{-2} \, \text{Torr}, \ t_m \ 15 \, \text{min}, \ m_a \ 0.050 \, \text{g}. \] Pyrolysis produced mainly diphenylamine 127 at all temperatures. At 900 °C diphenylamine 127 and carbazole 3 were produced in a 76:24 ratio upon analysis by ¹H NMR spectroscopy.

**Acridine synthesis.**

**Precursor synthesis.**

2-Methyl-2'-nitrodiphenylamine 70.

\[
\begin{array}{c}
\text{o-Toluidine (0.74 g, 7.1 mmol), o-fluoronitrobenzene (1.00 g, 7.1 mmol) and potassium carbonate (1.00 g, 7.2 mmol) were heated in nitrobenzene (5 cm}^3\text{) at 170 °C for 18 h. The nitrobenzene was then removed by bulb to bulb distillation and the residue dissolved in chloroform and washed with water (3} \times 100 \, \text{cm}^3\text{). The solvent was dried over MgSO}_4\text{ before being removed under reduced pressure. The residue was then purified by dry flash chromatography using hexane/EtOAc as the solvent to yield 2-methyl-2'-nitrodiphenylamine (0.291 g, 18%) mp 75 \, ^\circ C [lit., 157 76 \, ^\circ C]; } \\
\delta_H (250 \, \text{MHz, CDCl}_3) \ 9.38 \ (1H, \text{br, s}), \ 8.15 \ (1H, \text{dd, } ^3J 8.6, \ ^4J 1.6), \ 7.25 - 7.17 \ (5H, \text{m}), \ 6.78 \ (1H, \text{dd, } ^3J 8.7, \ ^4J 1.2), \ 6.65 \ (1H, \text{td, } ^3J 7.2, \ ^4J 1.3) \ \text{and 2.19 (3H, s); } \\
\delta_C 143.98, \ (\text{quat}), \ 137.09 \ (\text{quat}), \ 135.95 \ (\text{CH}), \ 134.57 \ (\text{quat}), \ 131.56 \ (\text{CH}), \ 127.25 \ (\text{CH}), \ 126.85 \ (\text{CH}), \ 126.78 \ (\text{CH}), \ 126.34 \ (\text{CH}), \ 117.06 \ (\text{CH}), \ 115.94 \ (\text{CH}) \ \text{and 18.07 (CH}_3\text{) (1 quat not apparent); } m/z \ 228 \ (\text{M}^+, 100%), \ 180 \ (58), \ 167 \ (48), \ 91 \ (39), \ 77 \ (58) \ \text{and 51 (37).}
\end{array}
\]
4-Methyl-2-nitro-2'-methyldiphenylamine 100.

4-Chloro-3-nitrotoluene (1.00 g, 5.8 mmol), o-toluidine (0.63 g, 5.9 mmol), copper powder (0.45 g) and potassium carbonate (1.00 g, 7.2 mmol) were heated in nitrobenzene (2 cm³) at 180 °C for 48 h. The nitrobenzene was then removed by bulb to bulb distillation and the residue dissolved in chloroform and washed with water (3 x 100 cm³). The solvent was dried over MgSO₄ before being removed under reduced pressure. The residue was then purified by dry flash chromatography using hexane/EtOAc as the solvent to yield 4-methyl-2-nitro-3'-methyldiphenylamine (0.198 g, 14%) mp 90 - 92 °C [lit.¹ 58 92.5 - 93.5 °C]; δH (250 MHz, CDCl₃) 9.16 (1H, br, s), 7.93 (1H, dd, J 1.0), 7.25 - 7.06 (5H, m), 6.71 (1H, d, J 8.7), 2.21 (3H, s) and 2.19 (3H, s); δc 144.69, (quat), 137.19 (quat), 137.13 (CH), 133.98 (quat), 132.30 (quat), 131.24 (CH), 126.91 (CH), 126.59 (quat), 126.21 (CH), 125.70 (CH), 125.82 (CH), 115.82 (CH), 19.95 (CH₃) and 17.82 (CH₃); m/z 242 (M⁺, 100%), 194 (76), 152 (15), 91 (31), 65 (46) and 39 (41).

Acridine preparation.

FVP of 2-methyl-2'-nitrodiphenylamine 80.

Small scale FVP.

[Tf 975 °C, T 70 - 80 °C, P 2.6 x 10⁻² Torr, tₘ 10 min, mₜ 0.031 g]. Pyrolysis produced acridine 88, 1-methylcarbazole 89 and 1-methylphenazine 90 in a ratio of 67:25:8. The ratio of the products were measured from their characteristic ¹H NMR peaks at δH 8.65, 2.44 and 2.85 respectively. The minor carbazole and phenazine products were identified by comparison with their literature spectra¹⁵⁹,¹⁶⁰ and by their M⁺ peaks by mass spectrometry at 181 and 194 respectively.

Preparative scale FVP.

[Tf 975 °C, T 70 - 80 °C, P 2.6 x 10⁻² Torr, tₘ 20 min, mₜ 0.185 g]. After purification by dry flash chromatography (hexane/ethyl acetate), pyrolysis produced acridine 88 (0.055 g, 38%) mp 107 - 108 °C [lit.,¹⁶¹ 110 °C]; δH (250 MHz, CDCl₃) 8.65 (1H, s), 8.14 (2H, d, J 8.8), 6.78 (2H, d, J 8.5), 7.76 - 7.69 (2H, m)
and 6.65 (2H, td, $^3J$ 7.0, $^4J$ 1.1); $\delta$C 148.65, (2 × quat), 135.67 (CH), 130.07 (2 × CH), 129.25 (2 × CH), 127.80 (2 × quat), 126.17 (2 × quat) and 125.27 (2 × quat); m/z 179 (M+, 100%), 152 (13), 126 (5), 91 (2), 89 (20) and 63 (11). The other products were not isolated due to loss upon purification.

**FVP of 2, 6-dimethyl-2'-nitrodiphenylamine.**

The precursor 2, 6-dimethyl-2'-nitrodiphenylamine was obtained from J.I.G. Cadogan sample store.\textsuperscript{33}

Small scale FVP.

$[T_f$ 975 °C, $T_i$ 80 - 100 °C, $P$ 3.2 × $10^{-2}$ Torr, $t_m$ 15 min, $m_a$ 0.053 g]. Pyrolysis produced 1-methylacridine and 1-methylphenazine in a 77 : 13 ratio as measured from their characteristic peaks $^1$H NMR peaks at $\delta$H 8.60 and 8.00 respectively. Data for both compounds are comparable to those of their respective literature spectra.\textsuperscript{162, 160}

Preparative scale FVP.

$[T_f$ 975 °C, $T_i$ 120 - 130 °C, $P$ 3.6 × $10^{-2}$ Torr, $t_m$ 25 min, $m_a$ 0.425 g]. After purification by dry flash chromatography (hexane/ethyl acetate), pyrolysis produced 1-methylacridine 98 (0.112 g, 33%) mp 88 - 89 °C [lit.\textsuperscript{163} 88 - 90 °C; $\delta$H (250 MHz, CDCl$_3$) 8.60 (1H, s), 8.18 (1H, dd, $^3J$ 8.4, $^4J$ 1.4), 7.86 (1H, dd, $^3J$ 8.4, $^4J$ 1.4), 7.72 (1H, dd, $^3J$ 8.5, $^4J$ 1.4), 7.67 (1H, dt, $^3J$ 6.6, $^4J$ 1.5), 7.50 (1H, dd, $^3J$ 6.7, $^4J$ 1.3), 7.42 (1H, dt, $^3J$ 6.5, $^4J$ 1.1), 7.33 (1H, m) and 2.86 (3H, s); $\delta$C (63 MHz, CDCl$_3$) 148.76, (quat), 148.54 (quat), 137.35 (quat), 136.05 (CH) 130.09 (CH), 129.86 (CH), 128.09 (CH), 127.45 (CH), 126.70 (quat), 126.52 (quat), 126.37 (CH), 125.65 (CH), 125.62 (CH) and 18.60 (CH$_3$); m/z 193 (M+, 100%), 153 (53), 84 (33) and 63 (20).
1-Methylphenazine 99 (0.024 g, 7%) mp 107 - 108 °C [lit.,164 109 °C]; \(\delta_H\) (250 MHz, CDCl\(_3\)) 8.23 – 8.13 (2H, m), 8.00 (1H, d, \(\text{J} 7.8\)), 7.76 – 7.72 (2H, m), 7.65 – 7.58 (2H, m), 7.67 and 2.86 (3H, s); \(\delta_C\) (63 MHz, CDCl\(_3\)) 143.75, (quat), 143.36 (quat), 143.20 (quat), 142.89 (quat) 138.09 (quat), 130.59 (CH), 130.42 (CH), 130.19 (CH), 130.07 (CH), 129.66 (CH) 129.52 (CH), 127.63 (CH) and 17.76 (CH\(_3\)); \(m/z\) 194 (M\(^+\), 100%), 181 (47), 179 (26) 144 (2) and 89 (34).

FVP of 4-Methyl-2-nitro-2'-methyl diphenylamine 97.
\([T_f\) 875 °C, \(T_i\) 80 - 140 °C, \(P_{3.2 x 10^{-2}}\) Torr, \(t_m\) 20 min, \(m_a\) 0.063 g]. Pyrolysis produced a mixture of 2-methylacridine 104, 3-methylacridine 101, 9,10-dihydro-2-methyl-acridine 111 and 9,10-dihydro-3-methylacridine 110. Ratios of the isomeric 2 and 3 dihydroacridines were calculated from the \(^{13}\)C NMR integrals of the dihydroacridine CH\(_2\). The ratio of the 2-isomer : 3-isomer is 42 : 58 ratio as measured from their characteristic peaks at 30.83 and 31.24 respectively. Spectra of both compounds are comparable to their respective literature spectra.\(^{30}\)

Carboline precursors.

\(N-\text{(3-Nitropyridin-2-yl)phenylamine 154.}\)

\(\text{N-NO}_2\)

2-Chloro-3-nitropyridine (3.0 g, 18.9 mmol) and potassium carbonate (5.3 g, 38.4 mmol) were heated in aniline (10 cm\(^3\)) with stirring for 6 h at 140 °C. Water (150 cm\(^3\)) was added and the mixture was steam distilled to remove the aniline. Additional water was added periodically to maintain its level. The remaining aqueous layer was extracted with DCM (3 \(\times\) 100 cm\(^3\)). The combined organic layers were washed with water (2 \(\times\) 50 cm\(^3\)) before being dried over MgSO\(_4\). The mixture was filtered and the solvent was evaporated under reduced pressure. 3-Nitropyridin-2-ylphenylamine was obtained (4.0 g, 98%). mp 75 – 76 °C [lit.,\(^{165}\) 75 °C]; \(\delta_H\) (250 MHz, CDCl\(_3\)) 10.22 (1H, br, s), 8.39 (2H, m) 7.55 (2H, d, \(\text{J} 8.2\)), 7.32 (2H, t, \(\text{J} 7.5\)), 7.14 (1H, d, \(\text{J} 7.4\)) and 6.74 (1H, dd, \(\text{J} 8.3, 4\), \(\text{J} 4.5\)); \(\delta_C\) (63 MHz, CDCl\(_3\)) 155.73, (CH), 150.72 (quat), 138.28 (quat), 135.99 (quat), 129.46 (2 \(\times\) CH), 129.05 (quat), 125.29 (CH), 123.01 (2 \(\times\) CH) and 114.34 (CH); \(m/z\) 215 (M\(^+\), 85%), 168 (100) and 77 (35).
4-Chloro-3-nitropyridine 158.

4-Hydroxy-3-nitropyridine (10 g) was added to POCl₃ (25 cm³) and warmed to 45 °C. Phosphorus pentachloride (7 g) was added and the mixture was heated to reflux (around 125 °C) and held at this temperature with stirring for 4 h. The mixture was then distilled under vacuum to yield a viscous yellow oil. The oil was chilled in an ice bath. DCM/water (50 cm³/20 cm³) was added with vigorous stirring. The organic layer was separated and the aqueous layer was extracted with DCM (4 × 50 cm³). The combined organic layers were washed with water (2 × 50 cm³) and dried over MgSO₄. The solvent was removed under reduced pressure to yield 4-chloro-3-nitropyridine (10.2 g, 90%) mp 45 - 46 °C [lit., 166 46 °C]; 1H, 8.63 (1H, d, 3J 5.3) and 7.49 (1H, d, 3J 5.6); m/z 160 (M⁺, 49%), 158 (M⁺, 91%), 50 (100) and 30 (70).

N-(3-Nitropyridin-4-yl)phenylamine 155.

4-Chloro-3-nitropyridine (3.0 g, 18.9 mmol), potassium carbonate (5.3 g, 38.4 mmol) and aniline (2.0 g, 21.5 mmol) were refluxed in ethanol (25 cm³) with stirring for 6 h. The mixture was concentrated onto silica and treated by dry-flash chromatography with hexane:ethyl acetate as eluant. Upon concentration of fractions containing product, 3-nitropyridin-4-ylphenylamine was obtained (2.86 g, 70%). mp 93-95 °C [lit., 32 95 °C]; δH (250 MHz, DMSO-d₆) 10.08 (1H, s), 9.33 (1H, s) 8.47 (1H, d, 3J 6.2), 7.76-7.57 (5H, m) and 7.11 (1H, d, 3J 6.2); δC: (63 MHz, DMSO-d₆) 153.16 (CH), 148.39 (CH), 146.91 (quat), 137.50 (quat), 130.34 (quat), 129.80 (2 × CH), 126.82 (CH), 125.79 (2 × CH) and 109.74 (CH); m/z 215 (M⁺, 100%), 140 (14), 115 (26), 77 (39) and 51 (50).

N-(2-Nitrophenyl)pyrid-2-ylamine 169.

2-Aminopyridine (1.0 g, 10.5 mmol) was stirred in DMSO (15 cm³) with potassium t-butoxide (1.7 g, 15.2 mmol) for 15 min. 2-Fluoronitrobenzene (1.5 g, 10.6 mmol) was added and the mixture was heated to 125 °C. The mixture was stirred at this temperature for 15 h before being cooled and diluted with brine and extracted with DCM (3 × 50 cm³). The combined
DCM layers were washed with water (3 x 50 cm³) and dried over MgSO₄. The mixture was concentrated onto silica and treated by dry-flash chromatography with hexane:ethyl acetate as eluant. Upon concentration of fractions containing product, N-(2-nitrophenyl)pyrid-2-ylamine was obtained (1.00 g, 44%). mp 67-68 °C [lit., [32] 68-69 °C]; δH (250 MHz, DMSO-d₆) 9.69 (1H, br, s), 8.21-8.16 (2H, m), 8.06 (1H, dd, 3J 8.5, 4J 1.8), 7.74-7.61 (2H, m), 7.15-7.08 (2H, m) and 6.92 (1H, dd, 3J 7.5, 3J 5.0, 4J 1.0); δC (63 MHz, DMSO-d₆) 153.96 (quat), 147.39 (CH), 138.29 (CH), 137.93 (quat), 136.65 (quat), 125.66 (CH), 122.01 (CH), 120.14 (CH), 117.15 (CH) and 112.97 (CH); m/z 215 (M⁺, 70%), 169 (100), 139 (40), 115 (17), 78(57) and 57 (48).

4,4'-Dipyridylamine 165.

4-Aminopyridine (5.0 g, 53.2 mmol) and PCl₃ (7 cm³) were mixed and pyridine (20 cm³) was added. The mixture was heated at 140 °C for 6 h. The excess pyridine and PCl₃ were removed by distillation at 180 °C over 1 h. The orange residue was dissolved in a mixture of water (70 cm³), ethanol (50 cm³) and concentrated HCl (20 cm³) and heated at 100 °C for 2 h. Insoluble material was removed by filtration, the filtrate was added to an excess of NaOH (7M) and left to stand for 1 h while a white precipitate formed. Some solvent was removed under reduced pressure and the residue was filtered and dried to give 4,4'-dipyridylamine (7.36 g, 81%). mp 273 – 274 °C [lit., 51 273 – 275 °C]; δH (250 MHz, DMSO-d₆) 9.32 (1H, br, s), 8.33 (4H, dd, 3J 4.8, 4J 1.6) and 7.10 (4H, dd, 3J 4.8, 4J 1.6); δC (63 MHz, DMSO-d₆) 148.02 (4 x CH), 145.32 (2 xquat) and 109.25 (4 x CH); m/z 171 (M⁺, 100%), 143 (15), 78 (10) and 51 (30).

N-(3-Nitropyridin-4-yl)pyridin-4-ylamine 166.

4,4'-Dipyridylamine (0.50 g, 2.90 mmol) was carefully dissolved in concentrated HNO₃ (1 cm³). The solution was allowed to cool to room temperature and a white precipitate formed. The precipitate was filtered and washed with water before being dissolved in concentrated H₂SO₄ (4 cm³). The mixture was carefully heated to 110 °C over 15 min and held at this temperature for 45 min with stirring. The solution was then basified with aqueous ammonia solution (SG
0.88). The yellow precipitate was filtered and dissolved in acetone and the waste salts were filtered off. The solvent was removed under reduced pressure to yield \( N-(3\text{-nitropyridin-4-yl})\text{pyridin-4-ylamine} \) (0.51 g, 81%). mp 122 – 124 °C [lit.,\(^{51}\) 124 °C]; \( \delta_H \) (250 MHz, DMSO-\(d_6\)) 9.93 (1H, br, s), 9.31 (1H, s), 8.71 (2H, dd, \( ^3J 4.6, ^4J 1.6 \)), 8.67 (1H, d, \( ^3J 6.0 \)) and 7.58 – 7.53 (3H, m); \( \delta_C \) (63 MHz, DMSO-\(d_6\)) 153.47 (CH), 150.62 (2 \( \times \) CH), 147.93 (CH), 145.48 (quat), 143.82 (CH), 132.47 (quat), 116.37 (2 \( \times \) CH) and 111.31 (CH); \text{m/z} 216 (\( M^+ \), 100%), 171 (54), 142 (46), 78 (51) and 57 (75).

**N-(2-Nitrophenyl)pyrazin-2-ylamine 156.**

A suspension of potassium \( t \)-butoxide (0.70 g, 6.25 mmol) in DMSO (10 cm\(^3\)) was cooled to 15 °C with stirring. \( o \)-Nitroaniline (0.76 g, 5.52 mmol) was added portionwise over 5 min. The solution was stirred at 15 °C for 30 min. Chloropyrazine (0.50 g, 6.25 mmol) was added portion-wise over 5 min. The solution was heated at 150 °C for 15 h. The suspension was allowed to cool before being diluted with water (50 cm\(^3\)). The aqueous mixture was extracted with DCM (3 \( \times \) 100 cm\(^3\)). The combined organics were washed with water (3 \( \times \) 100 cm\(^3\)) and dried over MgSO\(_4\). The mixture was then filtered and the solvent evaporated under reduced pressure and the residue pre-adsorbed onto silica. The mixture was separated by dry-flash chromatography (toluene/ethyl acetate) to give \( (2\text{-nitrophenyl})\text{pyrazin-2-ylamine} \) (0.60 g, 50%). mp 122-123 °C; (Found: C, 55.6; H 3.7; N 25.8. \( C_{17}H_{16}N_2 \) requires C, 55.6; H, 3.7; N, 25.9%); \( \delta_H \) (360 MHz, DMSO-\(d_6\)) 9.91 (1H, br, s), 8.43 (1H, d, \( ^4J 1.4 \)) 8.10 (1H, dd, \( ^3J 2.9, ^4J 1.4 \)), 8.07 (1H, dd, \( ^3J 2.9, ^4J 1.4 \)), 8.04 (1H, dd, \( ^3J 8.3, ^4J 1.4 \)), 7.99 (1H, dd, \( ^3J 8.3, ^4J 1.4 \)), 7.68 (1H, td, \( ^3J 7.9, ^4J 1.4 \)) and 7.22 (1H, dd, \( ^3J 7.9, ^4J 1.4 \)); \( \delta_C \) (63 MHz, DMSO-\(d_6\)) 150.58, (quat), 140.70 (quat), 139.27 (quat), 135.79 (CH), 135.66 (CH), 134.37 (2 \( \times \) CH), 125.23 (CH), 122.82 (CH) and 122.34 (CH); \text{m/z} 216 (\( M^+ \), 45%), 194 (5), 170 (73), 138 (97), 92 (97), 80 (40), 65 (100) and 52 (71).
**N-(2-Nitrophenyl)pyrimidin-2-ylamine 168.**

A suspension of potassium \( t \)-butoxide (0.70 g, 6.25 mmol) in DMSO (10 cm\(^3\)) was cooled to 15 °C with stirring. \( o \)-Nitroaniline (0.76 g, 5.52 mmol) was added portionwise over 5 min. The solution was stirred at 15 °C for 30 min. 2-Chloropyrimidine (0.50 g, 6.25 mmol) was added portionwise over 5 min. The solution was heated at 150 °C for 15 h. The suspension was allowed to cool before being diluted with water (50 cm\(^3\)). The aqueous mixture was extracted with DCM (3 × 100 cm\(^3\)). The combined organic extracts were washed with water (3 × 100 cm\(^3\)) and dried over MgSO\(_4\). The mixture was then filtered and the solvent evaporated under reduced pressure and the residue pre-adsorbed onto silica. The mixture was separated by dry-flash chromatography (toluene/ethyl acetate) to give (2-nitrophenyl)pyrimidin-2-ylamine (0.84 g, 71%). mp 135-137 °C [lit.\(^{167}\) 136-137 °C ]; \( \delta \) (250 MHz, DMSO-\( d_6\)) 8.51 (2H, \( d \), 3 \( \ J 8.9 \)), 8.21 (1H, \( dd \), \( J 7.8, 4J 1.1 \)), 8.07 (1H, \( dd \), \( J 7.6, 4J 1.5 \)), 7.72 (1H, \( td \), \( J 7.8, 4J 1.5 \)), 7.24 (1H, \( td \), \( J 7.8, 4J 1.5 \)) and 6.94 (1H, t, \( J 6.6 \)) (NH not apparent); \( \delta_c \) 159.07, (quat), 158.34 (2 × CH), 139.35 (quat), 134.78 (CH), 134.76 (quat), 125.76 (CH), 123.29 (CH), 122.72 (CH) and 114.39 (CH); \( m/z \) 216 (M\(^+\), 32%), 170 (100), 143 (8), 90 (14) and 53 (9).

**N-(5-Methyl-2-nitrophenyl)pyrazin-2-amine 179.**

Aminopyrazine (0.11 g, 1.16 mmol) was stirred with potassium \( t \)-butoxide (0.156 g, 1.39 mmol) in DMSO (10 cm\(^3\)) for 30 min. Fluoro-4-nitrotoluene (0.192 g, 1.24 mmol) was added and the mixture was heated at 100 °C for 15 h. The solution was diluted with water (50 cm\(^3\)) and extracted with DCM (3 × 100 cm\(^3\)). The combined organic extracts were washed with water (3 × 50 cm\(^3\)) before being concentrated under reduced pressure onto silica for purification by dry flash chromatography using toluene/DCM as eluant. The resulting red solid was then purified further by vacuum sublimation at 120-140 °C (3.0 × 10\(^{-2}\) Torr) to yield \( N-(5\text{-methyl-2-nitrophenyl})\text{pyrazin-2-amine} \) (0.067 g, 25%) mp 133-134 °C; (Found: M 230.08017, C\(_{36}\)H\(_{20}\)N\(_2\) requires M 230.08038); \( \delta \) (360 MHz, DMSO-\( d_6\)) 9.83 (1H, br s), 8.47 (1H, d, \( 4J 1.3 \)), 8.17 (1H, m), 8.11 (1H, d, \( 3J 2.7 \)), 8.00 (1H, d, \( 3J 8.5 \)), 7.96 (1H, s), 7.04 (1H, dd, \( 3J 8.5, 4J 1.6 \)) and 2.40 (3H, s); \( \delta_c \) (91 MHz, CDCl\(_3\)) 147.72,
(quat), 141.27 (CH), 137.55 (quat), 136.97 (CH), 136.91 (quat), 136.60 (CH), 133.26
(quat), 126.24 (CH), 122.09 (CH), 119.32 (CH) and 22.16 (CH3); m/z 230 (M+, 55%),
184 (100), 144 (7), 104 (27), 92 (12), 79 (60) and 52 (33).

**FVP of pyridylamines.**

All preparative scale FVP products were preadsorbed onto silica for purification by dry
flash chromatography (hexane/ethyl acetate). A solvent gradient was used by slowly
increasing the % of ethyl acetate in the solvent mixture.

**FVP of N-(3-nitropyrid-2-yl)phenylamine 154.**

Small scale FVP

\[ T_f \ 875^\circ C, \ T_i \ 100 - 110^\circ C, \ P \ 3.4 \times 10^{-2} \ \text{Torr}, \ t_m \ 30 \ \text{min}, \ m_a \ 0.044 \ \text{g}. \]

The ratio was determined by calculation of the \(^1\text{H} \) NMR integrals for \( \alpha \)-carboline and
benzo[4,5]imidazo[1,2-a]pyridine. The signals used were those at \( \delta \) 8.6 and 9.2 for
carboline and benzo[4,5]imidazo[1,2-a]pyridine respectively.

Intermediate preparative scale FVP.

\[ T_f \ 875^\circ C, \ T_i \ 100 - 110^\circ C, \ P \ 2.6 \times 10^{-2} \ \text{Torr}, \ t_m \ 30 \ \text{min}, \ m_a \ 0.437 \ \text{g}. \]

Pyrolysis produced \( \alpha \)-carboline 132 (0.188 g, 55%) mp 210 – 211 °C
[lit., \(^{40}\) 212 °C]; \( \delta \) (250 MHz, CDCl\(_3\) 11.88 (1H, br, s), 8.56 (1H, dd, \( ^3 \)J 7.7, \( ^4 \)J 1.5), 8.49
(1H, dd, \( ^3 \)J 4.9, \( ^4 \)J 1.6), 8.23 (1H, d, \( ^3 \)J 7.8), 7.58 – 7.54 (2H, m) and 7.33 – 7.26 (2H, m); \( \delta \) (63 MHz, CDCl\(_3\) 149.43, (quat), 143.59 (CH), 136.33 (quat), 125.92 (CH), 125.92
(CH), 124.12 (CH), 118.68 (CH), 117.91 (quat), 116.94 (CH), 112.79 (quat) and 108.78
(CH); m/z 168 (M+, 100%), 140 (15) 84 (9) and 39 (9).
Multigram preparative scale FVP.

\[ T_f \ 875 \degree C, \ T_i \ 80 - 130 \degree C, \ P \ 2.3 \times 10^{-2} \text{Torr}, \ t_m \ 4h \ 30 \text{ min}, \ m_a \ 3.08 \ g \]. Pyrolysis produced \( \alpha \)-carboline 132 (1.44 g, 60%) mp 209 - 211 \degree C [lit.,\(^{40} 212 \degree C\]; \( \delta \)\( _{\text{H}} \) (250 MHz, CDCl\(_3\)) 11.89 (1H, br, s), 8.56 (1H, dd, \( ^3J \ 7.7, ^4J \ 1.5 \)), 8.48 (1H, dd, \( ^3J \ 4.9, ^4J \ 1.6 \)), 8.24 (1H, d, \( ^3J \ 7.8 \)), 7.58 - 7.55 (2H, m) and 7.34 - 7.26 (2H, m); Pyrolysis produced benzo[4,5]imidazo[1,2-a]pyridine 138 (0.241 g, 10%) mp 176-177 \degree C [lit.,\(^{41} 179 \degree C\]; \( \delta \)\( _{\text{H}} \) (250 MHz CDCl\(_3\)) 8.38 (1H, d, \( ^3J \ 6.9 \)), 7.94 (1H, d, \( ^3J \ 8.3 \)), 7.84 (1H, d, \( ^3J \ 8.2 \)), 7.65 (1H, d, \( ^3J \ 8.4 \)), 7.42 (1H, t, \( ^3J \ 7.2 \)), 7.42-7.32 (2H, m) and 6.77 (1H, t, \( ^3J \ 6.8 \)).

FVP of \( N \)-(3-nitropyrid-4-yl)phenylamine 155.

\[ T_f \ 875 \degree C, \ T_i \ 150 \degree C, \ P \ 2.4 \times 10^{-2} \text{Torr}, \ t_m \ 25 \text{ min}, \ m_a \ 0.215 \ g \]. Pyrolysis produced \( \gamma \)-carboline 133 (0.101 g, 60%) mp 228 - 230 \degree C [lit.,\(^{38} 229 - 230 \degree C\]; \( \delta \)\( _{\text{H}} \) (250 MHz, DMSO-\( d_6 \)) 11.77 (1H, br, s), 9.37 (1H, s), 8.46 (1H, d, \( ^3J \ 5.7 \)), 8.26 (1H, d, \( ^3J \ 7.8 \)), 7.61 (1H, d, \( ^3J \ 8.1 \)), 7.54 - 7.47 (2H, m) and 7.30 (1H, td, \( ^3J \ 8.0, ^4J \ 1.1 \)); \( \delta \)\( _{\text{C}} \) 144.26, (CH), 143.30 (quat), 142.5 (CH), 139.31 (quat), 126.36 (CH), 120.49 (CH), 120.38 (CH), 119.75 (CH), 119.19 (CH), 111.25 (quat) and 106.14 (CH); m/z 168 (M\(^+\), 100%), 140 (14) 71 (12) and 43 (14).

FVP of \( N \)-(2-nitrophenyl)pyrid-2-ylamine 169.

Small scale FVP

\[ T_f \ 875 \degree C, \ T_i \ 120 \degree C, \ P \ 3.2 \times 10^{-2} \text{Torr}, \ t_m \ 18 \text{ min}, \ m_a \ 0.023 \ g \]. Pyrolysis produced a ratio of \( \alpha \)-carboline 132 : benzo[4,5]imidazo[1,2-a]pyridine 138 The ratio was determined by calculation of the \( ^1\text{H} \) NMR integrals for \( \alpha \)-carboline and benzo[4,5]imidazo[1,2-a]pyridine. The signals used were those at \( \delta \)\( _{\text{H}} \) 8.6 and 9.2 for carboline and benzo[4,5]imidazo[1,2-a]pyridine respectively.
Preparative scale FVP.

\[ T_f \ 875 \degree C, \ T_i \ 120 \degree C, \ P \ 3 \times 10^{-2} \text{Torr}, \ t_m \ 15 \text{ min}, \ m_a \ 0.070 \text{ g}. \]

Pyrolysis produced benzo[4,5]imidazo[1,2-a]pyridine 138 (0.036 g, 65%) mp 177-178 °C [lit., 41 179 °C]; \( \delta_H \) (250 MHz CDCl\textsubscript{3}) 8.39 (1H, d, \( ^3J \ 6.9 \)), 7.93 (1H, d, \( ^3J \ 8.3 \)), 7.84 (1H, d, \( ^3J \ 8.2 \)), 7.66 (1H, d, \( ^3J \ 8.4 \)), 7.42 (1H, t, \( ^3J \ 7.2 \)), 7.41-7.33 (2H, m) and 6.79 (1H, t, \( ^3J \ 6.8 \)); \( \delta_C \) (63 MHz, CDCl\textsubscript{3}) 148.29, (quat), 144.33(quat), 129.13 (CH), 128.47 (quat), 125.47 (CH), 125.00 (CH), 120.81 (CH), 119.71 (CH), 117.80 (CH), 110.22 (CH) and 110.06 (CH); \( m/z \) 168 (M\textsuperscript{+}, 100%), 140 (15), 129 (6), 114 (8), 84 (18), 63 (9) and 51 (10).

Note. \( \alpha \)-Carboline 132 was not isolated due to loss upon column chromatography.

FVP of N-(3-nitropyridin-4-yl)pyridin-4-ylamine 166.

\[ T_f \ 875 \degree C, \ T_i \ 140 - 160 \degree C, \ P \ 2.3 \times 10^{-2} \text{Torr}, \ t_m \ 40 \text{ min}, \ m_a \ 0.226 \text{ g}. \]

Pyrolysis produced \( \gamma,\gamma' \)-dicarboline 134 as a dark brown gum (0.124 g, 70%) mp 300 °C (decomp) [lit., 46 344-347 °C]; \( \delta_H \) (250 MHz, DMSO-d\textsubscript{6}) 9.40 (1H, d, \( ^3J \ 0.9 \)), 8.45 (1H, d, \( ^3J \ 5.7 \)) and 7.51 (1H, dd, \( ^3J \ 5.7, \ ^4J \ 0.9 \)); \( \delta_C \) (63 MHz, DMSO-d\textsubscript{6}) 145.19, (CH), 143.59 (quat), 142.89 (CH), 125.92 (quat), 117.53 (CH) and 106.76 (CH); \( m/z \) 169 (M\textsuperscript{+}, 100%), 140 (15) 84 (9) and 39 (9).

FVP of N-(2-nitrophenyl)pyrazin-2-ylamine 156.

Small scale temperature profile FVP.

\[ T_f \ \text{various} \degree C, \ T_i \ 120 - 140 \degree C, \ P \ 3.6 \times 10^{-2} \text{Torr}, \ t_m \ 15 \text{ min}, \ m_a \ 0.046 \text{ g}. \] The entire pyrolysate was dissolved in DMSO-d\textsubscript{6} and analysed by \( ^1\text{H} \) NMR spectroscopy. The products were pyrido[3,4-b]benzimidazole 167 and 1,4-diazacarbazole 135. The diazacarbazole was assigned by comparison with literature spectra. 52 For the pyrolysis at 975 °C that used silica, the silica was lightly packed into the exit end of the furnace prior to pyrolysis.
Temperature profile

Temperature Starting material % : pyrido[3,4-b]benzimidazole % : 1,4-diazacarbazole %

<table>
<thead>
<tr>
<th>Temperature</th>
<th>pyrido[3,4-b]benzimidazole</th>
<th>1,4-diazacarbazole</th>
</tr>
</thead>
<tbody>
<tr>
<td>975 °C/silica</td>
<td>0</td>
<td>55</td>
</tr>
<tr>
<td>975 °C</td>
<td>0</td>
<td>73</td>
</tr>
<tr>
<td>875 °C</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>825 °C</td>
<td>0</td>
<td>86</td>
</tr>
<tr>
<td>800 °C</td>
<td>5</td>
<td>85</td>
</tr>
<tr>
<td>775 °C</td>
<td>11</td>
<td>78</td>
</tr>
</tbody>
</table>

Preparative scale FVP.

Pyrolysis produced pyrido[3,4-b]benzimidazole 167 (0.201 g, 60%)
mp 196-198 °C [lit., 197-198 °C]; $\delta$ (250 MHz, DMSO-d$_6$) 9.43 (1H, d, $^3J$ 1.6), 9.26 (1H, dd, $^3J$ 4.6, $^4J$ 1.1), 8.55 (1H, dd, $^3J$ 7.9, $^3J$ 0.7), 8.13 (1H, d, $^3J$ 4.6), 8.09 (1H, dd, $^3J$ 8.2, $^3J$ 0.7), 7.78 (1H, td, $^3J$ 7.7, $^3J$ 1.2) and 7.66 (1H, td, $^3J$ 7.9, $^4J$ 1.1); $\delta$C (63 MHz, DMSO-d$_6$) 144.48, (CH), 143.40 (quat), 1441.51 (quat), 127.51 (quat), 126.61 (CH), 126.55 (CH), 122.50 (CH), 120.27 (CH), 119.62 (CH) and 112.80 (CH); m/z 169 (M$^+$, 100%), 142 (16) 115 (8), 102 (8) and 63 (2).

FVP of N-(2-nitrophenyl)pyrimidin-2-ylamine 168.

Small scale temperature profile FVP.

### Temperature profile

<table>
<thead>
<tr>
<th>Temperature</th>
<th>pyrrolo[2,3-b]quinoxaline %</th>
<th>pyrido[2,3-b]benzimidazole %</th>
</tr>
</thead>
<tbody>
<tr>
<td>975 °C/silica</td>
<td>92</td>
<td>8</td>
</tr>
<tr>
<td>975 °C</td>
<td>84</td>
<td>16</td>
</tr>
<tr>
<td>925 °C</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>875 °C</td>
<td>32</td>
<td>80</td>
</tr>
<tr>
<td>850 °C</td>
<td>16</td>
<td>84</td>
</tr>
<tr>
<td>825 °C</td>
<td>8</td>
<td>92</td>
</tr>
</tbody>
</table>

Preparative scale FVPs.

It was found that at the lower end of the temperature scale the pyrido[2,3-b]benzimidazole was the major product. A preparative scale FVP was carried out at 825 °C for yield determination and characterisation. At temperatures below 825 °C there was a significant quantity of starting material recovered. The quantity of pyrrolo[2,3-b]quinoxaline was optimised at 975 °C with silica wool packed into the furnace. For the pyrolysis at 975 °C that used silica, the silica was lightly packed into the exit end of the furnace prior to pyrolysis. A preparative scale FVP was carried out at 975 °C with the silica additive in order to determine the yield of pyrrolo[2,3-b]quinoxaline and to characterise the product.

Preparative scale FVP at 825 °C.

Pyrolysis produced pyrido[2,3-b]benzimidazole 172 (0.231 g, 72%) mp 204-205 °C [lit., 207 °C]; $\delta_h$ (250 MHz, DMSO-$d_6$) 9.54 (1H, dd, $^3J$ 7.8, $^4J$ 2.1), 8.85 (1H, dd, $^3J$ 5.1, $^4J$ 2.1), 8.32 (1H, d, $^3J$ 8.2), 7.87 (1H, d, $^3J$ 8.2), 7.56 (1H, t, $^3J$ 7.1), 7.44 (1H, t, $^3J$ 7.2) and 7.16 (1H, dd, $^3J$ 6.8, $^4J$ 4.1); $\delta_c$ (63 MHz, DMSO-$d_6$) 156.18, (CH), 149.86 (quat), 143.26 (quat), 135.62 (CH), 126.68 (quat), 125.87 (CH), 121.14 (CH), 118.96 (CH), 112.37 (CH) and 106.61 (CH); $m/z$ 169 (M+, 100%), 168 (10) 142 (39) 102 (13), 90 (10), 84 (10), 64 (6) and 39 (3).
Preparative scale FVP at 975 °C with silica.

\[ T_f \quad 975 \, ^\circ \text{C/silica wool}, \quad T_i \quad 140 \, ^\circ \text{C}, \quad P \quad 2.6 \times 10^{-2} \, \text{Torr}, \quad t_m \quad 45 \, \text{min}, \quad m_a \quad 0.530 \, \text{g} \]. Pyrolysis produced pyrrolo[2,3-b]quinoxaline 176 (0.160 g, 50%) mp 247-249 °C [lit., 248-250 °C]; \( \delta \)H (250 MHz, DMSO-d<sub>6</sub>) 12.17 (1H, br s.), 8.30 (1H, t, \( J \) 3.4), 8.2 - 8.05 (2H, m), 7.75 - 7.69 (2H, m) and 6.77 (1H, dd, \( J \) 4.2, \( J \) 1.1); \( \delta \)C (63 MHz, DMSO-d<sub>6</sub>) 142.43 (quat), 141.97 (quat), 139.96 (quat), 138.35 (quat), 138.23 (CH), 128.53 (CH), 127.25 (CH), 127.06 (CH), 126.07 (CH) and 99.43 (CH); \( m/z \) 169 (M<sup>+</sup>, 100%), 168 (14), 142 (15) 102 (22), 84 (30), 69 (37) and 43 (21).

FVP of N-(5-Methyl-2-nitrophenyl)pyrazin-2-amine 179.

\[ T_f \quad 825 \, ^\circ \text{C}, \quad T_i \quad 120 - 140 \, ^\circ \text{C}, \quad P \quad 4.0 \times 10^{-2} \, \text{Torr}, \quad t_m \quad 15 \, \text{min}, \quad m_a \quad 0.025 \, \text{g} \]. The pyrolysate was fully dissolved in CDCl<sub>3</sub> and examined by 1H NMR spectroscopy at 360 MHz. The products were assigned as 3-methylpyrido[3,4-b]-benzimidazole 182 and 1-methylpyrido[3,4-b]-benzimidazole 183 in a 60:40 ratio respectively. Analysis was based on the 1H NMR spectrum signals and multiplicity and was supported by NOESY and COSY NMR spectra at 360 MHz.

Deuterium exchange of N-(2-nitrophenyl)pyrazin-2-ylamine 156 and N-(3-nitropyrid-2-yl)phenylamine 156. Amine (50 mg) was heated in a flame-dried FVP inlet tube with MeOD. After a few minutes, the solvent was removed under vacuum. The resulting product was immediately treated by FVP. \[ T_f \quad 825 \, ^\circ \text{C}, \quad T_i \quad 140 \, ^\circ \text{C}, \quad P \quad 10^{-2} \, \text{Torr}, \quad t_m \quad 10 \, \text{min}, \quad m_a \quad 0.05 \, \text{g} \].

N-(2-nitrophenyl)pyrazin-2-ylamine 154.
Pyrolysis produced pyrido[3,4-b]benzimidazole 169 with deuterium incorporated. \( \delta \)D (55 MHz, DMSO-d<sub>6</sub>) 8.03 (1D, s).
**N-(3-nitropyrid-2-yl)phenylamine 154.**


δ₀ (55 MHz, DMSO-d₆) 7.6 (1D, s) (major) and 7.9 (1D, s) (minor) respectively.

**Investigation of pyrido[2,3-b]benzimidazole electrocyclic rearrangement.**

The nature of the pyrido[2,3-b]benzimidazole rearrangement was investigated by preparing analogues of the compound and subjecting them to FVP under the same conditions.

**FVP substrate synthesis.**

**Imidazo[1,2-a]pyrimidine 225.**

1,1,3,3-Tetramethoxypropane (1.24 g, 7.50 mmol) was heated under reflux in 1:1 glacial acetic acid/ethanol (50 cm³) with 2-aminimidazole sulfate (1.00 g, 7.50 mmol) for 7 h. The solvent was removed under reduced pressure and the residue dissolved in saturated aqueous potassium carbonate and extracted with DCM (5 × 100 cm³). The DCM was filtered through celite and then concentrated under reduced pressure to yield imidazo[1,2-a]pyrimidine (0.767 g, 86%) mp 124-127 °C [lit., 57 128 °C]; δₜ (250 MHz, DMSO-d₆) 9.01 (1H, dd, 3 J₆.8, 3 J₁.6), 8.54 (1H, dd, 3 J₃.8, 4 J 1.8), 7.95 (1H, d, 3 J 0.9), 7.74 (1H, d, 3 J 0.8) and 7.03 (1H, dd, 3 J 6.7, 3 J 4.1); δc (63 MHz, DMSO-d₆) 150.16 (CH), 148.29 (quat), 135.37 (CH), 111.98 (CH) and 108.72 (CH); m/z 119 (M⁺, 89%), 92 (49) 78 (100) 63 (98) and 45 (13).

**N-(Pyrid-2-yl)benzotriazole 243.**

Benzotriazole (3.0 g, 33.6 mmol) and 2-bromopyridine (2 g, 16.8 mmol) were heated in toluene at reflux for 24 h. Ethyl acetate (50 cm³) was added and the mixture allowed to stir for 5 min. The mixture was washed with 10% KOH (2 × 50 cm³) and the organic layer dried over anhydrous magnesium sulfate. The solvent was removed under reduced pressure after filtration to yield N-(pyrid-2-yl)benzotriazole (2.2 g, 90%) mp 179-180 °C [lit., 59 180 °C]; δₜ (250 MHz, CDCl₃) 8.56 (2H, m), 8.18 (1H, d, 3 J 8.3), 8.02 (1H, d, 3 J 8.3), 7.82 (1H, td, 3 J 8.3, 3 J 8.3), 7.32 (1H, d, 3 J 8.3), 6.92-6.85 (2H, m), 6.80 (1H, d, 3 J 8.3), 6.55 (1H, d, 3 J 8.3), 6.42 (1H, d, 3 J 8.3), 6.00 (1H, d, 3 J 8.3), 5.95 (1H, s), 5.45 (1H, s), 4.88 (1H, d, 3 J 8.3), 4.00 (2H, m), 3.85 (2H, m), 3.60 (2H, m), 3.30 (2H, m), 2.55 (2H, m), 2.35 (2H, m), 1.90 (2H, m), 1.70 (2H, m), 1.40 (2H, m), 1.20 (2H, m), 0.80 (2H, m), 0.50 (2H, m), 0.30 (2H, m), 0.10 (2H, m), 0.00 (2H, m); δc (63 MHz, DMSO-d₆) 152.16 (CH), 145.29 (quat), 136.37 (CH), 112.98 (CH) and 109.72 (CH); m/z 234 (M⁺, 89%), 197 (49) 117 (100) 102 (98) and 61 (13).
4J 1.8), 7.49 (1H, t, 3J 8.3), 7.35 (1H, d, 3J 7.4) and 7.20 (1H, d, 3J 7.4); δC 151.47 (quat), 148.13 (CH), 146.54 (quat), 138.62 (CH), 131.30 (quat), 128.58 (CH), 124.71 (CH), 121.08 (CH), 119.53 (CH), 114.64 (CH) and 114.21 (CH); m/z 196 (M⁺, 44%), 168 (86), 117 (29) 90 (18), 78 (100), 63 (51) and 51 (82).

**FVP of N-(pyrid-2-yl)benzotriazole 243.**

[Tf 700 °C, Tl 120 °C, P 3.0 x 10⁻² Torr, tm 30 min, ma 0.507 g].

Pyrolysis produced benz[4,5]imidazo[1,2-a]pyridine 229 (0.291 g, 67%)

mp 176-178 °C [lit., 59 179 °C]; δH (250 MHz CDCl₃) 8.37 (1H, d, 3J 6.9), 7.92 (1H, d, 3J 8.3), 7.83 (1H, d, 3J 8.2), 7.64 (1H, d, 3J 8.4), 7.44 (1H, t, 3J 7.2), 7.42-7.35 (2H, m) and 6.80 (1H, t, 3J 6.8).

**Imidazo[1,2-a]pyridine 228.**

2-Aminopyridine (6.0 g, 63.2 mmol), chloroacetaldehyde (45% w/w in water, 11.2 g) and sodium bicarbonate (6.0 g) were dissolved in water (15 cm³) and ethanol (50 cm³) and held under reflux for 3 h. The ethanol was removed under vacuum and the residue was extracted with DCM (3 x 100 cm³). The combined DCM layers were washed with water (2 x 100 cm³) and dried over MgSO₄ before being filtered and concentrated under reduced pressure to give a brown oil, which after vacuum distillation yielded imidazo[1,2-a]pyridine as a pale yellow oil (6.7 g, 90%)

bp 95 °C (0.8 mbar) [lit., 58 103 °C (1 mbar)]; δH (250 MHz, DMSO-d₆) 8.60 (1H, dt, 3J 6.8, 4J 1.3), 7.99 (1H, s), 7.63-7.59 (2H, m), 7.22 (1H, td, 3J 6.7, 4J 1.3) and 6.90 (1H, td, 3J 6.8, 3J 1.1); δC (63 MHz, DMSO-d₆) 144.37 (quat), 133.24 (CH), 127.11 (CH), 124.50 (CH), 117.07 (CH), 112.20 (CH) and 112.09 (CH); m/z 118 (M⁺, 100%), 91 (21), 78 (23) and 64.

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4-Aminopyrimidine 244.

Potassium metal (2.44 g, 62.50 mmol) was slowly added to liquid NH$_3$ at -78 °C. Once the solution turned blue, ferric nitrate (150 mg) was added and the mixture stirred for 15 min. Potassium addition was continued. After addition, the dispersion of potassium amide was stirred for a further 30 min and then warmed to reflux. Pyrimidine (2.00 g, 25.00 mmol) was slowly added to the dispersion of potassium amide in liquid NH$_3$ at reflux and allowed to stir for 10 min. Potassium permanganate (25 g) was added and the mixture was stirred for 15 min. Ammonium sulfate (20 g) was added and the mixture was allowed to stir for 15 min. Methanol (100 cm$^3$) was added and the ammonia was allowed to evaporate. Silica (10 g) was added and the methanol was removed under reduced pressure. The silica was packed into a chromatography column and eluted with DCM to yield 4-aminopyrimidine (1.54 g, 65%) mp 149-150 °C [lit.,$^{60}$ 151-152 °C]; δ$_H$ (250 MHz, DMSO-$d_6$) 8.34 (1H, s), 7.99 (1H, d, $^3$J 5.8), 6.83 (2H, br s) and 6.42 (1H, d, $^3$J 5.6); δ$_C$ (63 MHz, DMSO-$d_6$) 163.42 (quat), 158.49 (CH), 154.91 (CH) and 105.16 (CH); m/z 95 (M$^+$, 100%), 68 (38) and 41 (46).

N-(2-Nitrophenyl)pyrimidin-4-amine 246.

4-Aminopyrimidine (0.60 g, 6.30 mmol) was dissolved in DMSO (25 cm$^3$) and potassium t-butoxide (0.90 g, 8.00 mmol) was added. The mixture was allowed to stir for 30 min. 2-Fluoronitrobenzene (0.9 g, 6.4 mmol) was added and the mixture was heated at 125 °C for 15 h. After cooling saturated aqueous sodium bicarbonate (50 cm$^3$) was added and the mixture was extracted with DCM (3 x 100 cm$^3$). The DCM extracts were combined and concentrated onto silica for purification by dry flash chromatography using DCM/EtOAc to yield N-(2-nitrophenyl)pyrimidin-4-amine (0.54 g, 40%) mp 127-129 °C; (Found: M 216.06495, C$_{10}$H$_8$N$_4$O$_2$ requires M 216.06473); δ$_H$ (250 MHz, DMSO-$d_6$) 9.94 (1H, br s), 8.53 (1H, s), 8.37 (1H, d, $^3$J 5.9), 8.03 (1H, d, $^3$J 8.2), 7.80 (1H, d, $^3$J 8.1), 7.72 (1H, t, $^3$J 7.8), 7.34 (1H, t, $^3$J 8.2) and 6.93 (1H, d, $^3$J 5.9); δ$_C$ (63 MHz, DMSO-$d_6$) 158.86, (quat), 158.13 (CH), 156.47 (CH), 136.31 (quat), 135.97 (quat), 135.41 (CH), 125.96 (CH), 121.86 (CH), 121.69 (CH) and 109.14 (CH); m/z 216 (M$^+$, 45%), 194 (17), 170 (100), 143 (20), 92 (46) and 52 (40).
2-Nitroaniline (27%) was isolated from a further fraction mp 75-76 °C [lit.,169 74-76 °C]; \( \delta \) (250 MHz, CDCl\(_3\)) 7.97 (1H, dd, \(^3J 8.7, ^4J 1.5\)), 7.43 (2H, br s), 7.41 (1H, ddd, \(^3J 8.5, ^3J 6.8, ^4J 1.8\)), 7.02 (1H, dd, \(^3J 8.7, ^4J 1.3\)) and 6.63 (1H, ddd, \(^3J 8.2, ^3J 6.7, ^4J 1.3\)); \( \Delta \) (63 MHz, CDCl\(_3\)) 146.36, (quat), 136.34 (CH), 135.82 (CH), 125.47 (quat), 119.26 (quat) and 115.54 (CH); \( m/z \) 138 (M\(^+\), 100%), 92 (85), 80 (50), 65 (80) and 39 (34).

**FVP of N-(2-nitrophenyl)pyrimidin-4-amine 229.**

\[
\text{No} \quad \text{N} \quad \text{N} \quad \text{N} \\
\text{N} \quad \text{N} \quad \text{N} \\
\text{N} \quad \text{N} \quad \text{N} \\
\text{N} \quad \text{N} \quad \text{N} \\
\text{N} \quad \text{N} \quad \text{N} \\
\text{N} \quad \text{N} \quad \text{N}
\]

The crude pyrolysate was pre-adsorbed onto silica Purification by dry flash chromatography (hexane/ethyl acetate) produced pyrido[4,5-b]benzimidazole (0.094 g, 60%) mp 203-206 °C; (Found: M 169.0640, C\(_{10}\)H\(_7\)N\(_3\) requires M 169.0640); \( \delta \) (360 MHz, DMSO-d\(_6\)) 9.95 (1H, d, \(^4J 1.5\)), 8.43 (1H, dt, \(^3J 8.9, ^4J 1.9, ^5J 0.9\)), 8.12 (1H, d, \(^3J 6.7\)), 7.87 (1H, d, \(^3J 8.2, ^4J 1.8, ^5J 0.9\)), 7.63 (1H, td, \(^3J 8.1, ^4J 1.5\)), 7.58 (1H, ddd, \(^3J 8.2, ^4J 1.1\)) and 7.49 (1H, td, \(^3J 8.1, ^4J 1.1\)); \( \Delta \) (91 MHz, DMSO-d\(_6\)) 146.66, (quat), 144.07 (quat), 143.39 (CH), 141.98 (CH), 126.83 (quat), 126.77 (CH), 122.23 (CH), 121.09 (CH), 112.77 (CH) and 111.91 (CH); \( m/z \) 169 (M\(^+\), 100%), 118 (15), 90 (3) and 64 (2).

**FVP of rearrangement substrates.**

The method of purification (if applicable) is stated in each experimental.

**FVP of Imidazo[1,2-a]pyrimidine 225.**

\[
\text{H} \quad \text{N} \quad \text{N} \\
\text{N} \quad \text{N} \quad \text{N} \\
\text{N} \quad \text{N} \quad \text{N} \\
\text{N} \quad \text{N} \quad \text{N} \\
\text{N} \quad \text{N} \quad \text{N} \\
\text{N} \quad \text{N} \quad \text{N}
\]

[\( T_f 975 \) °C/silica wool, \( T_i 150-180 \) °C, \( P 3.0 \times 10^{-2} \) Torr, \( t_m 25 \) min, \( m_a 0.048 \) g]. The pyrolysate was not purified and produced crude pyrrolo[3,2-b]pyrazine 227 (0.029 g, 60%); mp 151-155 °C [lit.,187 155-156 °C]; \( \delta \) (250 MHz, DMSO-d\(_6\)) 12.10 (1H, hr s), 8.39 (1H, dd, \(^3J 2.6, ^4J 1.3\)), 8.24 (1H, d, \(^3J 2.6\)), 7.88 (1H, t, \(^3J 2.8\)) and 7.80 (1H, m); \( \Delta \) (63 MHz, DMSO-d\(_6\)) 138.40, (quat), 136.35 (quat), 135.21 (CH), 133.38 (CH), 128.28 (CH) and 97.58 (CH); \( m/z \) (electrospray) 120 (MH\(^+\)).
FVP of Benzo[4,5]imidazo[1,2-a]pyridine 228.

\[ T_f \ 975^\circ C/\text{silica wool}, \ T_i \ 140-160^\circ C, \ P \ 3.0 \times 10^{-2} \ \text{Torr}, \ t_m \ 10 \ \text{min}, \ m_a \ 0.037 \ \text{g} \]. No reaction occurred. Repeated at \( T_f \ 1150^\circ C/\text{silica wool}. \) Only decomposition occurred.

FVP of Imidazo[1,2-a]pyridine 227.

\[ T_f \ 975^\circ C/\text{silica wool}, \ T_i \ 30^\circ C, \ P \ 3.0 \times 10^{-2} \ \text{Torr}, \ t_m \ 20 \ \text{min}, \ m_a \ 0.122 \ \text{g} \]. No reaction occurred. Repeated at \( T_f \ 1150^\circ C/\text{silica wool}. \) Only decomposition occurred.

Pyrido[4,5-b]benzimidazole 229.

\[ T_f \ 975^\circ C/\text{silica wool}, \ T_i \ 100-140^\circ C, \ P \ 3.4 \times 10^{-2} \ \text{Torr}, \ t_m \ 17 \ \text{min}, \ m_a \ 0.050 \ \text{g} \].

Pyrolysis produced a mixture of starting material 229, pyrrolo[2,3-b]quinoxaline 173 and \( \alpha,\gamma \)-carboline 247. The ratio of products was 50:30:20 respectively. The assignment of \( \alpha,\gamma \)-carboline was based on the analysis the respective \( ^1 \text{H} \) NMR spectrum signals by COSY and NOE experiments.

FVP of 7-Azabenzimidazole 230.

Small scale FVP.

\[ T_f \ 1150^\circ C/\text{silica wool}, \ T_i \ 110-140^\circ C, \ P \ 3.2 \times 10^{-2} \ \text{Torr}, \ t_m \ 10 \ \text{min}, \ m_a \ 0.05 \ \text{g} \].

Pyrolysis produced a mixture of 2-cyanopyrrole 248, 3-cyanpyrrole 249, 2-amino-3-cyanopyridine 250 and 3-amino-2-cyanopyridine 251 in a 25:25:25:25 ratio respectively. Pyrolysis at lower temperatures contained starting material.

Preparative scale FVP.

\[ T_f \ 1150^\circ C/\text{silica wool}, \ T_i \ 110-140^\circ C, \ P \ 3.2 \times 10^{-2} \ \text{Torr}, \ t_m \ 10 \ \text{min}, \ m_a \ 0.2 \ \text{g} \]. Note only small quantities were recovered due to decomposition of the starting material on the silica in the furnace tube. A blackening of the silica was observed over the course of the reaction. The material that was recovered was subjected to repeated purification by dry flash chromatography (hexane/ethyl acetate) and due to loss of material on work up, no preparative yields are reported. The fractions from the chromatography that were
analysed were mixtures. Characterisation was carried out by comparison to literature spectra and by high resolution mass spectrometry.

2-Cyanopyrrole 248 (Found: M 92.0375, C₅H₄N₂ requires M 92.0375) δ₁ (250 MHz, DMSO-δ₆) 9.23 (1H, br s), 6.96 (1H, m), 6.87 (1H, m) and 6.27 (1H, m). Identified by comparison with literature ¹H spectrum.¹⁷¹

3-Cyanopyrrole 249 (Found: M 92.0375, C₅H₄N₂ requires M 92.0375) δ₁ (250 MHz, DMSO-δ₆) 9.90 (1H, br s), 7.24 (1H, m), 6.65 (1H, m) and 6.41 (1H, m). Identified by comparison with literature ¹H spectrum.¹⁷²

2-Amino-3-cyanopyridine 250 (Found: M 119.0484, C₆H₅N₃ requires M 119.0484) δ₁ (250 MHz, DMSO-δ₆) 7.99 (1H, dd, 3J 4.5, 4J 1.5), 7.20 (1H, dd, 3J 8.5, 3J 4.4), 7.05 (1H, dd, 3J 8.4, 4J 1.3) and 4.47 (2H, br s). Identified by comparison with literature ¹H spectrum.¹⁷³

3-Amino-2-cyanopyridine 251 Found: (M 119.0483, C₆H₅N₃ requires M 119.0484) δ₁ (250 MHz, DMSO-δ₆) 8.19 (1H, dd, 3J 5.0, 4J 1.9), 7.63 (1H, dd, 3J 7.7, 4J 1.9), 6.64 (1H, dd, 3J 7.7, 3J 5.0) and 5.23 (2H, br s). Identified by comparison with literature ¹H spectrum.¹⁷³

Synthesis of pyridylamines.

N-Phenylpyridin-4-ylamine 189.

4-Chloropyridine hydrochloride (5.0 g, 33.3 mmol) and aniline (3.1 g, 33.3 mmol) were dissolved in DMF (30 cm³) and heated with stirring at 120 °C for 5 h. The solution was cooled to room temperature and added to a solution of potassium carbonate (5.0 g) in water (150 cm³). A precipitate formed and was filtered before being recrystallised from toluene to give N-phenylpyridin-4-ylamine (3.85 g, 68%) mp 176 – 177 °C [lit.³⁸ 177 – 178]; δ₁ (250 MHz, CDCl₃) 8.22 (2H, d, 3J 6.3), 7.27 (2H, t, 3J 7.3), 7.13 (2H, dd, 3J 7.4, 4J 1.6), 7.10 (1H, t, 3J 7.3) and 6.75 (2H, dd, 3J 4.8, 4J 1.6 ); δ₂ (63 MHz, CDCl₃) 151.03 (quat), 150.77 (2 × CH),
140.07 (quat), 130.00 (2 \times CH), 124.55 (CH), 122.05 (2 \times CH) and 109.90 (2 \times CH); m/z 170 (M^+, 100%), 115 (9), 77 (11) and 51 (26).

**N-Benzylphenylpyrid-4-ylamine 186.**

A solution of *N*-phenylpyridin-4-ylamine 189 (0.50 g, 2.94 mmol) in DMF (10 cm³) was added to a stirred suspension of sodium hydride (0.14 g, 5.88 mmol) in DMF (5 cm³) and stirred at room temperature for 1 h. Benzyl bromide (0.50 g, 2.94 mmol) was then added and stirred for 1.5 h. The solution was then diluted with water (100 cm³) and extracted with ether (4 x 50 cm³). The organic layers were combined and washed with water (3 x 100 cm³) before being dried over MgSO₄. The solvent was then removed under reduced pressure and the residue recrystallised from hexane (0.382 g, 50%) mp 85 - 86 °C (from hexane); (Found: C, 83.1; H 6.2; N 10.8. C₁₅H₁₆N₂ requires C, 83.0; H, 6.3; N, 10.7%); δH (250 MHz, CDCl₃) 8.08 (2H, d, J 5.3), 7.20-7.10 (1H, m), 6.48 (2H, d, J 6.4) and 4.89 (2H, s); δC (63 MHz, CDCl₃) 153.78 (quat), 150.33 (2 \times CH), 145.89 (quat), 130.50 (2 \times CH) 129.23 (2 \times CH), 127.72 (CH), 127.36 (2 \times CH), 126.99 (CH), 126.88 (2 \times CH), 109.31 (2 \times CH) and 56.27 (CH₂); m/z 260 (M^+, 52%), 91 (100) and 51 (26).

**2-(Benzy1amin)pyridine 192.**

Di-tert-butyl dicarbonate (1.000 g, 4.6 mmol) was dissolved in tert-butyl alcohol (30 cm³). 2-Aminopyridine (0.395, 4.2 mmol) was added and the solution was allowed to stir for 24 h. The solvent was removed under reduced pressure and the residue was recrystallised from isopropyl alcohol before being dissolved in anhydrous DMF (20 cm³) and cooled to 0 °C in an ice bath. Sodium hydride (0.177 g, 60% dispersion in oil, 5.3 mmol) was added to the DMF solution and the suspension left to stir at room temperature for 30 min while maintaining the temperature below 5 °C. Benzyl bromide (0.57 cm³, 4.8 mmol) was added and the mixture was allowed to stir at below 5 °C for 30 min before being warmed to room temperature. The mixture was stirred at room temperature for 1 h and water (5 cm³) was added. The solution was diluted with water (20 cm³) and ether (150 cm³). The organic layer was separated and extracted with water (1 x 50 cm³), aqueous HCl (0.1 M), aqueous saturated
sodium bicarbonate (1 × 50 cm³) and brine (1 × 50 cm³) before being dried over MgSO₄. The solvent was then removed under reduced pressure and the residue was dissolved in chloroform (5 cm³) and carefully treated with trifluoroacetic acid (95% aqueous solution, 5 cm³) before being stirred overnight at room temperature. The reaction mixture was cooled to 0 °C and the pH was adjusted to pH 12 with NaOH (3M) before being diluted in ether (100 cm³). The organic layer was separated and extracted with water (2 × 50 cm³) and brine (2 × 50 cm³) before being dried over MgSO₄. The solvent was removed under reduced pressure and the residue was pre-adsorbed onto silica. Separation by dry flash chromatography (hexane/ethyl acetate) gave 2-(benzylamin)pyridine (0.696 g, 90%) mp 94-95 °C [lit., 174 94-96]; δH (360 MHz, CDCl₃) 8.10 (1H, d, 3J 4.0), 7.41 (1H, ddd, 3J 8.5, 3J 7.2, 4J 1.9), 7.37 - 7.25 (4H, m), 6.59 (1H, ddd, 3J 6.6, 3J 5.1, 4J 0.9), 6.38 (1H, d, 3J 8.4), 5.02 (1H, br, s) and 4.50 (2H, d, 3J 5.8); m/z (electrospray) 185 (MH⁺).

N-Benzylphenylpyrid-2-ylamine 188.

2-(Benzylamino)pyridine 192 (0.5 g, 2.7 mmol) and iodobenzene (0.55 g, 2.7 mmol) were heated at reflux in DMF (10 cm³) in the presence of copper bronze (0.5 g) and potassium carbonate (0.45 g, 3.3 mmol) for 18 h. The reaction mixture was then allowed to cool to room temperature and was filtered through celite. The DMF solution was then diluted with water (20 cm³) and extracted with DCM (3 × 50 cm³). The organic fractions were combined and washed with water (5 × 50 cm³) before being dried over MgSO₄. The solvent was removed under reduced pressure and the residue was pre-adsorbed onto silica. Separation by dry flash chromatography (hexane/ethyl acetate) yielded N-benzylphenylpyrid-2-ylamine (0.22 g, 31%) mp 69-70 °C; (Found: M⁺, 260.1312. C₁₈H₁₆N₂ requires M⁺, 260.1312); δH (360 MHz, CDCl₃) 8.30 (1H, ddd, 3J 5.0, 3J 1.9, 3J 0.8), 7.43-7.23 (11H, m), 6.70 (1H, ddd, 3J 6.5, 3J 5.0, 3J 0.9), 6.62 (1H, d, 3J 8.6) and 5.35 (2H, s); δC (91 MHz, CDCl₃) 158.19 (quat), 147.72 (CH), 145.26 (quat), 139.23 (quat), 136.35 (CH) 129.49 (2 × CH), 128.88 (2 × CH), 127.28 (2 × CH), 126.55 (2 × CH), 126.49 (CH), 125.39 (CH), 113.35 (CH), 108.99 (CH) and 53.26 (CH₂); m/z 260 (M⁺, 100%), 182(75), 168 (61), 91 (94), 69 (74) and 57 (90).
**N-Benzyl-4,4'-dipyridylamine 187.**

Benzyl bromide was used. Purification was by recrystallisation from toluene/hexane. (45%) mp 102 °C (from toluene/hexane) (Found: C, 77.9; H, 5.8; N, 16.15. C_{17}H_{15}N_{3} requires C, 78.15; H, 5.75; N, 16.1); δ_{H} (250 MHz, DMSO-d_{6}) 8.35 (4H, d, 2J 6.2), 7.30 - 7.17 (5H, m), 6.99 (4H, d, 2J 4.8) and 5.00 (2H, s); δ_{C} (63 MHz, CDCl_{3}) 152.18 (2 × quat), 151.13 (4 × CH), 136.59 (quat), 129.12 (2 × CH), 127.72 (CH), 126.22 (2 × CH), 114.89 (4 × CH) and 54.74 (CH_{2}); m/z 261 (M^{+}, 63%), 171 (17), 91 (100) and 57 (100).

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**FVP of N-alkylpyridylamines**

**FVP of N-Benzylphenylpyridin-4-ylamine 188.**

[T_{f} 825 °C, T_{i} 130 °C, P 3.2 × 10^{-2} Torr, t_{m} 14 min, m_{a} 0.054 g]. The crude pyrolysate was preadsorbed onto silica for separation by dry flash chromatography which produced benz[4,5]imidazo[1,2-a]pyridine 138 (0.026 g, 75%) mp 177-178 °C [lit., 41 179 °C]; δ_{H} (250 MHz CDCl_{3}) 8.36 (1H, d, 2J 6.8), 7.91 (1H, d, 2J 8.2), 7.83 (1H, d, 2J 8.2), 7.65 (1H, d, 2J 8.3), 7.45 (1H, t, 2J 7.3), 7.43-7.36 (2H, m) and 6.81 (1H, t, 2J 6.9); m/z (electrospray) 169 (MH^{+}).

**FVP of N-Benzylphenylpyridin-4-ylamine 186.**

[T_{f} 975 °C, T_{i} 80 - 110 °C, P 4.6 × 10^{-2} Torr, t_{m} 20 min, m_{a} 0.047 g]. The products were deduced to be phenylpyrid-4-ylamine 189, γ-carboline 133 and isonicotinonitrile 194 by 1H NMR spectroscopy (200 Hz, DMSO-d_{6}). The integrals of the characteristic 1H NMR peaks (δ_{H} 8.2, 9.4 and 8.8 194 respectively) give the ratio of phenylpyrid-4-ylamine to γ-carboline (69:31). The integral for the peak that may be isonicotinonitrile was not measured on this occasion as it was not recorded by the NMR software.
FVP of N-Benzyl-4,4'-dipyridylamine 187.

Small scale FVP.

$[T_f \text{ 975 } ^\circ\text{C}, T_i \text{ 50 } ^\circ\text{C}, P \text{ 2.0 } \times \text{ 10}^{-2} \text{ Torr, } t_m \text{ 15 min, } m_a \text{ 0.05 g}].$

The products were deduced to be 4,4'-dipyridylamine 165, possibly γ,γ' - carboline 134 and some isonicotinonitrile 194 by $^1$H NMR spectrum (200 Hz, DMSO-d$_6$). The integrals of the characteristic $^1$H peaks ($\delta_\text{H} \text{ 8.3, 9.4 and 8.8}$ respectively) of the these compounds gave a ratio of 33 : 12 : 55. The ratio of to 4,4'-dipyridylamine to isonicotinonitrile was 37 : 63.

Preparative scale FVP.

$[T_f \text{ 975 } ^\circ\text{C}, T_i \text{ 140 } ^\circ\text{C}, P \text{ 2.3 } \times \text{ 10}^{-2} \text{ Torr, } t_m \text{ 25 min, } m_a \text{ 0.215 g}].$ The crude pyrolysate was dissolved in DCM and the insoluble material filtered off. The DCM washings were treated by dry flash chromatography (hexane/toluene) to give isonicotinonitrile 193 which was isolated with small amounts of impurities present (0.026 g, 30%). (Found: $M^+$, 104.0376. C$_6$H$_4$N$_2$ requires $M$, 104.0375); $\delta_\text{H} \text{ (200 MHz, CDCl}_3\text{) 8.75 (2H, d, }^3J \text{ 5.9) and 7.47 (2H, d, }^3J \text{ 6.2); } \delta_\text{C} \text{ 150.67 (2 } \times \text{ CH), 125.13 (2 } \times \text{ CH), 120.33 (quat) and 116.25 (quat); } m/z \text{ 104 (M}^+, \text{ 100%) (no breakdown peaks reported due to sample being impure).}$

Preparation of N-benzylidene-pyridin-4-amine 201.

4-Aminopyridine (5.7 g, 60.6 mmol), benzaldehyde (6.43 g, 60.6 mmol) and a catalytic amount of $p$-toluenesulfonylic acid were heated at reflux in xylenes (30 cm$^3$) under Dean-Stark conditions until the appropriate quantity of water had been azeotropically distilled off. The solution was distilled under reduced pressure to yield a pale yellow oil, which solidified upon scratching with a metal spatula to give a yellow/white solid (80%) mp 116-119 °C [lit., 176 118-120]; $\delta_\text{H} \text{ (250 MHz, CDCl}_3\text{) 8.52-8.49 (2H, m), 8.31 (H, s), 7.85 (2H, dd, }^3J \text{ 7.7, }^4J \text{ 1.8), } 7.49-7.39 (3H, m) \text{ and } 6.97-6.95 (2H, m); \delta_\text{C} \text{ (63 MHz, CDCl}_3\text{) 162.56 (CH), 158.68 (quat), 150.36 (2 } \times \text{ CH), 153.02 (quat), 131.98 (CH), 128.89 (2 } \times \text{ CH), 128.59 (2 } \times \text{ CH) and 115.38 (2 } \times \text{ CH); } m/z \text{ (electrospray) 183 (MH}^+\text{).}$
N-(Pyridine-4-yl-methylene)pyridin-4-amine 209.

4-Aminopyridine (1.0 g, 10.6 mmol) and pyridine-4-carboxylic acid (1.37 g, 11.1 mmol) were heated at reflux in toluene for 8 h in the presence of a catalytic amount of p-toluenesulfonic acid. The solvent was removed under reduced pressure to give N-(pyridine-4-yl-methylene)pyridin-4-amine after recrystallisation from light petrol (bp 60-80 °C) (1.57 g, 80%) mp 77-79 °C [lit., 177 77-80]; δH (200 MHz, DMSO-d₆) 8.80 (2H, 3 J 5.1), 8.68 (1H, s), 8.61 (2H, 3 J 5.1), 7.88 (2H, 3 J 5.1) and 7.25 (2H, 3 J 5.1); m/z (electrospray) 184 (MH⁺).

FVP of of N-benzylideneypyridin-4-amine 201.

[Tf 975 °C, T, 120 °C, P 2.6 × 10⁻² Torr, tₘ 15 min, mₙ 0.054 g]. Analysis of the pyrolysate by ¹H NMR spectroscopy showed that no reaction occurred.

FVP of N-(pyridine-4-yl-methylene)pyridine-4-amine 209.

[Tf 975 °C, T, 125 °C, P 2.8 × 10⁻² Torr, tₘ 18 min, mₙ 0.067 g]. Analysis of the pyrolysate by ¹H NMR spectroscopy showed that no reaction occurred.

Synthesis of N-arylated carbazoles.

9-(2-Nitrophenyl)carbazole 25.

Carbazole (3.0 g, 18 mmol) and 2-fluoronitrobenzene (2.5g, 18 mmol) was dissolved in DMSO (50 cm³). Cesium carbonate (6.4 g, 20 mmol) were added to the solution with stirring. The suspension was stirred for 15 h before being diluted with water (50 cm³) and a yellow precipitate formed. The mixture was extracted with DCM (3×100 cm³). The DCM layers were combined and washed with water (3×100 cm³) before being dried over MgSO₄. The DCM was removed by distillation under reduced pressure to yield 9-(2-nitrophenyl)carbazole (4.9 g, 95%) mp 155-156 °C [lit.,² 156 °C]; δH (250 MHz, CDCl₃) 8.15 – 8.08 (3H, m), 7.79 (1H, dt, ³J 7.5, ⁴J 1.5), 7.68 – 7.58 (2H, m), 7.36 (2H, td, ³J 7.7, ⁴J 1.4), 7.27(2H, td, ³J 7.5 ⁴J 1.2) and 7.09 (2H, d, ³J 7.8, ⁴J 1.0); δC (63 MHz, CDCl₃) 140.62, (2 x quat), 134.14 (CH), 131.28 (CH), 131.11 (quat) 129.03 (CH) 126.20 (2 ×
9-(4-Amino-2-nitrophenyl)carbazole 260.

Carbazole (1.00 g, 6 mmol) and 4-fluoro-3-nitrobenzene (0.93 g, 6 mmol) were dissolved in DMSO (20 cm³). Cesium carbonate (2.15 g, 6.6 mmol) was added to the solution with stirring. The suspension was stirred for 18 h at 140 °C before being cooled and diluted with brine (50 cm³) whereupon a red precipitate formed. The suspension formed was extracted with DCM (4×100 cm³). The DCM layers were combined and washed with water (2×100 cm³) before being dried over MgSO₄. The DCM solution concentrated under reduced pressure and the residue was pre-adsorbed onto silica for purification by dry flash chromatography (hexane/ethyl acetate) to yield 9-(4-amino-2-nitrophenyl)carbazole (1.51 g, 83%) mp 162-164 °C [lit., 164-165 °C]; δₓ (250 MHz, DMSO) 8.22 (2, 1H, d, 3J 7.9), 7.41 - 7.37 (4H, m), 7.27 (2H, t, 3 J 7.6), 7.12 - 7.07 (3H, m) and 6.24 (2H, br, s); δₑ (63 MHz, DMSO) 150.55, (quat), 147.99 (quat), 141.31 (2 x quat), 131.20 (CH) 126.36 (2 x CH), 122.73 (2 xquat), 120.60 (2 x CH) 119.99 (2 x CH), 118.95 (CH), 116.17 (quat), 109.33 (2 x CH) and 108.96 (CH); m/z 303 (M⁺, 22%), 256 (15), 167 (85), 156 (88), 110 (85), 98 (32), 83 (100), 58 (53) and 43 (78).

9-(4-Bromo-2-nitrophenyl)carbazole 261.

Carbazole (1.48 g, 8.9 mmol) and 5-bromo-2-fluoronitrobenzene (1.67 g, 8.9 mmol) was dissolved in DMSO (30 cm³). Cesium carbonate (3.45 g, 10.7 mmol) was added to the solution with stirring. The suspension was stirred for 15 h before being diluted with water (50 cm³) and an orange precipitate formed. The mixture was extracted with DCM (3×100 cm³). The DCM layers were combined and washed with water (3×100 cm³) before being dried over MgSO₄. The DCM layer was concentrated under reduced pressure and the residue was pre-adsorbed onto silica for purification by dry flash chromatography (hexane/ethyl acetate) to yield 9-(4-bromo-2-nitrophenyl)carbazole (2.35 g, 72%) mp 151-153 °C [lit., 152-154 °C]; δₓ (250 MHz, CDCl₃) 8.22 (1H, d, 4J
9-(4-Cyano-2-nitrophenyl)carbazole 262.

4-Chloro-3-nitrobenzonitrile (2.00 g, 11 mmol), carbazole (1.83 g, 11 mmol) and potassium carbonate (1.80 g, 11 mmol) were heated, with stirring in nitrobenzene (5 cm³) for 15 h at 180 °C. The nitrobenzene was then removed by bulb to bulb distillation under vacuum. The residue was then dissolved in ether and extracted with water (3 × 100 cm³). The organic layer was dried over MgSO₄ before the solvent was removed under reduced pressure. The residue was pre-adsorbed onto silica and then treated by dry flash chromatography (hexane/toluene) to give 9-(4-cyano-2-nitrophenyl)carbazole (2.20 g, 64%) mp 171-173 °C [lit., 2 172-174 °C]; δH (250 MHz, CDCl₃) 8.33 (1H, s), 8.00 (2H, d, 3J 7.1), 7.92 (1H, dd, 3J 8.3, 4J 1.9), 7.73 (1H, d, 3J 8.3), 7.32 – 7.32 (4H, m) and 7.04 (2H, d, 3J 7.3); δC 147.97, (quat), 140.18 (2 × quat), 137.60 (CH), 135.90 (quat) 132.41 (CH), 130.54 (CH), 127.20 (2 × CH) 124.88 (2 × quat), 124.22 (2 × CH), 121.35 (2 × CH), 116.59 (quat), 112.93 (quat) and 109.25 (2 × CH); m/z 313 (M⁺, 7%), 266 (6), 167 (100), 91 (81) and 77 (9).

9-(5-Methyl-2-nitrophenyl)carbazole 270.

Carbazole (0.54 g, 3.22 mmol) and 3-fluoro-4-nitrotoluene (0.50 g, 3.22 mmol) was dissolved in DMSO (20 cm³). Cesium carbonate (1.26 g, 3.87 mmol) was added and to the solution with stirring. The suspension was stirred for 15 h at 100 °C before being diluted with water (50 cm³) and a yellow precipitate formed. The suspension formed was extracted with DCM (3×100 cm³). The DCM layers were combined and washed with water (3×100 cm³) before being dried over anhydrous magnesium sulfate. The DCM was concentrated onto silica and purified by dry-flash chromatography using
hexane/DCM followed by crystallisation from ethanol to yield 9-(5-Methyl-2-nitrophenyl)carbazole (32%) mp 106-107 °C (ethanol); (Found: M" 302.1053, C_{19}H_{14}N_{3}O_{2} requires M 302.1055); δ_H (250 MHz, CDCl_3) 8.12 (2H, dd, 3J 7.7, 4J 1.0), 8.11 (1H, d, 3J 8.2), 7.48-7.45 (2H, m), 7.39 (2H, td, 3J 7.8, 4J 1.3), 7.29 (2H, dt, 3J 7.5, 4J 1.2), 7.79 (2H, d, 3J 7.4) and 2.47 (3H, s); δ_C (63 MHz, CDCl_3) 145.84, (quat), 144.71 (quat), 140.65 (2 × quat), 131.55 (CH) 130.06 (quat) 129.58 (CH), 126.11 (2 × CH), 125.91 (CH) 123.64 (2 × quat), 120.42 (2 × CH), 120.40 (2 × CH), 108.98 (2 × CH) and 21.33 (CH₃); m/z 302 (M⁺, 100%), 241 (43), 167 (20) and 127 (20).

9-(2-Aminophenyl)carbazole 27.

9-(2-Nitrophenyl)-9H-carbazole (3.0 g, 11.6 mmol) was dissolved in DMF (30 cm³) and Pd/C (10%, 0.3 mg) was added. The mixture was hydrogenated at 50 °C/20 bar. Upon completion, the mixture was cooled and filtered through celite before being diluted with water (50 cm³). The resulting suspension was extracted with ether (3 × 100 cm³). The ether was washed with water (3 × 100 cm³) and then dried over MgSO₄ before being concentrated under reduced pressure to yield 9-(2-aminophenyl)carbazole (83%) mp 119-120 °C [lit., 2 119-121 °C]; δ_H (360 MHz, DMSO) 8.25 (2H, dd, 3J 8.3, 4J 0.8), 7.40 (2H, ddd, 3J 8.3, 3J 7.2, 4J 1.2), 7.32 – 7.25 (3H, m), 7.16 – 7.03 (4H, m), 6.77 (1H, ddd, 3J 8.8, 3J 7.8, 4J 1.4) and 4.82 (2H, br s); δ_C (63 MHz, DMSO-d₆) 145.66, (quat), 140.49 (2 × quat), 129.56 (CH), 129.16 (CH) 126.08 (2 × CH), 122.97 (2 × quat), 120.68 (quat), 120.56 (2 × CH), 119.67 (2 × CH), 116.79 (CH), 116.35 (CH) and 110.14 (2 × CH); m/z 258 (M⁺, 100%), 167 (54), 129 (86), 89 (14), 73 and 44 (39).

FVP of N-arylcarbazoles.

The FVP apparatus was set up as described in section for preparative scale FVP of nitro group containing precursors. The cold-finger trap used for condensation of the product was placed as close to the furnace as possible. This is done to limit decomposition of the product at the outlet by condensing the product on a cold surface as early as possible. Once pyrolyses were complete the apparatus was warmed to room temperature under an atmosphere of nitrogen. The product was collected by dissolution in dichloromethane.
unless otherwise stated. The solution of product was concentrated under reduced pressure and the product was purified by dry flash chromatography. The eluant used was hexane/ethyl acetate unless otherwise stated. Hexane was used as the initial eluant with an increasing gradient of ethyl acetate.

**FVP of 9-(2-Nitrophenyl)carbazole 25.**

\[ T_f \, 875 \, ^\circ C, \, T_i \, 120 - 160 \, ^\circ C, \, P \, 2.0 \times 10^{-2} \, \text{Torr}, \, t_m \, 3 \, h \, 10 \, \text{min}, \, m_a \, 3.2 \, g \]. Pyrolysis produced indolo[3,2,1-jk]carbazole 1 (1.9 g, 71%) mp 155-156 °C [lit.\(^2\) 156 °C]; \( \delta_1 \) (360 MHz, CDCl\(_3\)) 8.14 (2H, d, \(^3J\) 7.8), 8.04 (2H, d, \(^3J\) 7.4), 7.89 (2H, d, \(^3J\) 8.1), 7.59 (1H, t, \(^3J\) 7.3), 7.55 (2H, td, \(^3J\) 7.6, \(^4J\) 1.5), and 7.36 (2H, td, \(^3J\) 7.5, \(^4J\) 1.2); \( \Delta_c \) (63 MHz, CDCl\(_3\)) 143.59 (quat), 138.54 (2 × quat), 129.88 (2 × quat), 126.54 (2 × quat), 124.02 (2 × quat), 123.78 (CH), 121.15 (2 × CH), 120.37 (2 × CH), 119.24 (2 × quat), and 112.06 (2 × CH); \( m/z \) 241 (M\(^+\), 100%), 178 (38), 121 (21), 89 (6) and 57 (3).

**FVP of 9-(4-Amino-2-nitrophenyl)carbazole 260.**

\[ T_f \, 875 \, ^\circ C, \, T_i \, 220 - 260 \, ^\circ C, \, P \, 2.0 \times 10^{-2} \, \text{Torr}, \, t_m \, 50 \, \text{min}, \, m_a \, 0.550 \, g \]. Pyrolysis produced 5-aminoindolo[3,2,1-jk]carbazole 263 (0.266 g, 57%) mp 134-137 °C ; (Found: M\(^+\) 256.0996, C\(_{18}H_{12}N_2\) requires MH 256.1001); \( \delta_1 \) (360 MHz, CDCl\(_3\)) 8.15 (1H, dt, \(^3J\) 7.8, \(^4J\) 1.1, \(^5J\) 0.7), 8.05 (1H, d, \(^3J\) 7.4), 7.98 (1H, d, \(^3J\) 7.3), 7.83 (1H, dt, \(^3J\) 7.9, \(^4J\) 1.1, \(^5J\) 0.7), 7.67 (1H, d, \(^3J\) 7.4), 7.67 (1H, t, \(^3J\) 7.4), 7.57 (1H, td, \(^3J\) 7.4, \(^4J\) 1.2), 7.44 (1H, d, \(^3J\) 7.7, \(^4J\) 1.0), 7.35 (1H, dd, \(^3J\) 7.7, \(^4J\) 1.0), 6.91 (1H, dd, \(^3J\) 8.4, \(^4J\) 2.3) and 3.45 (2H, br s); \( \Delta_c \) (91 MHz, CDCl\(_3\)) 143.97 (quat), 141.14, (quat), 138.46 (quat), 132.57 (quat), 130.93 (quat), 129.31 (quat), 123.38 (CH), 122.88 (CH), 122.13 (CH), 120.82 (CH) 119.20 (CH), 119.07 (CH), 118.25 (quat), 118.18 (quat), 114.70 (CH), 112.32 (CH), 111.51 (CH) and 109.52 (CH); \( m/z \) 256 (M\(^+\), 35%), 187 (35), 167 (6), 143 (24), 99 (31), 87 (100), 71 (13) and 55 (45).
FVP of 9-(4-Bromo-2-nitrophenyl)carbazole 261.

\[ T_f \ 875 \, ^\circ C, \ T_i \ 160 - 220 \, ^\circ C, \ P \ 3.8 \times 10^{-2} \, \text{Torr}, \ t_m \ 40 \, \text{min}, \ m_a \ 0.594 \, \text{g} \]. Pyrolysis produced 5-bromoindolo[3,2,1-jk]carbazole 264 (0.312 g, 60%); mp 141-143 °C [lit., 178 144-145 °C]; \( \delta_H \) (360 MHz, CDCl₃) 8.25 (1H, d, \( J = 1.8 \)), 8.14 (1H, d, \( J = 7.9 \)), 8.06 (1H, d, \( J = 7.6 \)), 8.00 (1H, d, \( J = 7.6 \)), 7.86 (1H, d, \( J = 8.3 \)), 7.76 (1H, d, \( J = 8.6 \)), 7.65 (1H, dd, \( J = 8.3, 4J = 1.8 \)), 7.60 (1H, t, \( J = 7.9, 4J = 1.4 \)) and 7.38 (1H, td, \( J = 7.6, 4J = 1.1 \)); \( \delta_C \) (91 MHz, CDCl₃) 143.67 (quat), 138.22, (quat), 136.90 (quat), 131.34 (quat), 129.75 (quat), 128.98 (CH), 126.67 (CH), 125.76 (CH), 123.02 (CH), 122.92 (CH) 121.81 (CH), 119.83 (CH), 119.7 (CH), 118.40 (CH), 117.06 (quat), 114.33 (quat), 112.88 (quat) and 111.96 (CH); \( m/z \) 321 (M⁺, 49%), 319 (M⁺, 49%), 239 (19), 167 (100), 139 (11), 120 (21) and 84 (9).

FVP of 9-(4-Cyano-2-nitrophenyl)carbazole 262.

\[ T_f \ 875 \, ^\circ C, \ T_i \ 210 - 240 \, ^\circ C, \ P \ 3.2 \times 10^{-2} \, \text{Torr}, \ t_m \ 45 \, \text{min}, \ m_a \ 0.703 \, \text{g} \]. The pyrolysate was purified by dry, flash chromatography using toluene/ethyl acetate. Pyrolysis gave 5-cyanoindolo[3,2,1-jk]carbazole 265 (0.400 g, 67% mp 191 – 192 °C (toluene); (Found: C, 83.6; H, 3.8; N, 10.0. C₁₉H₁₀N₂.0.3H₂O requires C, 83.6; H, 3.9; N, 10.3); \( \delta_H \) (360 MHz, CDCl₃) 8.27 (1H, d, \( J = 1.1 \)), 8.08 (1H, dq, \( J = 7.8, 4J = 1.2, 5J = 0.7 \)), 7.98 (1H, d, \( J = 7.4 \)), 7.88 (1H, d, \( J = 7.5 \)), 7.69 (1H, d, \( J = 8.1, 4J = 1.1, 5J = 0.7 \)), 7.65 (1H, d, \( J = 7.4 \)), 7.63 (1H, d, \( J = 7.4 \)), 7.58 (1H, t, \( J = 7.5 \)), 7.53 (1H, td, \( J = 7.5, 4J = 1.2 \)) and 7.43 (1H, td, \( J = 7.5, 4J = 1.1 \)); \( \delta_C \) (91 MHz, CDCl₃) 143.82 (quat), 139.57, (quat), 137.89 (quat), 130.12 (quat), 129.92 (CH), 129.77 (quat), 127.02 (CH), 126.87 (CH), 123.70 (CH), 123.23 (CH) 122.86 (CH), 120.42 (CH), 119.64 (CH), 119.63 (quat), 118.69 (quat), 116.56 (quat), 112.35 (CH), 112.09 (CH) and 104.30 (quat); \( m/z \) 266 (M⁺, 100%), 238 (4), 133 (16), 97 (8) and 73 (18).
FVP of 9-(5-Methyl-2-nitrophenyl)carbazole 270.

\[
[T_f \text{ 875 °C, } T_l 140 - 180 \text{ °C, } P 2.0 \times 10^{-2} \text{ Torr, } t_m 15 \text{ min, } m_a 0.061 \text{ g}].
\]
The pyrolysate was analysed directly by \(^1\text{H},\) COSY and NOESY NMR spectroscopy at 360 MHz after dissolving the entire pyrolysate in CDCl\(_3\). The pyrolysate was also analysed by mass spectrometry. Pyrolysis produced 4- and 6-methylindolo[3,2,1-\(jk\)]carbazole (274:275 respectively) in a 50:50 ratio based on the integrals of the 2 methyl peaks at \(\delta_1 2.62\) and 2.90. It is clear that one of the two structures to the left has a 1,2,4-trisubstituted aromatic substructure on the ring bearing the methyl group. In the other product, the ring bearing the methyl group has a 1,2,3-trisubstituted aromatic substructure. NOESY correlations from each methyl group were used to assign their adjacent protons. COSY NMR spectroscopy was used to identify the coupling systems and the pyrolysate was found to contain the two substructures as described above. These data was used to confirm the two structures shown above. (Found: \(M^+ 255.1049, C_{18}H_{12}N_2\) requires \(M^+ 255.1049\)).

2-Bromoindolo[3,2,1-\(jk\)]carbazole 279.

\[
\text{Br}
\]
Indolo[3,2,1-\(jk\)]carbazole (1.17 g, 4.8 mmol) and \(N\)-bromosuccinamide (0.86 g, 4.8 mmol) were dissolved in DCM (50 cm\(^3\)) in the absence of light. Silica gel (10 g) was added and the mixture was left to stir for 15 h. The mixture was filtered and the silica was washed with DCM (5 \(\times\) 50 cm\(^3\)). The combined DCM fractions were washed with saturated aqueous sodium metabisulfite (3 \(\times\) 50 cm\(^3\)). The aqueous extracts were back extracted with DCM (2 \(\times\) 50 cm\(^3\)). The combined DCM fractions were washed with water (2 \(\times\) 50 cm\(^3\)) and dried over MgSO\(_4\) before being concentrated under reduced pressure to yield a pale brown solid. The solid was dissolved in the minimum quantity of glacial acetic acid. A small amount of solvent was distilled under reduced pressure before cooling was allowed to occur. A white solid precipitated and was filtered and washed with glacial acetic acid before being dried under vacuum to yield 2-bromoindolo[3,2,1-\(jk\)]carbazole 278 (0.86 g, 55%). An alternative work up
involves washing the crude product with warm ethanol, however the yield was variable with this procedure. mp 208-210 °C [lit.,² 205-210 °C]; δH (360 MHz, CDCl₃) 8.06 (2H, s), 7.99 (2H, d, J 7.8), 7.79 (2H, d, J 8.1), 7.54 (2H, td, J 7.9, J 1.1), and J 7.33 (2H, td, J 7.8, J 1.0); δC (63 MHz, CDCl₃) 141.65 (quat), 138.68 (2 × quat), 128.94 (2 × quat), 127.20 (2 × CH), 123.13 (2 × CH), 122.07 (2 × CH), 121.82 (2 × CH), 119.33 (quat), 115.54 (2 × quat), and 112.07 (2 × CH); m/z 321 (M⁺, 99%), 319 (M⁺ 100), 240 (82), 213 (14), 167 (32), 120 (7), 80 (7) and 56 (23).

The above reaction was also carried out on a small scale so that the entire crude product could be dissolved in CDCl₃ for direct analysis by ¹H NMR spectroscopy. Indolo[3,2,1-jk]carbazole (0.020 g, 0.083 mmol) was dissolved in DCM (2 cm³) and silica (0.2 g) was added to the solution. N-Bromosuccinamide (0.015 g, 0.083 mmol) was added and the mixture was stirred in the dark at room temperature for 4 h. The mixture was filtered and washed with DCM (5 cm³). The solvent was removed under reduced pressure and the product was dissolved in CDCl₃ and analysed directly by ¹H NMR spectroscopy. The crude sample was found to contain both the 2- and the 5-bromoindolo[3,2,1-jk]carbazole isomers in a 75 : 25 ratio using the characteristic signals at δH 8.06 and 8.25 respectively.

**Diazotisation of 9-(2-aminophenyl)carbazole 27.**

9-(2-Aminophenyl)carbazole (4.0 g, 15.5 mmol) was dissolved in glacial acetic acid (40 cm³) and concentrated sulfuric acid (10 cm³) and was cooled to 0 °C. A solution of sodium nitrite (1.1 g, 15.7 mmol) in water (10 cm³) was added dropwise to form a deep red solution. The solution was heated almost to reflux for 30 min. A brown solid formed and after cooling, was filtered and treated by dry flash chromatography (hexane) to yield indolo[3,2,1-jk]carbazole 1 (2.50 g, 67%) mp 154-156 °C [lit.,² 156 °C]; δH (360 MHz, CDCl₃) 8.15 (2H, d, J 7.8), 8.05 (2H, d, J 7.4), 7.91 (2H, d, J 8.1), 7.60 (1H, t, J 7.2), 7.57 (2H, td, J 8.1, J 1.3), and 7.37 (2H, td, J 8.0, J 1.1).

Note. Vigorous heating at reflux and heating for longer than 30 min produce an unworkable tar.
Isolation of diazonium salt of 9-(2-aminophenyl)carbazole 277.

9-(2-Aminophenyl)carbazole (0.04 g, 0.155 mmol) was dissolved in glacial acetic acid (0.5 cm$^3$) and concentrated sulphuric acid (0.1 cm$^3$) and was cooled to 0 °C. A solution of sodium nitrite (0.011 g, 0.159 mmol) in water (0.3 cm$^3$) was added drop-wise to form a deep red solution. The solution was allowed to stir for 20 min at 0-10 °C. DCM (2 cm$^3$) was added and the solution extracted. The extraction was repeated and the combined DCM fractions were washed with water (3 cm$^3$) and dried over anhydrous magnesium sulfate. The solvent was removed under reduced pressure at room temperature. $\delta_t$ (360 MHz, Acetone-$d_6$) 9.25 (1H, dd, $^3J$ 8.5, $^4J$ 1.4), 8.64 (1H, ddd, $^3J$ 8.4, $^3J$ 7.3, $^4J$ 1.6), 8.37 (1H, dd, $^3J$ 8.4, $^4J$ 0.9), 8.31(2H, ddd, $^3J$ 8.1, $^4J$ 1.2, $^5J$ 0.9), 8.16 (1H, ddd, $^3J$ 8.5, $^3J$ 7.4, $^4J$ 1.4), 7.71 (2H, ddd, $^3J$ 8.2, $^3J$ 1.2, $^4J$ 0.8), 7.57 (2H, ddd, $^3J$ 8.0, $^3J$ 7.4, $^4J$ 1.3) and 7.47 (2H, ddd, $^3J$ 7.9, $^3J$ 7.3, $^4J$ 1.0); $\delta_C$ (63 MHz, Acetone-$d_6$) 144.16, (CH), 141.38 (CH), 139.84 (quat), 136.42 (2 $\times$ quat) 131.22 (CH), 130.74 (CH), 127.69 (2 $\times$ CH) 125.24 (2 $\times$ quat), 123.24 (2 $\times$ CH), 121.53 (2 $\times$ CH) and 110.66 (2 $\times$ CH) 1 $\times$ quat not apparent; m/z (electrospray) 270 (MH$^+$, 70%) and 242 (100).

Indolo[3,2,1-jk]carbazole picric acid complex 278.

Indolo[3,2,1-jk]carbazole (0.050 g, 0.21 mmol) was added to a saturated ethereal solution of picric acid to yield a red solid which was filtered and recrystallised from glacial acetic acid to yield the indolo[3,2,1-jk]carbazole picric acid complex as long red needles. (0.069 g, 70%) mp 166 – 168 °C [lit., 2 165 – 169 °C]; $\delta_t$ (360 MHz, DMSO-$d_6$) 8.61 (2H, s), 8.31 (2H, d, $^3J$ 8.2), 8.30 (2H, d, $^3J$ 7.8), 8.21 (2H, d, $^3J$ 7.4), 7.67 (1H, t, $^3J$ 7.4), 7.66 (2H, td, $^3J$ 7.1, $^4J$ 1.2), and 7.45 (2H, td, $^3J$ 7.4, $^4J$ 1.0); $\delta_C$ (91 MHz, DMSO-$d_6$) 160.99 (quat), 143.03 (quat), 142.04 (2 $\times$ quat), 138.19 (2 $\times$ quat), 129.35 (2 $\times$ quat), 127.46 (2 $\times$ CH), 125.48 (2 $\times$ CH), 124.55 (quat), 123.60 (2 $\times$ CH), 123.41 (CH), 122.35 (2 $\times$ CH), 120.21 (2 $\times$ CH), 118.08 (2 $\times$ quat) and 113.00 (2 $\times$ CH); m/z (FAB) 242 (MH$^+$, indolo[3,2,1-jk]carbazole) and 230 (MH$^+$, picric acid).
Synthesis of N-arylated indoles.

9-(2-Nitrophenyl)indole 44.

Indole (2.0 g, 17.1 mmol) and 2-fluoronitrobenzene (2.4 g, 17.1 mmol) was dissolved in DMSO (50 cm$^3$). Cesium carbonate (6.12 g, 18.8 mmol) was added to the solution with stirring. The suspension was stirred for 15 h before being diluted with water (50 cm$^3$) and a precipitate formed. The mixture was extracted with DCM (3$\times$100 cm$^3$). The DCM layers were combined and washed with water (3$\times$100 cm$^3$) before being dried over MgSO$_4$. The DCM was removed by distillation under reduced pressure to yield 9-(2-nitrophenyl)indole (3.7 g, 90%) mp 83-84 °C [lit. 79 82-83 °C]; $\delta_H$ (250 MHz, CDCl$_3$) 8.05 (1H, dd, $^3J$8.0, $^4J$1.5), 7.76 (1H, td, $^3J$7.7, $^4J$1.5), 7.66 (1H, m), 7.62-7.56 (2H, m), 7.24-7.12 (4H, m) and 7.09 (1H, d, $^3J$3.3, $^4J$0.8); $\delta_C$ (63 MHz, CDCl$_3$) 145.98, (quat), 136.43 (quat), 133.56 (CH), 132.57 (quat) 129.52 (CH) 128.74 (quat), 128.18 (CH), 127.79 (CH), 125.31 (CH), 122.76 (CH), 121.14 (CH), 120.74 (CH), 109.28 (CH) and 104.79 (CH); $m/z$ 238 (M$^+$, 99%), 208 (51), 191 (100), 180 (86), 152 (43), 96 (50), 77 (45), 63 (53) and 51 (41).

3-Cyanoindole 268.

Indole-3-carboxaldehyde (2.0 g, 14.0 mmol), nitroethane (2.0 g, 26.6 mmol) and sodium acetate (2.4 g, 29.2 mmol) were heated at reflux with stirring in glacial acetic acid (20 cm$^3$) for 12 h. The resulting solution was poured onto ice and extracted with ether (2 $\times$ 100 cm$^3$). The ether fractions were combined, washed with water (2 $\times$ 100 cm$^3$) and dried over MgSO$_4$. The solvent was removed under reduced pressure to yield 3-cyanoindole (1.80 g, 91%) mp 180-181 °C [lit. 180 180-182 °C]; $\delta_H$ (200 MHz, CDCl$_3$) 12.22 (1H, br s), 8.31 (1H, s), 7.70 (1H, d, $^3J$8.0), 7.62 (1H, d, $^3J$8.0) and 7.41-7.24 (2H, m); $m/z$ 142 (M$^+$, 100%), 115 (35) and 88 (10).
9-(2-Nitrophenyl)-3-cyanoindole 267.

3-Cyanoindole (1.07 g, 7.53 mmol) and 2-fluoronitrobenzene (1.06 g, 7.53 mmol) were dissolved in DMSO (20 cm$^3$). Cesium carbonate (4.80 g, 14.73 mmol) was added to the solution with stirring. The suspension was stirred for 15 h before being diluted with water (30 cm$^3$) and a precipitate formed. The mixture was extracted with DCM (3 × 100 cm$^3$). The DCM layers were combined and washed with water (3 × 50 cm$^3$) before being dried over MgSO$_4$. The DCM was removed by distillation under reduced pressure to yield 9-(2-nitrophenyl)-3-cyanoindole (1.82 g, 92%) mp 151-152 °C [lit.,$^{181}$ 144-145 °C]; $\delta$ (250 MHz, CDCl$_3$) 8.48 (1H, s), 8.23 (1H, td, $^3$J 8.7, $^4$J 1.8), 7.90 (1H, td, $^3$J 8.7, $^4$J 1.8), 7.81-7.74 (2H, m), 7.67 (1H, m), 7.31-7.21 (2H, m) and 7.08 (1H, m); $\delta$ (63 MHz, CDCl$_3$) 145.22, (quat), 137.41 (CH), 135.79 (quat), 135.03 (CH) 130.73 (CH) 130.42 (CH), 129.63 (quat), 126.43 (quat), 125.87 (CH), 124.67 (CH), 122.85 (CH), 118.99 (CH), 111.99 (quat), 110.71 (CH) and 86.98 (quat). m/z 263 (M$^+$, 100), 246 (13), 218 (67), 217 (18), 205 (27) and 114 (7).


The FVP reactions were carried out as described for indolo[3,2,1-jk]carbazole.

FVP of 9-(2-nitrophenyl)indole 44.

$[T_f$ 875 °C, $T_i$ 120 - 140 °C, $P$ 3.0 x 10$^{-2}$ Torr, $t_m$ 2 h 45 min, $m_a$ 2.3 g]. The pyrolysate was purified by dry flash chromatography (hexane/ethyl acetate) to give pyrrolo[3,2,1-jk]carbazole 2 (1.1 g, 60%) mp 88-89 °C [lit.,$^{15}$ 89-90 °C]; $\delta$ (360 MHz, CDCl$_3$) 8.09 (1H, dq, $^3$J 8.4, $^4$J 1.9, $^5$J 0.7), 7.91 (1H, d, $^3$J 7.2), 7.82 (1H, d, $^3$J 7.5), 7.73 (1H, d, $^3$J 3.1), 7.68 (1H, dq, $^3$J 8.0, $^4$J 1.7, $^5$J 0.8), 7.54 (1H, t, $^3$J 7.3), 7.48 (1H, td, $^3$J 8.0, $^4$J 1.3), 7.34 (1H, dq, $^3$J 7.8, $^4$J 1.1) and 6.87 (1H, d, $^3$J 3.1); $\delta$ (63 MHz, CDCl$_3$) 140.70 (quat), 139.24 (quat), 130.80 (quat), 126.42 (CH), 123.32 (CH), 123.03 (CH), 122.35 (CH), 122.04 (CH), 121.53 (quat), 120.96 (CH), 118.83 (quat), 117.26 (CH), 111.32 (CH) and 109.26 (CH); m/z 191 (M$^+$, 78%), 190 (84), 156 (100), 128 (31), 95 (6), 78 (14) and 51 (4).
FVP of 9-(2-nitrophenyl)-9H-3-cyanoindole 267.

The pyrolysate was purified by dry flash chromatography (hexane/ethyl acetate) to give 4-cyano[3,2,1-jk]carbazole 266 (0.300 g, 70%) mp 177-178 °C (from isopropyl alcohol); (Found: C, 82.75; H, 3.85; N, 12.90. C15H3N2 requires C, 83.35; H, 3.7; N, 12.95);

(Purified by dry flash chromatography (hexane/ethyl acetate) to give 4-cyano[3,2,1-jk]carbazole 266 (0.300 g, 70%) mp 177-178 °C (from isopropyl alcohol); (Found: C, 82.75; H, 3.85; N, 12.90. C15H3N2 requires C, 83.35; H, 3.7; N, 12.95);


Pyrolo[3,2,1-jk]carbazole (0.02 g, 0.105 mmol) and picric acid (0.10 g, 0.418 mmol) were dissolved in the minimum volume of acetonitrile and then chilled to 0 °C. Red crystals formed and were filtered off and washed with cold acetonitrile to yield the pyrolo[3,2,1-jk]carbazole picric acid complex (0.03 g, 70%) mp 148-150 °C; (Found: C, 56.85; H, 2.85; N, 13.25. C20H10N4O6 requires C, 57.15; H, 2.85; N, 13.35); $\delta$H (250 MHz, CDCl3) 11.74 (1H, br s), 8.88 (2H, s), 8.00 (1H, d, $^3$J 7.7), 7.80 (1H, d, $^3$J 7.2), 7.72 (1H, d, $^3$J 7.5), 7.63 (1H, d, $^3$J 3.1), 7.62 (1H, d, $^3$J 7.7), 7.47 (1H, td, $^3$J 7.5, $^4$J 1.2), 7.46 (1H, td, $^3$J 7.3), 7.30 (1H, td, $^3$J 7.6, $^4$J 1.1) and 6.80 (1H, d, $^3$J 3.1); $\delta$C (63 MHz, CDCl3) 152.81 (quat), 140.31 (2 x quat), 138.94 (quat), 137.41 (quat), 136.71 (quat), 130.51 (quat), 126.67 (CH), 125.67 (2 x CH), 123.50 (CH), 122.98 (CH), 122.34 (CH), 122.28 (CH), 121.36 (quat), 121.06 (CH) 118.52 (quat), 117.24 (CH), 111.32 (CH) and 109.42 (CH); m/z (FAB) 192 (MH+)
Azaindolo[3,2,1-\textit{jk}]carbazole precursors.

9-(3-Nitropyridin-2-yl)carbazole 281.

Method 1

Carbazole (1.00 g, 6 mmol) and 2-chloro-3-nitropyridine (0.95 g, 6 mmol) were dissolved in DMSO (20 cm$^3$). Cesium carbonate (2.15 g, 6.6 mmol) was added to the solution with stirring. The suspension was stirred for 18 h at 100 °C before being cooled and diluted with brine (50 cm$^3$) and a precipitate formed. The mixture was extracted with DCM (4×100 cm$^3$). The DCM layers were combined and washed with water (2×100 cm$^3$) before being dried over MgSO$_4$. The DCM was concentrated under reduced pressure and the residue was pre-adsorbed onto silica. Separation by dry flash chromatography (hexane/ethyl acetate) yielded 9-(3-nitropyridin-2-yl)carbazole (0.87-1.04 g, 50-60%) mp 143-144 °C; (Found: C, 70.85; H, 3.90; N, 14.5. C$_{17}$H$_{11}$N$_3$O$_2$ requires C, 70.6; H, 3.8; N, 14.55); $\delta_H$ (250 MHz, DMSO-$d_6$) 9.06 (1H, dd, $^3$$J$ 4.7, $^4$$J$ 1.7), 8.82 (2H, dd, $^3$$J$ 8.2, $^4$$J$ 1.6), 8.27 (1H, m), 7.90 (1H, dd, $^3$$J$ 8.2, $^3$$J$ 4.8) and 7.49–7.33 (6H, m); $\delta_C$ (63 MHz, DMSO) 154.10, (CH), 142.48 (quat), 141.78 (quat), 139.09 (2 × quat) 136.24 (CH), 126.69 (2 × CH), 124.52 (CH) 123.69 (2 ×quat), 121.56 (2 × CH), 120.83 (2 × CH) and 110.07 (2 × CH); $m/z$ 289 (M$^+$, 100%), 242 (89), 215 (15), 189 (5), 167 (19), 140 (6), 121 (26), 95 (6), 69 (8) and 43 (12).

Note- A variety of base/solvent systems and reagent excesses have been tried. The above result is the best achieved by this method. The result is highly dependent upon the quality of the solvent (DMSO). Fresh DMSO that is as dry as possible is advised as the presence of water causes lowering of yield due to decomposition of the pyridine. The temperature must be 100 °C; if it is too low, the pyridine decomposes due to low reactivity of carbazole. If the reaction temperature is too high the reactive pyridine decomposes. When the optimised conditions are used, yields of 50-60% can be achieved.
Method 2

Carbazole (0.500 g, 3.0 mmol), 2-chloro-3-nitropyridine (0.475 g, 3.0 mmol) and potassium carbonate (8.270 g, 60.00 mmol) were pre-weighed. A solution of palladium acetate (0.027 g, 4 mol %) and rac-BINAP (0.075 g, 4 mol %) in toluene (10 cm$^3$) was stirred for 10 min under argon before being added to the pyridine/carbazole mixture under argon. The remainder of the catalyst mix was washed into the reaction mixture with toluene (15 cm$^3$). The mixture was heated under reflux for 24 h. The mixture was cooled to room temperature and diluted with DCM (100 cm$^3$). Water (50 cm$^3$) was added and the DCM was separated and washed with water (2×50 cm$^3$). The DCM extracts were filtered through a pad of celite and dried over MgSO$_4$. The DCM was concentrated onto silica for purification by dry flash chromatography (hexane/ethyl acetate) to yield 9-(3-nitropyridin-2-yl)carbazole (0.649 g, 75%) mp 144-145 °C; $\delta_H$ (200 MHz, DMSO-$d_6$) 9.07 (1H, dd, $^3J$4.7, $^4J$1.6), 8.82 (2H, dd, $^3J$8.2, $^4J$1.7), 8.26 (1H, m), 7.91 (1H, dd, $^3J$8.1, $^3J$4.7) and 7.45–7.35 (6H, m).

Note- The above preparation has not been optimised. If it is optimised the amount of base may be reduced as well as the catalyst/ligand quantity. Repetition of reaction without the base results in no product formation. It is recommended that method 2 be the method of choice for the preparation of 9-(3-nitropyridin-2-yl)carbazole due the ease of the purification in comparison to the SNAr methodology used in method 1.

9-(3-Nitropyridin-4-yl)carbazole 284.

Carbazole (1.05 g, 6.29 mmol) and 4-chloro-3-nitropyridine (1.50 g, 9.46 mmol) were dissolved in acetonitrile (30 cm$^3$). Cesium carbonate (2.50 g, 7.67 mmol) was added to the solution with stirring. The suspension was stirred for 30 h at reflux and a precipitate formed. The acetonitrile was concentrated under reduced pressure and the residue was re-dissolved in ethanol. This solution was pre-adsorbed onto silica for separation by dry flash chromatography (hexane/ethyl acetate) to yield 9-(3-nitropyridin-4-yl)carbazole (1.45 g, 80%) mp 181-182 °C; (Found: C, 71.15; H, 3.95; N, 14.4. C$_{17}$H$_{11}$N$_3$O$_2$ requires C, 70.6; H, 3.80; N, 14.55); $\delta_H$ (250 MHz, DMSO-$d_6$) 9.50 (1H, s), 9.16 (1H, d, $^3J$5.3),
8.30 (1H, d, 3 J 7.6), 8.11 (1H, d, 3 J 5.3) and 7.51–7.32 (6H, m); δ (63 MHz, DMSO-d6) 156.03, (CH), 147.04 (CH), 141.97 (quat), 139.12 (2 × quat) 137.81 (quat), 126.89 (2 × CH), 124.73 (CH) 123.75 (2 × quat), 121.61 (2 × CH), 121.00 (2 × CH) and 109.45 (2 × CH); m/z 289 (M+, 100%), 242 (52), 215 (24), 140 (5), 107 (23), 94 (8), 69 (6) and 39 (3).

Note- The S_NAr conditions described above for the preparation of 9-(3-nitropyridin-2-y1)carbazole do not work. 4-Chloro-3-nitropyridine is more reactive than 2-chloro-3-nitropyridine and is more susceptible to decomposition. The S_NAr procedure (method 1) was optimised for this example. The Buchwald method has not yet been attempted.

9-(3-Nitropyridin-2-yl)-α-carboline 282.

α-Carboline (0.328 g, 1.96 mmol) and 2-chloro-3-nitropyridine (0.464 g, 6 mmol) was dissolved in dry DMF (10 cm³). Cesium carbonate (0.763 g, 2.34 mmol) was added to the solution with stirring. The suspension was stirred for 18 h at 125 °C before being cooled and diluted with brine (50 cm³) whereupon a precipitate formed. The suspension formed was extracted with DCM (4 × 50 cm³). The DCM layers were combined and washed with water (2 × 50 cm³) before being dried over MgSO₄. The DCM solution was pre-adsorbed onto silica for separation by dry flash chromatography (hexane/ethyl acetate) to yield 9-(3-nitropyridin-2-yl)-α-carboline (0.209 g, 37%); mp 167-169 °C; (Found: M⁺ 290.0802, C₁₇H₁₁N₂O₂ requires M 290.0804); δ (250 MHz, DMSO-d6) 8.79 (1H, dd, 3 J 6.4, 4 J 1.7), 8.47 (2H, dd, 3 J 8.1, 4 J 1.7), 8.28-8.23 (2H, m), 8.01 (1H, dq, 3 J 7.8, 4 J 1.5, 5 J 0.7), 7.88 (1H, dq, 3 J 8.1, 4 J 1.7, 5 J 0.8), 7.51–7.39 (2H, m), 7.32 (1H, td, 3 J 7.7, 4 J 1.1) and 7.17 (1H, dd, 3 J 7.5, 3 J 4.5); δ (63 MHz, DMSO) 155.48, (quat), 152.17 (CH), 150.35 (quat), 145.81 (CH) 142.72 (quat), 138.00 (quat), 134.64 (CH) 128.53 (CH), 127.46 (CH), 122.31 (CH), 122.22 (quat), 122.05 (CH), 120.90 (CH), 117.61 (CH), 117.43 (quat) and 112.33 (CH); m/z 290 (M⁺, 3%), 190 (100), 168 (48), 155 (71), 128 (13) and 78 (7).
9-(3-Nitropyridin-2-yl)indole 283.

Indole (1.05 g, 9.0 mmol) and 4-chloro-3-nitropyridine (1.56 g, 9.9 mmol) were dissolved in DMSO (20 cm$^3$). Cesium carbonate (3.22 g, 9.9 mmol) was added to the solution with stirring. The suspension was stirred for 18 h at 100 °C before being cooled and diluted with brine (50 cm$^3$) whereupon a precipitate formed. The mixture was extracted with DCM (4×100 cm$^3$). The DCM layers were combined and washed with water (2×100 cm$^3$) before being dried over MgSO$_4$. The DCM was pre-adsorbed onto silica for separation dry flash chromatography (hexane/ethyl acetate) to yield 9-(3-nitropyridin-2-yl)indole (1.72 g, 80%) mp 110-111 °C; (Found: C, 64.4; H, 3.85; N, 16.9. C$_{13}$H$_9$N$_3$O$_2$ requires C, 65.30; H, 3.80; N, 17.60); (Found: M$^+$ 239.0822, C$_{13}$H$_9$N$_2$O$_2$ requires $M_H$ 239.0821); $\delta$H (250 MHz, CDCl$_3$) 8.64 (1H, dd, $^3$J 4.7, $^4$J 1.7), 8.23 (1H, dd, $^3$J 8.1, $^4$J 1.7), 7.57 (1H, m), 7.40 (1H, m), 7.28-7.10 (4H, m) and 6.83 (1H, m); $\delta$C (63 MHz, CDCl$_3$) 152.31, (CH), 144.27 (quat), 139.18 (quat), 135.06 (quat) 134.70 (CH), 129.81 (quat), 126.37 (CH) 123.46 (CH), 121.93 CH), 121.32 (CH), 121.20 (CH), 118.81 (CH) and 107.09 (CH); $m/z$ 239 (M$^+$, 100%), 181 (42), 154 (14), 89 (16), 63 (17) and 39 (15).

9-(3-Nitropyridin-2-yl)indole 285.

Indole (1.05 g, 9.0 mmol) and 4-chloro-3-nitropyridine (1.56 g, 9.9 mmol) were dissolved in acetonitrile (30 cm$^3$). Cesium carbonate (3.51 g, 10.76 mmol) was added to the solution with stirring. The suspension was stirred for 30 h at reflux and a precipitate formed. The acetonitrile was concentrated under reduced pressure and re-dissolved in methanol. The solution was pre-adsorbed onto silica for dry flash chromatography with hexane/EtOAc to yield 9-(3-nitropyridin-4-yl)indole (1.51 g, 70%) mp 117-118 °C; (Found: C, 65.75; H, 3.7; N, 17.15. C$_{13}$H$_9$N$_3$O$_2$ requires C, 65.30; H, 3.8; N, 17.6); $\delta$H (250 MHz, CDCl$_3$) 9.40 (1H, s), 9.03 (1H, d, $^3$J 5.4), 7.85 (1H, m), 7.75 (1H, d, $^3$J 5.4), 7.45-7.35 (3H, m), 7.28 (1H, d, $^3$J 3.5) and 6.97 (1H, d, $^3$J 3.5); $\delta$C (63 MHz, CDCl$_3$) 154.18, (CH), 147.28 (CH), 140.58 (quat), 139.93 (quat) 135.12 (quat), 129.63 (quat), 126.62 (CH) 123.72 (CH), 122.06 CH), 121.73 (CH), 121.50 (CH), 109.47 (CH) and
107.49 (CH); m/z 239 (M⁺, 100%), 194 (97), 166 (35), 154 (35), 139 (46), 89 (49), 63 (37) and 41 (23).

**FVP of aza precursors.**

All pyrolyses were carried out using dual trapping system as discussed in the general experimental section with the cold-finger (dry ice/acetone) to trap the product and a U-tube (liquid nitrogen) to trap the NOₓ gases. Care must be taken when mixing acetone and dry ice near furnace to avoid a potential flash fire. Each pyrolysate was dissolved in DCM and pre-adsorbed onto silica by concentration of the solvent for purification by dry flash chromatography.

**FVP of 9-(3-Nitropyridin-2-yl)carbazole 281.**

![Chemical Structure](image)

[Tf 875 °C, T; 170 °C, P 2.4 x 10⁻² Torr, tₘ 40 min, mₒ 0.500 g]. The pyrolysate was purified by dry flash chromatography (hexane/ethyl acetate) to give 7-azaindolo[3,2,1-jk]carbazole 286 (0.356 g, 85%) mp 149-150 °C; (Found: C, 82.75; H, 4.15; N, 11.4. C₁₇H₁₀N₂ requires C, 84.3; H, 4.15; N, 11.6); (Found: M⁺ 242.0842, C₁₇H₁₀N requires M 242.0842); δ₁ (360 MHz, CDCl₃) 8.53 (1H, dd, ³J 5.0, ⁴J 1.4), 8.33 (1H, dd, ³J 7.7, ⁴J 1.4), 8.28 (1H, dd, ³J 7.7, ⁴J 1.0), 8.10 (1H, d, ³J 7.8), 8.05 (1H, d, ³J 7.4), 7.98 (1H, d, ³J 7.5), 7.61 (1H, dd, ³J 7.7, ⁴J 1.4), 7.59 (1H, t, ³J 7.5), 7.39 (1H, t, ³J 7.7, ⁴J 1.5) and 7.31 (1H, dd, ³J 7.8, ⁴J 5.1); δ² (63 MHz, CDCl₃) 149.92 (quat), 145.11, (CH), 142.57 (quat), 137.81 (quat), 130.86 (CH), 129.95 (quat), 127.13 (CH), 123.70 (quat), 123.30 (CH), 122.74 (CH), 122.66 (CH) 120.21 (CH), 119.68 (CH), 118.94 (quat), 116.91 (quat), 115.49 (CH) and 113.92 (CH); m/z 242 (M⁺, 100%), 214 (20), 188 (7), 167 (15), 139 (3), 121 (52), 93 (17) and 81 (6).
FVP of 9-(3-nitropyridin-4-yl)carbazole 284.

\[
\begin{align*}
&\text{[}T_f 875^\circ C, T_i 150-190^\circ C, P 3.0 \times 10^{-2} \text{ Torr, } t_m 60 \text{ min, } m_a 0.492 \text{ g}] \text{. The pyrolysate was purified by dry flash chromatography (hexane/ethyl acetate) to give 5-azaindolo[3,2,1-jk]carbazole 288} \\
&(0.227 \text{ g, 55%}) \text{ mp 155-156^\circ C; (Found: C, 83.3; H, 4.2; N, 11.4. } \\
&C_{17}H_{10}N_2 \text{ requires C, 84.3; H, 4.15; N, 11.60; (Found: M}^+ 242.0847, C_{17}H_{10}N_2 \text{ requires M} 242.0878); \delta_H (250 \text{ MHz, CDCl}_3) 9.25 (1\text{H, s}), 8.63 (1\text{H, d, }^3J 5.6), 8.02 (1\text{H, dd, }^3J 7.8), 7.95 (1\text{H, d, }^3J 7.5), 7.93 (1\text{H, d, }^3J 7.4), 7.73 (1\text{H, d, }^3J 7.8), 7.63 (1\text{H, dd, }^3J 5.5), 7.54 (1\text{H, t, }^3J 7.5), 7.50 (1\text{H, td, }^3J 7.8, ^3J 1.1) \text{ and 7.35 (1H, td, }^3J 7.5, ^3J 0.9); &
&(63 \text{ MHz, CDCl}_3) 146.37 (\text{CH}), 144.39 (\text{CH}), 143.26 (\text{quat}), 142.09 (\text{quat}), 137.88 (\text{quat}), 130.40 (\text{quat}), 126.89 (\text{CH}), 125.81 (\text{quat}), 123.87 (\text{CH}), 123.11 (\text{CH}), 122.78 (\text{CH}), 120.01 (\text{CH}), 119.76 (\text{CH}), 118.52 (\text{quat}), 115.89 (\text{quat}), 112.55 (\text{CH}) \text{ and 107.22 (CH); } m/z 242 (M}^+, 100\%), 214 (14), 187 (5), 121 (17), 107 (17) \text{ and 93 (11).}
\end{align*}
\]

FVP of 9-(3-nitropyridin-2-yl)-α-carboline 282.

\[
\begin{align*}
&\text{[}T_f 875^\circ C, T_i 80-120^\circ C, P 4.0 \times 10^{-2} \text{ Torr, } t_m 20 \text{ min, } m_a 0.073 \text{ g]. The pyrolysate was purified by dry flash chromatography (hexane/ethyl acetate to give 7,8-diazaindolo[3,2,1-jk]carbazole 287} \\
&(0.37 \text{ g, 60%}) \text{ mp 152-153^\circ C; (Found: M}^+ 243.0797, C_{16}H_9N_3 \text{ requires M} 243.0797); \delta_H (360 \text{ MHz, CDCl}_3) 8.62 (2\text{H, dd, }^3J 5.0, ^4J 1.5), 8.35 (2\text{H, dd, }^3J 7.8, ^4J 1.6), 8.02 (2\text{H, d, }^3J 7.5), 7.61 (1\text{H, t, }^3J 7.5) \text{ and 7.8 (2H, dd, }^3J 7.4, ^3J 5.0); &
&(91 \text{ MHz, CDCl}_3) 150.16 (2 \times \text{quat}), 146.63, (2 \times \text{CH}), 141.67 (\text{quat}), 130.75 (2 \times \text{CH}), 123.69 (2 \times \text{quat}), 123.67 (\text{CH}), 120.72 (2 \times \text{CH}), 117.93 (2 \times \text{CH}) \text{ and 116.34 (2 \times \text{quat); } m/z 243 (M}^+, 30\%), 190 (72), 156 (100), 128 (26) \text{ and 78 (15).}
\end{align*}
\]
FVP of 9-(3-nitropyridin-2-yl)carbazole 283.

\[ T_f \ 875 \degree C, \ T_l \ 170 \degree C, \ P \ 2.4 \times 10^{-2} \ Torr, \ t_m \ 40 \min, \ m_a \ 0.500 \ g. \] The pyrolysate was purified by dry flash chromatography (hexane/ethyl acetate) to give 6-azapyrrolo[3,2,1-jk]carbazole 289 (0.221 g, 55%) mp 99-100 °C; (Found: C, 81.0; H, 4.25; N, 14.50. C_{13}H_{8}N_{2} requires C, 81.25; H, 4.2; N, 14.6); \delta_{t} (250 MHz, CDCl_{3}) 8.42 (1H, dd, \ 3J 5.1, \ 4J 1.6), 8.29 (1H, dd, \ 3J 7.7, \ 4J 1.6), 7.93 (1H, d, \ 3J 3.2), 7.86 (1H, d, \ 3J 7.3), 7.83 (1H, d, \ 3J 7.5), 7.53 (1H, t, \ 3J 7.4), 7.24 (1H, dd, \ 3J 7.7, \ 3J 5.1) and 6.91 (1H, d, \ 3J 3.7); \& (63 MHz, CDCl_{3}) 145.25 (quat), 140.17, (CH), 130.66 (quat), 124.55 (quat), 123.83 (CH), 122.41 (quat), 122.14 (CH), 122.01 (quat), 121.95 (CH), 117.90 (CH), 117.69 (CH) 115.95 (CH) and 110.84 (CH); m/z 192 (M^+, 100%), 164 (31), 138 (12), 96 (38), 82 (21) and 69 (10).

FVP of 9-(3-nitropyridin-4-yl)carbazole 285.

\[ T_f \ 875 \degree C, \ T_l \ 140 \degree C, \ P \ 4.0 \times 10^{-2} \ Torr, \ t_m \ 35 \min, \ m_a \ 0.506 \ g. \] The pyrolysate was purified by dry flash chromatography (hexane/ethyl acetate) to give 6-azapyrrolo[3,2,1-jk]carbazole 290 (0.203 g, 50%) mp 122-123 °C; (Found: M^+ 192.0690, C_{13}H_{8}N_{2} requires M 192.0688); \delta_{t} (250 MHz, CDCl_{3}) 9.25 (1H, d, \ 4J 0.9), 8.62 (1H, d, \ 3J 5.5), 7.91 (1H, d, \ 3J 7.3), 7.79 (1H, d, \ 3J 7.5), 7.67 (1H, d, \ 3J 3.2), 7.54 (1H, t, \ 3J 7.4), 7.52 (1H, d, \ 3J 5.8) and 6.91 (1H, d, \ 3J 3.2); \& (63 MHz, CDCl_{3}) 146.73 (CH), 144.25, (CH), 143.33 (quat), 140.78 (quat), 126.77 (quat), 124.36 (CH), 122.38 (CH), 121.90 (CH), 121.50 (quat), 118.28 (CH), 116.27 (quat), 111.89 (CH) and 106.87 (CH); m/z 192 (M^+, 100%), 164 (72), 138 (55), 114 (22), 96 (54), 83 (70), 63 (44) and 50 (24).


5-Azaindolo[3,2,1-jk]carbazole (0.251 g, 0.104 mmol) and dimethyl sulfate (0.653 g, 5.18 mmol) were heated at reflux in toluene (25 cm^3) for 7 h. A green/brown precipitate formed and was filtered. The solid was washed with toluene and dried.
under high vacuum to yield \textit{N-methyl-5-azaindolo[3,2,1-jk]carbazolium methyl sulfate} (96\%) mp 151-153 °C; FAB-MS (Found: M⁺ 257.1076, C₁₈H₁₃N₂ requires M 257.1079); δH (250 MHz, CDCl₃) 9.92 (1H, s), 9.06 (1H, dd, 3J 7.1, 4J 1.4), 8.92 (1H, d, 3J 7.0), 8.54 (1H, d, 3J 8.0), 8.42-8.32 (3H, m), 7.87 (1H, t, 3J 7.5), 7.76 (1H, td, 3J 7.5, 4J 1.3), 7.62 (1H, td, 3J 7.6, 4J 1.1), 4.48 (3H, s) and 3.40 (3H, s); δC (63 MHz, CDCl₃) 144.71 (quat), 142.87, (quat), 142.10 (CH), 141.08 (CH), 137.21 (quat), 130.68 (quat), 128.45 (CH), 126.47 (quat), 126.37 (CH), 125.58 (CH), 124.20 (CH) 123.28 (CH), 121.90 (CH), 119.53 (quat), 115.11 (CH), 111.44 (quat), 110.16 (CH), 52.94 (CH₃) and 47.23 (CH₃); m/z (FAB⁺) 257 (M⁺).

Quaternisation of 7-azaindolo[3,2,1-jk]carbazole was attempted with the above method, however no reaction occurred. The reaction was repeated using methyl tosylate and methyl iodide, however no reaction occurred.

\textbf{Electrochemical characterisation (section B).}

12.3 Electrochemistry experimental.

12.3.1 Chemicals.

12.3.1.1 Commercial chemicals.
Lithium perchlorate (Aldrich, 99.99\%), silver perchlorate hydrate (Aldrich, 99\%), ferrocene (Fluka AG >98\% Fe), carbazole (Acros Organics 96\%), pyrrole (Aldrich 98\%) were all used as received.

12.3.1.2 Solvents.
Acetonitrile (MeCN, Fisher Scientific, HPLC grade) and \textit{N,N-dimethylformamide} (DMF, Acros Organics, spectrophotometric grade 99+\%) were all used as received. All water was doubly deionised by means of a Millipore water system.
12.3.2 Electrochemistry.

All electrochemical experiments were carried out using a modular potentiostant/galvanostat with combined waveform generator and voltage sources (Oxford Electrodes Ltd). The rotating disc electrode (RDE) was controlled using a rotator and a motor controller (Oxford Electrodes Ltd). Data are collected on a PC with tailored programmes compiled using Visual Designer software (Intelligent Instruments).

The working electrode was a Pt rotating disc electrode (Oxford Electrodes Ltd) with a disc area of 0.387 cm$^2$. It was polished on a polishing cloth with a slurry of micropolish 0.3 μm alpha alumina (Buehler Ltd) in doubly deionised water. The counter electrode was a 2 cm$^2$ Pt gauze which was cleaned by rinsing in acetone and flaming in a Bunsen burner. The reference electrode (Bioanalytical Systems Inc.) consisted of a silver wire dipped in a 0.01 M solution of AgClO$_4$ in electrolyte in a glass body separated from the bulk electrolyte by a VYCOR plug. The electrolyte was a 0.1 M solution of LiClO$_4$ in acetonitrile. The Ag/Ag$^+$ reference electrode has a potential of +0.437 V with respect to the saturated calomel electrode and +0.681 V with respect to the standard hydrogen electrode. During electrochemistry experiments the electrolyte solution was degassed with N$_2$ gas. Polymer films were dissolved off the electrode surface into DMF for analysis by fluorescence spectroscopy.

12.3.3 Fluorescence spectroscopy.

12.3.3.1 Steady state fluorescence spectroscopy.

All steady-state fluorescence spectra were measured using a Jobin Yvon Spex Fluoromax™ spectrofluorometer (Instruments S.A. group). The excitation source is a 150 W continuous ozone-free xenon lamp, with modified Czerny-Turner spectrometers in both the emission and excitation positions. The data acquisition and data manipulation software used was Instruments S.A. Datamax. All experiments were carried out with fused silica cuvettes.
12.3.3.2 Time correlated single photon counting (TCSPC)
All experiments were performed at the Collaborative Optical Spectroscopy Micromanipulation and Imaging Centre (COSMIC) at The University of Edinburgh and were performed by Dr Steven Magennis. All decays were measured using an Edinburgh Instruments TCSPC spectrometer coupled with a Hamamatsu R3809U-50 series microchannel plate detector. Samples were excited using a mode-locked Ti-sapphire laser.

12.3.4 Preparation of samples for electrochemistry.
All non-aqueous electrochemistry was performed in acetonitrile with 100 mmol LiClO₄ as background electrolyte. Samples of varying concentration were made up in this electrolyte. Film products that were studied in aqueous systems were first prepared from a solution of monomer in acetonitrile/LiClO₄. The films were then slowly transferred to an aqueous solution by slowly dripping in the aqueous electrolyte to the non-aqueous electrolyte. This was carried out to avoid displacing the film from the electrode by build up of osmotic pressure.

12.3.5 Analysis of electro-oxidation products.
Films prepared on the electrode surface were removed for analysis by fluorescence spectroscopy, mass spectrometry and NMR spectroscopy by gentle scraping ensuring the electrode was not scratched. The sample was then dissolved in the appropriate solvent for fluorescence and NMR spectroscopy.

12.3.5 Cyclic voltammetry of authentic IC dimers prepared synthetically.
IC dimers were dissolved in THF and drop coated onto the electrode surface by placing small droplets onto the working electrode surface. The solvent was evaporated and the process repeated until a satisfactory film was present. Analysis by cyclic voltammetry was carried out in background electrolyte.
12.3.6 **Indolo[3,2,1-jk]carbazole film electrosynthesis.**

A 20 mM solution of indolo[3,2,1-jk]carbazole in MeCN containing 100 mM LiClO₄ was electro-oxidised at 1.19 V wrt Ag/Ag⁺ reference electrode as described in electrochemistry experimental section by a Pt disc electrode rotating at 4 Hz. Electro-oxidation was carried out for periods of 10 min. The film was then reduced by stepping the potential down to 0 V. The film was carefully scraped of the electrode surface. This process was repeated until about 10 mg of film was produced. The product was analysed by ¹H NMR spectroscopy and was found to give a mixture of 2, 2'-bisindolo[3,2,1-jk]carbazole, 5, 5'-bisindolo[3,2,1-jk]carbazole and 2, 5'-bisindolo[3,2,1-jk]carbazole in a 1:1:2 ratio (Found: MH⁺ 481.1628, C₃₆H₂₀N₂ requires MH⁺ 481.1660); δH (600 MHz, acetone-d₆/DMSO-d₆) 8.80 (2H, d, J 1.5), 8.79 (1H, d, J 1.5), 8.57 (2H, s), 8.56 (4H, s), 8.45 – 8.39 (6H, m), 8.37 – 8.28 (8H, m), 8.26 – 8.22 (10H, m), 8.14 (2H, dd, J 8.3, J 1.6), 8.13 (1H, dd, J 8.3, J 1.6), 7.73 – 7.66 (14H, m) and 7.51 – 7.43 (10H, m); m/z (FAB) 481 (MH⁺).

Note – Full analysis of ¹H NMR spectrum was carried out in conjunction with NOESY, COSY and HSQC ¹³C NMR spectra and is fully discussed in discussion Chapter 8.

12.3.7 **Organic synthesis and HPLC analysis.**

**Chemical oxidation of indolo[3,2,1-jk]carbazole.**

Indolo[3,2,1-jk]carbazole (0.064 g, 0.266 mmol) was dissolved in acetonitrile (7 cm³) under nitrogen. Anhydrous Fe(III)Cl₃ (0.043 g, 0.266 mmol) was dissolved in acetonitrile (2 cm³) under nitrogen and added to the solution of indolo[3,2,1-jk]carbazole. A deep purple colour appeared immediately. The solution was stirred at room temperature under nitrogen until the colour faded. A fine green/black suspension was formed. The solid was filtered and dried under vacuum to yield a mixture of 2, 2'-bisindolo[3,2,1-jk]carbazole, 5, 5'-bisindolo[3,2,1-jk]carbazole and 2, 5'-bisindolo[3,2,1-jk]carbazole in a similar ratio to that formed electrochemically (0.19 g, 30%) δH (600 MHz, acetone-d₆/DMSO-d₆) 8.81 (2H, d, J 1.7), 8.80 (1H, d, J 1.7), 8.61 (2H, s), 8.60 (4H, s), 8.47 – 8.41 (6H, m), 8.38 – 8.27 (8H, m), 8.27 – 8.23 (10H, m), 8.15-8.13 (3H, m), 7.73 – 7.68 (14H, m) and 7.50 – 7.42 (10H, m); m/z (FAB) 481 (MH⁺).
Electrochemically produced dimer analysis by $^1$H NMR spiking.
Electrochemically produced dimer mixture (1 mg), 2,2'-dimer (1 mg), 5,5'-dimer (1 mg) and 2,5'-dimer (1 mg) were separately dissolved in a 70:30 mixture of acetone-$d_6$ and DMSO-$d_6$ (1 cm$^3$). A $^1$H NMR spectrum was recorded of the pure electrochemically produced dimer and this dimer was spiked with each of the synthetic dimers at 360 MHz.

Electrochemically produced dimer analysis by HPLC spiking.
HPLC chromatograms were run on a Gilson HPLC as follows;
Column – Spherisorb S5-ODS1
Flow rate – 1 ml min$^{-1}$
Injection volume – 20 μL
Detection wavelength – 254 nm
Eluant gradient – A = 9:1 water/MeCN, 1% NH$_4$Ac and B = MeCN
The solvent gradient is shown in Table 14.

<table>
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<tr>
<th>Time/min</th>
<th>%B</th>
</tr>
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<tr>
<td>30</td>
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<tr>
<td>55</td>
<td>95</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
</tr>
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</table>

Table 14. HPLC solvent gradient.

A sample of the electrochemically produced dimer and each of the synthetic dimers was seperately dissolved in a small amount of DMF and diluted with 50:50 MeCN/water. An HPLC chromatogram was recorded of each sample under the conditions described above. A sample of electrochemical dimer was spiked with each synthetic dimer and run under the conditions described above. A sample of the chemically oxidised dimer was also run.
12. 4 IC dimer syntheses.

Boronic acid synthesis.

IC boronic acids.

Anhydrous THF (10 cm³) was added to a dry round bottomed flask under an atmosphere of argon. The flask and solvent were cooled to -78 °C in a dry-ice/acetone bath. nBuLi in hexanes (1.6 M, 1 cm³, 1.94 mmol) was added. A solution of heteroaryl bromide (1.56 mmol) in anhydrous THF (15 cm³) was added dropwise over 30 min at -78 °C via syringe pump to form a bright yellow solution. After addition of the bromo compound, the solution was allowed to stir at -78 °C for 45 min. A solution of triisopropyl borate (19.4 mmol) in anhydrous THF (10 cm³) was added over 30 min via syringe pump. The solution was allowed to stir for 30 min before being warmed to room temperature. The solution began to become cloudy and was allowed to stir for 30 min before being warmed to 60 °C and left to stir for 12 h. The solution was acidified with HCl (2M) and left to stir for a further 15 h. The resulting mixture was then diluted with water (5 cm³) and extracted with DCM (3 × 50 cm³). The combined DCM fractions were washed with water (2 × 50 cm³) and dried over MgSO₄ before being concentrated under reduced pressure to yield creamy white solids.

Note – Spectroscopic characterisation of both “boronic acids” has been carried out by ¹H, NOESY, COSY and ¹¹B NMR as well as electrospray/FAB mass spectrometry and IR. It was found that the ¹H NMR spectrum showed the correct characteristics for a correctly substituted IC molecule, however the ¹H integrals are not consistent. The spectrum was also shown to contain other impurity signals which could account for the extra integral. It was noted in the discussion section on boronic acid synthesis that there may some ester or boroxine present. Confirmation of the boron substitution was carried out by Suzuki coupling to form the homo-coupled dimer.

(0.399 g, 80% impure mixture); \(\delta_H (360 \text{ MHz, DMSO-}d_6)\) 8.67 (2H, s), 8.32 (2H, d, \(^3J 7.2\)), 8.30 (2H, d, \(^3J 7.3, ^4J 1.1\)), 8.22 (2H, d, \(^3J 7.2\)), 7.68 - 7.62 (4H, m), 7.46 - 7.42 (3H, m) and 7.34 (2H, br s); \(\delta_B (115 \text{ MHz, DMSO})\) 35.63 (br s) and 25.41 (br s, minor); \(m/z\) (Electrospray) 283 (\(^{10}B, M^+\), 30%) and 284 (\(^{11}B, M^+\), 100%); \(m/z\) (FAB) 370 (MH\(^+\)); \(\nu_{\max} 3397 \text{ cm}^{-1}\) (OH) and 1340 cm\(^{-1}\) (B-O).

Note – The integral count is for the \(^1H\) NMR spectrum is larger than required if it were only one compound. This indicates that there is more than one compound present. The \(^{11}B\) NMR spectrum shows that there is two different boron species in the mixture and thus may account for the extra integral count in the \(^1H\) NMR spectrum if there is a boroxine or borate ester present.


(0.400 g, 80% impure mixture); \(\delta_H (360 \text{ MHz, DMSO-}d_6)\) 8.71 (1H, s), 8.34 - 8.26 (5H, m), 8.24 - 8.18 (3H, m), 8.10 (1H, dd, \(^3J 8.2, ^4J 1.2\)), 7.68 - 7.62 (2H, m) and 7.47 - 7.40 (2H, m); \(\delta_B (115\text{MHz, DMSO})\) 34.58 (br s) and 22.67 (br s, minor); \(m/z\) (Electrospray - ) 283 (\(^{10}B, M^+\), 30) and 284 (\(^{11}B, M^+\), 100); \(\nu_{\max} 3419 \text{ cm}^{-1}\) (OH) and 1340 cm\(^{-1}\) (B-O).

Note – See comment for previous boronic acid.

Suzuki Coupling

Heteroaryl bromide (50.0 mg, 0.156 mmol), aryl boron species (44.5 mg, 0.156 mmol), potassium carbonate (43 mg, 0.312 mmol) and Pd(PPh\(_3\))\(_4\) (7.2 mg, 4 mol %) were heated at reflux with stirring in 3:1 dioxane/water (10 cm\(^3\)) for 4 h. The precipitate formed was filtered and washed with water and the dioxane before being dried under vacuum. The purification for each dimer is shown below if applicable.
Note- The dimers prepared were all found to be extremely insoluble in most solvents. They were found to be sparingly soluble in DMSO/acetone mixture and THF. All NMR spectroscopic data have been recorded in either DMSO-d$_6$ or THF-d$_8$. Each dimer was characterised by $^1$H, COSY, NOESY and HSQC NMR techniques. In the case of the 2,2'-dimer and the 5,5'-dimer 1D $^{13}$C NMR spectroscopy was in most cases not possible due to the sample strength rendering the experiment too time consuming therefore the $^{13}$C NMR spectroscopic data was carried out using HSQC and HMBC techniques so that full $^{13}$C data could be acquired (including $^{13}$C quaternary signals). Verification of the molecular formula was achieved by high resolution mass spectrometry. The following products were obtained by this method.

$2,2'$-Bisindolo[3,2,1-jk]carbazole 305.

(0.075 g, 80%) mp >360 °C; (Found: MH$^+$ 480.1622, C$_{36}$H$_{20}$N$_2$ requires M$^+$ 480.1627); $\delta$$_H$ (360 MHz, THF-d$_8$) 8.47 (4H, s), 8.21 (4H, dq, $^3$J 8.1, $^4$J 1.2, $^5$J 0.7), 8.04 (4H, dq, $^3$J 8.3, $^4$J 1.1, $^5$J 0.7), 7.54 (4H, ddd, $^3$J 8.3, $^3$J 7.6, $^4$J 1.1) and 7.34 (4H, ddd, $^3$J 8.0, $^3$J 7.2, $^4$J 1.1); $\delta$$_C$ (91 MHz, THF-d$_8$, CH resonances only) 144.29 (2 x quat), 140.97 (2 x quat), 140.27 (4 x quat), 131.22 (4 x quat), 127.65 (4 x CH), 123.90 (4 x CH), 122.62 (4 x CH), 121.12 (4 x CH), 119.62 (4 x quat) and 113.24 (4 x CH); m/z 480 (M$^+$, 100%), 240 (61) and 167 (13).


(0.061 g, 65%); mp >360 °C; (Found: M$^+$ 481.16205, C$_{36}$H$_{20}$N$_2$ requires M 480/16265); $\delta$$_H$ (360 MHz, THF-d$_8$) 8.66 (2H, d, $^4$J 1.9), 8.22 (2H, d, $^3$J 8.3), 8.21 (2H, dt, $^3$J 7.2, $^4$J 1.1, $^5$J 0.7), 8.20 (2H, d, $^3$J 7.5), 8.16 (2H, dd, $^3$J 7.7, $^4$J 1.0), 8.04 (2H, d, $^3$J 7.4), 7.62 (2H, t, $^3$J 7.6), 7.58 (2H, dt, $^3$J 8.3, $^4$J 1.4) and 7.48 (4H, t, $^3$J 7.9); $\delta$$_C$ (91 MHz, THF-d$_8$) 127.96 (2 x CH), 127.28 (2 x CH), 124.12 (2 x CH), 124.08 (2 x CH), 122.87 (2 x CH), 122.85
(2 × CH), 122.81 (2 × CH), 122.79 (2 × CH), 113.49 (2 × CH) and 113.47 (2 × CH); m/z 480 (M⁺, 2%), 190 (38), 156 (100), 128 (21) and 78 (14).


Purified by dry flash chromatography (hexane/ethyl acetate) to give 2,5′-bisindolo[3,2,1-jk]carbazole (0.051 g, 55%); mp 297 - 300 °C; (Found: M⁺ 481.1622, C₃₆H₂₉N₂ requires M⁺ 481.1627). δH (360 MHz, acetone-d₆/DMSO-d₆) 8.77 (1H, d, 4J 1.5), 8.64 (2H, s), 8.42 - 8.39 (3H, m), 8.38 - 8.34 (4H, m), 8.24 (2H, d, 3J 7.4), 8.12 (1H, dd, 3J 8.3, 4J 1.8), 7.72 - 7.66 (4H, m) and 7.34 (3H, m); δC (150 MHz, acetone-d₆/DMSO-d₆, CH resonances only) 130.77 (3 × CH), 130.77 (CH), 127.03 (2 × CH), 126.79 (CH), 126.71 (CH), 126.24 (CH), 125.60 (3 × CH), 123.45 (CH), 123.37 (CH), 123.13 (2 × CH), 116.21 (CH), 116.21 (2 × CH) and 116.13 (CH); m/z 480 (M⁺, 8%), 240 (5), 190 (78), 156 (100), 128 (26) and 78 (14).
References


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Sample of 2, 6-dimethyl-2'-nitrodiphenylamine obtained from J.I.G. Cadogan samples stock.


Appendix 1. X-Ray crystallography data for indolo[3,2,1-jk]carbazole (IC) excluding picric acid component.

Bond lengths [Å] and angles [deg] for IC.

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C(9)-C(8)-C(8A)  117.0(4)  C(7)-C(7A)-C(4A)  121.4(3)
C(9)-C(8)-H(8)  121.5  C(7)-C(7A)-C(4A)  121.4(3)
C(8A)-C(8)-H(8)  121.5  N(7b)-C(7A)-C(4A)  107.9(3)
C(10)-C(9)-C(8)  122.1(4)  C(3B)-N(7B)-C(7A)  107.3(3)
C(10)-C(9)-H(9)  118.9  C(3B)-N(17B)-C(8A)  107.1(3)
C(8)-C(9)-H(8)  118.9  C(7A)-N(7B)-C(8A)  145.6(3)
C(9)-C(10)-C(11)  120.4(4)  C(8)-C(8A)-N(7B)  129.8(3)
C(9)-C(10)-H(10)  119.8  C(8)-C(8A)-C(11A)  122.0(3)
C(11)-C(10)-H(10)  119.8  N(7b)-C(8A)-C(11A)  108.2(3)
C(11A)-C(11)-C(10)  118.9(4)  N(17b)-C(3B)-C(3A)  113.8(3)
C(11A)-C(11)-H(11)  120.5  N(7b)-C(3B)-C(1A)  113.3(3)
C(10)-C(11)-H(11)  120.5  C(11A)-C(3B)-C(1A)  132.9(3)
C(11)-C(11A)-C(8A)  119.5(3)  C(3B)-C(1A)-C(1)  113.0(4)
C(11)-C(11A)-C(4A)  133.8(4)  C(3B)-C(1A)-C(11A)  104.8(3)
C(8A)-C(11A)-C(1A)  106.6(3)
C(3B)-C(1A)-C(1)  113.0(4)
C(3B)-C(1A)-C(11A)  142.2(4)
C(2)-C(1)-C(1A)  117.5(4)
C(2)-C(1)-H(1)  121.3
C(1A)-C(1)-H(1)  121.3
C(3)-C(2)-C(1)  125.5(4)
C(3)-C(2)-H(2)  117.3
C(1)-C(2)-H(2)  117.3
C(2)-C(3)-C(3A)  117.9(4)
C(2)-C(3)-H(3)  121.0
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C(3B)-C(3A)-C(3)  113.2(3)
C(3B)-C(3A)-C(4A)  104.4(3)
C(3)-C(3A)-C(4A)  142.5(4)
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C(7A)-C(4A)-C(3A)  106.7(3)
C(4A)-C(4)-C(5)  118.8(4)
C(4A)-C(4)-H(4)  120.6
C(5)-C(4)-H(4)  120.6
C(6)-C(5)-C(4)  121.4(4)
C(6)-C(5)-H(5)  119.3
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C(6)-C(7)-C(7A)  117.7(4)
C(6)-C(7)-H(7)  121.2
C(7A)-C(7)-H(7)  121.2
Appendix 2. X-Ray crystallography data for PC.

Bond lengths [Å] and angles [deg] for PC (excluding picric acid component).

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Appendix 3. X-Ray crystallography data for 7-azaIC.

Bond lengths [Å] and angles [deg] for 7-azaIC.

\[
\begin{align*}
N(18)-C(19) & \quad 1.410(5) \\
N(18)-C(14) & \quad 1.362(4) \\
N(18)-C(17) & \quad 1.399(5) \\
N(7)-C(17) & \quad 1.337(5) \\
N(7)-C(6) & \quad 1.356(5) \\
C(11)-C(12) & \quad 1.383(5) \\
C(11)-C(10) & \quad 1.385(5) \\
C(11)-H(11) & \quad 1.002 \\
C(15)-C(14) & \quad 1.374(5) \\
C(15)-C(3) & \quad 1.395(5) \\
C(15)-C(16) & \quad 1.474(5) \\
C(19)-C(8) & \quad 1.354(5) \\
C(19)-C(12) & \quad 1.435(5) \\
C(14)-C(13) & \quad 1.379(5) \\
C(3)-C(2) & \quad 1.402(5) \\
C(3)-H(3) & \quad 0.995 \\
C(5)-C(4) & \quad 1.391(5) \\
C(5)-C(6) & \quad 1.379(5) \\
C(5)-H(5) & \quad 0.999 \\
C(9)-C(8) & \quad 1.377(5) \\
C(9)-C(10) & \quad 1.395(5) \\
C(9)-H(9) & \quad 0.998 \\
C(8)-H(8) & \quad 1.127 \\
C(17)-C(16) & \quad 1.428(5) \\
C(13)-C(12) & \quad 1.469(5) \\
C(13)-C(1) & \quad 1.399(5) \\
C(4)-C(16) & \quad 1.378(5) \\
C(4)-H(4) & \quad 0.997 \\
C(1)-C(2) & \quad 1.403(5) \\
C(1)-H(1) & \quad 1.006 \\
C(10)-H(10) & \quad 1.003 \\
C(6)-H(6) & \quad 1.006 \\
C(2)-H(2) & \quad 1.000
\end{align*}
\]
Appendix 4. 2,2'-bisindolo[3,2,1-<i>jk</i>]carbazole 360 MHz <sup>1</sup>H NMR spectrum in acetone-<i>d</i><sub>6</sub>/DMSO-<i>d</i><sub>6</sub> (top) and THF-<i>d</i><sub>8</sub> (bottom).
Appendix 5. 5,5'-bisindolo[3,2,1-jk]carbazole 360 MHz $^1$H NMR spectrum in acetone-$d_6$/DMSO-$d_6$ (top, pre column chromatography) and THF-$d_8$ (bottom, post column chromatography).

![NMR Spectrum](image-url)
Appendix 7. 1H NMR spectrum of IC electrochemically produced dimer spiked with 2,2'-bisindolo[3,2,1-\textit{jk}]carbazole.

Top $^1$H NMR spectrum is dimer mixture.
Bottom $^1$H NMR spectrum is spiked sample.
Appendix 8. 1H NMR spectrum of IC electrochemically produced dimer spiked with 5,5'-bisindolo[3,2,1-jk]carbazole.

Top $^1$H NMR spectrum is dimer mixture. Bottom $^1$H NMR spectrum is spiked sample.
Appendix 9. 1H NMR spectrum of IC electrochemically produced dimer spiked with 2,5'-bisindolo[3,2,1-\textit{jk}]-carbazole.

Top $^1$H NMR spectrum is dimer mixture. Bottom $^1$H NMR spectrum is spiked sample.
Appendix 10. HPLC trace of 2,2'-bisindolo[3,2,1-\(j\)k]carbazole.

![HPLC trace of 2,2'-bisindolo[3,2,1-\(j\)k]carbazole.](image-url)
Appendix 11. HPLC trace of 5,5'-bisindolo[3,2,1-\textit{jk}]carbazole.
Appendix 12. HPLC trace of 2,5'-bisindolo[3,2,1-jk]carbazole.
Appendix 13. 7-AzaIC 600 MHz TOCSY spectrum in DMSO-d$_6$. 

![7-AzaIC 600 MHz TOCSY spectrum in DMSO-d$_6$.]