POLARIZATION OF THE GROUND STATE NEUTRONS
FROM THE $^7\text{Li}(d,n)^{8}\text{Be}$ REACTION

Thesis

Submitted by

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for the degree of

DOCTOR OF PHILOSOPHY

Department of Physics,
University of Edinburgh,
December 1982
To my parents
DECLARATION

The work presented in this thesis was pursued following my completion of an M.Sc. project at Edinburgh University. The project, which was of very limited duration, also concerned with running a deuteron beam from the 500 keV Van de Graaff accelerator onto a lithium fluoride target. However, the accomplished experimental work within the short period of time allowed was so preliminary a nature that it has no effective overlap with the work forming the basis of the present thesis.

I declare that this thesis has been composed and typed by myself and the work presented has been performed entirely on my own except where indicated clearly otherwise.

Ara M. Ghazarian
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| 7.1 Conclusion                                        | 123  |

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The angular distributions of 14 MeV neutron polarization have been determined for the $^7\text{Li}(d,n)^8\text{Be}$ g.s. reaction at two incident deuteron energies, 450 and 500 keV, using a low potential Van de Graaff accelerator.

The measurements covered laboratory neutron emission angles from 25 to 125 degrees. The polarization values were deduced from the measured asymmetries in the scattering of the 14 MeV neutrons by helium into a pair of liquid NE213 detectors. Background problems are substantially reduced when $^4\text{He}$, as a scintillator, is used in a coincidence arrangement with the neutron detectors.

Contributions from lower energy neutron groups, emitted due to the formation of excited states of $^8\text{Be}$ and other competing reactions were excluded by proper pulse height discrimination and the presence of any gamma rays were rejected by pulse shape discrimination techniques facilitated by the NE213 scintillators.

Neutron relative differential cross section measurements were also performed for the ground state neutron group at similar deuteron energies.

The results were compared with the predictions of theoretical calculations based on the Distorted Wave Born Approximation (DWBA) approach to investigate the success or failure of this theory in predicting either polarization or differential cross section information, as some reports gave the
confirming Wolfenstein's point. At that time however, it was quite difficult to obtain reliable polarization values due to the presence of an uncertainty factor in the very indirect way by which the analysing powers were deduced.

1.4 Choice of the Analyser

Accurate knowledge of the neutron polarization $P_n$ depends on how well the analysing power of the scatterer $P_s$ is known, and since the two quantities $P_n$ & $P_s$ are not experimentally separable, the analysing power should be calculated independently by other procedures.

For polarization analysis, it is preferable to use scatterers for which the analysing power can easily be calculated and in a precise manner. The simplest case would be when neutrons interact with spin zero nuclei, in which the only open channel of interaction is elastic scattering, and the probability of exciting the nucleus is remote. This is actually possible for fast neutrons scattered by some light, spinless nuclei.

Helium-4, Carbon-12, and Oxygen-16 are typical nuclei used as polarization analysers, where inelastic scattering is limited by relatively high excitation energies of these nuclides. From the analysis of total and differential elastic scattering cross-section measurements, the resonance parameters, and hence the phase shifts for such nuclides can be well deduced[9]. For nuclides with non-zero spin, or when inelastic scattering is probable, the phase shift analysis becomes more complicated and correspondingly more uncertain.

Helium-4 in particular, has been an excellent polarization analyser. It has some notable features which make it even more
distinguished and often preferred over Carbon-12 and Oxygen-16. Some of these features are:

(a)- High magnitude of analysing power, which varies slowly with incident neutron energy, and at some angles, the analysing power is almost unchanged over a wide range of incident neutron energies. So by proper choice, one has the advantage of pre-selecting the most convenient angle for accurate and fast data collection.

(b)- Another important feature of helium-4 is that it can be used as a scintillation detector of recoiling \( ^4 \) He nuclei as well as a scatterer, therefore providing the means to overcome high background problems when used in coincidence with the scattered neutron detectors. Indeed, helium-4 (as gas or as liquid), has become the most widely used analyser in fast neutron polarization studies.

1.5 Review of Past Measurements on Neutron Polarization

The polarization of the outgoing neutrons for a number of charge particle induced reactions, such as \((p,n)\), \((d,n)\), \((\alpha,n)\)...etc, have been extensively studied. Some of these reactions are summarised briefly below.

As mentioned earlier, the \(^7\) Li\((p,n)^7\) Be reaction was amongst the first neutron producing reactions subjected to elaborate study. A complete account of this reaction together with early references is found in an article by Gibbons[10].

Barschall[11] measured the neutron polarization from this reaction at 50° laboratory emission angle, with incident proton energies between threshold \((E_p = 1.881 \text{ MeV})\) and 3.1 MeV, \((E_n = 0.3 \rightarrow 1.2 \text{ MeV})\).
P_n values were found then to exceed 40% in the region where the reaction cross-section shows a distinct peak. In fact the high magnitude of polarization was directly associated with the resonance of the reaction at that point, (E_p =2.25 MeV).

Minzatu et al[12] investigated the angular distribution of neutron polarization for E_p =4.5 MeV, thereby showing the P_n trend at slightly higher energies, using Carbon-12 as the analyser.

A significant paper published by Thornton et al[13], gave P_n angular distributions of the ^7Li(p,n)^7Be g.s.(ground state) reaction for E_p =3.0->5.5 MeV. In their measurements, neutrons emitted due to the formation of the first excited state (0.43 MeV) and other higher states of the ^7Be nucleus, (previously contributed to the published P_n values of the reaction) were excluded. Analysis with liquid Helium, showed P_n maxima at two emission angles: one observed at 90° lab. with a magnitude of 46% and another calculated at 135° lab. with a magnitude of 45%, for E_p =3.5 MeV and E_p =5.4 MeV respectively. Furthermore, they[13] successfully applied theoretical calculations to fit their experimental results, and gave a more convincing interpretation of the reaction mechanism.

Another reaction which has received a considerable amount of polarization work, both theoretical and experimental, is the ^2H(d,n)^3He reaction (D-D reaction). With low energy accelerators (500 keV or less), this reaction provides monoenergetic ~3 MeV neutron beams of well known polarization P_n magnitudes. It is therefore frequently used for neutron scattering experiments in that energy region. Neutron polarization values for this reaction, deduced from the asymmetry in the scattering by ^4He, have been published by Calloway et al[14,15,16], covering incident
deuteron energies from $E_d = 35$ keV to 5.4 MeV.

The dependence of the observed polarization on the angle of emission and on deuteron energy, were discussed in relation to both, the low energy theory (developed first by Boersma[24] then by Fick and Weiss[25]) and the approach cross-section description of the D-D reaction (developed by Beiduk, Pruett, and Konopinski[26]).

Measured $P_n$ values at the low energy region, show a maximum value of $-15\%$ for $E_d = 350$ keV, at $45^\circ$ laboratory emission angle. As the deuteron bombarding energy increases, the $P_n$ value approaches zero at about $E_d = 5.0$ MeV, thereafter changes sign to +ve $P_n$ values for higher incident deuteron energies.

The $^3\text{H(p,n)}^3\text{He}$ reaction is considered yet another source of polarized, monoenergetic neutrons. Neutron polarization from this reaction has been observed by Cramer and Cranberg[17] at an emission angle $\theta = 31^\circ$ lab. for $E_p = 1.3$ to 2.25 MeV, ($E_n = 1$ to 1.3 MeV). A maximum $P_n$ value of $+40\%$ was deduced with helium-4 as the analyser. The $P_n$ value decreased with decreasing energy of the incident protons to about $+3\%$ for $E_p = 1.3$ MeV ($E_n \sim 0.4$ MeV).

An in depth investigation of $P_n$ angular distributions was carried out by Smith and Thornton[18] for the same reaction, using liquid helium as the Polarization analyser, with incident proton energies from 1.5 to 5.0 MeV. The compiled data were subsequently used with theoretical calculations to get the best fit for the polarization angular distribution in relation to $E_p$.

With the incident proton energy just over 2.2 MeV, the general feature of $P_n$ showed two peaks, a positive value of $40\%$ at $\theta = 40^\circ$, and a negative value of $27\%$ at $\theta = 90^\circ$.

It is worth pointing out here that amongst the above mentioned
reactions, only the D-D reaction is exothermic and therefore obtainable with low potential accelerators. However, not all exothermic reactions provide polarized neutrons at low incident energies, the $^3$H(d,n)$^4$He (often referred to as D-T) reaction is an example. It shows negligible polarization in the emitted neutrons, yet at high incident energies (~3 MeV or more), neutrons start showing significant polarization. Therefore use of the reaction as a polarized neutron source is limited to high energy accelerators.

Polarization measurement for the $^9$Be(d,n)$^{10}$B reaction has been reported by Bains and Galloway[19] with incident deuterons of 400 keV. At 45° lab. emission angle the ground state neutron group ($E_n = 4.4\text{MeV}$) was found to be +35% polarized, which was deduced from the asymmetry in the scattering by helium-4. Although this reaction has not been studied as intensively as the previous ones, it certainly shows that high $P_n$ values are possible from reactions induced with low energy accelerators.

Polarization of the neutron groups from the $^9$Be(d,n)$^{10}$B reaction, leaving the Boron nucleus at ground state and other excited states, has been measured earlier by Miller and Biggerstaff[20], for $E_d=0.9$ to 2.48 MeV.

No neutron polarization measurements have been reported where particles heavier than alpha have induced the reactions. Reactions such as $^{13}$C(α,n)$^{16}$O [21] and $^9$Be(α,n)$^{12}$C [22] have also been studied as sources of polarized neutrons.

Recent investigations of neutron polarization phenomena have been reviewed by Walter[23] reporting polarization sources, analysers and description of new measurements done on the elastic scattering of polarized neutrons together with model calculation comparisons.
1.6 Model and Calculation Comparisons

Parameterisation of experimental data is usually achieved with theoretical calculations and models giving the best possible fit to the acquired data. Successful models put forward, often convey vital information and give clear interpretations of the nuclear processes involved.

The energy dependence of the neutron polarization has been discussed theoretically for (d,n) & (p,n) reactions involving light nuclei by several authors. For the D-D neutrons induced with low energy deuterons (200 keV or less) Boersma [24] adopted a DWBA (Distorted Wave Born Approximation) approach and deduced an expression relating the energy dependence of the neutron polarization, $P_n$, to the differential cross-section $\delta(\theta)$, while Fick and Weiss [25] followed an R-matrix approach but nevertheless obtained a similar expression for the same relationship.

The differential cross-section $\delta(\theta)$ was derived from the expansion terms of even order Legendre polynomial of the form:

$$\delta(\theta) = \sum_{n=0}^{\infty} A_{2n} P_{2n}(\cos\theta) \quad \text{(1.6)}$$

Where $P_n$ is the Legendre polynomial and $A_n$ is the anisotropy coefficient. The differential polarization, $P \theta \delta \theta$ is derived from the expansion of even order associated Legendre polynomial as:

$$P \theta \delta \theta = \sum_{n=0}^{\infty} a_{2n} P'_{2n} \cos\theta \quad \text{(1.7)}$$
Where $P'\text{n}$ is the associated Legendre polynomial, and $a_n$ is the anisotropy coefficient which differs from $A_n$ by an energy independent factor.

Equivalently, $P(\theta)\delta\theta$ can be expanded in the centre of mass coordinates as;

$$P(\theta)\delta\theta = \sum a_n \sin 2n\theta$$

(\theta in C.M.)

Such expressions provide convenient parameterisation for comparing experimental measurements with one another as well as with models of the reaction. This has been implemented and clearly discussed by Galloway et al[14,16] for the D-D reaction.

Thornton et al [13,18] successfully parameterised their measured polarization and differential cross-section data for the $^7\text{Li}(p,n)^7\text{Be}$ and $^3\text{H}(p,n)^3\text{He}$ reactions by relating the $\delta\theta$ in the C.M. system to the Legendre polynomials as in equation (1.6) and the differential polarization data to the first-order associated Legendre polynomial, as in equation (1.7).

1.7 Neutron Polarization Due to Elastic Scattering

With the polarization distribution of the neutrons well determined for a feasible source reaction, a beam of neutrons from that reaction can be utilised to study the polarizations that result from elastic scattering ($P_\text{s}$), with a great variety of nuclei, i.e., to study the analysing power of those nuclei in a particular energy range available from the reaction.

Analysing power data is essential in order to investigate the
expectation of the feasibility of its application at low incident deuteron energies.

The $^7\text{Li}(d,n)^{8}\text{Be}$ g.s. reaction as a source of polarized 14 MeV neutrons is discussed and the possible use of these neutrons for scattering experiments is assessed.
1.1 Introduction

The suggestion that most neutron producing reactions exhibit some degree of polarization (spin alignment) in those neutrons, initiated a series of investigations on spin dependent interactions, to study the forces involved causing this phenomenon.

Usually in neutron-producing reactions, the incident charged particles and the target nuclei are unpolarized, i.e. their spins are randomly oriented in space. The outgoing neutrons however, are in general partially polarized because of a strong spin-orbit coupling which occurs in nuclear reactions.

This effect was first pointed out in 1949 by Wolfenstein. Referring specifically to the $^2\text{H}(d,n)^3\text{He}$ reaction (better known as the D-D reaction), Wolfenstein stated that the emitted neutrons should be polarized due to a spin orbit coupling of the nuclei even when both, the incident deuteron beam and the deuterium target are initially unpolarized. Since then a large number of experiments have been performed to measure neutron polarization with the aim of obtaining more information about the nuclear forces involved in those interactions.

Among the first neutron producing reactions studied was the $^7\text{Li}(p,n)^7\text{Be}$ reaction, where high polarization magnitudes were observed.

The D-D reaction is another example. It proved to be a prominent and a prolific source of polarized, monoenergetic neutrons, readily obtainable with a wide range of particle
accelerators and is therefore a reaction which has undergone much scrutiny, consequently illustrating a number of successful techniques employed in this field along with the difficulties associated with polarization work.

Other reactions such as the $^3\text{H}(p,n)^3\text{He}$ & $^3\text{H}(d,n)^4\text{He}$ reactions have also been studied (the latter is often called the D-T reaction), and used as sources of polarized neutrons with a range of bombarding energies. Various other reactions are mentioned by Galloway[2], however, concluding that relatively few reactions have been investigated, generally over a very limited energy range, while measurements on polarization of neutron groups leading to different states of the final nucleus, have received even less attention.

1.2 The Principle of Polarization Measurement

As conventional neutron detectors used today are insensitive to neutron spin, the measurement of neutron polarization is therefore not a straightforward detection process. A special method has to be employed for that purpose.

An elaborate review article by Haeberli[3] in Fast Neutron Physics, quotes most of the important methods adopted for the assessment of nucleon polarization.

For fast neutrons, elastic scattering is the most common technique used to assess the degree of polarization, in which use is made of the fact that in the presence of spin-orbit coupling, neutrons with spin up are preferentially scattered to one side of the incident beam and those with spin down to the other. Thus, if there are more neutrons with spin down than up, there will be a net imbalance, causing an effect called "asymmetry" in scattering,
where the neutron flux scattered to one side differs from the flux scattered through the same angle to the other side, in the plane normal to the direction of polarization of the incident beam.

An outline of a convenient approach to measure neutron polarization is as follows;

Figure 1.1 shows a typical situation, where a beam of unpolarized charged particles of energy (E) and momentum along the direction (K) is incident on a target (T₁) and produces, at an angle (θ₁) neutrons of energy (Eₙ) and polarization (Pₙ) proceeding in the direction (K₁). The neutrons are then scattered by a sample (T₂), acting as the polarization analyser, through an angle (θ₂) with final momentum along the direction (K₂) with azimuthal angle (φ). The spin-orbit coupling between the neutrons and the nuclei of the scatterer T₂, causes an asymmetry in the scattering. This asymmetry is measured in the plane of the interaction by detecting the neutrons going to the right (φ = 0°), and those going to the left, (φ = π°). The ratio of right to left fluxes depends on two factors:

(a) The initial degree of polarization of the neutron beam.
(b) The extent to which the scatterer is sensitive to neutron spin i.e., the analysing power of the scatterer.

The number of neutrons moving in the direction (K₂) in a given time after scattering is:

\[ N(θ₂, φ) \propto \delta_{un}(Eₙ, θ₂) \left[ 1 + Pₙ(E, θ₁)A(Eₙ, θ₂) \cos φ \right] \]  \( \ldots \ldots \) (1.1)

where \( A \) is the differential cross-section for scattering.
Geometry of a

Figure 1.1 Typical neutron polarization experiment
an unpolarized neutron beam of energy \( E_n \) through an angle \( \theta_2 \) and \( A(E_n, \theta_2) \) is the analysing power of the scatterer \( T_2 \), (The Amplitude of azimuthal variation).

For elastic scattering, \( A(E_n, \theta_2) \) is equal to the polarization that would result if unpolarized incident neutrons of energy \( E_n \) were scattered through an angle \( \theta_2 \). Even with targets of non-zero spin, the previous statement still holds for strong interactions. So \( A(E_n, \theta_2) \) can be denoted as \( P_s(E_n, \theta_2) \). To collect data through an experiment for \( P_n \) value measurement, usually the number of neutrons scattered to the right, where \( \phi = 0 \) and to left, \( \phi = \pi \) are obtained, say \( N_R \) and \( N_L \) respectively, then the asymmetry \( \varepsilon \), is calculated.

\[
\varepsilon = \frac{N_R - N_L}{N_R + N_L} \quad \text{.........(1.2)}
\]

Alternatively the asymmetry can be calculated in terms of the ratio \( N_R/N_L \)

\[
\varepsilon = \frac{r - 1}{r + 1} = \frac{N_R}{N_L} = \frac{1 + P_n(E, \theta_1)P_s(E_n, \theta_2)}{1 - P_n(E, \theta_1)P_s(E_n, \theta_2)} \quad \text{.........(1.3)}
\]

and from (1.2) and (1.4)

\[
\frac{N_R - N_L}{N_R + N_L} = P_n P_s = \varepsilon \quad \text{.........(1.5)}
\]
Thus if $P_s$ is known then the value of the neutron polarization $P_n$ can be obtained for a great variety of source reactions. On the other hand if $P_n$ is known, then the polarization due to elastic scattering $P_s$ from a range of nuclei can be determined. From a practical point of view, accurate knowledge of the polarization magnitude of the emitted neutrons from the principle neutron producing reactions is important for their use in evaluating $P_s$ by elastic scattering with a wide range of nuclei.

A direct method for $P_s$ magnitude measurement would be two successive scatterings of an unpolarized initial neutron beam, through the same nucleus, (a technique called double scattering).

According to the convention of signs adopted at the International symposium[4] on "Polarization Phenomena of Nucleons" in Basel (1960), particles with spin pointing along the direction $\vec{K}_0 \times \vec{K}_1$ are positively polarized.

1.3 Polarization of Neutrons From Nuclear Reactions

Wolfenstein[1] first pointed out in 1949 that neutrons from the $^{2}D-D$ reaction should be polarized due to strong spin-orbit coupling in nuclear reactions. His suggestion was based on a paper by Konopinski & Teller[5] on the theoretical analysis of the total and differential cross-sections. It has since been pursued by scientists aiming to understand and utilise this phenomenon.

In 1952 Bishop et al[6] reported the first experiment which showed that nucleons emitted from reactions are polarized, by observing the protons from the $^{2}H(d,p)^3H$ reaction, and using helium as the polarization analyser. Meantime, Huber and Baumgartner[7] and Ricamo[8] observed the neutron polarization from the $^{2}H(d,n)^3He$ reaction using carbon as the analyser, thereby
spin dependence of the nucleon—nucleus interaction. To pursue an investigation, it is necessary first to use a sound theoretical description (model) of the interaction, which would obviously take into account the spin-orbit forces, together with other features involved in the scattering of nucleons by nuclei. However, theoretical models can only be fully tested when ample experimental data are made available for verification and correlation with theory. The model which gives a good fit to the $P_s$ data, will reveal information about the spin-orbit forces involved and permit reliable predictions of further relevant information.

The optical model is one which has been largely employed for such purposes. It was first introduced by Feshbach, Porter, and Weisskopf and later developed by Feshbach[27], in a successful approach of describing the nucleon—nucleus interaction in a complex potential well form, where the target nucleus was represented by a potential and the passage of the nucleon through the nuclear potential taken analogous to the passage of light through a material medium. Physically, this is equivalent to treating the nucleus as if it were made of a material of complex refractive index, so that it both refracts and absorbs the incident waves. Just as the index of refraction of such an optical medium, the nuclear potential is a complex quantity when absorption of the nucleon takes place. Thus, to determine the parameters which characterise the optical properties of nuclear matter, one has to solve the Schrödinger equation for a neutron (the same is true for protons with the addition of the coulomb field interaction) where the motion of the neutron is described by a wavefunction associated with a complex potential $V(r)$;
where \( V(r) = -U(r) - iW(r) \) \((1.9)\)

\( U(r) \) represents the average potential energy of the neutron inside the nucleus and \( W(r) \) describes the absorption effect due to the compound nucleus formation.

The solution of the Schrödinger equation with such an optical potential yields phase shifts from which the total cross-section, the differential cross-section for shape elastic scattering and also the cross-section for the compound nucleus formation can be calculated. Moreover, the compound elastic scattering cross-section which is particularly significant at energies below 5 MeV, can be estimated using a method proposed by Hauser and Feshbach\[28\]. This should be added to the shape elastic scattering.

Polarization of the nucleons is also predicted with the addition of a term proposed by Bjorkland and Fernbach\[33\] so that the optical potential is modified to:

\[
V(r) = -U(r) - iW(r) - V_{s.o}(r) \vec{l} \vec{\sigma} \quad (1.10)
\]

where \( \vec{l} \) and \( \vec{\sigma} \) are the angular momentum and Pauli spin operators respectively.

Although a great deal of success has been achieved between theory and experiment for neutron differential elastic scattering cross sections, the same cannot be said for neutron polarization, as systematic data are still needed on this respect with regards to energy and nuclei concerned, to render a more complete evaluation of the optical model. Only then can a conclusive assessment be drawn on the validity of the model and its predictions.
It has been pointed out by Galloway[36] from a survey of experiments on the angular dependence of polarization, that most of the neutron scattering tests had been carried out at energies of 4 MeV or less, within which the interpretation of data in terms of the optical model is complicated by the presence of the compound elastic scattering. No proper fit was found for the $P_s$ data compiled with nuclei lighter than Ti with energies less than 3 MeV.

With the allowance for compound elastic scattering based on Hauser-Feshbach theory [28], Ellgehausen et al[29] have shown that the polarization of 3.25 MeV neutrons elastically scattered by some medium weight nuclei (Ti, Fe, Cr, Cu and Zn), can be well described by the optical model (OM). Galloway and Waheed[30] have shown that O.M. calculations combined with Hauser-Feshbach formalism, using global parameters as well as parameters suggested by previous experiments for particular nuclei, were not successful in fitting both the differential cross-section and the polarization data of Waheed[31] with 2.9 MeV neutrons.

Begum and Galloway[32] in recent observations of 2.9 MeV neutrons scattered by W, Ti, Bi & U, compared their measurements with the results of combined (OM) and Hauser-Feshbach calculations based on global parameter sets and with the results of searches for optimum (OM) fits to the data. They showed that calculations which took account of the level width fluctuation correction (derived by Moldauer[71]), gave better fitting to the differential cross-section and polarization data.

For energies above 5 MeV, where the (OM) is expected to be much better tested, due to the remoteness of the compound nucleus contribution, only a few measurements have been accomplished.
Clearly to test the (OM) in relation to the polarization of elastically scattered neutrons, there is a need for more data of good quality, especially at energies considerably above 4 MeV so that the additional complication of allowing for compound elastic scattering may be avoided. Only few measurements have been performed in this respect and over a limited range of angles.

Hussein et al.[34] had their 10.4 MeV data well fitted with the (OM), so had Wong et al.[35], for their data obtained at 24 MeV.

It is of great interest to obtain neutron polarization data, near 14 MeV where much differential cross-section data exists, in order to consolidate the efforts already put in this area of research.

Thus a source of polarized 14 MeV neutrons was deemed necessary to fulfil this task in our laboratory.

1.8-a The DWBA Theory

Currently there are many theories of the stripping reaction. These include the semi-classical diffraction theories, the coupled-channel theory, and the perturbation theory. The theory that seems to combine the maximum utility with minimum unnecessary complexity is the Distorted Wave theory.

Wilkinson[85] suggested that if the Q-value of a reaction, induced with low energy deuterons, is high, the outgoing nucleon must acquire its high linear momentum from the ground state deuteron wave function, as there is little in the bulk motion of the deuteron. He assumed that distortions take place only when the neutron and the proton are close together at the instant of stripping (near the surface of the target nucleus), thus the outgoing nucleon would suffer considerable nuclear and coulomb
distortions due to proximity. The distortion effects were later found to exist not only in high Q-value, low energy deuteron induced reactions, but also in such reactions with low Q-values[86]. The presence of nuclear distortions at low incident energies were further substantiated by Robson and Weigold[87] when investigating the adequacy of the plane wave and the distorted wave theories for a low Q-value stripping reaction, namely the \(^{11}\text{B}(d,p)^{12}\text{B}\) with a Q-value of 1.14 MeV.

They[87] found that the reaction cross section is best described on the bases of the Distorted Wave theory. With the inclusion of a spin-orbit interaction term in the initial and final channels of the reaction, polarization effects of the emitted nucleon were also predicted.

1.8-b Review of the DWBA Theory

The deficiencies of the Plane Wave theory, formulated by Butler[88], which did not take account for such distortions, led to the development of the Distorted Wave theory by Tobocman[89]. The theory was subsequently refined by several other researchers[90].

As the name implies, the Distorted Wave theory considers the combined nuclear and coulomb distortion effects on the wave function of the stripped (outgoing) nucleon. The wave functions used for the incident particle and the emitted nucleon are those which satisfy the motion of the particles concerned in the combined nuclear and coulomb field of the target nucleus and final nuclei respectively. The values for these functions can be obtained from the optical potentials that describe the elastic
scattering interaction of the concerned particles from the target nuclei at the relevant energies. The optical potentials are in turn expressed in terms of a number of parameters that are adjusted to fit the experimental data.

Recently, a great deal of attention has been focussed on stripping reactions aiming to obtain adequate understanding of such direct interactions. Although a range of incident charged particles has been employed in these studies, particular emphasis has been placed on deuteron stripping, i.e., \((d,p)\) and \((d,n)\) reactions. Furthermore, as the analysis of deuteron stripping reactions using the Distorted Wave Born Approximation method requires optical potential parameters derived from elastic scattering data, investigations of the \((d,d)\), \((p,p)\) and \((n,n)\) elastic scattering from the concerned nuclei were carried out in parallel (at the relevant energies) in order to determine the set of potentials which would give the best overall fit to the experimental data. Investigations involving light nuclei have not been substantiated, in fact they were often avoided because of the uncertain applicability of the optical model in such cases, especially at low incident energies where compound nucleus contributions to the observed cross-sections can seriously complicate analysis. The available reports currently in the literature which involve light nuclei are a few, and the optical parameters used in such work have been either extrapolated from investigations at higher incident energies or derived from studies of neighbouring nuclei.

In the following, we shall review some of the relevant investigations that have been accomplished, typical results obtained and the general conclusions drawn regarding the success
and limitations of the DWBA theory.

Thomason et al[49] reported DWBA calculation comparisons for the $^6$Li(d,n)$^7$Be and the $^7$Li(d,n)$^8$Be g.s. reactions for incident deuterons of 3.7 MeV energy. The neutron-nucleus optical parameters were extrapolated from values for intermediate weight nuclei reported by Wilmore and Hodgson[108]. The deuteron-nucleus potentials were derived from those of reported by Ludecke et al[93] at 11.8 MeV, the only deuteron-nucleus optical parameter sets available then. Reasonable agreement with the experimental cross section distributions were found for both reactions, however, no convincing fits of the neutron polarization angular distributions were obtained for either reaction.

Lombaard and Friedland[109] later published optical potential parameters for the $^7$Li(d,d) elastic scattering in the energy range from 1.0 to 2.6 MeV. With those parameter values they[109] were able to produce cross section distributions for the $^7$Li(d,p)$^8$Li g.s. reaction in good agreement with the observed data. [The parameter values reported in this reference were included in the parameter search of the present work].

In the energy region between 2 to 5 MeV incident deuterons, Hodgson and Wilmore[110] reported successful attempts of fitting cross section data for the $^{12}$C(d,p)$^{13}$C g.s. and the $^{12}$C(d,n)$^{13}$N g.s. reactions. They took account of both, compound nucleus formation using Hauser-Feshbach[28] formalism, and direct stripping processes using the DWBA theory. The combined effects of these two channels were calculated adding the two calculated cross sections after normalisation with appropriate factors. The data for the $^{12}$C(d,p)$^{13}$C reaction cross section were obtained from the work of Gallmann et al[111], and those for the $^{12}$C(d,n)$^{13}$N reaction from Elwyn et al[112].
With the inclusion of an appropriate spin-orbit potential to the Distorted Wave theory applied, further attempts were made by Hodgson and Wilmore[110] to fit neutron polarization distributions for the $^{12}$C(d,n)$^{13}$N reaction. They were unable to produce satisfactory fits to the observed polarization angular distributions using the same optical potential parameters adopted for calculating the cross sections. In spite of this, their preliminary calculations held out some hope that it would be possible to account for the polarization data when the distorting potentials become more accurately known. The neutron polarization data were acquired from the extensive study of the $^{12}$C(d,n)$^{13}$N by Walters group[113-116].

With bombarding deuterons of 6 MeV energy, Gedcke et al[117] measured the angular distributions and neutron polarizations for the reaction $^{40}$Ca(d,n)$^{41}$Sc leading to the ground state and other excited states of the $^{41}$Sc nucleus. While good agreement was found between the observed and calculated neutron cross sections, the agreement between the measured and Distorted Wave predictions for the polarization angular distributions were far from satisfactory for any reasonable choice of optical parameters.

The polarization of the protons emitted from the ground state $^{40}$Ca(d,p)$^{41}$Ca reaction has been measured and compared with DWBA calculations by Leighton et al[118] for incident deuterons of 5 MeV. The theoretical calculations, including a vector type spin-orbit potential, gave polarizations opposite in sign to those observed experimentally and showed serious discrepancies for all the comparisons. The parameter values adopted in the DWBA calculations had provided a fair prediction of the reaction cross section in a previous study by Leighton et al[119].
Numerous other investigations[120] showed that good agreement could be found between the observed cross section distributions and DWBA predictions with the appropriate optical model parameters.

The general conclusion reached from all the critical tests of the DWBA theory is that it is capable to give good account of the cross section distributions but the fits to the polarization distributions are rather poor, even when the d-state waves functions for the deuteron are taken into account[122,123] and when optical parameters derived from scattering experiments with polarized deuteron sources are adopted[124].

Somewhat better polarization results are obtained for heavy nuclei particularly with the (d,p) reactions near the coulomb barrier[121], but even these are far from satisfactory.

An excellent review of the DWBA theory is provided by Hodgson[95], quoting the prominent achievements of this theory together with the limitations and the extent of its success and validity.

1.9 Thesis Objective

The objective of this thesis is to seek a source of polarized 14 MeV neutrons, using a low energy accelerator, anticipating its use for scattering experiments in that energy region.

Although high energy (2 to 3 MeV) accelerators readily produce such sources, it was thought to be more advantageous, from a practical point of view, to seek for a source with a low energy accelerator. This is because neutron scattering experiments in general and polarization measurements especially, require a considerable amount of time to perform, therefore it would no
longer be necessary to engage high potential accelerators over long periods when the process has been shown to be feasible with low energy accelerators. Furthermore, the latter are known to operate continuously over long intervals, at considerably lower costs and less maintenance requirements than the former.

The ultimate objective is therefore to extend the energy of polarized neutron sources to higher energies than previously available with low energy accelerators.

1.10-a Choice of Reaction

The reaction to provide the expected 14 MeV polarized neutrons at low bombarding energies, would be amongst those of high Q-values (typically 15 MeV or more).

The $^3$H(d,n)$^4$He reaction, with a Q-value of 17.5 MeV readily emits high yield, 14 MeV neutrons, but shows no polarization effects with low incident deuteron energies (less than 1 MeV)[37]. The incident energy must be well over one MeV before the neutrons show any significant polarization effects[38]. Consequently this reaction cannot be used as a source of polarized neutrons with low energy accelerators. Instead, it provides useful means of checking false polarizations introduced by instrumental asymmetries due to misalignment of equipment.

The $^7$Li(d,n)$^8$Be reaction, on the other hand, with a Q-value of 15.027 MeV was considered as potentially a good source of energetic neutrons. If the emitted neutrons were to exhibit a good degree of polarization, the reaction could well prove to be a modest substitute for high potential accelerators in producing polarized neutrons in the 14 MeV region.

A thorough investigation of the angular distribution of neutron
polarization was deemed necessary to assess the reaction's utility.

1.10—b Review of the $^7\text{Li}(d,n)^8\text{Be}$ reaction

Most of the early work reported on the $^7\text{Li}(d,n)^8\text{Be}$ reaction concerned measurements of the energy levels in the Beryllium-8 nucleus[39,40,41,42,43]. The neutron spectrum from this reaction comprises two distinct peaks, a high energy peak corresponding to the formation of the Beryllium-8 nucleus in its ground state and a lower energy peak due to the formation of the first excited state, plus a continuum of low energy neutrons emitted mainly from other channels of the reaction that take place simultaneously. The neutron producing reactions, induced by deuterons bombarding a pure $^7\text{Li}$ target, are:

(a) $^7\text{Li}(d,n)^8\text{Be}$ (g.s.)  \[ Q = 15.027 \text{ MeV} \]
(b) $^7\text{Li}(d,n)^8\text{Be}$ (2.9 MeV)  \[ Q = 12.127 \text{ MeV} \]
(c) $^7\text{Li}(d,n)^2\alpha$  \[ Q = 15.122 \text{ MeV} \]
(d) $^7\text{Li}(d,^5\text{He})^4\text{He}$  \[ Q = 14.164 \text{ MeV} \]
\[ ^5\text{He} \rightarrow ^4\text{He} + n \]  \[ Q = 0.958 \text{ MeV} \]

Reaction (c) is basically a three-body break-up process, contributing mainly to the continuum part of the spectrum. Reaction (d) is a two step process emitting neutrons of low energy, also contributing to the low energy continuum.

With low incident deuteron energies (0.5 MeV or less), reactions (a)&(b) produce neutrons of 14 and ~11 MeV energy respectively and constitute the high energy part of the spectrum.

Figure 1.2 shows neutron spectra observed by Johnson and
Neutron Spectra from $^7\text{Li}(d,n)^8\text{Be}$ Reaction

- Energy: $E_d = 1.98$ MeV
- Angle of observation: $0^\circ$
- Metallic Li Target
- Natural LiF Target

Figure 1.2
Trail[45] from this reaction at 0 degree emission angle, for 1.98 MeV deuteron bombardment of two forms of Lithium targets, namely metallic lithium (Li) and natural lithium fluoride (LiF). The spectra are normalised, and the neutron peaks due to reactions (a) & (b) are clearly evident for both targets. Lower energy neutron groups have been omitted by energy discrimination.

Neutrons from the $^{19}\text{F}(d,n)^{20}\text{Ne}$ reaction ($Q=10.6$ MeV) are also present due to the fluorine content of the LiF target. These neutrons form lower energy groups that appear on the continuum and some part of the first excited state group (broad peak) but do not interfere with neutrons from the ground state group.

A typical neutron spectrum produced in our laboratory, with 450 keV deuteron bombardment of LiF target is illustrated in figure 1.3. The spectrum is basically collected with a liquid NE213 scintillator and unfolded using a program coded "FORIST" (FERDOR with Optimized Resolution using an Iterative Smoothing Technique)[72]. The unfolded spectrum shows the two peaks and other less prominent groups which form the continuum.

Although the $^7\text{Li}(d,n)^{8}\text{Be}$ reaction has been described as one of many interesting features, particularly the exhibition of negative values of polarization in the emitted neutrons, for incident deuteron beams of less than one MeV[44], there are no reports of systematic tests to study the neutron polarization and cross-section distributions from this reaction over a wide range of deuteron bombarding energies. The available reports are few, and they vary significantly from each other.

The angular distribution of the neutron groups due to $^8\text{Be}(\text{g.s.})$ and $^8\text{Be} (2.9 \text{ MeV + continuum})$, were observed by Trumpy
21/09/82  Unfolded Neut. Spect. from (LiF+d)

Proton recoil spectrum (NE213)

Unfolded neutron spectrum

Figure 1.3
et al [41] with incident deuterons of 680 keV energy and by Johnson & Trail [45] with deuterons of 1.98 MeV energy.

Milone & Potenza [46] studied the angular distributions of the two neutron groups with incident deuterons of 1 MeV, Von Mollendorff [47] made observations on the ground state neutron group only, using deuterons of 640 ± 40 keV.

Saxena [48] used the emulsion technique to study the neutron cross section at $E_d=500$ keV of all the groups he observed, with somewhat poor statistics. A more elaborate study was carried out by Thomason et al [49] with deuterons of 2.5 to 3.7 MeV reporting polarization angular distributions of the ground state and the first excited state neutron group (hereafter shall be denoted as the "No" and the "Ni" group, respectively). They also applied DWBA calculations using Optical Model parameters from published values and found reasonable agreement with the cross-section data. The model calculations of neutron polarization bore some resemblance to the experimental data at angles less than 120 degrees.

The polarization of the "No" group was first observed at several emission angles by Heroferd and Topp [44], who also studied the variation of the neutron polarization for incident energies from 680 keV to 1.1 MeV, pointing out an interesting feature of their results, in that the polarization values were negative over the deuteron energies covered.

The striking conclusion drawn from all these studies, is that neutron cross-section results showed no consistency below one MeV incident deuteron energies; not even for similar deuteron bombardment observations. While data for over 2 MeV showed some resemblance in the cross section data, with somewhat different magnitudes.
Obviously, a sound assessment on the utility of the $^7\text{Li}(d,n)^8\text{Be}$ reaction as a source of polarized 14 MeV neutrons was difficult to make, considering the quality and amount of relevant data available, particularly for incident deuteron energies below one MeV. Therefore, certain measurements were to be undertaken in this work whereby a clear assessment of the reaction would be reached. They are as follows;

a) Angular dependence of neutron polarization, for the highest energy group (No), with at least two incident deuteron energies, (450 & 500 keV).

b) Neutron relative cross-section measurements for the same group (No) and the same deuteron energies.

c) Neutron yield dependence on deuteron energy below the known resonance of 680->720 keV of the reaction, for the ground state group (No).

d) Comparison of experimental results with theoretical models of the reaction, using Distorted Wave Born Approximation (DWBA) calculations with the anticipation that it would be possible to find physically reasonable optical-model parameter sets which would give predictions of the qualitative features of the reaction cross section and neutron polarization angular distributions, for the No group.

Based on the results obtained from all these measurements, conclusions are to be drawn on the suitability of the reaction as a source of polarized neutrons for use in scattering experiments.
CHAPTER 2

THE NEUTRON POLARIMETER

2.1 General Outline

A general picture of the experimental layout may be given with reference to figures 2.1 & 2.2a. Ions of Deuterium gas, accelerated to the required energy using a 500 keV Van de Graaff accelerator (High Voltage Engineering model AN-500), are brought to a focus on a chemical target of Lithium Fluoride (LiF), producing neutrons from the nuclear reaction $^7\text{Li}(d,n)^8\text{Be}$, which has a Q-value of 15.027 MeV. At a desired emission angle the neutrons are collimated and directed towards a high pressure Helium-4 gas scintillator detector which acts as a scatterer/polarization analyser of the incident neutron beam. The scattered neutrons are viewed in coincidence with the associated recoil helium particles by two neutron detectors. These detectors are placed symmetrically on each side of the helium scintillator. All the detectors are mounted on a rig which can rotate about the axis joining the centre of the target to the centre of the pressurised helium scintillator cell.

Pulses produced by these detectors are treated in the electronic system incorporating pulse shape discrimination for gamma ray rejection. The processed signals are passed to an ADC (Analogue to Digital Converter), which is interfaced with a PDP-11 computer storing the routed pulses as spectra in appropriate arrays. The accumulated data in the memory are processed and analysed with software of the system at a later stage.

The various elements involved are detailed in the following sections, but first we briefly review the history of the
(a)—collimator
(b)—shadow shield
(c)—helium cell
(d)—neutron detector
(e)—rear cradle disc

Figure 2.1 Top view of the rotating polarimeter

Figure 2.2 Detail view of polarimeter/collimator & shielding

paraffin wax wall
polarimeter employed in the present work and the applied modifications that were necessary to hasten up the data collection process.

The polarimeter (see fig. 2.2b) was first designed and built by Hall[50] to study the polarization of neutrons from the D-D reaction at low incident energies. Although the design considerations for beam collimation and shielding of the neutron detectors were based on the fact that the maximum neutron energy from this reaction would not exceed 3.5 MeV, the collimator incorporated shielding material enough to moderate 7 to 8 MeV neutrons without a significant change in the background neutron level (immediately behind the collimator bulk). Therefore, the collimator was built to provide a well defined beam while keeping the background level near the neutron detectors at its minimum.

The polarimeter was later used by Alsoraya[54] who also studied neutron polarizations from the D-D reaction at low incident energies. While the shielding remained unchanged, Alsoraya[54] improved the operation of the polarimeter system by incorporating an automatic motor control unit to the electronics for dictating different modes of cradle (holding the detectors) rotation. Thence, the process of interchanging the roles of the side detectors was done automatically.

In the present work, the same polarimeter has been employed to study the polarization of 14 MeV neutrons emitted from the Li(d,n) reaction. The shielding incorporated in the polarimeter system was found to be inadequate to carry out meaningful data accumulation due to the sharp increase in the background level caused by the spectrum of neutrons emitted from the reaction, varying from 14 MeV down to a few MeV energy. The increase in the background level caused a proportional increase in the random
Figure 2.2b The Polarimeter before modification
counts which often swamped the real events. With the addition of 1/2 inch iron plates behind the collimator, a small improvement was noticed, however, proper data collection still posed a formidable task[129].

Rectangular iron blocks were cut and shaped to form shadow shields for the neutron detectors. The shadow shields were mounted on the front cradle disc screening the two liquid scintillators from possible direct beam flux. The detectors were positioned at the backward scattering angles and attached to the rear cradle disc by a new pair of flexible holders designed for the present configuration of the polarimeter.

With this modification, drastic improvement was achieved as regards to decreasing the contributions of the random events to the overall counts (real+ random). Prior to the modifications, the ratio of the real counts (R), to the random counts (r) persisted at about 100/80, this was appreciably changed to about 320/80, an improvement of about a factor of three. Indeed, the statistical accuracies achieved in the present work took more or less one third the time necessary to achieve the same accuracy with the former configuration[129].

2.2 The Neutron Collimator and Shielding

To investigate the polarization of the emitted neutrons from a source reaction, a well defined beam of neutrons from that source has to be provided first for analysis. This is achieved by using collimators, the design and construction of which depend very much on the energy of the neutrons. Consideration for any accompanying gamma radiation should also be made.
Figure 2.2 shows details of the collimator used in the present work. The collimator is situated in front of the polarimeter basically to shield the neutron detectors from direct neutron flux coming from the target, while allowing a defined size of neutron beam to pass through its centre aperture and impinge on the helium scintillator cell.

The collimator is 46 cm long, narrower at the front near the target than the back. It is designed in this shape, fitted with three wheels and pivoted, to permit semicircular movement around the centre of the target for angular distribution measurements. The whole bulk rests on a very heavy steel table to which the pivot is clamped.

The collimator contains a cylindrical layer of lead at the front close to the target, 20 cm in diameter and 20 cm long, to reduce the neutron energy by inelastic scattering and to attenuate the annihilation gamma rays produced by deuterons interacting with carbon contamination on the target, $^{12}\text{C}(d,n)^{13}\text{N} \rightarrow \beta + ^{13}\text{C}$. A large part of the collimator volume is filled with paraffin wax, which is a hydrogenous compound that helps to slow down and capture the neutrons. Finally there is a layer of lead 7.5 cm thick at the rear of the collimator to stop gamma rays produced by neutron capture in the paraffin wax from reaching the neutron detectors.

The collimator aperture is throated by using inserts made of brass and polythene. Brass is used for the inserts near the throat and polythene for the rest. The inserts are tapered by increasing their diameter in the direction of the neutron beam to reduce neutron scattering from the wall of the collimator aperture.
Usually the distance between the target and the collimator is chosen so that the solid angle subtended by the helium gas scintillator cell at the target allows full illumination of the cell by the collimated neutron beam. If the diameter of the beam is made smaller than the diameter of the helium cell, a false asymmetry factor may be introduced due to accelerator voltage fluctuation which may shift the position of the deuteron beam spot on the target and consequently the neutron beam position on the helium cell; on the other hand, if the dimension of the collimated neutron beam is bigger than the diameter of the cell, neutrons that miss the cell will possibly be scattered by the surrounding material thereby increasing the background level.

The distance between the target surface and the collimator aperture has been fixed at approximately 15cm to obtain complete illumination of the helium cell. Small target area projection in the direction facing the incident deuteron beam (3mm in the reaction plane and 14mm normal to the reaction plane), achieved with especially designed target holders, gave immunity against the effects of beam spot wander due to any voltage fluctuation in the accelerator.

Although the shielding requirements of the polarimeter have been considerably reduced by the coincidence arrangement of the electronics system which will be detailed in the following chapter, the polarimeter is surrounded with neutron moderating material to reduce the background level of fast neutrons.

Concrete blocks (45x15x15cm) are assembled beneath and around the table carrying the polarimeter, paraffin wax contained in cartons (50x30x24cm) are placed around the sides and the top of the polarimeter to form thicknesses of about 90cm. Additional
shielding materials are also provided in smaller tin boxes of various sizes, containing either paraffin wax or borated water, with the latter filled in thick polythene bags to avoid leaks and spillage. The shielding configuration and assembly have been carried out carefully for each and every angular measurement to insure the reduction of the background to ineffective levels, not only for better experimental results but also to meet the radiation safety requirements in the laboratory.

2.3 The Rotatable Rig

Directly behind the collimator an iron frame is attached in which a rotating cradle is seated, as seen in figure 2.1. The cradle consists of two precision discs 2.5cm thickness and held parallel to each other at 50cm distance by three steel rods of 2.5cm diameter. There are central holes in the discs to allow the passage of neutrons and cables (back). The discs rest on four bearings allowing smooth and accurate rotation of the rig around an axis joining their centres with the centre of the collimator aperture.

Four microswitches fitted on the iron frame, triggered by a shaped pin fixed on the rear end disc plate, allow the rotation of the rig by a slow speed electric motor to be under remote control.

The cradle disc nearer to the collimator holds two iron blocks in position as additional shadow shielding to further protect the neutron detectors from direct neutron flux coming from the target. The neutron detectors are mounted on the rear disc with adjustable holders allowing accurate positioning of these detectors which receive the scattered neutrons from the gas detector.

The helium scintillator detector is held perpendicular to the
axis of rotation by one of the three steel rods which has a ring shape housing in which the detector body can be positioned and fixed accurately.

2.4 The Helium Gas Scintillator Detector

The basic form of this detector is adapted from those designed by Walter[51] and by Shamu[52]. It serves both as a helium scattering sample and a detector of helium recoil nuclei. Figure 2.3 shows the helium gas scintillator detector, body and interior. This detector consists of a high pressure (70 atmosphere) gas scintillator cell optically coupled to a photomultiplier (EMI-6255B) with a quartz window. The scintillator cell is made of a stainless steel cylinder closed at the top by a hemisphere with 2mm wall thickness. The total axial length is 6cm and the diameter is 5cm. The bottom end of the cylinder is closed by a 2.5cm thick quartz window tightly pressed on a teflon "O" ring seal with a stainless steel circular clamping flange with ten bolts. The circular clamping flange is threaded on the inside so that the brass body of the photomultiplier holder screws into it. The photomultiplier tube and the pre-amplifier circuit are held inside the brass body.

The inside wall of the steel cell is covered with reflective coatings and a thin layer of a wavelength shifter as follows:

After polishing the inside surface of the cell, a thin coating of aluminium is vacuum deposited first to improve reflection, then a 2mm thick coating of Magnesium oxide (MgO) is electrostatically deposited and manually compressed for better adhesion. The MgO serves as diffuse reflector. Finally a thin film of Diphenylstilbene (DPS), a wavelength shifter, is vacuum evaporated.
Figure 2.3 The helium gas scintillator detector
in such a way as to give a thickness of $300\,g/cm^2$ on the walls close to the viewing quartz window and $100\,g/cm^2$ on the area of the hemispherical end.

The quartz window is also coated with DPS as recommended[52].

The helium cell is filled with a mixture of helium and xenon gas up to a pressure of 70 atm. (65 atm. helium and 5 atm. xenon).

Xenon serves to improve light output in the scintillation process.

The procedure of filling the cell is as follows;

The helium cell is put under vacuum for 24 hours then helium is admitted to the cell up to about 10 atm. and then released out so that the pressure falls to atmospheric before being vacuum pumped to $10^{-5}$ torr. This process of flushing the cell with helium and pumping it down is repeated several times to make sure that the cell is free from any contamination.

Finally, the cell is filled with xenon and helium, one part to thirteen respectively.

A gradual drop in the pressure over few months, due to a very small leakage necessitated retopping the pressure up every six months to retain the neutron detection efficiency of the scintillator which would otherwise deteriorate.

2.5 The Neutron Detectors

The neutrons scattered in the helium gas scintillator detector are detected by two liquid scintillator detectors. The scintillators used are bubble free encapsulations of an organic liquid material type NE213, supplied by Nuclear Enterprises, Edinburgh. The scintillator has excellent pulse shape discrimination properties. These properties are effectively used
Figure 2.4 The neutron detector

- scintillator container (aluminium)
- capillary tube
- photomultiplier tube (EMI 9814B)
- brass body
- dynode chain
- pre-amplifier
- cable connectors
to reject gamma ray contributions.

Each scintillator cell is 5cm in diameter and 5cm long, optically coupled to an EMI-9814B photomultiplier tube. Figure 2.4 shows schematically the neutron detector. These two neutron detectors are accurately mounted on the rig so that the axis joining the centre of each side detector cell to the centre of the high pressure helium cell make a laboratory angle of 55 degrees with the collimated neutron beam. The distance between the gas scintillator and the liquid scintillator is 11 cm (centre to centre). These detectors have brass ring collars that can be fixed tightly to secure their exact locations with respect to the gas scintillator cell.

2.6 Target Yield Monitors

Two types of neutron detectors were employed as monitors of the neutron yield from the target. The first one being an NE400 grooved disc of boron polyester with ZnS(Ag) scintillator. This scintillator is insensitive to gamma rays and detects only thermal neutrons, therefore a shaped paraffin wax container was used surrounding the scintillator to moderate the fast neutrons for detection.

Pulses from the scintillator detector were amplified and fed into scalers displaying the relative rate of neutron production (per second), or optionally the total number of neutron counts over a certain period could be recorded. The display of the yield every second is useful when the accelerator controls are being adjusted to attain a good beam spot on the target for maximum neutron yield, whereas the total number of counts can be used for normalisation purposes.
The second type of target yield monitor (TYM) used consisted of a plastic scintillator of 5.08 cm diameter and 2.54 cm thickness coupled to an EMI 9514 type photomultiplier tube. This monitor was mainly used for normalisation purposes when 14 MeV neutron cross section measurements were being undertaken. This is because pulse height discrimination is possible with this type of detector also allowing discrimination against gamma ray background by setting the bias level to reject pulses below 12 MeV proton energy.

The TYM detectors were usually placed close to the neutron producing target and used effectively to monitor the yield of the neutrons from the target.

2.7 The Neutron Producing Target

The 14 MeV neutrons produced for polarization measurements were by means of the reaction:

\[ ^7Li + d \rightarrow ^6Be + n + 15.027 \text{ MeV} \]

The chemical form used throughout the preparation of \(^7\text{Li}\) targets has been lithium fluoride (LiF), one of the few stable anhydrous lithium compounds and therefore a convenient source for preparing targets.

Not less than 98% pure LiF compound was vacuum evaporated onto the designated area of the target holders. During this process a standard crystal oscillator inside the vacuum chamber constantly monitored the thickness of the LiF deposits, while a clean piece of slide positioned in the vicinity, receiving equal amount of LiF deposits was used later for direct measurement of the target thickness. A sensitive stylus point of a "Talystep", capable of measuring thicknesses of 20 Å, was used as a direct and accurate
measurement of the deposits also displaying a plot of the evaporated surface to convey the uniformity and smoothness of those targets.

Different designs of target holders were used, each serving a particular purpose in the experiment. Figure 2.5 shows the target assembly and various shapes of target holders used. The major part of this work was carried out using water cooled finger target holders (stainless steel), construction of which is described by Martinez[53]. These were of prime importance for maintaining a defined and stable cone of neutrons projected from the target onto the helium cell since the small rectangular area (14mm x 3mm) of the target exposed to the incident deuteron beam gave immunity against the effects of beam spot movement.

The target system as a whole was designed so that the target can be accurately located relative to the deuteron beam line and the collimator axis. Once the target system had been aligned the target holder can be removed and changed after target deterioration without the need to realign the system.

The target beam line was maintained under high vacuum (better than $4 \times 10^{-6}$ torr) with oil diffusion pumping augmented by liquid nitrogen trapping.

Air cooled target holders were designed and used for neutron cross section measurements at forward angles (0 to 70 degrees). In this target holder the bulk of the stainless steel is replaced by a thin copper disc soft soldered on a brass frame which can be mounted on the target assembly by three bolts.

Another form of target used for some measurements consisted of a LiF deposit on a threaded brass disc of 9mm radius. A number of these could be prepared with different thicknesses and areas of
Figure 2.5 The target assembly and the target holders
LiF deposits, and used as required by screwing into a water cooled holder.
CHAPTER 3
DATA COLLECTION SYSTEM

3.1 Introduction

Figure 3.1 shows a block diagram of the associated polarimeter electronics. This assembly of units forms a slow coincidence arrangement which drives routing pulses for the analysis of the helium recoils associated with different neutron scattering events. Delayed coincidences are set to simulate the conditions that give rise to events in which background neutrons are falsely identified as helium scattered neutrons (random coincidences). This is exploited for extracting the real events from a combination of real + random events.

The system incorporates pulse shape discrimination for gamma ray rejection.

Most of the electronics used (analogue & logic) were originally designed and developed by Davie[55] for earlier experiments carried out on the D-D reaction[57], These were later refined by Hall[50] achieving better resolving time for the system.

In the present work further modification has been introduced in the layout of the electronics, by replacing the energy discriminator unit of each side detector with an Ortec Timing Single Channel Analyser(TSCA), model 488. This allowed accurate selection of energy bands of output pulses identifying the detection of neutrons from the ground state group of the \(^7\text{Li}(d,n)^8\text{Be}\) reaction after scattering by helium nuclei. This modification has noticeably reduced the random counts and so in effect speeded the data accumulation process.
Table 3.1 "Key to figure 3.1"

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
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<tbody>
<tr>
<td>L</td>
<td>Left liquid scintillator detector.</td>
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<tr>
<td>G</td>
<td>Gas scintillator detector</td>
</tr>
<tr>
<td>R</td>
<td>Right liquid scintillator detector</td>
</tr>
<tr>
<td>EHT</td>
<td>Extra High Tension supply</td>
</tr>
<tr>
<td>Pa</td>
<td>Pre-amplifier</td>
</tr>
<tr>
<td>PSD</td>
<td>Pulse Shape Discriminator</td>
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<td>AMP</td>
<td>Linear Amplifier</td>
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<tr>
<td>DISC</td>
<td>Discriminator</td>
</tr>
<tr>
<td>TSCA</td>
<td>Timing Single Channel Analyser</td>
</tr>
<tr>
<td>AND</td>
<td>Triple Coincidence Unit</td>
</tr>
<tr>
<td>RAT</td>
<td>Analogue Ratemeter</td>
</tr>
<tr>
<td>DE</td>
<td>Delay unit</td>
</tr>
<tr>
<td>CODING</td>
<td>Coder &amp; Pulse Shaper</td>
</tr>
<tr>
<td>ADC</td>
<td>Analogue to Digital Converter</td>
</tr>
<tr>
<td>INT</td>
<td>Computer Interface</td>
</tr>
<tr>
<td>r</td>
<td>Routing input</td>
</tr>
<tr>
<td>l</td>
<td>Linear input</td>
</tr>
</tbody>
</table>
Figure 3.1 The Polarimeter Electronics
Logic levels, derived from a PDP11/45 computer, were used to operate an automatic control unit built by Alsorays[54] to remotely control the polarimeter rotation.

The following sections will detail the processes by which production, detection, and identification of nuclear radiation are achieved.

3.2 The Van de Graaff Accelerator (VDG)

The accelerator used as the neutron generator is by High Voltage Engineering model AN-500. It is a positive ion accelerator (used mainly for deuteron ions) capable of attaining potentials just over 500 keV. The VDG was installed in the Physics Department of Edinburgh University in the autumn of 1971 and came into use as a source of neutrons in February 1972.

This accelerator provides a magnetically analysed beam which is electrostatically and magnetically focussed on the neutron producing target, with a resolved current of typically 60 uA in favourable conditions.

A fault monitoring system devised by Hall[50] is connected to the control pannel of the VDG to give indications of any undesirable machine or beam conditions. The fault monitor can be set either to sound alarm bleeps to indicate a change of conditions or faults for the operator, or trigger a signal for automatic shut down of the accelerator during unattended periods (overnights).

The requirement of good statistics and running stability favoured the continuous operation of the accelerator, typically 5 to 10 days at a time for the present experiments.
3.3-a The Scintillation Process

The most common method of nuclear radiation detection has been through a process called scintillation. It is a response property that a number of transparent materials show when exposed to nuclear radiation. That is by emitting photons in the form of light.

A group of dielectric materials, including many of the noble gases, organic and inorganic single crystal, polycrystalline materials and organic liquids, are transparent to some part of the wavelength spectrum of the photons emitted by their excited atoms or molecules, along the path of the charged particle. These photons can therefore be viewed outside the transparent material by means of sensitive photomultipliers. The materials which exhibit this property are known as scintillators and the process as the scintillation process. The scintillations produced are converted into signals at the photomultiplier output. These signals can be fed into electronic circuits for amplification and further processing.

The first successful detection of alpha particles, protons, fast electrons, neutrons and gamma rays using a scintillator detector was reported in 1947 by Coltman and Marshall[58]. Since then, the scintillation detector has become the most versatile method for nuclear radiation detection.

The development of improved scintillators of higher efficiency, shorter resolving time and ability to distinguish between types of radiation, has taken place in parallel with improvements in the design of photomultipliers for better optical coupling, higher
quantum efficiency and better time resolution.

The theory of the process of scintillation in a variety of scintillators has been studied in detail by several authors[59,60]. In the present work the neutrons were detected using an organic liquid scintillator type NE213.

In organic materials the luminescence arises from the electronic structure of the constituent molecules. The light emission in the scintillation process has a finite rise time and the decay process consists of two components, fast (typically 2-3 nano-sec) and slow non-exponential decay over a period of a few microseconds.

When the excitation of molecules is produced by particles that result in high ionisation density in the scintillator, the number of photons emitted for a given energy deposited, is reduced. This effect is known as ionisation quenching and occurs for all organic scintillators. This mainly affects the intensity of the fast component but has little effect on the slow component. However the characteristic decay time of the two components is uninfluenced by quenching. As a result, the shape of the scintillation light pulse is changed and is dependent on the nature of the particle incident on the scintillator. Thus the quenching effect forms the basis for all particle identification techniques based on the principle of pulse shape discrimination in organic scintillators.
3.3-b Pulse Shape Discrimination

The organic liquid scintillator NE213 used in this work has the feature discussed in the last section where the intensity ratio of the fast component to the slow component, due to proton recoils from incident neutrons, is less than that due to electron recoils from incident gamma rays. Therefore discrimination between these two incident particles is possible by distinguishing the different current pulses appearing at the photomultiplier output due to the two intensity ratios.

The technique used in the present work to make the distinction, is the one commonly referred to as the zero cross over timing technique which is based on the fact that the zero cross over instant of an integrated and twice differentiated pulse from a single dynode carries information about particle identification. The time from the start of such a processed pulse to the zero crossing of the amplitude baseline is longer for neutron associated events (proton recoils) than those due to gamma events (electron recoils). Thus pulse shape discrimination can be obtained by measuring the time intervals between the origins of the pulses and their zero cross over instants, which can be converted to proportional pulse heights. A time difference of 20-30 nano-sec. can be easily obtained between the cross over of pulses produced by recoil electrons and by recoil protons.

The different stages that the pulses (taken from the 11th dynode) undergo are shown in fig.(3.2).

The circuit employed for the PSD process is shown in fig.(3.3) The linear pulse from the pre-amplifier is fed simultaneously to a linear amplifier and a PSD unit. A Single Channel Analyser (SCA)
Fig. 3.2 Pulse shapes in a zero crossing PSD system for gamma ($\gamma$) & neutron (n)
Figure 3.3 The arrangement of the electronics for pulse shape discrimination (PSD) against $\gamma$ rays.
is used to apply an energy selection to the output of the amplifier and a discriminator on the output of the PSD unit for rejecting pulses due to gamma rays. The SCA & DISC units incorporate variable delay used to synchronise the pulses entering the coincidence unit (AND). Fig. (3.4) shows typical PSD spectra from an Am-Be source before and after gamma rejection.

3.4 The Electronics

With reference to the block diagram in fig. (3.1) the arrangement of the electronic units can be outlined as follows;

Each side detector is optically coupled to an EMI 9814B type photomultiplier which in turn is connected to a proper dynode chain. The linear output is taken from the 11th dynode as the signals were found to be immune to any adverse effects that the rotation of the polarimeter might give rise to. The linear signal is fed into a pre-amplifier (pa) then simultaneously to a linear amplifier (AMP) and a pulse shape discriminator (PSD) unit, the latter being similar in principle to the one developed by Roush et al[56]. The output from the PSD unit is fed to a leading edge discriminator (DISC) which is set to reject pulses due to gamma rays and output logic pulses due to neutron events only. The AMP output is fed into an Ortec Timing Single Channel Analyser, TSCA (often will be referred to as SCA), whose window can be accurately set to accept pulse heights corresponding to any desired neutron energy, generally of those from the Ne group which have been scattered through a certain angle by the helium scintillator.

The output pulses of the DISC and TSCA units are fed into two triple coincidence units, (AND1 & AND2). The third input to each coincidence unit is derived from another TSCA unit connected to
PSD Spectrum From Am-Be Source

Ungated PSD output

Energy Gated PSD output

Gamma Peak rejected

Channel Number

Fig. 3.4
the linear amplifier of the gas detector output.

The TSCA unit in the latter case has been used rather than an ordinary leading edge discriminator mainly to achieve better resolving time for the system.

Proper adjustment of the timing allowed a resolving time of ~0.6 usec. to be attainable with this system.

AND1 is triggered by prompt pulses from all three inputs, hence designated for real + random events.

AND2 is triggered only by random events. The random events are simulated by introducing a delay of 3 µseconds, (which is longer than the resolving time of the system) to the TSCA signal of the gas detector fed into the third input of AND2 so that every time this unit is triggered, it is only due to a random event.

A delay of 3 µsec is added to the output of AND1 to bring the two coincidence outputs into the same time relation with respect to the linear helium recoil pulses.

Coincidence units AND3 & AND4 operate in a similar way as AND1 & AND2 for the other side detector.

The outputs of the four coincidence units AND1,2,3, & 4 are fed to a quad (4 unit) scaler which displays the number of events that trigger each coincidence unit. The same four inputs are fed into a coding unit that provides a gating pulse for an Analogue to Digital Converter type (256-ADC mod. 8213) made by Laben, used to analyse the helium recoil spectra. The coding unit also provides routing pulses with adjustable delays. These are fed into an interface unit (INT) which couples the data & control lines of an ADC unit to a computer which store the routed pulses (real + random and the corresponding random pulses) into selected group of channels as spectra in the memory store. The memory contents can
10/06/82 Gated He-recoil Spectra

Real + Random Events

Events Due to Randoms

Fig. 3.5
be recalled and displayed at will on a VDU (Video Display Unit) while running the experiment or after the collection of data for later treatment.

Fig.(3.5) shows typical gated He recoil spectra obtained during such experiments for neutrons scattered to "right" and to "left".

3.5 Polarimeter Rotation

Although the neutron side detectors were of identical make (construction & contents), they were by no means expected to have identical detection efficiencies. As this factor would introduce a false asymmetry into the system, the polarimeter was made to rotate in order to interchange the roles of the two detectors, so that any existing difference in their detection efficiencies would be cancelled out. In addition, the interchanging process would subsequently cancel out any instrumental asymmetries due to possible errors from the neutron detectors not being exactly equidistant from the helium cell.

The rotation of the polarimeter is governed by a control unit, details of which are given by Alsoraya[54], designed to operate a slow motor, mounted on the frame of the polarimeter. The operation of this motor is controlled by two relays, one for selecting the direction of the rotation i.e., clockwise or anticlockwise, and the other for feeding the a.c. mains to the motor. These two relays are energised by an output level from the computer, at intervals which can be set optionally through the software available for data collection.

Since a check on the freedom of the system from false asymmetry is frequently required, the modes of polarimeter
Fig. 3.6 Orientation of the detectors by rotation

L: Left neutron detector
R: Right
G: Gas (4He)

Pos. 1
L

Pos. 2
R

Pos. 3
G

Pos. 4
G

Left neutron detector
Right
Gas (4He)
rotation were made not only to interchange the position of the side detectors in the horizontal plane but also to place them in a vertical plane relative to the axis of rotation for measuring the asymmetry in that position (which should be zero). Different orientations of the detectors are illustrated in fig. (3.6).

3.6 Choice of the Scattering Angle

When utilizing $^4$He as the neutron polarization analyser, a few criteria should be considered in the selection of the scattering angle in order to reach the favourable conditions where quality data collection can be achieved.

The accuracy of the measured neutron polarization for a particular energy and scattering angle depends on how well the analysing power of helium is known for that energy and scattering angle. Extensive studies have been carried out on the elastic scattering of neutrons from $^4$He over a wide range of neutron energies, aiming to establish reliable n-alpha phase shift information from which accurate analysing power calculation could be performed. A survey of the available data, which includes measurements of the total cross section, the differential cross section and analysing power data, prior to 1973, has been made by Arndt and Roper[73,74]. Later a similar survey was also made by Bond and Firk[75].

Although the determination of the n-alpha scattering parameters has in the past (as those of Hoop and Barschall[9]), tended to rely on the p-alpha scattering data, being both more abundant and more accurate than the corresponding neutron scattering parameters, they were supported to a large extent by later n-alpha
scattering experiments. A survey of this work can be found in reference[76]. However, because of the complex manner in which the phase shift angles are interrelated, it was difficult to estimate the accuracy to which they and in turn the analysing power were known. Estimates of the uncertainty in the analysing power of helium were made by comparing values of calculated analysing power from various sets of phase shifts that fitted the experimental n-alpha scattering data and observing the differences in those fits [57].

A more accurate approach to calculate the analysing power of $^4$He has been performed by Bond and Firk[75] whose recent studies provided n-alpha scattering data for neutrons below 21 MeV. Using R-matrix formalism and analysing only the precision n-alpha data available, they obtained a self consistent set of phase shifts which were based on the neutron data alone.

The n-alpha analysing power data of Bond and Firk[75], are plotted in figure 3.7 for neutron energies of 3, 5, 7 and 14 MeV. The corresponding R-function calculations of the n-alpha differential cross section for the same neutron energies are shown in figure 3.8.

The uncertainties in the R function calculations of the n-alpha analysing power were derived from the covariance matrix given in ref.[75]. For neutron energies above 10 MeV the uncertainty of the analysing power calculation is slightly larger for the scattering angles between 80° to 105° lab where the polarization changes rapidly from large negative values to large positive ones. The analysing power in this region is very sensitive to the values of the phase shifts and not fully assisted by the available data. However, the precision of the analysing power at 14 MeV, which
Analysing Power of He-4

En=14 MeV

En=7 MeV

En=5 MeV

En=3 MeV

Angle in C.M. system

Fig. 3.7
03/08/62 n-He4 differential cross section

Differential Cross Section (mb/sr)

Angle (degrees) C.M. system

En = 3 MeV
En = 5 MeV
En = 7 MeV
En = 14 MeV

Fig. 3.8
this work is concerned, is superior to any of the previously published values, and the attached uncertainties at their worst are in the order of 1%.

Excellent reviews of the general R-matrix theory can be found in references [77] and [78].

A second criterion to be considered in the selection of the scattering angle is the rate at which information may be gathered. In an ideal situation, where a polarimeter is assumed to have a point scatterer and side detectors of small but finite size, for a given incident neutron flux of polarization $P$, ignoring background and counting for equal periods to the "right" and "left" with each side detector, the time to reach a given statistical accuracy $\Delta P$ in the measurement of $P$ is proportional to;

$$\frac{1 - P^2 P^2}{P^2 \delta(0)_{\text{Lab}}} \frac{1}{(\Delta P)^2}$$

\hspace{1cm} \ldots \ldots (3.1)

where $\delta(0)$ is the differential cross section for the scattering of unpolarized neutrons from $^4\text{He}$ through an angle $\theta$ in the laboratory frame. If the solid angle subtended by the side detector at the scatterer is kept constant, but $\theta$ the scattering angle is varied, the position of fastest data collection will occur for

$$\{1 - P^2 P^2 \frac{\delta(0)}{P^2 \delta(0)_{\text{He}}}\}$$

a minimum. In comparing two angles for fast data collection the numerator of expression (3.1) will vary little even for high $P^2$. Thus the denominator provides a convenient figure of merit, the maximisation of which will be a good guide to fast data collection.

This figure of merit is plotted in figure 3.9 using the analysing power and the differential cross section data of Bond.
Fig. 3.9
and Firk[75] for four neutron energies. The analysing power and the differential cross section data were converted from centre of mass system to the laboratory frame and plotted in figures 3.10 and 3.11, respectively.

It is evident from figure 3.9 that data accumulation for 5 and 7MeV neutrons will be substantially faster if scattering at the forward angle (corresponding to the peak) is employed. For the 3 MeV energy there is only a marginal difference between the forward and the backward scattering peaks, so there is little to choose between the two, hence, other relevant aspects or circumstances might be considered before favouring one or the other angle for fast data accumulation. The accuracy at which the analysing power of helium is known at either of the angles can be one aspect.

At 14 MeV the forward scattering angle shows a faster rate of data collection though not by so significant a factor as at 5 & 7 MeV. However, the peak at the forward angle does show a flat plateau which allows a wider choice of angles and obviously preferred to that of the backward scattering peak which shows relatively a narrow peak.

When considering the rate of data collection in a real polarimeter system, account should be taken of the finite dimensions of the scatterer and side detectors, and the resulting spread in the scattering angle.

With the polarimeter described in the present work and after considering the limitations of the flexible side detector mountings, a mean laboratory angle of 55 degrees was chosen to analyse the 14 MeV neutrons scattered by helium, being both a position of fast data collection with well defined analysing power and where the side detectors could be mounted for best protection.
24/06/82  Analysing Power of He-4

En=14 MeV

En=7 MeV

En=5 MeV

En=3 MeV

Lab Angle (degrees)

Fig. 3:10
Fig. 3.11 n-He4 differential cross section

- En = 3 MeV
- En = 5 MeV
- En = 7 MeV
- En = 14 MeV

Differential Cross Section (mb/sr) vs. Lab. Angle (degrees)
by the shadow iron shields.

### 3.7 Software for Data Collection

Several programs were available to operate the system and treat the collected data. These programs were written in a modified form of "IMP" language then compiled to machine language compatible with the computer in the Department of Physics (PDP 11/45 Digital Equipment Corporation). The programs were stored in the computer disc to be utilised for performing the experiments when required, with full and reliable control by the computer. The programs used are as follows:

A versatile Pulse Height Analysis program for collecting and displaying various spectra. This program could be run either separately for ordinary pulse height analysis or be invoked while running the experiment on asymmetry measurements, to monitor the spectra accumulation (useful for preliminary checks on the behaviour of the system).

The second program was written for asymmetry data collection, This program initiates the collection of data after defining certain modes of operation, these are:

**a:** The number of ADC units to be invoked for data collection (although one ADC unit was used in the experiments, a second ADC unit could have been optionally used to collect routed spectra from an extra pair of side detectors if necessary).

**b:** The running period required for the measurement with the polarimeter cradle held at each one of the four positions as in fig.(3.6).
The sequence of the cradle positions (defining a cycle) repeated if more than one cycle is required, and terminated by figure 0.

d:- The run number for identifying particular data (useful for tracing the sequence or concatenation of separate data).

e:- The name of the output file containing the accumulated data from a complete cycle of runs.

The program creates two output files after the end of a selected running cycle, the first file contains the individual sections joined together, each corresponding to a particular cradle position and identified by the run number and cradle position number. The second file is the sum of all the data accumulated after a completed cycle of runs, containing all the routed spectra i.e. real + random and the corresponding random events, as in fig.(3.5).

The first output file is manipulated by a third program which adds up the corresponding data for each cradle position and then subtracts the random events from the real + random events to deduce spectra due to real events only. A new file is therefore created containing four sections, each corresponding to the sum of the data resulting after several runs at a particular cradle position. Each section is identified by a cradle position and the last run number, i.e. the first section contains the sum of the real events from all the runs collected with the cradle at position 1, similarly the second section contains the sum of the data for position 2, and so on....

The output file from the third program becomes an input file for
a fourth program which calculates the asymmetries and their standard errors over selected channels. The spectra due to real events can be viewed by running a fifth program which creates a file suitable for displaying on the VDU (Tektronics) by calling on the pulse height analysis program.

The analysis of the data will be detailed in chapter 5.
4.1 Introduction

This chapter details the experimental procedure employed in the present measurements, which includes the alignment of the system, setting-up of the electronics and gain stability measurements on the neutron detectors. A demonstration of the accuracy and satisfactory performance of the system is made using neutrons from two well known reactions, namely the D-D and the D-T reactions.

All the necessary measures taken to avoid the sources that give rise to false and instrumental asymmetries are discussed, as well as methods to remedy their possible contribution to the data. A typical asymmetry measurement process with neutrons from the \( ^7\text{Li}(d,n)^8\text{Be}\) g.s. is described with emphasis on the energy band selection procedure to exclude contributions from the 2.9 MeV excited state neutron group. The measurements made on this reaction are compared with similar measurements done with neutrons from the D-D reaction, pointing out all the existing differences.

4.2-a Target and Polarimeter Alignment

In order to make reliable measurements of asymmetry in the scattering of neutrons, the polarimeter system should be accurately aligned with respect to the collimated neutron beam from the target. Every effort has been made to meet this essential requirement to avoid the introduction of false asymmetries.
Having the collimator levelled correctly with the deuteron beam line, the target was located in the right position by manipulating the three adjustable bolts on the target assembly until the centre of the target came in line with the axis of the collimator aperture. This was optically aligned using two cylindrical polythene inserts, each with an axial hole of 2mm diameter, fitted inside the collimator opening, one at each end. A telescope placed about one meter from the polarimeter viewed the axis of the neutron collimator. The target was positioned so that its centre came into line with the cross-hairs of the telescope.

The polarimeter in which the rotatable cradle sits, was aligned by a similar method using a pair of aluminium inserts made to fit the centre holes of the cradle discs. The vertical and horizontal positioning of the polarimeter was adjusted so that the centre holes of the polarimeter inserts were in line with the centre holes of the collimator inserts.

Once the axis of the polarimeter was aligned with the axis of the collimator, they were securely fixed so that the axial alignment of the system would not be distorted. The target alignment thereafter, each time a fresh target was fitted, has been performed using two inserts only, one placed in the collimator aperture and the other in the centre hole of the rear cradle disc and viewed by the telescope.

Optical alignment using the above method, allowed an accuracy better than 0.5mm for the system. In order to maintain this accuracy for all the measurements, the alignment of the system was checked for every alteration of polarimeter angular position, or when the targets were replaced after deterioration.
4.2-b Alignment of the Detectors

Proper alignment of all the detectors inside the rotatable cradle is equally important to avoid instrumental asymmetries which could otherwise occur and contribute to the measurements. Therefore, the helium detector was positioned so that the centre of the gas scintillator cell was located on the rotation axis of the cradle. The neutron detectors were mounted at equal scattering angles ($55^\circ$) and distances (5.8 cm) from the helium cell. Any false asymmetries introduced due to the side detectors not having equal efficiencies, would be evened-out when their roles are interchanged by rotation. The locations of all the detectors were marked using the ring collars as described in chapter 2. These helped to relocate the detectors in their exact positions when they were removed for any reason. This feature was especially useful for the helium detector as it was frequently removed to clear the axis view for target alignment.

4.3-a Setting of the Electronics

Prior to making any asymmetry measurements, several neutron spectra were collected with 3 MeV and 14 MeV neutrons to check the proton recoil response of the NE213 detectors. The neutron detectors were then calibrated with gamma sources to allow correct threshold settings, so that only relevant neutrons would be selected for data collection and processing, while events due to gamma rays were excluded using the PSD technique.

Figure 4.1 shows a typical proton recoil response of the NE213 detectors to 14 MeV D-T neutrons emitted at $75^\circ$ lab. Neutrons from the D-D reaction, which occurs due to the pile-up of
Fig. 4.1

14.6 MeV D-T neutrons

2.76 MeV D-D neutrons
deuterons from the beam on the target, are also present and show a significant contribution to the low energy part of the spectrum.

The procedure for calibration and appropriate energy band selection is outlined in the following.

With a Sodium-22 gamma source placed near each of the two liquid NE213 scintillators, the linear output of the corresponding amplifier was pulse height analysed to assess the gain of the photomultipliers by tracing the Compton edges for the 0.34 and 1.07 MeV recoil electrons. Preliminary adjustments were made to obtain equal P/M gains by varying their high voltages until this was achieved. The spectra obtained through pulse height analysis were verified by overlapping to confirm the achievement of gain equality. This is illustrated in figure 4.2.

The linearity of the P/M gains were further checked using higher energy gamma rays (2.61 MeV). Any noticeable gain difference was corrected by fine adjustment of the voltage supplies.

{ The 2.61 MeV gamma source was prepared in the radiation laboratory using an isotope of Thorium(Th-228), from which Pb-212 is formed through successive alpha emissions. As Pb-212 is a beta emitter, therefore the ionised atoms are attracted onto flat metallic surfaces to form deposits of Pb-212 by simply applying a high negative potential to the metal. Pb-212 decays into Bi-212 (Bismuth) by beta emission and the latter into Tl-208 (Thalium) by alpha emission. Tl-208 provides gamma rays of 2.614 MeV energy, which are useful for calibration purposes and the compton energy (2.39 MeV) was actually utilised for that specific purpose throughout all energy calibration procedures.}

The neutron detectors were then calibrated for electron recoil
Channel Number

Number of Counts

Compton Edges with Scint. "R"
Compton Edges with Scint. "L"

Spectra Overlapped
Compton Edges Coincide

Fig. 4.2
response using the Compton edges (0.34, 1.07 & 2.39 MeV) as reference points of known recoil electron energies. Typical spectra used for calibration are shown in fig. 4.4a. This energy calibration of the detectors was used, with due allowance for the difference in the response of the NE213 scintillator to electrons and protons[62], to set the single channel analyser (SCA) associated with each neutron detector.

The exact energies of the two neutron groups, due to the ground state (No) and the 2.9 MeV first excited state (N1) of $^8$Be were calculated through the kinematics of the nuclear reaction[61].

Figure 4.3 shows the energy angular dependence of the two neutron groups (No & N1) emitted from the reaction for incident deuteron energies from 50 to 500 keV in 50 keV steps. Allowance was then made for the degradation in energy due to elastic scattering by helium nuclei through a mean angle of 55° lab. This was found to reduce the incident neutron energy by 20%.

Using the light output response curves for proton and electron recoils available for the liquid NE213 scintillator[62,63,64], the equivalent energies were determined for recoil electrons to set the window edges of the TSCA unit of each detector at the corresponding channels as deduced from the energy calibration curves (fig.4.4a).

The window settings were further checked with proton recoil spectra collected with the NE213 detectors. Recoil proton spectra were obtained with neutrons from the $^7$Li(d,n)$^8$Be reaction, to observe the portion of the spectrum allowed by the SCA settings. The proton recoil response data, for the NE213 scintillator published by Verbinski et al[79] was used as a reliable reference
Fig. 4.3

Energy Distribution of No & N1 Groups

Lab Angle (Degrees)

Neutron Energy

Ed = 500 KeV

500 KeV

No

14.8

14.3

13.8

13.3

12.8

12.3

11.8

11.3

10.8

10.3

9.8

0  20  40  60  80  100  120  140  160  180
Na-22 & TI-208 gamma sources
Recoil electron energy (MeV)

Fig. 4.4a
NE213 Response to protons

Estimated error = 2% (for $E_p=0.3$ to 20 MeV)

Fig. 4.4b
for converting proton recoil energies into equivalent neutron energies (fig. 4.4b).

The width of the selected energy bands (about the calculated mean energy of the No group after scattering by helium) was chosen to be 1 MeV (neutron energy) for the forward angle measurements and about 0.8 MeV for the backward angles. This was seen as an optimum choice (for the present geometry of the detectors) whereby asymmetry data for the No group could be accumulated, though inevitably at a slower rate, but with confidence that the contribution of the Ni group would be excluded.

A pictorial illustration of the above statements, regarding the selection of an uncontaminated part of the "No" group for analysis, is presented in figures 4.5 to 4.9, where due considerations are made to all the aspects which contribute to the energy spread and cause partial overlap of the two neutron groups. It is here that the ~3 MeV difference in energy between the two neutron groups, becomes a significantly useful feature, allowing for the spread, yet leaving enough (uncontaminated) portion in the spectrum to be selected for analysis.

Figure 4.5 shows the energy angular dependence of the No & Ni groups emitted from the reaction for incident deuterons of 450 keV energy. A mean spread of 165 keV accompanied the neutron energy distributions (fig. 4.6), due to the target thickness (6 microns of LiF).

Figure 4.7 shows the energy distribution of the two groups after elastic scattering by helium, (denoted as No' & Ni') through a mean angle of 55° lab. (dashed curves) and the corresponding absolute maximum spreads about the mean energy, due to the finite
06/06/82 Energy distrib. of No & N1 groups

Ed = 450 KeV
Energy spread due to target thickness

Fig. 4.6

Neutron Energy (MeV)

Lab angle (Degrees)
Energy spread due to finite angle

Fig. 4.7
angle (+/−13°) subtended by the neutron detectors on the helium cell, indicated by solid lines. The selected 1 MeV band in the No group about the mean energy is illustrated in fig. 4.8, so that we need not be concerned about the spread in the No group but pursue those that occur in the Ni group.

Since the capability of the detectors to separate the two neutron groups, No & Ni, depends on the energy resolution of these detectors, the finite resolution introduces in effect another factor for energy spread.

The energy resolution of each neutron detector was determined from the proton recoil spectra (fig. 4.1) obtained with 14.6 MeV neutrons emitted at 75° lab from the D-T reaction.

A typical energy resolution of 1.6 MeV at full width half maximum (fwhm) was deduced for the neutron detectors at that energy, using the proton response curves for NE213 scintillator[79] and the data provided in figure 4.1.

The energy resolution of the NE213 detector is expected to be better than 1.6 MeV for lower energy neutrons (less than 14.6 MeV), as the resolution improves rapidly with decreasing neutron energy. Therefore the 1.6 MeV value, though quoted in our illustrations, is actually an exaggerated (worst possible) value of the detectors resolution for relevant (lower energy) neutrons, i.e. for the Ni group.

When considering an absolute maximum spread (1.6 x 2 = 3.2 MeV) about the mean energy of the Ni group, due to the finite resolution of the detector, plus a maximum spread of 1.74 MeV due to the finite angle subtended by the side detectors on the helium cell, we deduce a root mean square value (rms) of 3.64 MeV as the absolute maximum spread, (figure 4.9).
Energy spread due to finite angle

Fig. 4.8
NI Energy spread due to finite angle
&
Energy resolution of the neutron detectors

Fig. 4.9
It is evident from figure 4.9 that the 1 MeV band width selection in the No group keeps it clear (by a small margin) from any interference from the N1 group, even for these assumed extreme conditions.

A fairly acceptable approach to the situation can still be made when the fwhm values are considered rather than the absolute maxima. Therefore, a summary of the main aspects leading to energy spreads in N1 group are listed below, together with the effective values of energy spreads:

a)- LiF target thickness : (0.165 MeV).

b)- The finite angle(+/− 3.1°), subtended by the helium cell on the target : (0.0011 MeV).

c)- The finite angle(+/−13°) subtended by the side detectors on the helium cell : (0.87 MeV).

d)- Detector resolution at fwhm : (1.6 MeV).

The rms value of the total = 1.83 i.e. +/- 0.91 MeV fwhm spread about the mean energy of N1. This is shown in figure 4.10.

Hence, the 1 MeV energy band selection ensured the exclusion of all the unwanted neutron events but allowed those from the ground state group after scattering by helium to be processed.

The photomultiplier gain of the helium gas scintillator detector was adjusted using incident neutrons from the $^7\text{Li}(d,n)^8\text{Be}$ reaction, (or neutrons from any reaction undergoing asymmetry measurements). The output of the linear amplifier was pulse height analysed and the gain of the P/M assessed by setting the high voltage supply such that the recoil helium spectrum occupied 128 channels. The peak expected from the gated helium recoil
Energy spread due to finite angle

Fig. 4.10
spectrum would appear within the 128 channels.

After adjusting the timing requirements of the electronic set-up described in section 3.4, the system was therefore set ready to commence asymmetry measurements on neutrons from the $^7$Li(d,n)$^8$Be g.s. reaction.

Asymmetry measurements were also performed on neutrons from the D-D and the D-T reactions following the same procedure outlined above, except for the energy band selection, as the kinetic energy of the neutrons emitted vary according to the kinematics of each nuclear reaction.

Figure 4.11 illustrates a typical gated helium recoil spectrum obtained with neutrons from the D-D reaction emitted at a reaction angle of 45° lab. The incident deuteron energy for that particular measurement was 390 keV and the scattering angle 120° lab. The Spectrum comprises a prominent peak and a low energy tail which extends under the peak.

The energy band width was found to have a direct effect on the extent of the (unpolarized) tail presence in the spectra. This fact was actually utilised later for the 14 MeV polarization data collection. The significance of the tail presence will be clarified in the sections that follow.

4.3-b Gain Stability of the Neutron Detectors

Although the set-up of the electronics associated with the neutron detectors are the same, these detectors are not expected to have identical detection efficiencies, (the efficiency being determined by the P/M gain, the PSD discriminator threshold and the energy band selected by the TSCA unit connected to the linear amplifier of each detector). This effect which causes false
Gated Recoil Helium Spectrum

Fig. 4.11
asymmetries is cancelled out by interchanging the positions of the detectors. It is essential however that the gains of the P/M tubes remain unaltered when the polarimeter rotates to interchange the positions of the detectors, otherwise the small factor of false asymmetry expected would be enhanced by rotation rather than be cancelled-out.

The gain stability of each neutron detector was periodically tested by fixing a Cobalt-60 gamma source between the two side detectors. With the polarimeter in position 1, pulses from the linear amplifier of detector "R" were analysed for 900 seconds (using accurate clock pulses from the computer) and the accumulated spectrum stored in the memory of the computer. The polarimeter was signalled to rotate automatically and stop at position 3. Another spectrum was collected with detector "R" (now at position 3) for the same time interval. The spectra collected for the two positions were compared by total overlapping. The same procedure was carried out for detector "L".

No gain shifts were observed at any time during these tests, demonstrating the absence of any drifts in the P/M gain.

Figure 4.12a illustrates a typical set of spectra collected with each side detector in both positions. Figure 4.12b shows the spectra from position 3 superimposed on those obtained from position 1 for each detector.

Asymmetry values obtained from these tests over 60 channels, with the lower integration limit taken from channel number 41, were found to be around;

$$0.0012 \pm 0.001$$

With the lower integration limit taken from channel 90 (fig.4.12b), corresponding to a compton (electron recoil) energy
Gain Stability (Neutron Detectors)

"L" detector in pos.3.

"L" detector in pos.1.

"R" detector in pos.3.

"R" detector in pos.1.

Channel Number

Fig. 4.12 a
Gain Stability (Neutron Detectors)

Fig. 4.12.b
of 1.12 MeV (~3.5 MeV neutrons), and an upper integration limit at channel 110, the asymmetry value was found to be:

\[ 0.008 \pm 0.002 \]

The integration limits (channel 41 to 100), are directly relevant to the energy level settings in the asymmetry measurements performed with 3 MeV neutrons from the D-D reaction. There, the upper level energy threshold of the side detectors were set at approximately 3.5 MeV neutron energy (channel 90). The integration limits taken a fraction more than this energy level setting, (20 channels beyond channel 90), depicts the asymmetry at a slightly higher energy setting.

Judging from these small values one can conclude that no gain shifts occurred in the neutron detectors by rotation of the polarimeter and the small asymmetry values quoted above are negligible, being significantly smaller than the statistical accuracy associated with the measured polarization.

4.4 Accuracy of the System

Before commencing asymmetry measurements with the \(^7\text{Li}(d,n)^8\text{Be}\) g.s. reaction it was decided to check the satisfactory performance of the polarimeter system with a known source of polarized neutrons, namely the D-D reaction. Since both, the energy and angular dependence of the neutron polarization are well established for this reaction\(^{[14,15,16]}\), it provided useful means of determining the accuracy of the polarimeter system and hence reflect the reliability of the collected data.

A reaction angle of 45° lab. was chosen to perform the
measurements and incident deuteron energy of 460 keV to bombard a water cooled Ti-D target (Titanium Deuteride). The electronics were set as described in section 4.3—a with the exception of the energy band selection, since the neutrons emitted from this reaction are monoenergetic (~3 MeV), and not complicated by any excited state groups. The energy thresholds of the side detectors were set using as reference points the Compton edges of 0.33 and 1.07 MeV recoil electron energies. With the lower level discriminator (LLD) of the TSCA unit of each side detector set to reject pulses lower than 0.33 MeV recoil electron energy (~1.5 MeV proton recoil) and the upper level discriminator (ULD) set to reject pulses over 1.1 MeV recoil electron energy (~3.5 MeV proton recoil), only pulses between these two thresholds were processed (although the neutron energy was not expected to reach 3.5 MeV at that particular angle since the Q-value is only 3.2 MeV for the D-D reaction).

The scattered neutrons were detected in coincidence with the helium recoils and the polarization $P_n$ was determined from the asymmetry of scattering in the plane of the reaction (horizontal plane) through $55^\circ$ lab, a $P_n$ value of;

$$-0.142 \pm 0.023$$

was obtained. This value was compared with that obtained by Hall[50,16] for the same reaction angle and incident deuteron energy, and found to agree quite well within the statistical accuracy of the measurements, the $P_n$ value being;

$$-0.151 \pm 0.012$$
Measurements in the scattering plane normal to the reaction plane were also made as a test for instrumental asymmetries, which was found to be:

\[ +0.004 \pm 0.020 \]

The asymmetry data which the above polarization values were deduced from, have been corrected for both, random event contributions and contribution of the low energy (unpolarized) tail under the peak region of the gated helium recoil spectrum.

The random events are due to the background neutrons that are accidentally detected in the NE213 scintillators within the coincidence resolving time of the detection of a helium recoil whose scattered neutron is not itself detected by one of the NE213 scintillators. The delayed coincidence arrangement within the system (described in chapter 3) simulates their contribution to accumulate spectra that are caused by those random events. These are subsequently subtracted from the corresponding gated spectra comprising real + random events, to obtain real scattering events only.

The amount of random scattering contribution to the data depends on many factors, e.g; the background neutron level, the energy bias level setting of the detectors and the time resolution of the coincidence system arrangement. The random contributions could reach up to one or two percent of the real scattering events depending on the above conditions.

Figure 4.13 shows gated helium recoil spectra with neutrons from the D-D reaction scattered to the left and to the right (after subtraction of the random events from the real + random events) i.e. real left and real right and two spectra showing the
Gated He-4 spectra with D-D Neutrons

Fig. 4.13
summation of the real events from left and right scattering. One of these is used to extrapolate a plausible shape of the tail falling under the peak (to deduce a correction factor) after observing the asymmetry value distribution which is plotted along the other identical spectrum. This is based on the fact that the tail extending under the peak region causes a noticeable reduction in the asymmetry values as will be seen in section 4.5.

After confirming the satisfactory performance of the system with the D-D neutrons, a series of asymmetry measurements were made on the 14 MeV neutrons from the $^7\text{Li}(d,n)^8\text{Be}$ g.s. reaction. The encouraging results, (which showed some high polarization magnitudes), were stored in the computer's memory after analysis.

It was deemed necessary to carry out further tests on the polarimeter system, this time with more comparable energies, utilising the unpolarized neutrons emitted from the D-T reaction. A 14 MeV monoenergetic neutron beam provided from this reaction served as an accurate probe to investigate the freedom of the system from any misleading false asymmetry contributions which might have passed unnoticed with the previous test, as the D-T neutrons would be submitting the entire system, including the shielding arrangement, to a comparable situation in so far as the energy is concerned, to that obtained from the $^7\text{Li}(d,n)^8\text{Be}$ g.s. reaction.

A neutron emission angle of 75° lab was chosen to make the asymmetry measurements at, with incident deuterons of 300 keV. The electronics were set as described before. The energy thresholds of the TSCA units of the neutron detectors were set to accept the expected energy of the scattered neutrons. Since the emitted neutrons from the D-T reaction are monoenergetic, the
energy band width selection is not as critical as for the \(^7\text{Li}(\text{d},\text{n})\ ^8\text{Be}\) reaction. Therefore a band width of \(-3.5\) MeV was selected with the LLD and the ULD of the TSCA units to hasten the data accumulation process without introducing any significant changes to the quality of the measurements.

After 12 hours of asymmetry data accumulation, a \(P_n\) value was calculated to be:

\(-0.006 \pm 0.016\)

This near zero polarization obtained for the D-T neutrons, is in accordance with the observations done on the neutron polarization from the D-T reaction with low energy deuterons\([65,66]\). This demonstrated conclusively the accuracy and the capability of the polarimeter employed to perform asymmetry measurements on 14 MeV neutrons to fulfill the objective of this thesis.

Figure 4.14 shows the gated helium recoil spectra with neutrons scattered to the left and to the right, from the D-T reaction after correction for random event contributions which constituted one percent of the total spectrum. The last two spectra are the sum of the left and right scattering events, as for the D-D reaction, plotted to extrapolate graphically a tail configuration on one, for assessing the correction factor "\(F\)" required to the asymmetry data. The slope of the falling tail is judged by observing the asymmetry variation along integrated sections of the spectrum, as illustrated in the last section of fig. 4.14.

The tail contribution and the corrections needed are detailed in the next section.
Gated He-4 spectra with D-T Neutrons

Fig. 4.14
4.5 The Unpolarized Tail Contribution

The presence of the low energy tail in the gated helium recoil spectra as seen in figures 4.11, 4.13 & 4.14, has been attributed to neutrons scattered both from the helium and by the solid material surrounding the helium scintillator (in either order) before being detected by the liquid scintillators [70]. Similar tail contributions have been observed before [69], and discussed in detail by Davie [55,67] and by Maayouf [68], where various tests have been carried out to simulate the conditions which give rise to such a background tail effect. Modifications were introduced to minimise this effect by changing the orientation of the gas detector with respect to the collimated neutron beam to reduce the bulk of the solid material in front of the incident neutron flux which may cause excess background scattering.

The contribution of this unpolarized tail (which shows zero asymmetry) to the asymmetric peak has to be accounted for, in order to correct the errors introduced in the asymmetry measurements. This is usually done by extrapolating manually plausible shapes of the tail falling under the observed peak. A Monte Carlo program used by Davie [67] to simulate the formation of the unpolarized tail (following the main routes of neutron scattering), had shown similar tail shapes to those obtained through the experiments. However, one could not rely completely on such simulated spectra when extrapolating the experimentally observed tail since several approximate assumptions were made in the program and contributions of neutrons scattered through other possible routes were ignored (e.g. scattering from the cradle and the brass body of the side detectors).

Thus, a manual extrapolation to the tail seemed then to be a
more realistic method of estimating the fall of the tail under the peak.

The method of tail extrapolation is actually based on observation of the asymmetry value distribution along the recoil helium spectra due to neutrons scattered to the left and to the right. This is exemplified using the data of figure 4.11, where asymmetry calculations made over an area of the recoil spectrum between points A&B, B&C and A&C shown in figure 4.15, where A, B and C represent the midpoint of the low energy edge of the peak, the summit and the midpoint of the high energy edge of the peak, respectively. The results of these calculations showed that the asymmetry values (before corrections), taken between these points agree within the statistical accuracy, although the value between points (A&B), nearest the tail, is slightly lower. These asymmetries are listed below:

\[-0.097 \pm 0.013\] between (A) and (B)
\[-0.108 \pm 0.012\] between (B) and (C)
\[-0.104 \pm 0.009\] between (A) and (C)

A more elaborate analysis of the asymmetry variation along the recoil spectrum is illustrated in figure 4.16. The first section of the plot shows the asymmetry variation over the whole recoil spectrum with an increase of 4 channels to the lower limit of the integration, and the second section of the plot shows the behaviour of the asymmetry along the same recoil spectrum in groups of 10 channels with an interval of 5 channels between two successive groups. In the first section, the effect of the tail on the results is evident from the low asymmetry values under the tail region. In the other section of the plot the asymmetry
Fig. 4.15
"Real" (Left + Right) Asymmetry variation

Fig. 4.16
values under the tail region are close to zero within their statistical accuracies. Thus the tail shows no polarization and is attributed to neutrons scattered by helium and by the surrounding material (in either order), before being detected by the liquid scintillators. The asymmetry values show a steady rise as they are scanned further from the tail and valley region and reach a consistent higher value under the peak, indicating that the tail falls rapidly under the peak, as the extrapolation shows in figure 4.15.

The asymmetry data obtained on the D–D and the D–T neutrons were corrected by extrapolating the tail beneath their respective peaks, in a similar method (see figs. 4.13 & 4.14).

The correction factor "F" is deduced as follows; If T is the number of counts in the area between the selected limits under the extrapolated tail i.e. the area under curve DE, associated with the left and right scattered neutron events combined, and R is the total number of counts between the same limits, in the recoil spectrum associated with the left and right scattered neutrons combined, then the factor;

\[ F = \frac{R}{R-T} \]

is the correction factor for the unpolarized tail contribution, by which the asymmetry (between points A&C) should be multiplied to obtain the correct value.

The asymmetry values are usually assessed from an area of the recoil spectra starting from a few channels after the midpoint (A) of the low energy edge of the peak to a few channels after the midpoint (C) of the high energy edge of the peak in order not to
lose much of the statistical accuracy while avoiding those parts of the spectrum where the asymmetry is obscured by the presence of a larger portion of the unpolarized tail and those with substantial statistical uncertainties.

During the course of such experiments, it was noticed that the presence of the low energy part of the tail was dictated to a large extent by the energy settings of the TSCAs associated with the neutron detectors, so that when a relatively narrow band was selected, the tail was substantially reduced and the resolution of the recoil peak improved. This is clearly illustrated in figure 4.17, where the helium recoils for D-T neutrons were gated with different energy band widths. However, the elimination of the prominent part of the tail was not favoured as that would have led to inaccurate extrapolation beneath the peak. Furthermore, as far as the monoenergetic neutrons from the D-D and the D-T reactions were concerned, the energy band width was not very crucial, and the tail presence did not hinder the calculation of the asymmetries, in fact it helped to estimate correctly the fall of the tail under the peak.

In the asymmetry measurements performed on the 14 MeV neutrons from the $^7\text{Li}(d,n)^8\text{Be}$ g.s. reaction, the tail showed negligible contribution in the gated helium spectra. This was directly attributed to the narrow band settings of the energy thresholds for each neutron detector necessary in selecting the appropriate group for the measurements. Figure 4.18 shows a typical group of helium recoil spectra of real + random events with their corresponding random events plotted directly beneath them.

It is clearly evident from the low energy part of the peak that the unpolarized tail has virtually disappeared. The random
Tail contribution for two energy settings

3.5 MeV band

2.0 MeV band

Fig. 4.17
Fig. 4.18
events, now less than 0.5% of the real events, have also been substantially reduced under the peak region as compared with over 1% in the previous measurements, namely with the D-D & D-T reactions.

These features eliminate the uncertainties associated previously with the tail and the errors that might result from the estimate of the tail correction factor "F".

The absence of the tail implies that those neutrons which were scattered first by the solid surrounding material then by helium before entering the side detectors were rejected because of the high energy threshold level setting of the LLD. The neutrons which scattered first by helium and then suffered further energy degradation by scattering in the surrounding material, before entering the side detectors were also rejected for the same reason.

Conversely, when high energy neutrons had suffered little energy loss after scattering by helium, yet entered the neutron detectors because of their finite angles subtended on the helium cell, they too were ignored because of the ULD setting of the SCA units. The few counts observed in the expected tail region (fig.4.18) are due to the allowance of the energy band width fixed between the LLD and the ULD to select the Nø group neutrons.

As for the reduction in the random events under the peak region, it is attributed to the restrictions imposed by the band width at high energies which in effect reduces the probability of occurrence of such events being recorded by the coincidence arrangement. The few counts near the lower energy part of the peak were due to high energy background neutrons allowed by the band width to be recorded.
The advantages observed however were undoubtedly accompanied with the disadvantage of a very slow data accumulation rate. This necessitated long experimental running periods to reach reasonable statistical accuracies.

4.6 Data Collection and File Handling

The approach to the data collection was directed by certain experimental constraints. As described previously, the arrangement of the electronics allowed data collection in the form of four gated helium recoil spectra routed into a 512 channel array of the computer memory. These spectra contained information about neutron events due to;

1- "Real + Random" scattering to the "left"
2- "Real + Random" scattering to the "right"
3- "Random" scattering to the "left"
4- "Random" scattering to the "right"

Separate records were kept for each individual run until a complete cycle of runs was completed, containing information on all the different positions of the detectors due to rotation. Conditions of the stability of the accelerator and the electronics decided the run time, normally 7,200 to 10,800 seconds per run over a period of 24 hours for 5 continuous days or longer at some angles until a reasonable accuracy was achieved.

The programs used for data file handling were described earlier in chapter 3, and are mentioned briefly again for clarity. The first program creates summing files for the accumulated
spectra of different polarimeter orientations. These are used to make decisions about sets of data collected under different machine conditions. Other programs enable the subtraction of the random events from the real plus random events to obtain the Real spectra, also enable comparisons of the real spectra for left and right scattering for asymmetry calculation by integration over the whole recoil spectrum or over areas between selected limits.

The spectra could be displayed or monitored while running the experiments on a Video Display Unit (VDU) available in the neutron physics laboratory coupled with the PDP-11/45 computer.

4.7 Running the 7Li(d,n) Reaction

Reliable and steady data collection required stable accelerator running conditions. These conditions were met through continuous operation of the Van De Graaff machine while maintaining the beam lines under good vacuum pressure by regular topping up of the nitrogen traps over the diffusion pumps. Pressures down to 10^-6 Torr were typically obtained before running the 7Li(d,n) 8Be reaction.

An average of 20 μA deuteron beam current was maintained on the LiF targets as a compromise between the rate of neutron production for fast data collection and the need to preserve the lithium fluoride, which is a fairly vulnerable chemical target, to endure the long bombarding periods for steady and uninterrupted data accumulation.

The beam spot on the target was controlled by fine adjustments of the quadrupole magnet to obtain the best possible yield of collimated neutrons.
As the neutron yield gradually dropped, due to target deterioration, the deuteron beam current was raised to restore the initial level of the yield. By doing so, the intensity of the collimated neutron beam incident on the helium scintillator cell was kept virtually unchanged. This was confirmed by the readings on the analogue ratemeter, connected to the helium detector. When it was no longer possible to restore the yield, due to excessive target deterioration, data collection was terminated and the target was replaced.

Asymmetry data collection, for the ground state neutrons, was characterised by a very slow accumulation of related events, (less than 0.25 count/min), compared to 6-8 counts/min, for the same process in the D-D reaction and under the same machine conditions. However, the ratio of the random event occurrences to the real + random events, was far less in the \( ^7\text{Li}(d,n)^8\text{Be} \) g.s. reaction than that typically recorded during a D-D reaction. Moreover, the unpolarized low energy tail showed very little contribution (fig.4.18), to the recoil helium peak for the reaction under study, compared to that observed in the D-D measurements (fig.4.13).

During unattended running periods, (overnights), the inevitable effects on the rate of data accumulation by gradual drop in the yield, due to either changes in machine operation or target consumption, were remedied by normalising them with the initial set of data. The readings of the quad monitor scaler, (an integral part of the electronics, used to record the number of events in each of the four routed spectra), were used as reliable means of normalisation.
The frequency of the polarimeter rotation to interchange the positions of the side detectors, relied very much on the state of the machine, where longer intervals were set for more stable running conditions.

On the average, 3 hour runs were set for each polarimeter position and shorter intervals under less favoured conditions.

Checks were periodically carried out for possible electronic drifts, by monitoring any spectral shifts and duly corrected by readjusting all the electronics. When evidence of such drifts were found, the data collected under such conditions were excluded from the analysis and rated as unreliable.
5.1 Introduction

In addition to the asymmetry data and the deduced polarization values for the ground state neutron group, "No", this chapter also presents the yield measurements for this neutron group with a range of incident deuteron energies from 100 to 510 keV and target thickness measurements, from which the average deuteron energy in the target and the corresponding mean energy of the emitted ground state neutron group were deduced.

Relative neutron differential cross sections for the $^7\text{Li}(d,n)^8\text{Be}$ g.s. reaction are also presented here for two incident deuteron energies at which asymmetry measurements were performed, since total cross section information and reliable differential cross section data on the reaction were not available at the relevant energies (450 & ~500 keV).

Finally, a theoretical approach to the reaction's mechanism is made (assuming direct stripping process of the incident deuteron) using DWBA calculations. The validity of this theory at low incident energies is assessed by comparing its predictions of both, reaction cross section and the angular distribution of neutron polarization with the experimental results.

Other theoretical approaches are suggested for interpreting the mechanism of the reaction under study, namely the R-matrix and the S-matrix theories of nuclear reactions.

Comparisons of the present measurement of the "No" group differential cross section are made with some relevant published reports.
5.2 "No" Yield Dependence On Deuteron Energy

The yield of the "No" group was measured at 0° and 75° emission angles for incident deuteron energies from 100 to 500 keV at 50 keV intervals. At each observation angle, a set of proton recoil spectra were collected for the range of deuteron energies covered, with a calibrated liquid NE213 detector.

The incident beam current on the target was maintained at 10 μA for spectra collection and the duration of each measurement was set for an interval of 5 minutes.

The deuteron energy was raised by 50 keV steps up to 500 keV and decreased again to 100 keV, repeating the measurements in reverse order.

The number of the ground state neutrons was deduced by integrating through the relevant sections of the calibrated proton recoil spectra due to neutrons of > 11 MeV energy for each individual proton recoil spectrum. The yield curves deduced from these measurements are presented in two scales, logarithmic and linear (figs. 5.1.a & 5.1.b). The error bars attached to the data points are due to the uncertainty in the energy calibration curves used, which introduced an error in locating the exact channel at which to set the lower limit of integration. The magnitude of the error was estimated as equivalent to +/-1.5 channels. The efficiency of the detector was assumed constant over the slight energy variation of the neutrons in the range of the incident energies covered.

Fresh targets were used to avoid the effects of any carbon build up on the target surfaces or premature deterioration, as
Neutron Yield vs. Deuteron Energy

Fig. 5.1.a

Angle of observation = 0°
Angle of observation = 75°

Number of g.s. Neutrons

Incident Deuteron Energy (keV)
"No\textsuperscript{6}\textsuperscript{a} Yield vs. Deuteron Energy

Fig. 5.1.b

Integrated number of g.s. Neutrons

Incident Deuteron Energy (keV)

observed at 0°
observed at 75°
these were likely to cause false variations in the rate of neutron emission.

It is evident from figures 5.1.a and 5.1.b that the "No" yield shows a strong energy dependence above ~360 keV deuterons, which is possibly due to the resonance observed [97] at that incident energy.

5.3-a Determination of Target Thickness and Effects

Throughout the asymmetry measurements the incident deuteron beam impinged on straight target holders (finger shaped), which were coated with six microns thick of lithium fluoride, vacuum evaporated in uniform layers.

The target thickness, in terms of energy (keV), has been calculated using the stopping cross section (SCS) data (units of $10^{-15}$ ev.cm$^2$) published by Bader et al [81] for natural ($^7$Li) and lithium fluoride (LiF).

The atomic SCS of fluorine has been deduced with reasonable accuracy by subtracting the atomic SCS of Li from the molecular SCS of LiF, as suggested by Bader [81]. The molecular SCS of LiF and the atomic SCS's of Li & F are plotted in figure 5.2 with a probable error of +/-3% attached to the points, according to Whaling [82].

The molecular stopping cross section of LiF, in units of MeV/cm, has been calculated by multiplying the atomic stopping cross sections (units $10^{-15}$ ev.cm$^2$), of each constituent element (Li & F) by an appropriate conversion factor [82], and the results added.

The thickness exhibited by 6 microns of LiF in terms of energy, for two incident deuteron energies are listed in table 5.1 together with the stopping cross section data.
In reality, the actual target is expected to be slightly thicker as LiF was found to diffuse into the copper backing. This was realised when neutrons from the Li(d, n) reaction were still emitted when bombarding a thoroughly cleaned target holder (previously coated with LiF). The clean target was used to determine the extent of background D-D neutrons caused by beam accumulation in the copper backing.

The LiF diffusion would probably put a low energy tail on the neutron (No) spectra, as indicated in figures 5.3 and 5.4 by dashed extrapolations. However, since the rate of neutron emission falls drastically with decreasing deuteron energy (figs.5.1.a, b), the effect of the tail was considered marginal on the average "No" energy.

5.3-b Average Deuteron Energy Calculation and "No" Energy Spread

A spread in the emitted neutron energy occurs as a result of continuous deuteron energy degradation when the incident beam

Table 5.1

<table>
<thead>
<tr>
<th>Ed(keV)</th>
<th>Atomic SC$^2$</th>
<th>SCS (10$^{-15}$ eV.cm$^2$)</th>
<th>MeV/cm</th>
<th>LiF(keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li, F</td>
<td>450</td>
<td>6.6, 13.5</td>
<td>305.9</td>
<td>183</td>
</tr>
<tr>
<td>510</td>
<td>6.3, 12.9</td>
<td>292.0</td>
<td>175</td>
<td></td>
</tr>
</tbody>
</table>
LiF (183 keV), $E_d = 450$ keV
Mean deuteron energy = 399 keV
Effective mean neutron energy spread = ±82 keV

Fig. 5.3
LiF (175 keV), $E_d = 510$ keV
Mean deuteron energy = 461 keV
Effective mean neutron energy spread = ±77 keV
traverses the target. Moreover, as the reaction cross section is deuteron energy dependent, the neutron yield changes accordingly (falls in our case). These effects which take place simultaneously, have been evaluated for the "No" group neutrons at two incident deuteron energies, 450 & 510 keV, using the yield curves presented earlier in section 5.3-a, (figs.5.1.a,b).

The corresponding shapes of the "No" spectra are shown in figures 5.3 and 5.4 for Ed=450 & 510 keV respectively.

Considering the shapes of these spectra, the average deuteron energy in the target Ed cannot be deduced simply by calculating the mean deuteron energy at the centre of the target, nor by using the full width at half maximum (fwhm) to quote for this. A more precise method should be adopted for estimating the average deuteron energy for such cases, since the shape of the neutron spectra is obviously a dominant factor in the calculations.

One appropriate method would be by weighted means of estimation, where the graphical shapes of the neutron spectra are taken into consideration.

The number of neutrons along equally distributed points on the descending curve, (which reflects the shapes of the yield curves), divided by the total number of neutrons under the curve, provide the weighing factors for evaluating both, the average deuteron energy in the target and the mean energy of the emitted neutrons.

The deduced results, following the above method, are listed in table 5.2. We shall denote the term effective(eftve.) for the spread in the emitted "No" energies, deduced by weighted means of estimation.
Table 5.2

Average Ed and Mean Energy of "No" Emission at 0°

<table>
<thead>
<tr>
<th>Incid.Ed (keV)</th>
<th>Average Ed (keV)</th>
<th>Mean En (MeV)</th>
<th>Effve. Mean En spred. (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>399</td>
<td>14.367</td>
<td>+/- 82</td>
</tr>
<tr>
<td>510</td>
<td>461</td>
<td>14.467</td>
<td>+/- 77</td>
</tr>
</tbody>
</table>

5.4 Relative Differential Cross Section Measurements

The angular distribution of the ground state neutron (No) emission has been measured for two incident deuteron energies, \( E_d = 450 \) & \( 510 \) keV. The range of angles covered in the measurements was from zero to 140 degrees, at ten degree intervals.

The process involved the use of two kinds of target holders, namely air cooled disc targets and water cooled finger targets (described in section 2.7 of chapter 2). The reason for using air cooled disc target holders was to correct for the effects which the bulk of material immediately behind the target (steel and water coolant) would have in varying the yield by scattering the neutrons. The angles which were obstructed by the material of one target holder were substituted by those measured using the other after normalisation.

Two TYM's were used simultaneously, one of which had a discrimination level applied to its output pulses so that only those pulses due to high energy neutrons (12 MeV or more) were
recorded. The high discrimination level helped to minimise gamma ray contributions in the monitor recordings, as there was no pulse shape discrimination applied against gamma rays. The other TYM was used to monitor the beam spot conditions on the target on which adjustments relied for best neutron yield production. The total number of the recorded neutrons with the former TYM was used as means of normalising the collected spectra. The measurements obtained with the two target holders for the same deuteron energy were normalised again at 100° laboratory emission angle.

The results are illustrated in figures 5.5.a,b & 5.6.a,b.

Fig.5.5.a illustrates the relative differential cross section of the ground state neutrons for $E_d=450$ keV for the two types of target holders and figure 5.5.b shows the distributions after normalisation at 100°. Similarly, figures 5.6.a and 5.6.b illustrate the relative cross section measurements of "No" for $E_d=510$ keV.

For all the cross section measurements, the incident deuteron beam current was maintained at 10 µA and proton recoil spectra collected for three minute intervals to deduce the number of the ground state neutrons "No", by integrating through the relevant sections of those spectra.

The differential cross sections for both incident deuteron energies, feature predominantly a forward angle peak which falls gradually to a flat plateau near 80° and remains somewhat unchanged over the rest of the backward angles covered.

5.5-a Helium Analysing Power Calculation

In general, the analysing power of scatterers with nuclei of zero spin, such as helium and carbon, can be calculated for a
Fig. 5.5.1

Relative Neut. X-Section (E_d=450 KeV)

Air cooled 'Disk' target
Water cooled 'Finger' target

Lab. Angle of emission (degrees)

Number of Neutrons (f.s.)

2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000 13000 14000 15000 16000 17000 18000
Air cooled "Disk" target
Water cooled "Finger" target
[shifted one degree to separate the error bars]
Fig. 5.6.a

Air cooled 'Disk' target
Water cooled 'Finger' target
Fig. 5.6. b

Air cooled "Disk" target
Water cooled "Finger" target
[shifted one degree to sep.
the error bars]
particular incident energy and angle of scattering using the expression given by Baumgartner et al [83] and the corresponding set of phase shifts. The phase shift angles are deduced from the resonance parameters which in turn are obtained from the total and differential (n-alpha) scattering cross section data. The formula as given in reference [3] is;

\[ p = \frac{-2\text{Im}(g^*h)}{|g|^2 + |h|^2} \]  \hspace{1cm} (5.1)

where \((g)\) and \((h)\) are the non spin flip and spin flip wave amplitudes, respectively [55].

\[ g = \frac{1}{k} \sum_{\ell} P_{\ell}(\cos \theta) \left[ (\ell+1) \sin \delta_+^{\ell} e^{i\delta_+^{\ell}} + \ell \sin \delta_-^{\ell} e^{-i\delta_-^{\ell}} \right] \]

\[ h = \frac{1}{k} \sum_{\ell} P_{\ell}^\prime \sin (\delta_+^{\ell} - \delta_-^{\ell}) e^{i(\delta_+^{\ell} + \delta_-^{\ell})} \]

\(P_{1} = \text{Legendre Polynomial}\)

\(P_{1} = \text{Associated Legendre Polynomial}\)

\(\delta_+^{1/2}\) and \(\delta_-^{1/2}\) are the phase shifts for \(J=1+1/2\) and \(J=1-1/2\) respectively.

A more detailed account of (n-alpha) analysing power calculation can be found in an internal report submitted by Hall [50].
5.5-b The Mean Analysing Power Calculation

As the finite sizes of the detectors render a polarimeter system less than ideal due to the solid angles they involve, the variation in the helium analysing power over these angles should be considered in order to deduce the neutron polarization in a realistic manner when using the asymmetry data which has been acquired with such a system. Moreover, because the distance between the helium scintillator and the neutron producing target is also finite, the helium scintillator subtends a solid angle at the target, therefore due considerations should be made for the variation of the $^7\text{Li}(d,n)^8\text{Be}$ reaction cross section over the range of angles involved across the diameter of the cell, otherwise it would introduce a factor of false asymmetry, the magnitude of which will depend upon the extent of the cross section variation at the particular neutron emission angle chosen for data collection.

The analysing power calculation with due account taken for the finite geometry of the system and the variation of reaction cross section over the range of angles subtended by the helium scintillator is called the mean analysing power $<A''>$, and is detailed below.

When a uniform neutron beam of flux $\Phi$ and energy $E$ (fig. 5.2a) is incident on the helium scintillator/scatterer, the number of neutrons detected per second by a small volume element ($dv'$) in the right NE213 detector $R$, after being scattered by a small volume element ($dv$) of the helium scintillator, can be expressed (with reference to expression 1.1 of Chapter 1), as:
\[
\Phi_{P,N_{he}} \frac{\sigma(\theta) [1 + A(\theta) \cos \phi]}{r^2} \, dv \, dv' \]  
\hspace{1cm} (5.2)

is the probability of a scattered neutron being detected in the R detector per unit distance travelled therein. 

\(N_{he}\) is the number of helium nuclei per unit volume.  

\(r\) is the distance between \(dv'\) and \(dv\).  

\(\sigma(\theta)\) is the \(n-\alpha\) scattering cross section in the laboratory frame.  

\(A(\theta)\) is the analysing power of helium for the incident neutrons of energy \(E\).  

Thus the total number of neutrons detected per second in the R detector, after scattering by the helium scintillator will be:

\[
\Phi_{P,N_{he}} \int \frac{\sigma(\theta) [1 + A(\theta) \cos \phi]}{r^2} \, dv \, dv' = \Phi_{P,N_{he}} \left( I_R \right) \]  
\hspace{1cm} (5.3)

where \(I_R\) is the double volume integral evaluated throughout the sensitive volume of both, the gas scintillator and the "R" detector.  

Similarly, for the left NE213 detector "L", the number of neutrons detected per second after scattering in the effective volume of the helium scintillator, will be:
\[
\Phi_{P_{L}N_{he}} \left( \frac{\sigma(\theta)[1 - A(\theta)P_{n,\cos\Phi}]}{r^2} \right) dv \; dv' = \Phi_{P_{L}N_{he}} (I_{L})
\]

(5.4)

\(I_{L}\) is the double volume integral evaluated throughout the effective volumes of the gas scintillator and the "L" detector, as for \(I_{R}\). Thus the asymmetry \(\epsilon\), which is obtained by rotating the polarimeter to cancel out the differences in detector efficiencies, i.e. to cancel \(P_{R} \& P_{L}\), and any possible variation in the neutron flux, will be:

\[
\epsilon = \frac{I_{R} - I_{L}}{I_{R} + I_{L}}
\]

from expression (1.4)

\[
\epsilon = P_{n} \frac{\int \frac{\sigma(\theta)A(\theta)\cos\Phi}{r^2} dv \; dv'}{\int \frac{\sigma(\theta)}{r^2} dv \; dv'}
\]

\[
\epsilon = P_{n} <A'>
\]

(5.5)

where \(<A'>\) is the analysing power after taking account of the finite geometry effects only.

Since the distance between the target and the helium scintillator is finite, say \(k\), then this, as a radius sweeps an arc in the helium cell which passes through the centre point \((x,y,z)\), of the cell. Along this arc one should expect the following effect:
The neutron flux along the y-coordinate will increase due to the accompanying increase in the reaction cross section with decreasing angle of neutron emission. Thus, the effective centre of neutron scattering in the gas scintillator will not actually lie on the z-axis as expected but will have a slight positive y-coordinate. This effect would obviously introduce a false asymmetry factor to the measurements which can not be remedied by the polarimeter rotation, thus, other means should be adopted for correcting this.

The emitted neutrons at a reaction angle (θ) may be scattered at a point (a,b,c) relative to the origin (x,y,z). Keeping x constant, then θ is expressed as[55]

\[ θ = <θ> - b/c + k \]  \hspace{1cm} \text{………(5.6)}

where \(<θ>\) is the mean reaction angle.

As the fractional variation of the reaction cross section over a small deviation from \(<θ>\) can be considered as constant, say α, then the neutron flux \(\Phi\) at a point (a,b,c) within the gas scintillator will be of the form:

\[ \Phi = \frac{\Phi'}{a^2 + b^2 + c^2} \left(1 - \frac{ab}{c + k}\right) \]  \hspace{1cm} \text{………(5.7)}

and since \(k\) is \(\gg\) a, b and c the expression can be approximated to a parallel neutron flux varying as:

\[ \Phi = \Phi''(1 + γb) \]  \hspace{1cm} \text{………(5.8)}
where $\gamma$ is the fractional variation of the $^7\text{Li}(d,n)^8\text{Be}$ reaction cross section per unit length traversed in the $y$ direction within the cell.

$\gamma$ depends on the incident deuteron energy and the polarimeter geometry and is evaluated at the centre of the gas scintillator.

Thus, the total number of neutrons detected per second in the "R" detector after scattering once by helium becomes:

$$\phi'' P_R N_{he} \int \sigma(\Theta)(1+\gamma b)(1+A(\Theta) P_n \cos\phi) \, dv \, dv'$$

Similarly for the "L" detector

$$\phi'' P_L N_{he} \int \sigma(\Theta)(1-\gamma b)(1-A(\Theta) P_n \cos\phi) \, dv \, dv'$$

Thus, the measured asymmetry becomes:

$$\varepsilon = P_n \left\{ \left[ \frac{\sigma(\Theta) A(\Theta) \cos\phi}{r^2} \, dv \, dv' + \frac{\gamma}{P_n} \int \frac{b \sigma(\Theta)}{r^2} \, dv \, dv' \right] \right\}$$

$$\varepsilon = P_n \left\{ \left[ \frac{T + \frac{\gamma}{P_n} T'}{W + \gamma P_n W'} \right] \right\}$$

$$\varepsilon = P_n \langle A'' \rangle$$

$\langle A'' \rangle$ is the mean analysing power of the helium after corrections have been made for both, the finite geometry and the
effect of cross section variation over the diameter of the helium scintillator cell, the integrals being evaluated over the same volume as $I_R$.

$PW'$ being very small, it can be ignored and expression (5.10) can further be approximated to:

$$\epsilon = P \frac{T}{W} + \frac{\gamma T'}{W}$$

$$\epsilon = P<A''> + X \quad \ldots \ldots (5.11)$$

where $X$ is the false asymmetry introduced by the variation of the reaction cross section across the helium cell.

Corrections for multiple scattering effects within the gas scintillator have been ignored as they were found to be in the order of 1% [55].

A Monte Carlo program [50], developed and used earlier by Davie [55] and by Maayouf [68], has been utilised to evaluate the mean analysing power of the helium polarimeter at each reaction angle where asymmetry data had been collected.

The program, which has been updated and modified to suit the geometry of the present polarimeter, is based on the expressions given in sections 5.5-a and follows the approach outlined above.

In this program, the volumes of the helium scintillator and the liquid scintillators are sampled in a random fashion using a power residue method [84].

The program should be supplied with n-alpha scattering phase
shift values ($s^{1/2}$, $p^{1/2}$ & $p^{3/2}$) and an estimate of the neutron polarization $P_n$.

Corrections needed for the false asymmetry "X", are determined by supplying values of the fractional variation in the principle reaction cross section over the angle (3.1°) subtended by the helium cell on the target.

The phase shifts, for the relevant energies, were deduced from the reliable data of Bond and Firk[75]. The fractional variation of the cross section at each angle of asymmetry measurement, was calculated from the data acquired from section 5.4, shown in figs. 5.5.b & 5.6.b.

The output from the Monte Carlo program gave results for $<A'>$, $<A''>$ and "X", where X was found to be significantly smaller than the statistical uncertainties involved in the asymmetries measured, varying between 0.0015 and 0.0001, as maximum and minimum values respectively.

5.6 Asymmetry Data and Polarization Results

Asymmetry data compiled for the "No" group neutrons at two incident deuteron energies are listed on tables 5.3 and 5.4. These have been selected from a series of measurements performed under stable machine conditions, allowing reliable data accumulation over long running periods (typically 5 to 6 days).

Corrections for the unpolarized tail presence have been ignored since it showed insignificant contribution to the gated helium recoil spectra, therefore to attempt such corrections would only mean the possible introduction of new uncertainties to the results. Instead, careful selection of channels were made when
Table 5.3
Asymmetry and Polarization Values
For Ed = 450 keV

<table>
<thead>
<tr>
<th>Emission Ang. Lab.</th>
<th>Avge.En MeV</th>
<th>Asymmetry %ε</th>
<th>Mean Anal.Power at 55, &lt; A''&gt;</th>
<th>Polarization %Pn</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>25.70</td>
<td>-4.47 + 1.43</td>
<td>-0.492</td>
<td>+9.08 + 2.90</td>
</tr>
<tr>
<td>35</td>
<td>35.94</td>
<td>-12.18 + 1.42</td>
<td>-0.488</td>
<td>+24.96 + 2.91</td>
</tr>
<tr>
<td>45</td>
<td>46.20</td>
<td>-7.18 + 1.55</td>
<td>-0.495</td>
<td>+14.50 + 3.13</td>
</tr>
<tr>
<td>55</td>
<td>56.36</td>
<td>-5.42 + 2.70</td>
<td>-0.503</td>
<td>+10.77 + 5.36</td>
</tr>
<tr>
<td>65</td>
<td>66.49</td>
<td>+4.52 + 2.68</td>
<td>-0.482</td>
<td>-9.37 + 5.55</td>
</tr>
<tr>
<td>75</td>
<td>76.60</td>
<td>+1.57 + 1.49</td>
<td>-0.447</td>
<td>-3.51 + 3.33</td>
</tr>
<tr>
<td>85</td>
<td>86.65</td>
<td>+6.02 + 2.79</td>
<td>-0.491</td>
<td>-12.26 + 5.68</td>
</tr>
<tr>
<td>95</td>
<td>96.64</td>
<td>+0.10 + 1.67</td>
<td>-0.525</td>
<td>-0.19 + 3.17</td>
</tr>
<tr>
<td>100</td>
<td>101.62</td>
<td>-1.63 + 3.75</td>
<td>-0.414</td>
<td>+3.93 + 9.04</td>
</tr>
<tr>
<td>105</td>
<td>106.59</td>
<td>-7.57 + 1.76</td>
<td>-0.496</td>
<td>+15.26 + 3.54</td>
</tr>
<tr>
<td>115</td>
<td>116.49</td>
<td>-12.97 + 2.35</td>
<td>-0.497</td>
<td>+26.09 + 4.73</td>
</tr>
<tr>
<td>125</td>
<td>126.30</td>
<td>-12.42 + 3.40</td>
<td>-0.500</td>
<td>+24.84 + 6.80</td>
</tr>
</tbody>
</table>
### Table 5.4

Asymmetry and Polarization Values

For Ed = 510 keV

<table>
<thead>
<tr>
<th>Emission Ang. Lab. C.M.</th>
<th>Avge.En MeV</th>
<th>Asymmetry %</th>
<th>Mean Anal.Power &lt;A''&gt;</th>
<th>Polarization ZPn</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>30.85</td>
<td>-7.58 +1.48</td>
<td>-0.489</td>
<td>+15.50 +3.02</td>
</tr>
<tr>
<td>35</td>
<td>36.00</td>
<td>-9.47 +1.05</td>
<td>-0.491</td>
<td>+19.28 +2.14</td>
</tr>
<tr>
<td>40</td>
<td>41.09</td>
<td>-4.13 +1.51</td>
<td>-0.499</td>
<td>+8.27 +3.02</td>
</tr>
<tr>
<td>65</td>
<td>66.54</td>
<td>-3.69 +1.20</td>
<td>-0.511</td>
<td>+7.22 +2.34</td>
</tr>
<tr>
<td>75</td>
<td>76.65</td>
<td>+7.43 +1.74</td>
<td>-0.486</td>
<td>-15.28 +3.57</td>
</tr>
<tr>
<td>85</td>
<td>86.70</td>
<td>+2.93 +1.33</td>
<td>-0.492</td>
<td>-5.95 +2.70</td>
</tr>
<tr>
<td>105</td>
<td>106.60</td>
<td>+2.02 +1.13</td>
<td>-0.496</td>
<td>-4.07 +2.27</td>
</tr>
<tr>
<td>125</td>
<td>126.39</td>
<td>-6.29 +1.48</td>
<td>-0.500</td>
<td>+12.58 +2.96</td>
</tr>
</tbody>
</table>
21/12/82  Polarization Angular Dist. of "No"

Fig. 5.7b
Fig. 5.7c
integrating over sections of the recoil helium peak to avoid the inclusion of any possible tail events.

The measured Pn angular distributions (before and after finite geometry corrections) are illustrated in fig.5.7b. For clarity, the points are displaced by one degree to separate the error bars. Fig.5.7c shows all the measured polarization values superimposed, illustrating the general trend of the Pn distributions for the two deuteron energies used in this work.

5.7 DWBA Calculations

Distorted Wave Born Approximation calculations were applied to the experimental results obtained in the present work with the anticipation that it would be possible to find a plausible set of Optical Model parameters which would give predictions of both, qualitative features of the reaction cross section and the neutron polarization angular distribution.

The computer program utilised to perform the DWBA calculations was stored on disc at the Rutherford laboratory. It is based on B.E.Macefield’s[91] particle stripping code which assumes a direct stripping of the incident deuteron and uses spin-dependant, zero-range interaction potentials. It calculates the differential cross section for single and two nucleon transfer reactions as well as the polarization of the emitted particle, (in the Li(d,n) reaction, the measurements concern one particle transfer only).

The Distorted waves adopted in the DWBA program are generated from optical model potentials defined by;
\[ V_{OM} = V_c(r) - V_f(r,a) - \frac{iW_f(r,A)}{2} \times d/dr f(r_W,A_W) + 4iW_{D^W_D^W} \times d/dr f(r_{WD},A_{WD}) \]

\[ + \left( \frac{h}{m} \right)^2 \sigma_{so} \left( \frac{1}{r} \right) \times d/dr f(r_{so},A_{so}) \]

where \( f(r_x,a_y) = \left[ \frac{1}{1 + \exp\left(\frac{r - r \cdot A^3}{a_x}\right)} \right]^{-1} \)

\( V_c \) is the Coulomb potential due to a uniformly charged sphere of radius \( \frac{1}{3} \), i.e.

\[ V_c(r) = \frac{Z_1 Z_T^2}{2R_c^2} \left( 3 - \frac{r^2}{R_c^2} \right) \text{ for } r \leq R_c, \quad R_c = r \cdot A_\frac{1}{3} \]

\[ V_c(r) = \frac{Z_1 Z_T^2}{r} \text{ for } r > R_c \]

\( i \) = incident particle

\( T \) = target nucleus

A partial description of the numerical methods used in the program is given by Buck and Hodgson[92].

The program was first tested by attempts to reproduce the results of DWBA predictions for the \(^{11}\text{B}(d,p)^{12}\text{B}\) reaction previously reported by Robson and Weigold[87]. However, as the set of (OM) parameters included in the report missed out some parameters important to DWBA calculations, (e.g., the captured neutron potential parameters), it was difficult to reproduce identical predictions even when plausible values were assumed for
the missing parameters. However, the cross section and the polarization distribution patterns obtained, resembled those illustrated in reference[87] to a reasonable extent.

The initial parameters used to carry out DWBA calculations on the $^7$Li(d,n)$^8$Be reaction were those given by Thomason et al[49], where the deuteron-nucleus ($d + ^7$Li) potential was basically that reported by Ludecke et al[93] for higher incident energies (11.8 MeV), interpolated to lower energies (4.0 MeV). The rest of the parameters were taken from a list of references compiled by Perey and Perey[94]. Realistic values were assigned to those which were not found in publications (these were found to have little or no obvious effects on the DWBA predictions).

A complete list of the parameters is presented in table 5.5.

Although a complete account of the DWBA sensitivity can not be made by simply varying one parameter at a time while ignoring the effects caused by simultaneous variation of two or more parameters on the DWBA predictions, nevertheless it is essential to establish first the effects of individual parameter variation before attempting more rigorous tests on this theory. Moreover, since most of the OM parameters adopted here have already received a fair amount of scrutiny, the search was limited to the parameter set of table 5.5.

The search for an optimum parameter set was anticipated for the $^7$Li(d,n)$^8$Be g.s reaction near 0.5 MeV deuterons, since Robson and Weigold[87] already demonstrated the success of such attempts on the $^{11}$B(d,p)$^{12}$B reaction.
Definition of Optical Model parameters

V    Real Potential Depth.
R    Radius of the Potential.
A    Diffuseness Parameter.

W    Volume Imaginary Potential. (Saxon-Woods)
RW   Radius of the Potential.
AW   Diffuseness Parameter.

WD   Surface Imaginary Potential. (Saxon-Woods Derivative)
RWD  Radius of the Potential.
AWD  Diffuseness Parameter.

Vs.o Real spin-orbit Potential.
Rs.o Radius of the Potential.
As.o Diffuseness Parameter.

Ws.o Spin-Orbit Imaginary Potential.

Rc   Coulomb Radius Parameter.
### Table 5.5

**Basic O.M. Potential Parameters**

**Used in DWBA Calculations**

<table>
<thead>
<tr>
<th>UNITS</th>
<th>INCIDENT(d)</th>
<th>EMITTED(n)</th>
<th>UNITS</th>
<th>CAPTURED(p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V MeV</td>
<td>120.00</td>
<td>46.30</td>
<td>V MeV</td>
<td>55.00</td>
</tr>
<tr>
<td>R Fermi</td>
<td>1.80</td>
<td>1.32</td>
<td>R Fermi</td>
<td>1.20</td>
</tr>
<tr>
<td>A Fermi</td>
<td>1.40</td>
<td>0.66</td>
<td>A Fermi</td>
<td>0.70</td>
</tr>
<tr>
<td>W MeV</td>
<td>30.00</td>
<td>0.75</td>
<td>Vs.o MeV</td>
<td>6.25</td>
</tr>
<tr>
<td>RW Fermi</td>
<td>0.84</td>
<td>1.26</td>
<td>Rs.o Fermi</td>
<td>1.25</td>
</tr>
<tr>
<td>AW Fermi</td>
<td>0.85</td>
<td>0.58</td>
<td>As.o Fermi</td>
<td>0.65</td>
</tr>
<tr>
<td>WD MeV</td>
<td>6.87</td>
<td>8.10</td>
<td>Rc Fermi</td>
<td>1.27</td>
</tr>
<tr>
<td>RWD Fermi</td>
<td>1.98</td>
<td>1.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AWD Fermi</td>
<td>0.59</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vs.o MeV</td>
<td>8.50</td>
<td>9.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rs.o Fermi</td>
<td>1.00</td>
<td>1.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>As.o Fermi</td>
<td>0.94</td>
<td>0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ws.o Fermi</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rc Fermi</td>
<td>1.30</td>
<td>1.30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
DWBA sensitivity to each individual parameter was investigated using the basic set of OM parameters listed in table 5.5 as an average set about which parameter search was considered feasible.

A range of values were assigned to each parameter at a time while freezing the rest. The observed effects varied from a mere change in the magnitude of the predicted reaction cross section to some significant effects on both, polarization and cross section distributions, in magnitude and shape.

We shall include here some of the sensitivity tests accomplished with pictorial illustrations for clarity.

Most of the following figures are self explanatory, therefore it would suffice just to mention the prominent features observed from these tests. The range of the parameter values used in the DWBA sensitivity tests are given on the respective plots, together with the corresponding curve identification.

With reference to table 5.5 and the symbol definitions on the preceding page, the effects of varying the deuteron-nucleus potential parameter $(V \text{ of } d)$ on the reaction cross section and the polarization distributions are illustrated (fig. 5.8). It is evident that the cross section increases with increasing potential depth and causes the large negative polarization at the forward angles to decrease to the extent of changing sign. Similar effects were observed when the radius of the deuteron-nucleus potential $(R \text{ of } d)$ was increased(fig.5.9).

When the diffuseness parameter of the real potential $(A \text{ of } d)$ was varied, the effects on the cross section were found to be similar to those of the previous two parameter changes, however the large negative polarization, previously seen at the forward angles, shifted to more intermediate and backward angles
26/11/82 DWBA Sensitivity to: R of d

---

**Diff. X-Section (mb/str.) x 10^-2**

- **R = 1.80 Fermi**
- **R = 1.40 Fermi**
- **R = 1.20 Fermi**
- **R = 0.80 Fermi**

---

**Fig. 5.9**

---

**% Polarization (Pn)**

- **R = 1.80 Fermi**
- **R = 1.40 Fermi**
- **R = 1.20 Fermi**
- **R = 0.80 Fermi**

---

**Angle C.M. (degrees)**

---
Fig. 5.10

\begin{align*}
\frac{\text{Diff. X-section (mb/str.)}}{X \times 10^{-2}} \text{ vs } \theta_{\text{C.M.}} (\text{degrees})
\end{align*}

\begin{align*}
\text{A} = 0.20 \text{ Fermi} \\
\text{A} = 0.50 \text{ Fermi} \\
\text{A} = 0.74 \text{ Fermi} \\
\text{A} = 0.94 \text{ Fermi} \\
\text{A} = 1.40 \text{ Fermi}
\end{align*}
More systematic changes were observed on both, polarization and differential cross section distributions, when the diffuseness of the volume imaginary potential, (AW of d), was varied (fig.5.11). The same effects were also noticed when the surface imaginary potential (WD) was tested for parameter sensitivities(fig.5.12).

No drastic effects on the predicted polarization were evident when the neutron real potential strength (V of n), was assigned values about those given by Thomason et al[49], and the magnitudes of the cross section distributions were somewhat similar to those observed when the real potential (V of d) was altered (fig.5.13).

Changes in spin-orbit potential of the neutron (Vs.o of n) surprisingly showed little effects on the polarization and cross section distributions, hence was excluded here.

The spin-orbit diffuseness parameter of the neutron (As.o of n) showed systematic changes in magnitude of both, cross section and polarization distributions(fig.5.14), which is why the spin orbit potential is often considered to be surface peaked and not so sensitive to the real spin-orbit potential (Vs.o of n) [96]. The differential cross section distributions were characterised with different patterns compared with those previously observed, with somewhat low magnitudes. A prominent peak at a c.m. angle of 80° appeared to be consistent for the range of the Ws.o parameter changes. The additional curve, taken from fig.5.10, was plotted here to compare the magnitudes as well as the general shape of the previous predictions.

Finally, no parameters in the captured proton potentials showed any drastic effects on the DWBA predictions apart from the diffuseness of the real potential (A of p) where polarization
$\omega = 20.00 \text{ MeV}$

$\omega = 9.80 \text{ MeV}$

$\omega = 6.87 \text{ MeV}$

$\omega = 3.42 \text{ MeV}$
DWBA Sensitivity to: $V$ of $n$

- $V = 15.0$ MeV
- $V = 30.0$ MeV
- $V = 46.3$ MeV
- $V = 60.0$ MeV
- $V = 75.0$ MeV

Fig. 5.13

Angle C.M. (degrees)

% Polarization (Pn)
DWBA Sensitivity to As.0 of n

\[
\begin{align*}
\text{As.0} &= 0.15 \text{ Fermi} \\
\text{As.0} &= 0.18 \text{ Fermi} \\
\text{As.0} &= 0.23 \text{ Fermi} \\
\text{As.0} &= 0.30 \text{ Fermi} \\
\text{Vd=120 MeV, As.0=1.4 Fermi}
\end{align*}
\]

Fig. 5.14
magnitudes exceeded 70%, which is by far the highest value predicted in this search (fig.5.15).

Parameter search and sensitivity tests were pursued further by altering a combination of two or more parameters successively, using the basic set of table 5.5. No significant differences were observed in the predicted patterns by the DWBA calculations for either the cross section or the polarization distributions.

Numerous attempts were made to match the experimental data (polarization and cross section distributions) to those predicted by the DWBA calculations with no tangible success. None of the distributions gave a convincing fit to the experimental data, and the closest degree of agreement achieved for the differential cross section distributions are illustrated in fig.5.16a with the corresponding parameter values used. The experimental cross section data were normalised at zero degrees with the theoretical predictions, in order to assess the goodness of fit. Figure 5.16.b shows the comparisons prior to the normalisation, clearly indicating that the theory predicts cross section distributions that are smaller in magnitude than the observed data by about a factor of three.

The polarizations predicted by DWBA calculations for the same parameters, are shown in figure 5.17.

The potential parameters that gave the closest fit to the measured cross section, produced a poor fit to the polarization distributions. On the other hand, the parameter set that gave somewhat similar polarization distributions to the measured data, gave cross sections in complete disagreement with the observed data.

Obviously the poor agreement which is evident between the
Fig. 5.15

Diff. X-Section (mb/st.) X 10^2

[Graphs showing data for different cases, likely related to polarizability or another scientific measurement]
14/12/62

14/12/62

**DWBA calculation Comparison**

**Fig. 5.16a**
Fig. 5.16.b
Fig. 5.17

Measured Polarization (Ed = 450 keV)
(V d = 140 MeV, A d = 0.94 F, Wso = 0.0 F)

Measured Polarization (Ed = 450 keV)
(V d = 120 MeV, A d = 1.4 F, Wso = 0.0 F)

Measured Polarization (Ed = 450 keV)
(V d = 120 MeV, A d = 0.94 F, Wso = 25 F)
theoretical predictions and the experimental results leads one to conclude that the reaction concerned cannot be interpreted on the basis of the distorted wave, direct stripping theory. Other processes such as compound nucleus formation should be considered, especially when the reaction is known to resonate at about 360 and ~700 keV incident deuteron energies[97]. Therefore, for the incident energy range used here, the DWBA approach alone is inadequate to give satisfactory predictions for the $^7\text{Li}(d,n)^8\text{Be}$ g.s reaction. When stripping processes predominate, the DWBA theory is found to give successful interpretations of the reaction even at low incident energies, as it has reproduced the cross section distributions for the $^{11}\text{B}(d,p)^{12}\text{B}$ reaction[87] at about 1 MeV proton energy.

Other theories that are more likely to give successful interpretations of the reaction's mechanism are the R-matrix and the S-matrix theories of nuclear reactions. A brief account of these two versatile theories is made in the following section.

5.8 The R-Matrix and the S-Matrix Approach

The R-matrix formalism was established following a series of theoretical interpretations and suggested approaches to the problem of nuclear interactions, particularly those which undergo intermediate states like the compound nuclear formation and resonant states of the nuclei.

The R-matrix theory was first expounded by Wigner and Eisenbud[125] in 1947. Since then it has been refined and a more recent established phenomenon has been fitted into the framework of the theory. This is the possibility that colliding nuclei can
interpenetrate each other without necessarily forming a compound nucleus. A significant fact which was deduced in 1953 by Feshbach, Porter and Weiskopf[126] from the energy dependence of total neutron cross sections. Previously, it had been assumed that any particle entering a nucleus must inevitably lose energy and thereby cause the formation of a compound nucleus. Therefore, although the theory is formulated such that its most immediate application is to the compound nucleus mechanism, it can be adapted to describe direct mechanisms too.

The R-matrix theory is so rigorous that in principle it can be applied to all types of reaction phenomena. On the other hand, although the essential basis of this theory is quite straightforward, the full development is rather lengthy and involves considerable algebraic manipulations, and one tends to lose track of the main arguments because of distraction by detail. Nonetheless, the theory is versatile, accurate and successful.

A vast number of detailed application that have been made to experimental data can be found in reviews by Peaslee[127] and by Burcham[128].

In a more specialised approach to interpret the resonant states of nuclei, Humblet and Rosenfeld[129] proposed a formalism of the general theory of nuclear reactions called the S-matrix theory, defining the resonant states as decaying states corresponding to complex eigenvalues of the total energy of the compound system. They derived from "natural" boundary conditions a characterisation of these states expressing the absence of incoming waves in all reaction channels.

Thus, the presentation of Humblet and Rosenfeld, besides being simpler than the elaborate R-matrix one, has over the latter the
advantage of eliminating every arbitrary element from specification of the resonances and of the non-resonant background. These elements of the description are, in particular, independent of the choice of the channel radii and appear altogether as intrinsic properties of the compound system.

The accent in the S-matrix theory is that it is free from arbitrary features and the resonances appear as intrinsic properties of the compound system.

The two theoretical approaches, (R-matrix and S-matrix) are likely to give a much better interpretation of the Li(d,n) reaction at the incident energies used than the DWBA approach which assumed direct stripping of the deuteron. However, it is not possible to make any meaningful verifications of either theory since there is not enough body of data available at the present, particularly on the reactions cross section over a range of incident deuteron energies. Furthermore, the width of the resonances are not accurately established for the Li(d,n) reaction for incident energies below 1 MeV, the knowledge of which is essential for determining the resonant parameters to render the application of these theories possible.

5.9 Comparison With Published Cross section Data.

As mentioned in chapter 1, the published reports on the Li(d,n) reaction are few particularly over a similar range of bombarding energies, therefore a fair comparison unfortunately is not possible to make. For the sake of completeness however, the present cross section measurement for $E_d = 500$ keV has been
compared with the available cross section data below 1 MeV. These include cross sections reported by Saxena[48], Trumpy et al[41] and those reported by Milone & Potenza[46]. The data have been normalised at zero degree emission angle and plotted in figure 5.18. The disagreement is clearly evident amongst all the reports. There would possibly have been a better agreement between the present work and that reported by Saxena[48] if the 2.0 MeV excited state of $^8$Be, claimed by the author, was not considered while counting the proton recoil tracks on the photo emulsion plates, since no such state has been established for the excited Beryllium-8 nucleus.

The results from the present cross section measurements were compared with the observations of Johnson and Trail[45] for $E_d = 1.98$ MeV and with the measurements of Nussbaum[98] for $E_d = 1.93$ MeV (fig. 5.19).

It was rather surprising to find such close resemblance in the shape of the distributions considering the difference in deuteron energies used in each measurement. This could only be attributed to coincidence rather than any significant similarities in the reaction mechanisms. But it is worth noting that the reaction is known to resonate at about 1.8 MeV[97] at which energy Johnson and Trail[45] conducted their cross section measurements, just as it resonates near the incident energies used in the present work.

Further comparisons were made with a set of differential cross section data presented by Nussbaum[98] for incident deuteron energies of 910, 940 and 970 keV. The normalised cross sections (fig. 5.20), show a marked difference in their trends, in fact they reflect each other almost like mirror images.

It is difficult to make a fair comparison here since there exists a considerable energy difference in the incident deuterons
Comparison of Diff. Cross Sections

Fig. 5.18

- Present work (Ed=500 keV)
- Saxena [48] (Ed=500 keV)
- Trumpy [41] (Ed=680 keV)
- Milese [46] (Ed=1 MeV)
Fig. 5.19

Comparison of Diff. Cross Sections

- Present work (Ed=500 keV)
- Johnson [45] (Ed=1.98 MeV)
- Nussbaum [98] (Ed=1.93 MeV)

Normalized Diff. X-sec.
Comparison of Diff. X-secs. Ed < 1 MeV

Nussbaum[98], Ed = 970 keV
Present work, Ed = 510 keV

Nussbaum[98], Ed = 940 keV
Present work, Ed = 510 keV

Nussbaum[98], Ed = 910 keV
Present work, Ed = 510 keV

Fig. 5.20
used for these measurements. Moreover, knowing the fact that there also exists a resonance (Ed=700 keV), at which the reaction cross section shows a different pattern of angular distribution (Milone & Potenza[46] fig. 5.18), and below this energy reliable cross section data of the ground state neutrons "No", are practically non-existent.

More differential cross section data are therefore needed for deuteron energies well below one MeV, in order to investigate more rigorously the shapes of the cross sections and the extent to which they show dependence on incident deuteron energy, especially in the vicinity of the resonances, before any meaningful comparisons can be presented for the existing data.
6.1 The $^7\text{Li}(d,n)^8\text{Be}$ Reaction as a Source of Polarized Neutrons

In order to assess the usefulness of the $^7\text{Li}(d,n)^8\text{Be}$ g.s. reaction as a source of polarized 14 MeV neutrons induced with low energy accelerators, we specify first the characteristics of a neutron producing reaction that would be ideal for scattering experiments.

An ideal source reaction would produce monoenergetic neutrons and would have a large differential cross section at the emission angle employed relative to the total neutron producing reaction cross section. The neutron producing target should withstand high incident beam currents and yield neutrons with fairly large polarization magnitudes.

In reality, most reactions give several neutron groups so that their usefulness may be limited to laboratories with pulsed beam, time-of-flight apparatus, particularly if the neutron groups are emitted from closely lying states of the product nucleus. However, this drawback has been overcome in some of the laboratories today by the use of the associated particle method for discriminating against unwanted neutron groups or other backgrounds. This technique bypasses the pulsed beam requirement, as fast time-of-flight measurements become feasible when employing the associated particle for timing pulses. (This will be detailed in sec. 6.2)

Although the neutrons emitted from the $^7\text{Li}(d,n)^8\text{Be}$ reaction
are not monoenergetic, nevertheless the ground state neutron group is well separated from the lower energy neutron groups that are due to the excited states of the $^8$Be nucleus, or other groups that are emitted from various channels of the Li + d interaction (see ch.1, sec.1.6-b), largely proceeding through a three-body break-up process [102,103].

These unwanted neutron groups can easily be excluded by setting an appropriate energy discrimination level against them. The energy bias requirement is not a setback in scattering experiments since it is necessary even when the polarized neutron source employed is monoenergetic, to reject inelastic scattering and background contributions.

Regarding the characteristics required of the neutron producing target, lithium targets can be prepared either in metallic form or more commonly as LiF which is one of the few stable anhydrous lithium compounds.

Metallic lithium is, of course, the ideal form, since it gives higher neutron yield, but being chemically very active, elaborate steps must be taken in order to produce and preserve a clean target[10]. LiF features several advantages accompanied by only one significant disadvantage, these are:

Uniform layers of this compound can readily be evaporated under vacuum and monitored effectively, allowing the target thickness to be determined precisely. Further the targets may be stored for a considerable length of time without appreciable change in structure or chemical composition.

LiF targets can also withstand fairly high beam currents (30 to 50 $\mu$A) for long periods, provided the evaporation technique and the backing material offer good adhesion.
The only disadvantage is that the fluorine content in the target reduces the neutron production per unit energy interval of the incident beam. Therefore less neutrons would be emitted from a LiF target than from a pure lithium target containing equal number of $^7\text{Li}$ atoms when these are bombarded with the same deuteron beam.

Within the angular distributions covered in this work, the ground state neutrons showed fairly high polarization values. A suitable angle was therefore selected to represent the $^7\text{Li}(d,n)^8\text{Be}$ g.s reaction as a polarized source of 14 MeV neutrons.

The selection was based on the fact that the most profitable angle of neutron emission to be employed in scattering experiments would be that which would provide maximum accuracy in a minimum amount of time. This is actually proportional to the product of the neutron production cross section and the square of the reaction polarization, $P^2\sigma$ (mb/str) [65].

This figure of merit may also be used to compare the efficiencies of several sources of polarized neutrons. Often the product $P^2\sigma$ is divided by the value of the beam energy loss in the target to standardise flux comparisons, i.e $P^2\sigma/e$, where $e$ is the stopping cross section of the target material ($10^{-15}$ eV.cm$^2$).

For the purpose of comparing the $^7\text{Li}(d,n)^8\text{Be}$ reaction with other polarized sources, the differential cross section distributions of the ground state neutrons were determined approximately, following an indirect method. This was done by comparing the 14 MeV neutron yield of the "No" group at zero degree emission angle with that obtained from the D-T reaction at the same angle. The measurements were carried out under identical beam energies and currents (2μA) and equal data collection
intervals. A high energy discrimination level (~12 MeV) was set on the pulses of the detector employed, to maintain a constant detection efficiency for all the measurements, as both reactions emit neutrons of about 14 MeV.

In order to relate the 14 MeV neutron yields obtained from the two reactions, first the mean deuteron energy in each target was estimated by calculating the thickness exhibited by these targets at each deuteron energy.

The thickness of the Ti-$^3$H target was calculated using the stopping cross section data of Titanium and Hydrogen [82,100].

Details of the correlated results obtained for both, Ti-$^3$H and LiF targets are listed in table 6.1.

<table>
<thead>
<tr>
<th>D-T Reaction</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_d$ (keV)</td>
<td>$c \times 10^{-15}$ (eV.cm$^2$)</td>
</tr>
<tr>
<td>450</td>
<td>29.2</td>
</tr>
<tr>
<td>510</td>
<td>18.8</td>
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</table>

<table>
<thead>
<tr>
<th>7Li(d,n)8Be g.s reaction</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_d$ (keV)</td>
<td>$c \times 10^{-15}$ (eV.cm$^2$)</td>
</tr>
<tr>
<td>450</td>
<td>6.6</td>
</tr>
<tr>
<td>510</td>
<td>6.3</td>
</tr>
</tbody>
</table>
The tritium target used for the yield measurements composed of 0.16 curie per cm$^2$ absorbed in 0.23 mg/cm$^2$ of Titanium, i.e. a proportion of 0.10 to 1.0 of Tritium to Titanium respectively.

The number of the $^3$H atoms in the Ti-$^3$H target and the $^7$Li atoms in the LiF target were calculated. Since the ratio of the measured neutron yield from each target to the corresponding number of atoms can be directly related to the cross section of each reaction, the unknown cross section of the $^7$Li(d,n)$^8$Be g.s reaction was determined from the constant of the proportionality to a fair degree of accuracy, using the well established cross section data of the D-T reaction\[^{99}\], (fig. 6.1).

An interesting result should be pointed out here, that is, the thicknesses exhibited by the Ti-$^3$H and the LiF targets employed cause equal spreads in the emitted neutron energies for the particular deuteron energies used in the yield measurements, as indicated in table 6.1.

The deduced differential cross section for the ground state neutrons at zero degrees was found to be 1.46 mb/str and 1.68 mb/str for deuterons with mean energy of 400 and 460 keV respectively. The rest of the differential cross section distribution was approximated using the relative cross sections in the previous chapter, normalised with the above deduced values.

The differential cross section data for $E_d = 450$ and 510 keV are presented in tables 6.2 and 6.3 respectively and plotted (fig. 6.2), both, in the laboratory and centre of mass frames.

Applying the figure of merit, $P^2 A$ to the $^7$Li(d,n)$^8$Be g.s reaction, the most suitable angle for scattering experiments was found to be the laboratory emission angle of 35°, incorporating
Diff. X-Sec. for D-T & D-D Reactions

$\theta^0$ Lab. Angle

Fig. 6.1
Approx. Diff. X-Sec., 7Li (d, n) 8Be g.s

Fig. 6.2
the highest figure of merit for both deuteron bombarding energies, 
\( E_d = 450 \text{ & } 510 \text{ keV}. \)

### Table 6.2

\( E_d = 450 \text{ keV} \); (\( E_d = 400 \text{ keV} \))

Differential cross section for "No"

<table>
<thead>
<tr>
<th>Angle (lab) Degrees</th>
<th>( \delta ) (lab) mb/str</th>
<th>Angle (c.m) Degrees</th>
<th>( \delta ) (c.m) mb/str</th>
<th>Mean En (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.46</td>
<td>0.0</td>
<td>1.38</td>
<td>14.37</td>
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<tr>
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<td>1.21</td>
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<td>0.85</td>
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Table 6.3

$E_d = 500 \text{ keV} ; \ (E_d = 460 \text{ keV})$

Differential cross section for "No"

<table>
<thead>
<tr>
<th>Angle (lab) Degrees</th>
<th>$\delta$ (lab) mb/str</th>
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<th>$\delta$ (c.m) mb/str</th>
<th>Mean En (MeV)</th>
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Table 6.4  
(Ed = 450 keV)  

Choice of angle for fast data collection

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<th>Angle (lab) Degrees</th>
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<th>$P^2\delta \times 10^{-5}$ mb/str</th>
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<td>1080</td>
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<td>1173</td>
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### Table 6.5

*(Ed = 500 keV)*

**Choice of angle for fast data collection**

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<th>Angle (lab) Degrees</th>
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<th>$P^2\delta \times 10^{-5}$ mb/str</th>
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<td>35</td>
<td>0.193</td>
<td>1.42</td>
<td>5289</td>
</tr>
<tr>
<td>40</td>
<td>0.083</td>
<td>1.36</td>
<td>940</td>
</tr>
<tr>
<td>65</td>
<td>0.072</td>
<td>1.04</td>
<td>539</td>
</tr>
<tr>
<td>75</td>
<td>0.153</td>
<td>0.94</td>
<td>2195</td>
</tr>
<tr>
<td>85</td>
<td>0.060</td>
<td>0.90</td>
<td>325</td>
</tr>
<tr>
<td>105</td>
<td>0.041</td>
<td>0.90</td>
<td>151</td>
</tr>
<tr>
<td>125</td>
<td>0.126</td>
<td>0.90</td>
<td>1428</td>
</tr>
</tbody>
</table>
Since there are no reports of polarized 14 MeV neutron sources available with unpolarized incident beams below 500 keV energy to compare with the \(^7\text{Li}(d,n)^8\text{Be}\) reaction, an alternative comparison would be with the polarized 3 MeV neutrons emitted from the D-D reaction, being the most useful source of polarized neutrons employed for scattering experiments in that energy range.

The polarization data of Hall[50], for the D-D neutrons obtained with incident deuteron energies below 500 keV are quoted here for the purpose of comparison. The comparisons are listed in table 6.6 from which it is evident that while the D-D reaction has a superior figure of merit, the figure of merit associated with the \(^7\text{Li}(d,n)\) reaction is reasonably high for it to serve as a useful source of polarized neutrons, especially when considering that there are no other 14 MeV sources available under similar conditions.

### Table 6.6

D-D Reaction (TiD target used)

<table>
<thead>
<tr>
<th>(E_d) (keV)</th>
<th>Angle deg. lab.</th>
<th>Target thickness</th>
<th>(P)</th>
<th>(d') (mb/str) lab. frame</th>
<th>(P^2d'\times10^{-5}) mb/str</th>
</tr>
</thead>
<tbody>
<tr>
<td>385</td>
<td>46</td>
<td>thin</td>
<td>0.166</td>
<td>6.12</td>
<td>16804</td>
</tr>
<tr>
<td>460</td>
<td>45</td>
<td>thin</td>
<td>0.151</td>
<td>6.88</td>
<td>15668</td>
</tr>
<tr>
<td>500</td>
<td>46</td>
<td>thin</td>
<td>0.155</td>
<td>7.25</td>
<td>17418</td>
</tr>
</tbody>
</table>

\(^7\text{Li}(d,n)^8\text{Be}\) g.s. Reaction

<table>
<thead>
<tr>
<th>(E_d) (keV)</th>
<th>Angle deg.</th>
<th>Target thickness</th>
<th>(P)</th>
<th>(d') (mb/str)</th>
<th>(P^2d'\times10^{-5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>35</td>
<td>183</td>
<td>0.250</td>
<td>1.23</td>
<td>7718</td>
</tr>
<tr>
<td>510</td>
<td>35</td>
<td>175</td>
<td>0.193</td>
<td>1.42</td>
<td>5289</td>
</tr>
</tbody>
</table>
The only other reaction that can possibly be used for scattering experiments, would be the D-T reaction, provided the double scattering technique is employed, since the emitted neutrons are not polarized. However, double scattering requires massive shielding and is plagued with low yield and high background problems, so that the real scattering events are overwhelmed by the background effects. Consequently, very few attempts have been made to utilise this technique and the most of the existing reports hitherto have been for light nuclei such as $^4\text{He}$ and $^{12}\text{C}$.

One example is the double scattering measurements by Tornow[104] of 15 MeV neutrons from two high pressure helium gas scintillators. The success of the measurements, in this particular case, can be attributed to the fast coincidence arrangement between the pulses from the two gas scintillators, acting as the scattering samples, to overcome the background problems. Furthermore, the proper choice of the scattering angles (high cross section and analysing power offered by helium) optimised the conditions to overcome the low yield problems. However, the advantages in using helium as a scatterer cannot be expected from heavier scattering samples, so the problems incorporated with double scattering techniques still remain.

6.2 Associated Particle Measurements

Anticipating the practical use of the 14 MeV polarized neutrons from the Li(d,n) reaction, attempts were made to utilise the associated particle time-of-flight technique, as a step further to bring the reaction into possible future application in scattering work.
This technique provides the means for electronic collimation of the neutron beam by utilising the fact that the energy and the angle of emission of the 14 MeV neutrons and the $^8$Be g.s. nuclei are interdependent. The detection of the $^8$Be nuclei (or the two alpha particles due to their break-up), of known energy in a given solid angle uniquely defines the energy and the cone of the outgoing neutrons. Scattering experiments may be carried out by placing a sample in this cone so that the pulses from the $^8$Be particle detector identifying the instant of emission of the neutrons in the defined cone can be used as "start" pulses for a time-of-flight system, the "stop" pulses being driven from the detection of the neutrons scattered by the sample.

A computer program was written using the formulae of the reaction kinematics[61] to study the relationship between the energy and angle of the 14 MeV neutrons and the corresponding energy and angle of the $^8$Be particles from the reaction. Figures 6.3-6.5 illustrate the results calculated for deuteron bombarding energies from 50 to 500 keV in 50 keV steps, covering the emission angles from 0 to 180 degrees.

From these calculations the energy and the emission angle of the $^8$Be particles, associated with the 14.3 MeV neutrons emitted at 35°, were found to be 1.17 MeV and 170° respectively. A basic associated particle arrangement was set up, which consisted of a cylindrical chamber housing the LiF target and a silicon surface barrier charged particle detector under vacuum. The charged particle detector was used in conjunction with a recent "Ortec" charge sensitive preamplifier, model H2428, to provide the energy and fast timing pulses. The set-up of the electronics are illustrated (figs 6.6 & 6.7), preceded by the symbol definitions.
Fig. 6.3
Fig. 6.4
Fig. 6.5

Associated emission angles of 8Be & N

Lab angle, No emission (degrees)
Definition of Symbols (figs. 6.6 & 6.7)

TFA ........Timing Filter Amplifier
TAC ........Time to Amplitude Converter
ADC ........Analogue to Digital Converter
AMP ........linear Amplifier
SCA ........Single Channel Analyser
CFD ........Constant Fraction Discriminator
HT ........High Tension
sbd ........Surface barrier detector
csp ........Charge sensitive pre-amplifier
Ea ........pre-amp energy out-put
T ........pre-amp timing pulses.
d ........deuteron beam
n ........neutrons
Fig. 6.6
Fig. 6.7
First, the energy spectrum of the charged particles emitted from all the competing reactions was collected and the peaks identified having calibrated the system with a standard triple alpha source and the \(^4\text{He}\) particles of known energy from the D-T reaction. (fig.6.8)

It is evident that a considerable number of reactions are taking place simultaneously, but the predominant one is due to the \(7\text{Li}(d,a)^5\text{He}\) g.s reaction[101].

After performing a set of time of flight (T.O.F) measurements, the following results were obtained. Figure 6.9 illustrates the T.O.F spectra using the electronic set-up in fig. 6.6 gated with alpha particle energies up to 3 MeV. The background was found to be considerably high due to the presence of a high level of low energy particles. When the electronic set-up of figure 6.7 was used, i.e using 14 MeV neutrons to gate the T.O.F. spectra, a remarkable improvement was observed in the background level reduction, (fig.6.10). Following this encouraging result, the neutron detector was placed about one metre from the target (at a comparable distance for actual scattering measurements) and the T.O.F. measurements were repeated for this distance. Fig.6.11 shows the T.O.F. spectra before and after applying the energy gating.

A typical resolution of 0.2 nano seconds per channel was attained. The difficulty experienced in these measurements was the inability to apply high beam currents, since the alpha detector was close to the target and was easily swamped by the scattered deuterons. However, the whole procedure proved that the 14 MeV neutrons could be associated successfully with the \(^8\text{Be}\) g.s. particles and a few refinements could yield much better results.
Energy spectrum of the alpha particles (Ed = 450 KeV)

- 7Li(d,α)5He g.s.
- 5.15 MeV
- 5.48 MeV
- 5.8 MeV
- 2.1 MeV
- 7.1 MeV
- 1.17 MeV
- 8Be g.s.
- 6Li(d,p)7Li
- 6Li(d,α)α
- 10.2 MeV

Fig. 6.8
Fig. 6.9

- Ungated T.O.F Spectrum
- Gated T.O.F spec. with up to 3 MeV alphas
- Gated T.O.F spec. with .5 to 1.5 MeV alphas
Fig. 6.10

Ungated T.O.F spectrum
Gated spectrum (14 MeV neutrons)
Fig. 6.11

Associated Particle T.O.F Spectra

Ungated T.O.F spectrum
Gated T.O.F spectrum (14 MeV neutron energy)
7.1 Conclusion

This project was initiated with the aim of investigating the polarization angular distribution of the 14 MeV neutrons emitted from the $^7\text{Li}(d,n)^8\text{Be}$ g.s. induced with unpolarized, low energy deuteron beams. The measurements were performed with the anticipation that such energetic neutrons can be useful for scattering experiments provided that the reaction exhibits sufficiently high polarization in the emitted neutrons. Indeed, the investigations revealed fairly high magnitudes of polarization in the emitted neutrons, and was found to be particularly high at the forward reaction angle of 35° where the value approaches 25%. Judging from the figure of merit obtained for the present reaction and comparing it with that associated with the D-D reaction, it was found to be quite adequate for it to serve as a useful source of polarized 14 MeV neutron for scattering experiments.

Undeniably there are other means today for producing efficient sources of polarized 14 neutrons with low incident deuteron energies, mainly by using polarized incident beams where a substantial proportion of the the vector polarization of the incident beam is transferred to the outgoing neutrons that can then be collimated at a convenient emission angle to perform scattering experiments. However, this method is rather limited to the laboratories with polarized ion source facilities (P.I.S).

Brock et al[105] have used P.I.S techniques using the D-T
reaction with incident deuterons of ~100 keV energy and obtained 14 MeV neutrons with polarization values of about 50%. Similar work has recently been reported by Floyd et al[106] where 63% polarized neutron beams were obtained at 0° emission angle using the D-D reaction. Up to 90% polarization transfer was reported from a 70% polarized deuteron beam.

A review by Walter[23] summarises the most recent sources together with the technical advances hitherto achieved regarding polarization transfer techniques.

Lisowski et al[107] studied the vector transfer process of the (d,n) reaction with heavier nuclei namely 12C, 14N, 16O and 28Si. While high efficiency polarized neutron sources may be produced and utilised in laboratories with polarized ion facilities, we strongly feel that the 7Li(d,n)8Be g.s. reaction offers a modest source of 14 MeV polarized neutrons that may be produced with low energy, unpolarized deuteron beams.
Appendix

Calculation of the statistical accuracy in the asymmetry measurements.

The asymmetries in the n-α scattering were obtained from the gated helium recoil spectra, accumulated in a series of runs.

If \([R_{T1}]\) is denoted for the total number of "real + random" events triggered by pulses from the detector occupying position "R" (right, in the first run).

\([R_{r1}]\), denoted for the corresponding "random" events only, triggered by the same detector in the first run.

\([L_{T1}]\), denoted for the "real plus random" events triggered by the other detector, occupying position "L", in the first run, and \([L_{r1}]\), for the corresponding "random" events for this detector, in the first run.

Similarly, \(R_{T2}, R_{r2}, L_{T2}, L_{r2}\) for the corresponding events accumulated from the second run.

The "real" events, \(W\), are extracted by subtracting the "random" events from the "real + random" events for the corresponding positions for each individual run.

\[
\begin{align*}
R_{T1} - R_{r1} &= W_{R1} \\ 
L_{T1} + L_{r1} &= W_{L1} \\
\text{and} \quad R_{T2} - R_{r2} &= W_{R2} \\ 
L_{T2} - L_{r2} &= W_{L2}
\end{align*}
\]  

With reference to fig. 1.1 and the definition in formula 1.1 the differential cross section for the scattering of a polarized
neutron beam is given by the formula:
\[ \delta(\Theta_2, \phi) = \delta_u(\Theta_2)[1 + P_n(\Theta_1)P_s(\Theta_2)\cos\phi] \]

from expression 1.2, the asymmetry is given as
\[ \varepsilon = \frac{\delta(\Theta_2, 0) - \delta(\Theta_2, \pi)}{\delta(\Theta_2, 0) + \delta(\Theta_2, \pi)} \]

These can be expressed in terms of real events measured by the left and right detectors, so that
\[ \varepsilon = \frac{W_R - W_L}{W_R + W_L} = p_n p_s(\Theta) \]

where
\[ W_R = N f_R \delta(\Theta)[1 + p_n p_s(\Theta)] \]
\[ W_L = N f_L \delta(\Theta)[1 - p_n p_s(\Theta)] \]

\( N \) is the number of neutrons incident on the scatterer \( f_R \) and \( f_L \) are the detection efficiencies for the right and left detectors, respectively.

\[ \varepsilon = \frac{W_R - W_L (f_R/f_L)}{W_R + W_L (f_R/f_L)} \]

\( f_R/f_L \) is eliminated by interchanging the roles of the left-right detectors so that for the first run
\[ \varepsilon = \frac{W_{R1} - W_{L1} (f_{R1}/f_{L1})}{W_{R1} + W_{L1} (f_{R1}/f_{L1})} \]

for run number 2
\[ \varepsilon = \frac{W_{R2} - W_{L2} \left( \frac{f_{R2}}{f_{L2}} \right)}{W_{R2} + W_{L2} \left( \frac{f_{R2}}{f_{L2}} \right)} \]

Since the rotation of the polarimeter does not effect the efficiencies of the detectors, therefore

\[ \frac{f_{R2}}{f_{L2}} = \frac{f_{L1}}{f_{R1}} \]

and

\[ \varepsilon = \frac{A - 1}{A + 1} \]

where

\[ A = \sqrt{\frac{W_{R1} \times W_{R2}}{W_{L1} \times W_{L2}}} \] ........................ (b)

The statistical counting errors were treated by applying formula;

\[ (\Delta s)^2 = \left( \frac{\partial s}{\partial m_1} \right)^2 (\Delta m_1)^2 + \left( \frac{\partial s}{\partial m_2} \right)^2 (\Delta m_2)^2 + \ldots \ldots \ldots (c) \]

where \( s \) is a function of \( m_1 \) and \( m_2 \), ....... Applying (c) to \( A \), the uncertainty \( \Delta A \) can be obtained

\[ \Delta A = \frac{A}{2} \left[ \left( \frac{\Delta W_{R1}}{W_{R1}} \right)^2 + \left( \frac{\Delta W_{L1}}{W_{L1}} \right)^2 + \left( \frac{\Delta W_{R2}}{W_{R2}} \right)^2 + \left( \frac{\Delta W_{L2}}{W_{L2}} \right)^2 \right]^{1/2} \] ........................ (d)

Since \( R_{T1}, R_{11}, \) \( L_{T1}, L_{11} \) involve ordinary counting statistics then

\[ \Delta R_{T1} = \left( R_{T1} \right)^{1/2} \]

\[ \Delta R_{11} = \left( R_{11} \right)^{1/2} \]

\[ \Delta L_{T1} = \left( L_{T1} \right)^{1/2} \] etc.
and for

\[ \Delta W_{R1} = (R_{T1} + R_{r1})^{1/2} \]

\[ \Delta W_{L1} = (L_{T1} + L_{r1})^{1/2} \] \hspace{1cm} \text{(e)}

\[ \Delta W_{R2} = (R_{T2} + R_{r2})^{1/2} \]

Applying (e) to (d) and the results obtained from (b) the final expression is deduced as

\[ \Delta \varepsilon = \frac{2\Delta A}{(1 + A)^2} \]

\[ = \frac{A}{(1 + A)^2} \left[ \frac{R_{T1} + R_{r1}}{(R_{T1} - R_{r1})^2} + \frac{L_{T1} + L_{r1}}{(L_{T1} - L_{r1})^2} + \frac{R_{T2} + R_{r2}}{(R_{T2} - R_{r2})^2} + \frac{L_{T2} + L_{r2}}{(L_{T2} - L_{r2})^2} \right]^{1/2} \] \hspace{1cm} \text{(f)}

This approach for statistical error treatment was adopted in all the asymmetry measurements and formula (f) was actually an integral part of the software used to compute the statistical accuracies automatically.
References

1: L.Wolfenstein, Phys. Rev. 75 (1949), 342.
2: R.B.Galloway, Nuc.Inst.and Meth. 92 (1971), 537
   + Errata NIM 95 (1971), 393.
3: W.Haeberli, Fast Neutron Physics 2(Interscience,
6: G.R.Bishop, G.Preston, J.M.Westhead and H.H.Halban,
   Nature 170 (1952), 113.
10: J.H.Gibbons and H.W.Newson, Fast Neutron Physics
   (Interscience, New York 1963), 133.
12: I.Minzuatu, A.Calboreanu, N.Martalogu, R.Dumitrescu and
    M.Molea, Physical Lett. 4 (1963), 357.
13: S.T.Thornton, C.L.Morris, J.R.Smith and R.P.Fogel,
14: R.B.Galloway, A.S.Hall, R.M.A:Maayouf and D.G.Vass,
19: B.S.Bains and R.B.Galloway, Nucl.Inst. and Meth.,
    143 (1977), 295.
References (Contd.)

References (Contd.)

References (Contd.)

61: J.B.Marion and F.C.Young, Nuclear Reaction Analysis, North Holland publishing company - Amsterdam (1968).
References (Contd.)

92: B.Buck and P.E.Hodgson, Phil.Mag.6 (1961), 1371.
94: C.M.Perey and F.G.Perey, Atomic Data and Nuclear Data Tables, 17 (1976), 1.
References (Contd.)

95: P.E. Hodgson, Nuclear Reactions and Nuclear Structure
97: W.L. Imhof, L.F. Chase, Jr., and D.B. Fossan,
    Phys. Rev. 139 (1965), B904.
99: H. Liskien and A. Paulsen, Nuclear Data Tables
    11 (1973), 586, 601.
100: J.H. Coon, Fast Neutron Physics
102: P.A. Assimakopoulos, N.H. Gangas and S. Kossionides,
    Nucl. Phys. 81 (1966), 305.
103: V. Valkovic, W.R. Jackson, Y.S. Chen, S.T. Emerson
105: J.E. Brock, A. Chisholm, J.C. Duder and R. Grrett,
    Nuc. Inst. & Meth. 164 (1979), 311.
106: C.E. Floyd, P.P. Guss, K. Murphy, C.R. Howell, R.C. Byrd,
    G. Tungate, S.A. Wender and R.L. Walter, (to be published).
107: P.W. Lisowski, R.C. Byrd, G. Mack, W. Tornow and
    82 (1966), 161.
References (Contd.)

112: A. Elwyn, J. V. Kane, S. Offr, and D. H. Wilkinson

113: J. R. Sawers, F. O. Purser and R. L. Walter,

114: M. M. Meier, L. A. Schaller and R. L. Walter,

115: C. E. Hollandsworth, F. O. Purser, J. R. Sawers and

116: G. L. Morgan, R. L. Walter, C. S. Soltesz and T. R. Donoghue,

117: D. A. Gedcke, S. T. Lam, S. M. Tang, G. M. Stinson,
    J. T. Sample, T. B. Grandy, W. J. McDonald, W. K. Dawson and

118: H. G. Leighton, G. Roy and D. P. Guard,

119: H. G. Leighton, G. Roy and D. P. Guard and T. B. Grandy,


121: A. A. Debenham, J. A. R. Griffith, M. Irshad and S. Roman,


126: Feshbach, Porter and Weiskopf,
    Phys. Rev. 90 (1953), 166.

References (Contd.)


Acknowledgements

It has been a privilege to work under the supervision of Dr. R.B. Galloway to whom I owe a great deal of gratitude. Without his guidance, help and continuous encouragement this work would never have been completed.

I would like to thank Dr. D.G. Vass for his help and many useful discussions, and my colleague Mr. N. Erduran for his interest and willing assistance.

The assistance given by Mr. H. Napier and G. Turnbull on technical matters is much appreciated. The efforts put by the staff in the techniques laboratory to prepare the Lithium Fluoride targets promptly and efficiently are duly thanked for.

I am indebted to my parents for all the moral and financial support given by them and for enduring my absence through very difficult periods.

The financial assistance received from Edinburgh University in the first three years of this project is profoundly acknowledged.

Ara M. Ghazarian

December 1982