THE DEVELOPMENT OF A MULTICHANNEL PULSE-HEIGHT ANALYSER USING TRANSISTORS, AND ITS USE IN THE STUDY OF NUCLEAR REACTIONS IN LIGHT ELEMENTS.

THESIS

submitted by

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THE DEVELOPMENT OF A MULTI-CHANNEL PULSE-HEIGHT ANALYSER USING TRANSISTORS.  

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Part I

THE DEVELOPMENT OF A MULTI-CHANNEL
PULSE-HEIGHT ANALYSER USING TRANSISTORS.
CHAPTER 1.

PROPERTIES OF THE PULSES AND THEIR INFLUENCE ON THE DESIGN OF A PULSE-HEIGHT ANALYSER

A pulse-height analyser is an instrument which sorts incoming pulses into groups according to their height and counts the relative number of pulses in each group. The pulses may arise from the detection of ionising radiation resulting from a nuclear reaction or the disintegration of radioactive material, and the height of a pulse may then convey information about the energy of the radiation which caused it.

A number of the properties of these pulses may affect the design of a pulse-height analyser. The range of pulse-heights to be analysed, the length of the pulses and the rate at which pulses arrive could all be factors which influence the choice of the electronic circuits which are to perform the analysis.

1.1 The Range of Size of the Pulses

The pulses from a detector are usually so small that they have to be amplified using a high-gain amplifier. In some cases the amplified pulses are not very much bigger than the electrical noise from the amplifier. The analysis has then to be performed with an intense background of noise pulses. A similar situation can be encountered when studying γ-ray spectra, since Compton scattering of γ-rays near to the detector can give rise to a large number of small pulses while the number of larger pulses, corresponding to photo-electric processes in the detector, may be quite small.

The reverse of this situation can also occur, since cosmic rays can give rise to exceptionally big pulses from a large scintillation counter.
In many cases the range of pulse heights is such that the smallest pulses are lost among the electrical noise and the largest ones overload the amplifier. The circuits which are to perform the analysis must behave well under these extreme conditions, analysing larger pulses correctly in the presence of a multitude of small pulses and recovering quickly after being overloaded by exceptionally large pulses.

1.2 The Distribution of Pulse-Heights

The type of spectrum to be analysed depends on the nature of the ionising radiation which causes the pulses and on the type of counter used to detect the radiation.

An α-particle spectrum, for example, usually consists of a number of very narrow lines, since pulses arising from the detection of monoenergetic α-particles vary in height by only about 1 per cent when a gas filled counter is used and by 0.4 per cent if a solid state ionization chamber is used.

On the other hand, the spectrum obtained when studying γ-rays with a sodium iodide scintillation counter will consist of a number of rather broad peaks. Monoenergetic γ-rays do not give rise to a single line because there are three absorption processes by which a γ-ray can be detected. Photoelectric absorption gives rise to a pulse, corresponding to the full energy of the γ-ray. Compton scattering usually results in the electron being detected and the scattered γ-ray escaping detection, though it is possible for both the electron and the scattered photon to be detected giving pulses in the full energy peak of the spectrum. If only the electron
is detected the height of the pulse will correspond to the electron energy, which can be anywhere in the range zero to $E_o$

$$E_o = \frac{E_1}{1 + \frac{m_e c^2}{2 E_1}}$$

$E_1$ is the incident photon energy.

$m_e c^2 (= 0.51 \text{ MeV})$ is the rest energy of the electron.

Pair production can give three possibilities:

1. The electron and positron are detected but the radiation emitted when the positron is annihilated escapes.

2. The electron and positron are detected and so is one of the annihilation quanta.

3. The electron, the positron and both annihilation quanta are detected.

The third of these possibilities adds to the pulses in the full energy peak of the spectrum, the second gives a peak in the spectrum $0.51 \text{ MeV}$ below the photo-peak, the first gives a peak $0.51 \text{ MeV}$ lower still.

The whole of this distribution is "smeared" slightly by statistical fluctuations in the fraction of the light emitted in the phosphor which reaches the photo-cathode of the photomultiplier, and is "smeared" further by statistical fluctuations in the electron multiplication process in the photomultiplier. Because of these fluctuations the resolution in the $\gamma$-ray spectrum (i.e. the ratio of the energy width of the peak at half height to the energy of the peak) is usually about 10 per cent.

If the recorded distribution of pulse-heights is to be correct the analyser must be able to accept the whole of a given pulse-height
range. There must be no gaps between channels and no overlapping of adjacent channels. This is particularly important in the case of the \( \alpha \)-particle spectrum where one of the narrow peaks could be lost in a gap between channels, or apparently increased in intensity and broadened if it coincided with the overlapping parts of two channels.

1.3 The Length of the Pulses

The length of pulse depends markedly on the type of detector used, but in practice it is usually possible to shape these pulses before they reach the analyser so that, at the input to the pulse-height analyser, they are one or two microseconds long.

The pulses from a sodium iodide scintillation counter need very little shaping to achieve this since the decay time of the light from the phosphor is 0.25\,\mu s.

The pulses from a scintillation counter using an organic scintillator are much shorter, the decay time of the fluorescence being around 10\,\mu s. It is however a fairly simple matter to lengthen these pulses to about 1\,\mu s.

The proportional counter presents a rather different problem. The output pulses are made up of a fast component (due to the collection of electrons formed in the multiplication process in the counter) and a slow component (due to the collection of positive ions). The whole pulse may be about 100\,\mu s long. Fortunately, for most applications, it is only necessary to use the fast component, which, integrated in a circuit having a time constant of about 1\,\mu s, gives a suitable length of pulse for analysis.
1.4. The Random Arrival of Pulses

Since the pulses arise from a nuclear reaction or from the disintegration of radioactive material they arrive at the analyser in a random manner. When one pulse has been accepted for analysis it is interesting to know whether the next pulse is likely to arrive after a long or a short time.

The probability of a pulse arriving in a small time interval \( \delta t \) is proportional to \( \delta t \) and can be written as \( P \delta t \), where \( P \) is proportional to the average counting rate. The probability of no pulses arriving in this time interval is then \( (1 - P \delta t) \).

The probability that no pulse will arrive in the larger time interval is thus \( (1 - P \delta t)^k \) where \( k = \frac{T}{\delta t} \). If we make \( \delta t \) small and \( k \) large in such a way that \( k \delta t = T \) then the probability that no pulse will arrive in the interval \( T \) becomes

\[
\lim_{\delta t \to 0} (1 - P \delta t)^{\frac{T}{\delta t}} = \lim_{\delta t \to 0} \left[ 1 - P \frac{T}{\delta t} (\frac{T}{\delta t}) + \frac{P^2}{2} \frac{T^2}{\delta t^2} (\frac{T}{\delta t}) (\frac{T}{\delta t} - 1) - \ldots \right]
\]

\[
= 1 - \frac{PT}{1} + \frac{PT^2}{1 \cdot 2} - \ldots
\]

\[
= e^{-PT}
\]

The probability that no pulse shall arrive in the interval \( T \), but that the next pulse shall then arrive in the small interval \( dt \) after time \( T \) has elapsed is thus \( P \cdot e^{-PT} dt \).

The value of \( P \cdot e^{-PT} \) is largest when \( T \) is small, so short intervals between pulses are the most likely ones. This can lead to distortion of the spectrum if the electronic circuits, which are to perform the analysis, misbehave when two pulses arrive close together.
1.5 The Counting Rate

The average rate at which pulses arrive at the pulse-height analyser depends to a very large extent on the type of experiment which is being performed.

Coincidence or correlation experiments usually have exceptionally low counting rates. It may be necessary to count for several days in order to obtain statistically significant information about the spectrum. If this is the case, it is clear that the circuits in the analyser must be exceptionally stable.

The opposite extreme is often met in work with sources which have very short life times. Here the counting rate has to be high if statistically adequate information is to be obtained before the source dies. Most pulse-height analysers have a certain dead-time after accepting a pulse. Unless this dead-time is short the analyser will miss most of the pulses at high counting rates.

Experiments using pulsed accelerators bring together these two extremes. The average counting rate may be low, due to the low duty cycle of the machine, but during the time for which the machine is switched on very high counting rates can be encountered. This calls for a stable pulse-height analyser with a short dead-time, or alternatively some method of storing pulses so that they can be analysed during the idle part of the machine's duty cycle.
CHAPTER 2.

AN OUTLINE OF SOME OF THE METHODS USED TO ANALYSE PULSES

The state of the techniques of pulse-height analysis was reviewed by Churchill and Curran\(^{(1)}\) in 1956. This review covers the methods used to analyse pulses up to 1955. Some of the same ground is covered by the report on a conference on pulse-height analysers\(^{(2)}\), which was held in Gatlinburg, Tennessee in 1956. The report goes on to indicate the techniques which were being considered at that time by the designers of new pulse-height analysers. The types of pulse-height analysers which are now being manufactured in the United States show that the predictions made at the Gatlinburg conference were mainly correct.

Since the early work on pulse-height analysers has been reviewed already, only an outline of the basic methods of analysing pulses will be given, with an indication of the variations which are possible for each basic method. As far as possible the discussion will be confined to the manner in which the analyser as a whole works, and details of the electronic circuits will be ignored; descriptions will be in terms of block diagrams rather than circuit diagrams whenever this is possible.

2.1 Voltage Discriminators

The simplest instrument which can give information about a pulse-height spectrum is a discriminator; that is a device which gives an output signal for a pulse which exceeds a preset threshold level but no output if the pulse's height does not reach this level. If the threshold level is changed in equal steps and the number of
output signals in a fixed time is counted for each threshold setting, one can plot the counting rate as a function of threshold voltage and obtain the "integral" curve of the pulse height distribution. Alternatively one can subtract successive counts and obtain the "differential" curve of the pulse-height distribution. This is the curve which is generally most useful, as in nuclear physics the interesting things are usually the positions and widths of peaks in the spectrum of pulse heights.

A wide variety of types of discriminator has been used, the simplest being a biased diode. Biased triodes or pentodes have the advantage over the diode in that they deliver an amplified output signal, but this is counteracted to some extent by the fact that the cut-off characteristics of diodes are usually much sharper than those of triodes and pentodes. In these simple discriminator circuits the dead-time following the acceptance of a pulse depends on the size and shape of the accepted pulse. Discriminators which have a fixed dead-time, thus permitting accurate estimation of counting losses, have been developed (e.g. by Wells\(^{(3)}\)).

2.2 Single Channel Pulse-height Analysers

The single channel pulse-height analyser is a logical development from the voltage discriminator. Two discriminators are set to different threshold levels. The output signals from these are fed to an anticoincidence circuit. A count is only registered when an input pulse is large enough to overcome the bias on the lower discriminator, but not large enough to operate both discriminators. If the difference between the discriminator levels is kept fixed and
the level of discrimination is adjusted in steps equal to this difference, it is possible to scan the pulse height spectrum and obtain the "differential" curve of pulse-height distribution directly.

The superiority of the single channel analyser over the discriminator as an analysing device is further seen if we inspect the statistical significance of results obtained using the two methods of analysis to examine the same pulses. Suppose the number of counts registered in time \( t \) with a single discriminator is \( n \) for threshold setting \( V \), and \( n + s n \) for a threshold setting \( V - s V \). The number of counts in the range \( s V \) would be quoted as \( s n \pm (2n + s n)^{\frac{1}{2}} \). With a single channel analyser the number of counts in the range \( s V \) will be measured directly as \( s n \pm (s n)^{\frac{1}{2}} \) in time \( t \). Since \( s n \) is always less than \( 2n + s n \) the statistical significance of the counts obtained using the single channel analyser in a given time is always better than it would have been using a single discriminator.

Although the concept of a single channel analyser is exceptionally simple, it presents problems which do not arise when dealing with a single discriminator. The pulses to be analysed have finite rise and fall times, so a pulse exceeds the threshold of the upper discriminator a short time after it crosses the lower threshold. Also the pulse spends less time above the upper threshold than it does above the lower one. A number of circuits which overcome the difficulties caused by the pulse's finite rise and fall times have been described (e.g. by Park\(^{(4)}\)).
2.3 Multi-channel Analysers using Voltage Discrimination

The next step in the logical development from the single discriminator is to have many discriminators with equally spaced thresholds, and anticoincidence circuits to select the highest discriminator which was triggered. Pulse-height analysers which use this principle have been designed (e.g. by Westcott and Hanna\(^{(5)}\)).

Anticoincidence techniques are not the only method that can be used to select the highest discriminator triggered. The analyser described by Johnstone\(^{(6)}\) mixes square negative output pulses from one level with a differentiated output from the level below it so that the mixed output is entirely negative if both discriminators are triggered, but has a positive part if only the lower level is operated.

The analyser described by Cooke-Yarborough et al.\(^{(7)}\) uses a sorting ladder which serves to select the channel in which a count will be recorded. A signal is then fed into the selected channel. The circuit of the sorting ladder is shown in Fig. 1. Initially the diodes \(V_1\) to \(V_4\) are cut off and the left halves of the double triodes are conducting. As the input terminal moves negatively first \(V_7\), then \(V_8\) trigger over and so on. Each of the valves in the sorting ladder triggers over in turn as the input signal increases and the triggering of a circuit cuts off all the double triodes higher in the ladder. The channel into which the peak falls is left with the right side of a double triode conducting. This is used to route a signal to the correct scaler.

Gatti\(^{(8)}\) has described an analyser in which the channel width is determined by the size of a pulse generated internally. The
Fig. 1. Sorting Ladder (Cooke-Yarborough et al. (7)).
input pulse is first lengthened and, a short time after the beginning of the pulse, a step is added to the lengthened pulse. The size of this step determines the channel width of the analyser, while a series of discriminators set the lower edges of the channels. If the input pulse is to be recorded in the $n^{th}$ channel the first $(n - 1)$ discriminators will be triggered by the leading edge of the pulse. The $n^{th}$ discriminator will be triggered by the step which is added to the lengthened pulse. Coincidence circuits determine which discriminator was triggered by the step and route a signal to the corresponding scaler. This is illustrated in Fig. 2.

Pulse-height analysers which use multi-discriminator techniques all have the same disadvantages. The channel boundaries are set independently and can drift independently. In some analysers this can give rise to inequalities between the widths of different channels, to gaps between channels and to overlapping channels. Gatti's analyser has been seen to overcome the problem of differing channel widths, but it is still possible to have gaps between channels or to have overlapping channels. In Cook-Yarborough's analyser on the other hand, an input pulse can land in one and only one of the channels, but the channels are not necessarily all of the same width.

We have already seen that differing channel widths, gaps between channels and overlapping channels are undesirable features. If many channels are used the setting-up procedure is laborious; and it has to be carried out frequently if these troubles are to be avoided.
Fig. 2. 20-Channel Pulse-Height Analyser (Gatti(8)).
The main advantage of the multi-discriminator analyser is that it can accept high counting rates.

2.4 Analysers using a Cathode Ray Oscilloscope to Measure the Pulse-Height

By far the simplest method of using a cathode ray tube to investigate a pulse-height distribution is to apply the pulses to the \( y \)-input of a commercial oscilloscope and use a triggered time-base. The screen is photographed, the exposure being extended to record a large number of pulses. All the pulses have about the same rise-time, so by scanning the resulting film with a photodensitometer along a correctly chosen line parallel to the \( y \)-axis an estimate of the relative distribution of pulse-heights can be obtained. The choice of scanning line can be made less critical if the incoming pulses are lengthened slightly to give them flat tops.

Hunt et al.\(^{(9)}\) have described a pulse-height analyser in which the pulses are first lengthened a little to give them flat tops, and then applied to the \( y \)-input of an oscilloscope. During the flat top of the pulse the beam of the oscilloscope is intensified. The result is photographed on moving 35 mm. film as a series of dots, and analysed later using an "automatic electromechanical reader". Hunt et al. claim to be able to sort the events into 100 discrete channels by this method.

The most popular pulse-height analysers using the oscilloscope to measure the pulse-heights are variations on the "grey wedge" analyser. Maeder\(^{(10)}\) reviewed the "grey wedge" techniques in 1958, indeed the name Maeder occurs throughout the development of this method of analysis. It was he who described the original "grey wedge"
13.

analyserv (11) in 1947. The input pulse is lengthened so that it has a flat top, and applied to the x-plates of a cathode ray tube. At the same time a linear sweep is applied to the y-plates of the tube. The screen of the oscilloscope is photographed through an optical wedge made of neutral density glass, the exposure being extended to record a large number of pulses. Printing the photograph on high contrast photographic material will make a "line of equal density" stand out clearly. That this will give the spectrum of pulse-heights on a logarithmic intensity scale is seen from the following analysis.

If \( N(x) \) is the differential number of counts as a function of the pulse-height co-ordinate, \( x \), points of equal density on the photograph will occur where \( N(x) T(y) = \) constant.

\( T(y) \) is the "transmission" of the wedge as a function of the \( y \)-co-ordinate, and with a high quality optical grey wedge \( T(y) = \frac{1}{f_0} e^{-ay} \) where \( f_0 \) is the "filter factor" of the wedge at its most transparent end (i.e. at \( y = 0 \)).

Combining these two expressions gives the equation

\[
\log N(x) = ay + \text{constant}
\]

as a representation of the isodensity curves, indicating that the intensity scale of the spectrum is logarithmic.

If, instead of using a grey wedge with an exponential transmission function, an absorbing plate for which \( T(y) \propto \frac{1}{y} \) were used, the intensity scale of the spectrum would be linear.

"Wedges" with these characteristics are difficult to obtain, but the same result has been achieved by a different method in the
"electronic grey wedge analyser"\(^{(12)}\). In this instrument the linear sweep applied to the \(y\)-plates is replaced by an exponential sweep. With an exponential sweep the velocity of the beam is proportional to its deflection. This is equivalent to a wedge with a transmission function \(T(y) \propto \frac{1}{y}\) and so gives the spectrum with a linear intensity scale.

A pulse-height analyser which uses a special cathode ray tube to give the pulse-height a digital representation has been described by Porter and Borkowski\(^{(13)}\). The input pulses deflect the beam of the cathode ray tube across a target grid with 30 equal webs and spaces. Whenever the beam passes through a space in the grid a pulse is obtained on a signal plate mounted behind the grid. The number of pulses recorded on this signal plate gives a digital representation of the height of the pulse. The pulses are counted on a scaler; the final state of the scaler indicates the channel in which a count has to be added. This leads on to the next general classification of pulse-height analysers.

2.5 Analysers using Analogue to Digital Conversion

The first analyser of this kind was designed by Wilkinson\(^{(14)}\). He charged a capacitor to the peak value of the input pulse, and then discharged it linearly so that the time of discharge of the capacitor was proportional to the height of the input pulse. During the linear run-down the circuit gave out a square pulse which was used to gate a free running oscillator, so obtaining a number of pulses proportional to the input pulse's height. The pulses from the oscillator were counted on two "ring-of-ten" scaling circuits in
series and the state of these rings was used to set relays which routed a count on to one of 100 registers. The instrument was extremely slow in operation, the speed being limited primarily by the performance of the mechanical registers, which could accept a counting rate of only 10 counts per second.

Many analysers have been built using the Wilkinson analogue-to-digital conversion principle, but capable of faster operation. An example of this is the Argonne 256-Channel Analyser which is described by Schumann and McMahon\(^{(15)}\). In this analyser the digital representation of the pulse-height is in binary form. The information is stored in a magnetic core memory, and displayed in binary notation as dots on the face of a cathode ray tube.

A variation on the Wilkinson theme is to discharge the capacitance which lengthens the input pulse in equal steps instead of using a linear sweep. Transistors have been used in an analyser using this technique by Kandiah\(^{(16)}\) at Harwell and also in an analyser developed at Chalk River\(^{(17)}\). Both these analysers use magnetic core memories.

The happy marriage of transistors and magnetic core memories has had a marked effect on the commercial development of pulse-height analysers. The analysers which have come on to the market in the United States during the last year or two all appear to use variations of the Wilkinson method with fast analogue-to-digital conversion. They use transistors in the electronic circuits and magnetic core memories. The number of channels tends to be higher than in the original Wilkinson analyser, 400 channels being common. The
analysers can usually be split up into several smaller units so that more than one spectrum can be obtained at the same time.

2.6 The Hutchinson-Scarrott Technique

The main difference between the Hutchinson-Scarrott method of pulse-height analysis and the methods mentioned in the previous section is the type of memory used. The information about the spectrum of pulse-heights is stored in binary notation as pulses on a delay line. The original analyser of this type was described by Hutchinson and Scarrott. They used a mercury delay line in the original analyser, but later this was changed, and a nickel wire magnetostrictive delay line was used. In the United States analysers using the same principle have been developed using quartz delay lines.

The way in which the Hutchinson-Scarrott type of analyser works is illustrated by the block diagram of Fig. 3. The stored information is transmitted down the "delay line" as a series of "acoustic" pulses. After a period of time the pulses arrive at the "receiver" where they are converted into electrical pulses which are then shaped by the "adding gate" and retransmitted. The information circulates round this closed loop without change unless a signal is applied to the "adding gate" to cause a change.

The "linear sweep" circuit generates a sawtooth waveform which is synchronised by signals from the "receiver" so that the time between successive sweeps is the same as the delay time. The period of the "linear sweep" is divided into a number of equal time intervals by the "channel oscillator". During each of these intervals a binary number passes through the "adding gate" on its way round the memory
Fig. 3. Hutchinson-Scarrot type of Analyser.
loop. The period of the "channel oscillator" is itself divided up by the "digit oscillator" which determines the period between digits in the binary numbers.

An input pulse which is to be sorted is first lengthened. The "comparison" circuit compares the amplitude of the lengthened pulse with the changing voltage of the "linear sweep" and gives an output when the sweep voltage becomes equal to the amplitude of the lengthened pulse. The output signal from the "comparison" circuit primes the "coincidence" circuit so that it gives out a signal coincident with the next channel pulse and causes the next binary number which passes through the "adding gate" to be increased by unity.

The synchronisation between "channel and digit oscillators" and the "linear sweep" ensures that each binary number corresponds to a certain range of sweep voltage, and so to a certain range of pulse-height.

The speed of a Hutchinson-Scarrott type of analyser is determined mainly by the length of the delay line. A fast analyser could be made by using a short delay, but it would have either fewer channels or lower storage capacity per channel or both. Scarrott\textsuperscript{(21)} has outlined a method of using a temporary store to enable a fast version of the analyser to be made without losing any storage capacity.

2.7 \textit{Summary}

The trend in the design of pulse-height analysers is at the moment towards transistorized analysers with magnetic core memories. In spite of this the choice of design for an analyser will, to some extent, depend on the circumstances in which it is to be used.
The fastest analysers are the multi-discriminator type, but they tend to have only few channels. The cheapest are grey-wedge analysers but the results are not expressed in an accurate quantitative manner. The analysers which offer the highest precision use either the Wilkinson technique or the Hutchinson-Scarrott method.
CHAPTER 3

FUNCTIONAL DESCRIPTION OF A TRANSISTORISED
30-CHANNEL PULSE-HEIGHT ANALYSER

The need for a reliable multi-channel pulse-height analyser in this laboratory became apparent in 1957 when Galloway was attempting to investigate complex gamma-ray spectra using a 5-channel analyser (A.E.R.E. type 1074A). Subsequently his experience with a Hutchinson-Scarrott type of analyser (manufactured by Survic Controls Ltd.) showed that multi-channel analysers using thermionic valves tend to develop frequent faults.

About this time transistors were beginning to become readily available and Galloway outlined a design for a 30-channel pulse-height analyser which would take advantage of the claimed reliability of semiconductor devices. The proposed analyser included an analogue-to-digital converter of a novel kind. This is illustrated in Fig. 4 and was to work in the following manner:- An input pulse is made to circulate round a loop consisting of a "subtractor", a "delay" and an "amplifier". The "amplifier" is included solely to compensate for the attenuation introduced by the "delay". Each time the pulse passes round the loop a fixed amount is subtracted from it, so the number of times a pulse circulates is a digital representation of the height of the input pulse.

An attempt was made to build a pulse-height analyser using this method, but it failed because it was found to be impossible to remove completely reflections which occurred in the delay line, and so the circulating pulse would not decrease in size in a linear manner.
Fig. 4. Analogue-to-Digital Converter (Galloway\textsuperscript{(22)}).
The analyser which eventually was built uses a more conventional method of analogue-to-digital conversion. It uses transistors in all the electronic circuits and the storage and display of information is on "dekatron" counting tubes and mechanical registers. A block diagram of the pulse-height analyser is shown in Fig. 5.

The input pulses come from a conventional amplifier (Dynatron Radio Ltd. type 1008), and if the complete linear range of the amplifier is to be used, the size of pulse can be as large as 60 volts. The "attenuator" at the input of the analyser scales down the size of an input pulse so that it is more suitable for use with transistor circuits. The attenuated pulse is then passed on to the "bias circuit" which determines the lower end of the range of pulse-heights which can be accepted by the analyser. The "limit circuit" clips the size of large pulses to ensure that they are not big enough to break through the gate when it is closed. Provided that a pulse is not already being sorted by the analyser the "gate" will be open and the input pulse can pass through, with some attenuation, to an "amplifier" which inverts the pulse and increases its size slightly, so that the range of pulse sizes accepted by the gate is also the range which can be accepted by the "analogue-to-digital converter".

A block diagram of the "analogue-to-digital converter" is shown in Fig. 6. The operation is as follows:— A pulse fed into the converter triggers the "reset" circuit. This resets the "lengthener" and the "staircase generator". Meanwhile the pulse is shaped so that it has a standard length and then delayed for 10 µsec. to allow time for the resetting operation, which takes about 9 µsec. The delayed input pulse is then lengthened, 2 µsec. after the end of
Fig. 5. Block Diagram of the 30-Channel Pulse-Height Analyzer.
the resetting operation a signal is fed to the "start" trigger circuit which switches the "control circuit" to its ON state and causes a train of pulses to be generated by the "blocking oscillator". These pulses are clipped to standard size in the "shaping circuit" and then fed on to the "staircase generator". Because the pulses which form the staircase have a standard size the staircase has equal steps. The train of pulses continues until the staircase has reached the height of the lengthened pulse when the "comparison circuit" gives out a signal which operates the "stop" trigger circuit and switches off the train of pulses. The number of pulses in the train is thus a digital representation of the height of the input pulse.

Returning to the block diagram of Fig. 5, it can be seen that the signals fed out from the "analogue-to-digital converter" are:

1. The "reset signal", which is fed to the display unit to reset the channel selection circuits.

2. The "digit signal" (i.e. the train of pulses which form a digital representation of the input pulse's height). These pulses go to the display unit where they are used to select the required channel.

3. A "delayed reset signal", which operates the "dead-time" trigger circuit.

The "dead-time" trigger circuit applies a signal to the "gate control" which closes the "gate" in the input circuit and keeps it closed for the duration of the "dead-time" signal. This signal is a pulse 350 usec. long which allows adequate time for the selection
Fig. 6. Block Diagram of the Analogue-to-Digital Converter.
(i) Input to the analogue-to-digital converter seen at the base of $T_{14}$.

(ii) Shaped input pulse seen at the emitter of $T_{15}$.

(iii) Input pulse, delayed and lengthened; seen at the base of $T_{22}$.

(iv) Reset signal seen at the emitter of $T_{40}$.

(v) Digit pulses at the emitter of $T_{49}$.

(vi) Staircase waveform at the base of $T_{23}$.

(vii) "Start" signal at the collector of $T_{42}$.

(viii) "Stop" signal at the collector of $T_{48}$.

(ix) "Control" waveform seen at the collector of $T_{46}$.

Fig. 7. Waveforms in the Analogue-to-Digital Converter.
(i) Dead-time signal seen at the collector of $T_{36}$.

(ii) Look signal seen at the collector of $T_{33}$.

(iii) Gate Control waveform seen at the emitter of $T_6$.

(iv) Digit pulses at the emitter of $T_{49}$. The input pulse is recorded in channel 20.

(v) The Look signal as it is fed out to the Display Unit.

(vi) Digit pulses at the emitter of $T_{49}$. The input pulse is too big for the analyser.

(vii) The Suppress Look signal seen at the collector of $T_{28}$.

(viii) The suppressed Look signal. This pulse is too small to trigger the drive circuits in the Display Unit.

Fig. 8. Some Waveforms in the Sorting Unit.
of the channel in which a count should be recorded. At the end of the "dead-time" pulse a signal is fed back into the "analogue-to-digital converter" to make sure that the train of digit pulses has stopped, and at the same time the "look-pulse generator" is fired. The output from the "look-pulse generator" is a pulse 30 usec. long. During this pulse the "gate" in the input circuit remains closed because of a signal fed from the "look-pulse generator" to the "gate control" circuit. The "look signal" itself is fed through an "anticoincidence" circuit to the "display unit" where it causes a count to be recorded in the selected channel. If an input pulse is too large to be recorded in any channel of the analyser a signal from the "display unit" is fed to the other input of the "anticoincidence" circuit in order to suppress the "look signal". The total time for which the instrument is incapable of accepting another input pulse, when once a pulse has been accepted for sorting, is the sum of the lengths of the "dead-time" and "look" signals, i.e. 380 usec.

Oscillograms of some of the waveforms in the "analogue-to-digital converter" are shown in Fig. 7, and waveforms from other parts of the sorting unit appear in Fig. 8.

The operation of the "display unit" is illustrated in Fig. 9. First of all the "rings of five and six" are set to their initial states by the "reset signal". The "digit pulses" are then counted on these scaling circuits. When the train of pulses is complete the "ring of five" has one stage switched ON and the rest OFF. The stage which is ON holds open the "gate" which is associated with that stage. This selects a "drive" circuit associated with a column of the matrix of "scalers". In the same way the final state
Fig. 9. Block Diagram of the Display Unit.
of the "ring of six" selects a "drive" circuit associated with a row of "scalers". The two "drive" circuits selected in this way are triggered by the "look signal".

Each of the "scalers", numbered 1 to 30, consists of a dekatron counting tube followed by a mechanical register. Before a dekatron can be stepped round by one count, two pulses must be applied to it, one to the first guide ring followed immediately by the second pulse applied to the second guide ring. A "drive" circuit associated with a row of dekatrons feeds a signal only to the first guide rings of all the dekatrons in the row. A "drive" circuit associated with a column feeds correctly timed signals to the second guide rings of the dekatrons in that column. Since only two "drive" circuits are triggered, one associated with a row, the other with a column, only the dekatron common to both the selected row and the selected column will receive the two pulses required to drive it.

If an input pulse is too big to be recorded in the analyser the "ring of six" will be stepped through more than one complete cycle when counting the digit pulses. When this happens the "ring of six" gives out a pulse which is used to prevent the "look signal" being applied to the "display unit".

The complete analyser is built as three units, the sorting unit, the display unit, and the power unit. These are all built behind standard panels 19 inches wide so that they can be mounted in a standard rack. A photograph of the pulse-height analyser is shown in Plate I.
Plate I.
The 30-Channel Pulse-Height Analyser.
CHAPTER 4.

DESCRIPTION OF THE ELECTRONIC CIRCUITS
USED IN THE SORTING UNIT OF THE
30-CHANNEL PULSE-HEIGHT ANALYSER

A complete circuit diagram of the sorting unit of the 30-channel pulse-height analyser is shown in Fig. 10, which is in the pocket at the back of the thesis, but to facilitate explanation, this has been broken up into a series of smaller circuits, Figs. 11 to 17, corresponding very roughly to the blocks in the block diagrams of Figs. 5 and 6.

4.1 The Input Circuit

Fig. 11 is the circuit diagram of the input stages of the pulse-height analyser. It corresponds to the "attenuator", "bias circuit" and "limit circuit" of Fig. 5.

The attenuator is a straightforward emitter follower, the input to which is fed through a potential divider. The input pulse is applied to one end of the variable resistor, V.R.1, but only a fraction of this pulse arrives at the base of T1. The amount of attenuation is determined by the ratio of the input resistance of the emitter follower to the value of the variable resistor.

The bias circuit is a biased diode discriminator made up of the two diodes D1 and D2. Both the signal and the bias voltage are applied to the discriminator through an emitter follower, T2. The bias is adjusted by means of a 10 turn potentiometer, V.R.2, which varies the potential on the base of T2.

The limit circuit is a long-tailed pair in which T3 is conducting and T4 is cut off by a bias applied to its base. When a
Fig. 11. The Input Circuit.
positive pulse is applied to the base of $T_3$, it behaves as an emitter follower unless the potential of its emitter becomes sufficiently positive to cause $T_4$ to conduct. If this happens $T_3$ cuts off and the potential of the common emitters of $T_3$ and $T_4$ is held steady for the duration of the pulse by the bias on the base of $T_4$. The capacitors in the circuitry around $T_4$ apply a certain amount of feedback and so reduce the amount of "ringing" which occurs when a large pulse is clipped by the circuit. The clipping level is not very critical, it is set by the potentiometer V.R.3.

The signal comes out from the common emitters of $T_3$ and $T_4$ and is fed on to the gate by an emitter follower, $T_5$.

4.2 The Gate Circuit

The gate circuit is shown in Fig. 12. This circuit corresponds to the "gate", "amplifier" and "gate control" of Fig. 5.

The gate itself is the diode $D_5$. If the transistor $T_{11}$ is conducting $D_5$ can be arranged to be unbiased by adjusting the setting of V.R.4. The diode can then pass any positive signal and so the gate is said to be open. When $T_{11}$ is not conducting the diode, $D_5$ has a reverse bias applied to it and so will not pass a signal; the gate is then closed.

The pulse from the input circuit is fed into the gate through a transformer. To ensure that most of the signal from the secondary winding of this transformer will appear at the anode of $D_5$ rather than at the other end of the transformer winding, a low resistance path to earth, through a $0.02 \mu F$ capacitor and a $470 \Omega$ resistor, is arranged for any signal appearing at the upper end of the transformer winding.

Whether or not the gate is open is determined by the state of
the transistors $T_6$ and $T_7$. If neither $T_6$ nor $T_7$ is conducting
the currents in $T_9$ and $T_{10}$ are such that the potential of the base
of $T_{11}$ is negative. $T_{11}$ conducts and the gate is therefore open.
If either $T_6$ or $T_7$ is made to conduct heavily the base of $T_9$ will
become more negative causing $T_9$ to conduct more heavily. As a
result the base of $T_{10}$ becomes less negative and $T_{10}$ conducts less
heavily. The potential on the base of $T_{11}$ attempts to become
positive but is caught by $D_4$ at zero potential. $T_{11}$ cuts off and
so the gate is closed.

The 0.02 $\mu F$ capacitor, which effectively shunts the 6.8k $\Omega$
resistor in the collector load of $T_{11}$, reduces the speed with which
the gate can open or close. To avoid this unpleasantness it is
arranged that the opening or closing of the gate shall not alter
the potential difference between the plates of this 0.02 $\mu F$
capacitor. The same signal is made to appear at each side of
the capacitor whenever the gate is opened or closed. This is
the purpose of the emitter follower, $T_8$.

The output from the gate is amplified by $T_{12}$ and the resulting
negative pulse is fed out through the emitter follower, $T_{13}$.

4.3 The Reset Circuit

Fig. 13 shows the reset circuit in which $T_{37}$ and $T_{38}$ form a
monostable circuit which can be regarded as a grounded base amplifier,
$T_{37}$, feeding an emitter follower, $T_{38}$. In the circuit's stable
state $T_{37}$ is conducting and $T_{38}$ is cut off. A negative trigger
pulse from the output of the gate circuit is applied to the common
emitters of these two transistors and triggers the circuit. The
output signal from the collector of $T_{38}$ is a positive pulse the
length of which is determined by the time constant in the coupling
Fig. 13. The Reset Circuit.
between the collector of $T_{37}$ and the base of $T_{38}$. The resistors in the circuit are chosen so that in the circuit's stable state the collector voltage of $T_{38}$ is more negative than the most negative possible excursion of either the "staircase" or the "lengthener" waveforms. In the circuit's metastable state the collector voltage of $T_{38}$ becomes positive. Emitter followers $T_{39}$ and $T_{40}$, are directly coupled to the collector of $T_{38}$. They feed the reset signal to various parts of the analyser. The way in which the reset signal is then used will be discussed when the circuits of these parts of the analyser are described.

4.4 The Shaping Circuit

The pulse which emerges from the gate circuit requires shaping before being fed on to the 10 $\mu$sec. delay, because the characteristics of the delay line make it unable to transmit faithfully any very fast changes. A square voltage step fed into the delay will appear at the other end of the delay line with a rise time of about 1 $\mu$sec., so if the height of a pulse is to be maintained faithfully when it is passed along the delay line, a pulse length considerably more than 1 $\mu$sec. is needed.

The diagram of the circuit which lengthens the pulses before feeding them on to the delay line is shown as Fig. 14. The output from the gate circuit is fed by $T_{14}$ on to a 0.005 $\mu$F capacitor. The capacitor is charged to the height of the pulse, but when the pulse collapses $T_{14}$ cuts off and the capacitance remains charged.

At the end of the "reset" signal the trailing edge of the "reset" waveform produces a short pulse at the collector of $T_{19}$. 
Fig. 14. The Shaping Circuit.
This triggers the monostable circuit, $T_{17}$ and $T_{18}$, and causes the potential of the collector of $T_{17}$ to become positive for a time. The emitter of $T_{16}$ follows the collector of $T_{17}$ until its excursion is stopped by the diode $D_7$. $T_{16}$ then cuts off and current flows through the 10K resistor and $D_7$ to discharge the 0.005/µF capacitor to its original potential.

The shaped pulse is fed out to the 10/µsec. delay by an emitter follower, $T_{15}$.

4.5 The Pulse-Train Generator

The Pulse-Train Generator is comprised of the "start", "stop", "control", "blocking oscillator" and "shaping" circuits of Fig. 6. Its circuit diagram is shown in Fig. 15.

The train of pulses is generated by the blocking oscillator, $(T_{43}$ and associated circuitry). If the base of $T_{43}$ is held at a small negative potential, the blocking oscillator is free-running at a frequency of about 100 Kc/sec. If, however, the base of $T_{43}$ is at a positive potential, $T_{43}$ will be cut off by this bias and the blocking oscillator will be switched off.

The "control" circuit is a bistable circuit of the Eccles-Jordan type. $T_{45}$ and $T_{46}$ are the transistors in this bistable circuit. When the circuit is in the state in which $T_{45}$ is conducting, the collector potential of $T_{45}$, and therefore the emitter potential of $T_{44}$, is sufficiently positive to ensure that the base of $T_{43}$ experiences a positive potential. The blocking oscillator is therefore switched off. If on the other hand the bistable circuit is in the state in which $T_{45}$ is cut off, then the potential at the collector of $T_{45}$ is more negative and provides a
Fig. 15. The Pulse-Train Generator.
negative potential on the base of $T_{43}$. The blocking oscillator is then free-running.

The "start" circuit is a monostable circuit in which $T_{41}$ is normally conducting and $T_{42}$ is cut off. The signal which triggers this circuit is obtained from the trailing edge of the reset signal after the reset pulse has been delayed by 2 μsec. This ensures that the train of digit pulses does not start until the resetting operation on the "lengthener" and "staircase" circuits is complete. The positive-going output signal from the collector of $T_{42}$ is the "start" signal. It is applied through the diode $D_9$ to the base of $T_{45}$ and switches the bistable circuit into the state in which $T_{45}$ is cut off. This switches the blocking oscillator on and so starts the train of digit pulses.

The train of digit pulses continues until a signal from the comparison circuit triggers the "stop" trigger circuit. This is a monostable circuit similar to the "start" circuit. $T_{47}$ and $T_{48}$ are the two transistors used and the output pulse from the collector of $T_{47}$ is the "stop" signal. The "stop" signal is fed through the diode $D_{10}$ to the base of $T_{46}$ and switches the bistable "control" circuit into the state in which $T_{45}$ is conducting. This switches the blocking oscillator off and so stops the train of digit pulses.

The digit pulses are shaped by the biased emitter follower, $T_{49}$, and the limiting diode $D_{11}$, so that all the pulses are of equal size. The pulses are then fed through an emitter follower, $T_{50}$, to the staircase generator. The digit signal which is fed to the display unit comes from the emitter of $T_{49}$ through an emitter follower, $T_{51}$. 
4.6 The Lengthener, Staircase and Comparison Circuits

The circuit shown in Fig. 16 is the heart of the pulse-height analyser.

The delayed input pulse is fed on to the lengthener by cascaded emitter followers $T_{20}$ and $T_{21}$. The lengthening circuit itself is made up of the diode $D_{12}$, the transistor $T_{22}$, and two 0.005 $\mu$F capacitors. The negative input pulse is fed through the first of the 0.005 $\mu$F capacitors and the diode $D_{12}$ on to the second 0.005 $\mu$F capacitor. In fact the two capacitors form a potential divider so only about half the input pulse is received by the second capacitor. When the input pulse collapses $D_{12}$ cannot remove the charge which has been fed on to the second capacitor so it remains charged to a voltage proportional to the input pulse's height. The transistor $T_{22}$ ensures that the potential difference across $D_{12}$ is kept small, reducing the leakage of charge off the lengthening capacitor.

The staircase generator is a circuit very similar to the "lengthening" circuit. It consists of the diode $D_{17}$, the transistor $T_{23}$ and two capacitors, one a 0.001 $\mu$F capacitor which feeds the train of digit pulses from the pulse train generator to the staircase circuit, the other a 0.005 $\mu$F capacitor on which the staircase waveform is generated. The digit signal is a train of negative pulses. When the first pulse of the train arrives a fraction of it is fed on to the 0.005 $\mu$F capacitor, and when the pulse collapses $T_{23}$ ensures that the cathode of $D_{17}$ does not follow the collapsing pulse, but remains at the same potential as its anode. So $D_{17}$ has zero bias on it when the next pulse arrives and the second pulse is
treated in exactly the same way as the first pulse of the train.
Each successive pulse adds an equal step to the voltage on the 0.005 μF capacitor.

Before the arrival of an input pulse at the lengthener or the beginning of a train of pulses at the staircase generator, these two circuits have to be reset. The diodes $D_{13}, D_{14}, D_{15}, D_{16}$ are used in this operation. The anodes of $D_{14}$ and $D_{15}$ are connected to the emitter of $T_{39}$ in the reset circuit. When the reset circuit is in its stable state the anodes of $D_{14}$ and $D_{15}$ are held at a more negative potential than their respective cathodes so $D_{14}$ and $D_{15}$ are cut off. When the reset circuit is operated the anodes of $D_{14}$ and $D_{15}$ attempt to become positive, current flows through these two diodes and the 500 Ω resistor (which forms the emitter load of $T_{39}$) to discharge the lengthener and staircase capacitors. The diodes, $D_{13}$ and $D_{16}$, divert the current to earth when the discharge of the capacitors is complete.

$T_{24}$ and $T_{25}$ make up the "comparison" circuit. The lengthened input pulse is applied to the emitter of $T_{24}$ which is therefore cut off. The staircase waveform is applied to the base of $T_{24}$. $T_{24}$ remains cut off until the staircase waveform becomes more negative than the lengthened input pulse, when it starts to conduct. The step on the staircase which causes $T_{24}$ to begin conducting is amplified by $T_{24}$ and $T_{25}$ and the negative signal from the collector of $T_{25}$ is used to stop the train of digit pulses.

4.7 The Dead-Time Circuit, and the Circuits which Produce or Suppress the Look Signal

In the circuit diagram of Fig. 17 the "dead-time" trigger
Fig. 17. The Dead-Time Circuit and Circuits which Produce or Suppress the Look Signal.
circuit is a monostable circuit in which $T_{36}$ is normally conducting and $T_{35}$ normally cut-off. The circuit is triggered by the leading edge of the "delayed reset signal" which is applied to the base of $T_{36}$. The collector of $T_{36}$ is connected to the base of $T_7$ in the "gate" circuit. When the "dead-time" trigger circuit is in its stable state and $T_{36}$ is conducting, the potential at the collector of $T_{36}$ is such that $T_7$ is cut off. Provided that the look pulse generator is also in its stable state, the gate will be open.

When the "dead-time" circuit is triggered $T_{36}$ cuts off and so $T_7$ conducts causing the gate to close. The gate remains closed (because $T_7$ is conducting) until the "dead-time" circuit reverts to its stable state. This time is determined by the components in the coupling between the collector of $T_{35}$ and the base of $T_{36}$.

When the "dead-time" circuit reverts to its stable state a negative-going signal appears at the base of $T_{34}$ and is amplified by $T_{34}$. The resulting positive signal triggers the "look-pulse generator", which is also a monostable circuit. The transistors in this circuit are $T_{32}$ and $T_{33}$, and in the circuit's stable state $T_{33}$ is conducting. The collector of $T_{33}$ is connected to the base of $T_6$ in the gate circuit. When the "look-pulse generator" is in its stable state $T_6$ is cut off by the potential at the collector of $T_{33}$, so provided that $T_7$ is also cut off the gate is open.

When the "look-pulse generator" operates at the end of the dead-time waveform $T_{33}$ becomes cut off and so $T_6$ conducts. The "gate", which is already held closed by the "dead-time" signal, will therefore remain closed during the "look signal".

The "look signal" itself is taken from the collector of $T_{32}$. 
It is a positive going pulse which is fed to the display unit through $T_{30}$ and the emitter follower $T_{31}$, provided that $T_{29}$ is not conducting.

If a pulse is too big for the analyser a signal from the display unit indicates this fact. The signal is negative going and is amplified by $T_{26}$ to produce a positive signal which triggers a monostable circuit consisting of the transistors $T_{27}$ and $T_{28}$. This monostable circuit is called the "suppress look-pulse" circuit. When this circuit is triggered $T_{29}$ becomes cut off and $T_{29}$ will therefore conduct and so suppress any positive going change at the common emitters of $T_{29}$ and $T_{30}$. Any look pulse which is generated during the operation of the "suppress look-pulse" circuit will not be passed on to the display unit.

4.8 The Test Circuit

This circuit has not been mentioned in the functional description of the analyser, but since it is included in the sorting unit it seems logical to describe the test mode of operation here along with the circuit which produces the test signals.

In the test mode of operation counts are added in turn to each of the channels. To do this the reset circuit is disconnected from the display unit and pulses are then fed alternately to the "digit input" and the "look input" of the display unit. A pulse fed to the "digit input" steps the channel selection circuits by one channel, the pulse fed to the "look input" then adds a count in whichever channel is selected.

The test circuit is shown in Fig. 18. The test pulses originate initially from a multivibrator, $T_{54}$ and $T_{55}$, which oscillates at about 30 cycles per second. The square wave output
Fig. 18. The Test Circuit.
from the collector of $T_{55}$ is differentiated and amplified by $T_{56}$, giving negative pulses at the collector of $T_{56}$ whenever the multivibrator switches from the state in which the transistor $T_{55}$ is cut off to the state in which it conducts. These negative pulses are used to advance the channel selection circuits by one channel for each oscillation of the multivibrator.

When the multivibrator switches over in the opposite direction (i.e. $T_{55}$ is switched off and $T_{54}$ switched on), a monostable circuit, in which $T_{52}$ and $T_{53}$ are the transistors, is triggered by the positive going waveform at the collector of $T_{54}$. The positive pulse at the collector of $T_{52}$ replaces the "look signal" in the test mode of operation and causes a count to be registered in the selected channel.
CHAPTER 5.

DESCRIPTION OF THE ELECTRONIC CIRCUITS
USED IN THE DISPLAY UNIT OF THE
30-CHANNEL PULSE-HEIGHT ANALYSER

The circuit diagram of the display unit is shown in Fig. 19 which is in the pocket at the back of the thesis. As in the description of the sorting unit, this will be dealt with in small pieces, the circuit diagrams of these pieces being shown as Figs. 20 to 23.

5.1 The Ring Scaling Circuits

The ring scaling circuits are derived from a thermionic valve circuit described by Sharpless and used by Wilkinson in his pulse-height analyser. The circuit of the ring-of-five is shown in Fig. 20. The ring-of-six circuit is similar to it.

The circuit is made up of a series of five bistable elements. In any one of these bistable elements only one of its two transistors can be conducting; if the right-hand one is conducting then the left-hand one is cut off, and vice versa. When the right hand transistor is conducting it is said that the stage is ON. If, on the other hand, the left hand transistor in the bistable element is conducting the stage is OFF. In the ring-of-five circuit all the left hand transistors have their emitters connected together and the emitter current for all these transistors flows through a 250 Ω resistor. Similarly all the right hand transistors have their emitters connected together and to a 1000 Ω resistor. This arrangement makes the emitter potential of the right hand transistors the same as that of the left hand
Fig. 20. The Ring-of-Five Scaling Circuit.
transistors when one stage of the ring is switched ON and the rest OFF; it is states of this kind which the circuit assumes.

In the ring-of-six scaling circuit the emitter current for the left hand transistors is fed through a 200 Ω resistor; in general, for a ring-of-n, the value of the emitter resistor should be \( \frac{1}{n-1} \times 1000 \Omega \).

The digit pulses which are to be counted on the ring-of-five are applied to the common emitters of the right hand transistors. They are negative pulses and so tend to switch off the transistors to whose emitters they are applied. As only one of the right hand transistors is conducting, only this transistor is affected in the first instance. It tends to cut off, and regenerative feedback in the bistable element of which it is part switches the stage OFF. As the stage is switched to its OFF state, a negative going signal from the collector of the right hand transistor is fed through a 0.001 μF coupling capacitor to the base of the right hand transistor of the next stage, which therefore switches ON. The ON state is thus passed in steps round the ring, each input pulse moving it by one step.

The ring-of-six works in exactly the same way. The pulses which drive it are obtained from the collector of \( T_{60} \). \( T_{60} \) is only switched off when its binary stage is switched ON. When this occurs a negative going signal appears at the collector of \( T_{60} \). This is differentiated and fed through an emitter follower, \( T_{127} \) (see Fig. 19) to provide input pulses for the ring-of-six. The ring-of-six thus receives one input pulse for every five pulses fed to the ring-of-five.
The two ring scaling circuits are set to their initial condition by the reset signal. This signal comes from the emitter of \( T_{40} \) (see Fig. 13). Normally the emitter of \( T_{40} \) is sufficiently negative to ensure that the diodes \( D_{20-24} \) and \( D_{40-45} \) are cut off. During the reset signal, however, the emitter of \( T_{40} \) is at approximately earth potential and so the diodes conduct and the transistors to which they are connected cut off. The ring-of-five is thus set to the state in which \( T_{65} \) is the only right hand transistor which is conducting, and the ring-of-six to the state in which \( T_{101} \) is the conducting right hand transistor. This odd-looking reset condition is chosen because the train of digit pulses always contains at least three pulses. These three pulses merely indicate that a pulse which is big enough to be recorded in the first channel has entered the analyser, so they are used to step the ring scaling circuits into the state which selects the first channel. The three pulses occur because the "start" signal lasts long enough for two pulses to be generated by the "blocking oscillator", the third pulse or any later pulse may then switch the "blocking oscillator" off.

When a pulse is too big for the analyser the ring-of-six returns for a second time to the state with \( T_{91} \) conducting and \( T_{90} \) cut off (see Fig. 19). A negative-going signal from the collector of \( T_{90} \) is then fed back to the sorting unit to suppress the look signal. The fact that a similar signal is produced at the collector of \( T_{90} \) when the ring-of-six records its first count is not of any consequence, as this signal dies away long before the look pulse is due to be applied.
5.2 The Gate Circuits

The gate circuits are a series of long tailed pairs, one associated with each stage of the rings of five and six. A circuit diagram of one of these gates is shown as Fig. 21.

The base of the right hand transistor in the gate circuit \( T_{71} \) in the diagram shown as Fig. 21) is connected to the collector of one of the right hand transistors of the ring scaling circuits. If the stage of the ring to which it is connected is OFF the potential of the base of \( T_{71} \) is about the same as the potential of the base of the left hand transistor, \( T_{70} \). A positive "look signal" applied to the base of \( T_{70} \) will simply cut \( T_{70} \) off without producing an appreciable signal at the common emitters of \( T_{70} \) and \( T_{71} \).

If, on the other hand, the stage of the ring scaling circuit is ON, then \( T_{71} \) is cut off by the potential applied to its base from the collector of the conducting right hand transistor in the ring scaling circuit. If a positive-going "look signal" is applied to the base of \( T_{70} \) under these conditions, then \( T_{70} \) will behave as an emitter follower until its emitter excursion is sufficient to cause \( T_{71} \) to conduct. The emitter potential is then clamped. The signal from the common emitters of the gate transistors is fed on to one of the drive circuits which operate the matrix of scalers.

5.3 The Drive Circuits

The drive circuits are blocking oscillators similar to those used by Warman and Bibb (24) to operate dekatron selector tubes in a telephone exchange register. In Fig. 22 diagrams of two drive circuits are shown, one a drive circuit associated with
Fig. 21. One of the Gates.
a row of scalers, the other associated with a column.

The signal from one of the gates is fed through a 0.01 μF capacitor and a CC10E diode to the base of an XC101 transistor, connected as an emitter follower, which feeds the signal on to the $W_4$ winding of the blocking oscillator transformer. The signal which is then induced in the winding $W_4$ overcomes the reverse bias on the base of the other XC101 transistor, causing it to conduct sufficiently to give a loop gain greater than unity in the blocking oscillator circuit. A typical blocking oscillator waveform of pulse and overshoot is produced by the circuit, and the output signal appearing at the $W_3$ winding of the transformer is sufficiently large to operate a dekatron counting tube. The specification for the blocking oscillation transformers is as follows:

- **Laminations:** Mumetal type 288, core type 402
- **Windings:**
  - $W_4$: 60 turns, 39 s.w.g.; $W_2$: 60 turns, 36 s.w.g.;
  - $W_3$: 700 turns, 46 s.w.g.; $W_4$: 160 turns, 32 s.w.g.;

It was explained in Chapter 3 that the drive circuits apply correctly timed pulses to the guide rings of the dekatron tubes. To ensure that the pulses are correctly timed (i.e., that a pulse applied to the second guide ring follows immediately after a pulse to the first guide ring), it is necessary to make the lengths of the output signals from all the drive circuits the same. The 25 Ohm variable resistors in the emitter leads of the blocking oscillator transistors are adjusted to make the pulses which are to be applied to the first guide rings 90 μsec. long, and the pulses fed to the second guide rings, which are in fact the "overshoots" of the typical blocking oscillator waveform, are made
Fig. 22. Dekatron Drive Circuits

(a) Associated with a Row of Scalers.
(b) Associated with a Column of Scalers.

(a) Associated with a Row of Scalers.
to begin 90 μsec, after the circuit is triggered.

The pulses which are fed to the first guide rings, from a drive circuit associated with a row of dekatrons, are passed through a 6EX58 diode. This diode prevents any spurious triggering of the drive circuit due to unwanted signals being fed through the dekatsrons and back to the drive circuit.

5.4 The Scaling Circuits

The scaling circuits each consist of a dekatron stage followed by a mechanical register. The circuit diagram of a scaling circuit is shown in Fig. 23.

The pulses to drive the dekatron tube are obtained from two drive circuits, the pulse to the first guide ring being from a drive circuit associated with a row of dekakrons, and the later pulse to the second guide ring being from a drive circuit associated with a column of dekakrons. Only when both these pulses are present does the dekatron register a count.

Whenever the discharge in the dekatron moves on to the "zero cathode" a positive going signal is applied through the 0.1 μF capacitor and the 0A10 diode to the base of a 6ET14 transistor, which then produces a negative amplified signal at its collector. This negative going signal is applied through an emitter follower (the 0C72 transistor) to an 8 μF capacitor. When the signal collapses the 0C72 transistor becomes cut off and the charge on the 8 μF capacitor leaks away as the base current of the 0C16 transistor, causing the 0C16 transistor to conduct for sufficient time to operate the mechanical register, the coil of which forms the 0C16's emitter load. The registers used are type ATC.2425 made by Sodeco. They are capable of operating at speeds up to
Fig. 23. One of the Thirty Scaling Circuits.
25 counts per second.

When the discharge in the dekatron tube is on the "zero cathode", and the dekatron receives only one of the two drive pulses, a negative-going signal appears at the "zero cathode", followed by a positive-going signal when the single drive pulse collapses. To prevent this operating the register circuit the 0.005\(\mu\)F capacitor is connected across the "zero cathode" load of the dekatron.

The resistor which is shown dotted in the circuit diagram of Fig. 23 is included in some of the register circuits because the gain of each of the 0C16 transistors is not the same. A high gain 0C16 transistor will discharge the 8\(\mu\)F capacitor too slowly and as a result the register circuit will be able to count only very slowly. The presence of the resistor will then speed up the discharge of the 8\(\mu\)F capacitor slightly and make the signal applied to the coil of the register the optimum length for fast counting. Eight of the register circuits needed resistors of various values between 27 K\(\Omega\) and 68 K\(\Omega\); the rest behaved satisfactorily without any resistor being included.

The dekatron tubes can be reset to their zero position at the beginning of a count by operating thirty biased switches, one for each scaler. The switches break the connection in the common cathode lead of the dekatron and introduce high resistances into the guide ring circuits and so force the discharge to the "zero cathode." The registers can be reset manually. Since resetting the dekatron can introduce a count on the associated register the dekatron should always be reset before resetting the register.
CHAPTER 6.

POWER SUPPLIES FOR THE 30-CHANNEL PULSE-HEIGHT ANALYSER

There are four independent stabilised D.C. supplies which provide power for the pulse-height analyser; their circuit diagrams are shown in Figs. 24-27. Three of these power supplies are commercially made transistorised power units, the fourth, which provides the high tension supply for the dekatrons, uses neon stabilisers to provide a fairly stable 450 volt D.C. supply.

Most of the circuitry in the analyser is fed from a Farnell type T.S.O. 12/2 transistorised power unit, which supplies the -12 volts line, and a Farnell type T.B.O. power unit, which supplies the +10 volts and +12 volts lines. A current of about 1.3 amps is drawn from the T.S.O. 12/2 power unit and about 0.5 amp is taken from the T.B.O. power unit.

A separate power supply is used for the register circuits since very large variations in current are encountered there. If the same power unit had been used for all the -12 volt supplies the variations of current might have led to unsteady voltages being applied to the sorting circuits. A T.S.O. 12/5 power unit provides the power for the register circuits. The current drawn from this power unit depends on the rate at which the analyser is counting. About 0.5 amp is taken under quiescent conditions.

The high tension supply for the dekatron counting tubes is obtained from a simple full-wave rectifier. Three 150C4 neon stabilisers in series are used to provide a reasonably stable 450 volt line for the dekatrons. The analyser takes about
Fig. 24. Farnell type T.S.O. 12/2 Power Unit.
Fig. 27. H.T. Supply for the Dekatrons.
15 milliamps from the 450 volt supply.

The output voltages of all the power supplies can be checked by a milliammeter mounted on the front panel of the power unit. A 4-position switch selects the supply whose output is to be monitored and suitable resistors make the milliammeter give a half-scale deflection if the power supply provides the correct output voltage.

The current drawn by the analyser from the 240 volt A.C. mains is about 0.5 amps so the total power consumption is about 120 watts.
CHAPTER 7

THE PERFORMANCE OF THE 30-CHANNEL PULSE-HEIGHT ANALYSER

It is very difficult to check the performance of a pulse-height analyser in a way which is relevant to the manner in which the analyser will be used in practice by testing it with a pulse generator. Certain tests can be made however to show that the analyser is likely to behave well, and then the analyser must be tested further by using it to analyse well known spectra.

7.1 Tests using a Pulse Generator

Tests with a pulse generator showed that the widths of all the channels except the first and second were the same. These two channels were very much narrower than the rest; they must therefore be ignored. The accuracy to which these measurements could be made was only about 2 per cent using a measuring oscilloscope (Solartron type CD643.8) to measure the height of the pulses from the pulse generator.

It was also seen that introducing a large bias at the input of the analyser did not affect the channel width. With a bias equivalent to 90 channels, the change in input pulse height required to shift the pulse by 20-channels was noted, and found to be the same as when the analyser was unbiased.

The pulse generator was capable of operating at several different pulse repetition frequencies. The performance of the analyser was examined with frequencies ranging from 2 pulses per second to 1000 pulses per second, and it was found that, with a fixed size of output from the pulse generator, the pulses were all
recorded in the same channel of the analyser, regardless of counting rate.

Two different lengths of input pulse were also used, 1 μsec. and 10 μsec. Changing the length made no difference to the channel in which the pulses were recorded.

Tests were made on the long term stability of the analyser. The output from the pulse generator was set so that the pulses were recorded in a channel near the top of the analyser. Over a period of 6 hours there was no change in the channel in which the pulses were recorded. Over a period of 24 hours, however, the counts were found to be divided between two adjacent channels. As no measurements could be made of the stability of the pulse generator it is possible that this drift is caused by the pulse generator and not by the analyser, but drifts of about 1.5 per cent cannot be ruled out over a period of 24 hours.

7.2 Tests using Radioactive Sources

The analyser was used to look at the spectra of γ-rays from various radioactive sources. The γ-rays were detected by a sodium iodide scintillation counter and the resulting pulses, after amplification by a type 1008 amplifier, were fed to the analyser. The gain of the system was adjusted to give a reasonable number of points round a peak in the spectrum.

The γ-rays from Cs$^{137}$ (0.66 MeV) and Co$^{60}$ (1.17 MeV and 1.33 MeV) were examined with the same analyser settings and it was seen that the response of the system was linear. This is illustrated in Fig. 28.

To look at the 2.62 MeV γ-ray from ThC$^{228}$ with the same amplifier setting it was necessary to use the bias control at
Fig. 28. Ca\textsuperscript{137} and Co\textsuperscript{60} γ-ray Spectra.
the input of the analyser and examine the spectrum in steps. If the parts of the spectrum fit together accurately this shows that the channel widths throughout the analyser are equal.

Fig. 29 shows the spectrum of pulses from the 2.62 MeV γ-ray from ThC". The higher energy part of the spectrum was examined first and the points indicated by circles in Fig. 29, resulted. The bias at the input of the analyser was then reduced by the equivalent of 14 channels and the lower energy part of the spectrum was obtained. The results are indicated by crosses in Fig. 29. In the part of the spectrum for which two sets of results were obtained there is excellent agreement between the two sets of results, except for the bottom three points of the first set. It appears that these three channels are not as reliable as the rest of the analyser. The energy calibration again indicates that the analyser has a linear response.

From these tests it can be seen that the top 25 channels of the 30-channel pulse-height analyser behave very well. The next three channels are not quite as reliable and the bottom two channels are rather meaningless. The response of the analyser is linear and its stability is good.
In designing any large and complex piece of equipment it is quite common to find that some of its component parts have other uses or that the concepts used have other applications. The scalers used as the display of the 30-channel pulse-height analyser do not require much modification to make them into general purpose dekatron scalers, and the ring scaling circuits which are used to select channels in the analyser may form the basis for a faster transistorised scaler.

8.1 A Dekatron Scaler Employing Transistorised Drive Circuits

A description of this scaler has been published \(^{(25)}\) so only a very brief outline will be given here. The scaler has two dekatron stages followed by a mechanical register; its circuit is shown in Fig. 30.

The dekatrons are driven by blocking oscillator circuits similar to those used in the 30-channel pulse-height analyser, and the mechanical register is operated by a monostable circuit recommended by Sodeco, who make the mechanical register.

The first scaler of this design was built 3\(\frac{1}{2}\) years ago and is still giving trouble-free service. This is a tribute to the reliability of transistors and correctly driven dekatron tubes. Several other scalers have been made using the same design, and have all behaved admirably. A photograph of one of these scalers is shown in Plate II.
Fig. 30. Transistorised Dekatron Scaler.
Plate II.

The Transistorised Dekatron Scaler.
8.2 A Suggestion for a 1 Mc/s Scaler

It appears that it should be possible to make a fast decade scaler by preceding a ring-of-five scaling circuit, similar to the one used in the 30-channel pulse-height analyser, by a binary stage. To make a 1 Mc/s scaler, the binary stage would have to be able to count at 1 Mc/s and the ring-of-five at 500 Kc/s.

A binary stage which is capable of counting faster than 1 Mc/s has been built and tested, but the ring-of-five in the form used in the 30-channel analyser will only count up to speeds around 250 Kc/s. Improvements on this performance should be possible, maybe by using transformer coupling between the stages of the ring instead of the present capacitative coupling.

Most transistorised scaling circuits use a meter to indicate the state of the circuit. The meter is usually the most delicate part of the instrument and probably the most expensive single component. A method of indicating the state of a circuit with 6V 0.1A incandescent filament lamps has been developed. This method of indication is used with the 1 Mc/s binary stage, the circuit of which is shown in Fig. 31. The same method of indication can be used with a ring scaling circuit.
Fig. 31. A 1 Mc/s Binary Element.
Part II

THE USE OF THE THIRTY-CHANNEL PULSE-HEIGHT
ANALYSEER IN THE STUDY OF NUCLEAR REACTIONS IN
LIGHT ELEMENTS.
Many experiments have been performed to gain information about the energy levels of light nuclei and Boron-10 has not been neglected. The low lying levels (below 4 MeV) of B-10 have been studied in various ways but, in spite of this, there is still some uncertainty not only about the properties of some of the levels but even about their existence. It is generally agreed that there are levels in B-10 at 0.72, 1.74, 2.15, and 3.58 MeV; in addition levels have been reported at 0.39, 1.3, and 2.86 MeV. Some reactions leading to B-10 appear to yield evidence for one or more of these three levels; other reactions yield evidence for only those levels about which there is general agreement. Even with the same reaction some workers have found evidence supporting one or more of the additional levels, while others favour only the generally accepted ones.

The energy levels and spins of those states of B-10 which have the same parity as the ground state have been calculated by Kurath assuming a two-body interaction and an intermediate strength of spin-orbit coupling. The results for the first four excited states agree well with the experimental results for the well established levels, but there is no suggestion of additional levels.

The reactions which have been used to study the level structure of B-10 are Li-6(α,γ)B-10, Li-7(α,n)B-10, Li-7(α',n)B-10, Be-9(p,γ)B-10, Be-9(d,n)B-10, Be-9(Be-3,d)B-10, B-10(p,p')B-10*, B-10(n,n')B-10*, B-10(d,d')B-10*, B-10(α,α')B-10*, C-10(3+,d)B-10, C-10(3+,n)B-10, C-10(3+,p)B-10, C-10(d,t)B-10, C-12(α,α')B-10, N-14(γ,α)B-10. The results of most of these experiments are summarised by Ajzenberg-Selove and Lauritsen; their summary...
shows that only two of these reactions appear to yield evidence for any of the three low lying levels of $B^{10}$ about which there is disagreement. These are the reactions $Li^7(\alpha, n)B^{10}$ and $Be^9(\alpha, n)B^{10}$.

9.1 Evidence about a 0.39 MeV level in $B^{10}$

The only evidence for a 0.39 MeV level in $B^{10}$ comes from the $Li^7(\alpha, n)B^{10}$ reaction. Nemilov and Pisarevskii(26) studied the $\gamma$-rays from a Po-Li neutron source and observed $\gamma$-rays of energy 0.39, 0.47, and 0.8 MeV. The 0.8 MeV $\gamma$-ray comes from the decay of Po$^{210}$ and the 0.47 MeV $\gamma$-ray from inelastic scattering of $\alpha$-particles by $Li^7$. They found the 0.39 MeV $\gamma$-ray to be in coincidence with neutrons from the source and so interpreted their results as evidence for the reaction $Li^7(\alpha, n)B^{10}$ giving rise to a level in $B^{10}$ at 0.39 MeV.

Breen and Hers(27) have also studied the $\gamma$-rays from a Po-Li neutron source. They found only two $\gamma$-rays, the 0.8 MeV line from Po$^{210}$ and the 0.48 MeV line from $Li^7(\alpha, \alpha^')Li^7$. More recently Galloway(28) has repeated the work of Nemilov and Pisarevskii, and failed to find any evidence for $n-\gamma$ coincidences from a Po-Li source. Also the experiments on $Li^7(\alpha, n)B^{10}$ by Haxel and Stuhlinger(29), by Robbins(30) and by Bichsel and Bonner(31) give no indication of a neutron threshold corresponding to a 0.39 MeV level in $B^{10}$.

9.2 Evidence about a 1.3 MeV level in $B^{10}$

The first evidence for a 1.3 MeV level in $B^{10}$ came in 1939 from an experiment by Haxel and Stuhlinger(29). They used boron loaded counters to detect neutrons from the $Li^7(\alpha, n)B^{10}$ reaction and found the threshold $\alpha$-particle energies for the production of $B^{10}$ in its ground state and first three excited states. The excitation energies of the first three levels were found to be 0.77, 1.31 and 2.09 MeV.
In 1955 Robbins\textsuperscript{(30)} used a proton recoil telescope to obtain the energy spectrum of neutrons from $^{7}\alpha(n)B^{10}$ and also determined the reaction threshold for each of the first three excited states, using a BF$_3$ counter to detect the neutrons. He gives the excitation energies for the three levels as 0.74, 1.31 and 1.72 MeV.

More recently Kjellman et al\textsuperscript{(32)} have studied this reaction using higher energy $\alpha$-particles. They used a time-of-flight method to measure the neutron energies and found neutron groups corresponding to the ground state and four excited states of $B^{10}$. They found no evidence for a level at 1.3 MeV and gave the first four excited levels of $B^{10}$ as 0.72, 1.74, 2.15 and 3.58 MeV.

Evidence for a level at about 1.3 MeV has been obtained also by Genin\textsuperscript{(33)} from a nuclear emulsion study of the neutrons from $^{9}Be(d,n)B^{10}$, and Galloway and Sillitto\textsuperscript{(34)}, after studying the spectrum of $\gamma$-rays from this reaction, suggest that some minor discrepancies in their results might be removed if a level at about 1.25 MeV were excited in the $^{9}Be(d,n)B^{10}$ reaction. Other workers who have observed the neutrons and $\gamma$-rays from this reaction have not found any indication of the existence of this level.

9.3 Evidence about a 2.86 MeV level in $B^{10}$

All the evidence in favour of a 2.86 MeV level in $B^{10}$ comes from the $^{9}Be(d,n)B^{10}$ reaction. Dyer and Bird\textsuperscript{(35)} used nuclear emulsions to study the neutrons emitted in this reaction, and found a group of neutrons corresponding to a level in $B^{10}$ at 2.85 MeV. Reid\textsuperscript{(36)}, using a recoil proton telescope, obtained a spectrum showing neutrons corresponding to a level at 2.88 MeV, and Genin\textsuperscript{(33)}, using nuclear emulsions, found a neutron group corresponding to a
level at 2.95 MeV in $^{10}\text{Be}$. Similar experiments by Ajzenberg\(^{(47)}\), by Pruitt et al\(^{(48)}\), and by Green et al\(^{(49)}\) give no indication of a level near 2.86 MeV. Galloway and Sillitto\(^{(34)}\) have pointed out that the experiments which yield evidence for a level near 2.86 MeV were all performed using deuteron energies of less than 800 KeV while those which yield no evidence for the level were carried out with higher deuteron energies. It can also be pointed out that the experiments which show the presence of this level were all performed using thick targets so that a considerable fraction of the deuterons would be of rather low energy when the reaction took place.

A straightforward study of the spectrum of $\gamma$-rays from $^{9}\text{Be}(d,n)^{10}\text{Be}$ can itself give no evidence for or against the existence of a 2.86 MeV level. Also the results of the $\gamma-\gamma$ coincidence experiment carried out by Shafroth and Hanna\(^{(37)}\) do not yield any clear evidence for or against this level. Galloway and Sillitto\(^{(34)}\), however, studied the $\gamma$-cascades which were likely to give evidence about the existence of a 2.86 MeV level much more thoroughly than did Shafroth and Hanna, and interpret the coincidence spectra which they obtained as providing evidence in favour of this level's existence.

9.4 The Present Investigation

Fig. 32 shows the spectrum of $\gamma$-rays from the reaction $^{9}\text{Be}(d,n)^{10}\text{Be}$ obtained by Galloway and Sillitto\(^{(34)}\) using a sodium iodide scintillation spectrometer. In the valley just below the 1.43 MeV photo-peak the observed points are seen to lie above the
In this region of the spectrum the statistical accuracy is indicated by the size of the circles round the observed points.

Fig. 32. $^{10}$B $\gamma$-ray Spectrum (Galloway and Sillitto).
solid line which is the sum of the estimated effects from single energy $\gamma$-rays. A careful analysis of a $\gamma$-ray spectrum obtained under conditions similar to those of Galloway and Sillitto's experiment is carried out in the hope of determining whether this discrepancy is caused by a 1.3 MeV level in $B^{10}$ being excited in this reaction, or whether there is some other explanation for it. The line shapes for monoenergetic $\gamma$-rays, which Galloway and Sillitto used when analysing their $\gamma$-ray spectrum, were estimated from known line shapes associated with the 0.66 MeV $\gamma$-ray from Co$^{137}$, the 1.17 MeV $\gamma$-ray from Co$^{60}$ (obtained from a coincidence spectrum), and the 2.62 MeV $\gamma$-ray from Th$^{232}$. Unfortunately these do not quite cover the range of $\gamma$-ray energies encountered in the reaction; also the low energy part of the pulse-height distribution from the 2.62 MeV $\gamma$-ray cannot be observed very accurately, because a number of lower energy $\gamma$-rays are also emitted by the source. In the present experiment the pulse-height distributions from a variety of monoenergetic $\gamma$-rays were investigated and a method of interpolation was developed which gives the line shape for any monoenergetic $\gamma$-ray with energy in the range from about 0.6 to 4.4 MeV.
CHAPTER 10.

THE PULSE-HEIGHT DISTRIBUTION
FROM MONOENERGETIC \(\gamma\)-RAYS

The \(\gamma\)-rays from various sources were detected by a scintillation counter which consisted of a NaI(Tl) crystal, 1\(\frac{1}{2}\) inches in diameter by 1 inch long, mounted on an E.M.I. type 6262B 14-stage photomultiplier. The pulses from the 9\(^{\text{th}}\) dynode of the photomultiplier were amplified by a type 1008 amplifier, with its differentiation time constant set at 1.5 \(\mu\)sec., and its integration time constant at 0.15 \(\mu\)sec., and passed on to the 30-channel pulse-height analyser for analysis. The E.H.T. voltage for the photomultiplier was taken from an Isotope Developments type 532/B power unit, and was set at 1,275 volts, since with this E.H.T. voltage the scintillation spectrometer gave its best resolution. The attenuator setting on the 1008 amplifier was chosen as 10 \(\text{db}\) so that the pulses arising from the detection of 4.43 MeV \(\gamma\)-rays from a Po-Be neutron source were as large as was possible without overloading the amplifier. The attenuator at the input of the 30-channel pulse-height analyser was then set so that the 30-channels covered a range of pulse-heights corresponding to a \(\gamma\)-ray energy range of about 1 MeV.

When the analyser's bias control was at its minimum setting the photo-peak of the 0.66 MeV \(\gamma\)-rays from Cs\(^{137}\) was recorded in the bottom few channels of the analyser and the 1.33 MeV peak from Co\(^{60}\) \(\gamma\)-rays near the top. With a bias control setting equivalent to about 90 channel widths the photo-peak of the 4.43 MeV \(\gamma\)-rays from the Po-Be neutron source was observed.
With the apparatus set up in this way, the 30-channel pulse-height analyser was used to investigate the pulse-height distributions from monoenergetic $\gamma$-rays using $\gamma$-ray sources which were known to emit only a single energy of $\gamma$-ray in the energy ranges where this is possible, and using sources which emit a limited number of energies of $\gamma$-ray to cover the remainder of the energy range up to $4.45$ MeV.

10.1 Sources of $\gamma$-rays

The $0.66$ MeV $\gamma$-ray from Cs\textsuperscript{137}

Cs\textsuperscript{137} emits monoenergetic $\gamma$-rays of energy $0.66$ MeV. The pulse-height distribution above $0.5$ MeV resulting from the detection of $\gamma$-rays from a $1 \mu$G Cs\textsuperscript{137} source, placed about $4$ ft. 6 ins. from the counter, is shown in Fig. 33. The distribution is normalised to give an intensity of 10 counts on the $\gamma$-ray's photo-peak.

The $0.8$ MeV $\gamma$-ray from Po\textsuperscript{210}

The source used to provide these $\gamma$-rays was a $5 \mu$C mixture of Po\textsuperscript{210} and lithium carbonate. This source also emits $0.47$ MeV $\gamma$-rays (from $\text{Li}^7(\alpha, \gamma')\text{Li}^7$) but the pulse-height distribution above $0.55$ MeV is almost entirely due to the $0.8$ MeV $\gamma$-rays from Po\textsuperscript{210}. The source was placed very close to the counter and even then the counting rate was sufficiently low to make necessary a correction for electrical noise. The pulse-height distribution for the $0.8$ MeV $\gamma$-ray, corrected for noise and normalised to give a photo-peak intensity of 10 counts, is shown in Fig. 34.

The $1.28$ MeV $\gamma$-ray from Na\textsuperscript{22}

A $200 \mu$C Na\textsuperscript{22} source was placed about $3$ ft. away from the counter. $\gamma$-rays of two energies are emitted, $0.51$ MeV and
Fig. 33. The Line Shape for 0.66 MeV $\gamma$-rays from Cs$^{137}$. 
Fig. 34. The Line Shape for 0.8 MeV γ-rays from Po\textsuperscript{210}. 
Fig. 35. The Line Shape for 1.28 MeV γ-rays from Na$^{22}$. 
1.28 MeV. Above 0.6 MeV the pulse-height distribution is almost entirely due to the 1.28 MeV γ-rays. The normalised pulse-height distribution from these γ-rays is shown in Fig. 35.

The 1.17 MeV and 1.33 MeV γ-rays from Co\textsubscript{60}

A 10\(\mu\)Co\textsubscript{60} source placed about 1 inch from the counter was used. The resulting pulse-height distribution is shown in Fig. 36. The line shape for the 1.28 MeV Na\textsuperscript{22} γ-ray was used as a guide to estimate the pulse-height distribution for each of the two components of the Co\textsubscript{60} γ-ray spectrum, enabling the pulse-height distribution of Fig. 36 to be analysed into its component parts. The normalised pulse-height distribution from the 1.17 MeV Co\textsubscript{60} γ-rays is shown in Fig. 37; the line shape for the 1.33 MeV γ-rays in Fig. 38. The distribution curves for these two γ-rays show that the higher energy peak is slightly broader than the lower one and that the contribution from Compton scattering is more intense for the higher energy γ-ray.

The 1.38 MeV and 2.75 MeV γ-rays from Na\textsuperscript{24}

The Na\textsuperscript{24} source was prepared by bombarding a sodium bromide target with deuterons from the Department’s H.T. set, the Na\textsuperscript{24} being formed by the reaction Na\textsuperscript{23}(d, p)Na\textsuperscript{24}. The Na\textsuperscript{24} source was placed about 1 inch from the counter; the resulting pulse-height distribution is shown in Fig. 39. The 1.28 MeV γ-ray line shape (from Na\textsuperscript{22}) was used as an indication of the shape of the contribution from 1.38 MeV γ-rays and the pulse-height distribution of Fig. 39 was analysed to obtain the line shapes for the two γ-ray energies involved. The line shape for the 1.38 MeV γ-ray is shown in Fig. 40; its peak is slightly broader than that of the 1.28 MeV Na\textsuperscript{22} γ-ray and Compton
Fig. 56. Co$^{60}$ γ-ray Spectrum.
Fig. 37. The Line Shape for 1.17 MeV $\gamma$-rays from Co$^{60}$. 
Fig. 38. The Line Shape for 1.33 MeV $\gamma$-rays from Co$^{60}$. 
Fig. 39. $^{24}\text{Na}$ $\gamma$-ray Spectrum.
Fig. 40. The Line Shape for 1.38 MeV γ-rays from Na$^{24}$. 
Fig. 41. The Line Shape for 2.75 MeV γ-rays from Na$^{24}$. 

ENERGY MeV.

RELATIVE NUMBER OF COUNTS
scattering gives a greater contribution for the 1.38 MeV $\gamma$-ray than for the 1.28 MeV $\gamma$-ray. The 2.75 MeV $\gamma$-ray line shape is shown in Fig. 41. At this higher energy pair production gives a considerable contribution to the pulse-height distribution.

The 2.37 MeV $\gamma$-rays from $^6\text{Li}^12(p, \gamma)^{13}\text{N}$

500 KeV protons from the Department's H.T. set were used to bombard a carbon target formed by holding a piece of brass in a smoky flame from a bunsen burner. The 2.37 MeV $\gamma$-rays from the resonance in the reaction $^6\text{Li}^12(p, \gamma)^{13}\text{N}$ (proton resonance bombarding energy 4.57 KeV) were detected by the counter mounted about 3 inches away from the target. 0.51 MeV $\gamma$-rays are also emitted from the target (annihilation radiation following the decay of $^13\text{N}$ by positron emission) but the presence of these annihilation $\gamma$-rays has very little effect on the pulse-height distribution above 0.6 MeV. The counting rate was rather low making a noise correction necessary. The pulse-height distribution from the 2.37 MeV $\gamma$-rays, corrected for noise and normalised, is shown in Fig. 42.

The 2.62 MeV $\gamma$-ray from $\text{Th}^9$

The source used was a mixture of ThB and ThC. The 2.62 MeV $\gamma$-ray from the decay of $\text{Th}^9$ is the highest energy $\gamma$-ray to be emitted by the source, and the pulse-height distribution above 1.3 MeV is almost entirely due to this $\gamma$-ray. $\gamma$-rays of seven energies between 0.5 MeV and 1.1 MeV are emitted by the source, so the low energy part of the pulse-height distribution from the 2.62 MeV $\gamma$-rays cannot be estimated very accurately without performing a rather complicated analysis. The normalised pulse-height distribution (above 1.3 MeV) for the 2.62 MeV $\gamma$-rays is shown in Fig. 43.
Fig. 42. The Line Shape for 2.37 MeV γ-rays from $^{12}_p \gamma N^{13}$.
Fig. 43. The Line Shape for 2.62 MeV $\gamma$-rays from ThC$^\text{n}$. 

RELATIVE NUMBER OF COUNTS

ENERGY MeV
The 4.43 MeV $\gamma$-ray from $\text{Be}^9(\alpha, n)\text{C}^{12}$

A 50 mC Po-Be neutron source, placed about 1$\frac{1}{2}$ inches from the counter, was used to provide these $\gamma$-rays, which come from the decay of the first excited state of $\text{C}^{12}$. The only other $\gamma$-rays from this source are the 0.8 MeV $\gamma$-rays from $\text{Po}^{210}$. As the line shape for the 0.8 MeV $\gamma$-rays was already known, their contribution was subtracted from the observed pulse-height distribution and the remaining component, due to 4.43 MeV $\gamma$-rays, is shown in Fig. 44.

10.2 Line Shapes with the Source inside the Target Holder

If the line shapes which have been observed are to be useful in analysing a $\gamma$-ray spectrum obtained from a nuclear reaction using the H.T. set, the effect of the target holder on the shape of the $\gamma$-ray lines must be investigated. That there is an effect can be seen by comparing the 2.37 MeV line shape with the line shape for 2.75 MeV $\gamma$-rays. The Na$^{24}$ source was not inside the target holder when the 2.75 MeV line shape was determined; the 2.37 MeV $\gamma$-rays came from the $\text{C}^{12}(p, \gamma)\text{N}^{13}$ reaction, which used the H.T. set, and so originate from inside the target holder. It can be seen that the intensity of the pulse-height distribution from 2.37 MeV $\gamma$-rays rises more rapidly at low energies than does that from 2.75 MeV $\gamma$-rays. This is consistent with the idea that many of the pulses in the low energy tail of a distribution are caused by $\gamma$-rays being scattered into the counter by any material near to it.

The effects of the target holder on the pulse-height distributions for the $\gamma$-rays from Na$^{24}$ and $\text{Be}^9(\alpha, n)\text{C}^{12}$ were investigated since these sources were of suitable strength to be
Fig. 44. The Line Shape for 4.43 MeV γ-rays from Be$^9(α, n)$C$^{12}$. 

Energy MeV.
used with the counter in the same position as for studying reactions which involve the use of the H.T. set. The normalised line shapes for the individual energies of γ-rays from these sources were determined with the sources inside the target holder. These are shown in Figs. 45-47 with line shapes obtained with the sources outside the target holder shown dotted for comparison. The differences between the line shapes obtained under the two different sets of conditions only become large below the lower escape peaks of the higher energy γ-rays and there is hardly any difference for the 1.38 MeV Na$_{24}$ γ-ray.

10.3 A Method of Interpolating Line Shapes

The way in which the pulse-height distribution for monoenergetic γ-rays changes with γ-ray energy can be seen qualitatively by looking at the line shapes in Figs. 33-44, but to determine the line shape for any energy of γ-ray with reasonable certainty, a method of interpolation is needed. Nordhagen (38) describes a method in which the number of counts at "prominent points" in the pulse-height distributions from known γ-rays relative to the number of counts in the full energy peak are plotted as functions of the respective γ-ray energies. A technique similar to this was used in the present experiment to enable the line shape for any γ-ray energy in the range 0.6 to 4.5 MeV to be determined.

On each of the single energy line shapes the intensity relative to the photo-peak intensity was noted at 0.1 MeV intervals from 0.2 MeV above the photo-peak down to 1.2 MeV below the photo-peak. These observations were plotted as functions of γ-ray energy to give the fourteen curves of Fig. 48. Using these curves
Fig. 45. The 1.38 MeV Line Shape with the Na$_{24}$ Source in the Target Holder.
The 2.75 MeV line shape with the Na^24 source in the target holder.
Fig. 47. The 4.43 MeV Line Shape with the Po-Be Source in the Target Holder.
the line shape for any energy of $\gamma$-ray in the range investigated can be constructed by simply reading off the relative intensity at points 0.1 and 0.2 MeV above the photopeak and at 0.1 MeV intervals down to 1.2 MeV below the photo-peak. This gives the shape of the pulse-height distribution over the photo-peak, the Compton peak and the two escape peaks. Below the lower escape peak the line shapes become very dependent on the amount of material near the counter, and only three of the observed single energy line shapes for which this would be important were obtained with the $\gamma$-ray source in the H.T. set's target holder. Since two of these $\gamma$-ray sources, $^{12}$C($p, \gamma$)$^{13}$N and $^{24}$Na, emit $\gamma$-rays with similar energies interpolation curves for the low energy part of the pulse-height distributions would not be very accurate. Because of this interpolation curves were not plotted for the low energy parts of the distributions, but the line shapes can be estimated fairly reliably from the 2.37, 2.75 and 4.43 MeV distributions, since the features of the low energy tail do not change very quickly with energy.
Fig. 48. Curves showing how the pulse-height distribution for monoenergetic $\gamma$-rays varies with $\gamma$-ray energy. For each curve the abscissa is the photo-peak energy of the $\gamma$-ray and the ordinate is the intensity relative to a photo-peak intensity of unity. The curves show the intensity at 0.1 MeV intervals from 0.2 MeV above to 1.2 MeV below the photo-peak energy.
CHAPTER 11.

THE SPECTRUM OF \( \gamma \)-RAYS FROM \( \text{Be}^9(d, n)\text{B}^{10} \)

The spectrum of \( \gamma \)-rays observed from the reaction \( \text{Be}^9(d, n)\text{B}^{10} \), with a deuteron bombarding energy of 600 KeV, extends from 0.41 MeV to 3.58 MeV. The spectrum, above 0.5 MeV in energy, was observed with the gain of the analysing apparatus set in the manner described at the beginning of Chapter 10. It was obtained in six overlapping parts, each part covering an energy-range of about 1 MeV, which were then fitted together to give the required spectrum. The lower-energy part of the spectrum was obtained with a higher amplifier-gain setting, the energy range from 0.3 MeV to 0.8 MeV being covered in two steps.

600 KeV deuterons from the Department's H.T. set were used to bombard a thick beryllium target in the form of a metal disc. A deuteron current of about 0.05 µA was used, and the \( \gamma \)-rays were detected by the scintillation counter mounted about 8 cm from the target. Since the deuteron current could not be kept absolutely steady during the experiment, the time taken to record the data for each part of the spectrum was determined by counting the total number of pulses from the scintillation counter; the time to record each part of the spectrum was the time required for a monitor scaler to count \( 10^6 \) pulses. This time varied for the individual parts of the spectrum between 55 and 70 minutes. Before each run the noise spectrum from the counter was checked for 1 hour, and immediately afterwards the noise check was repeated, counting for 15 minutes, to enable an accurate estimate of the contribution of background pulses to the spectrum to be made.

The term "noise" is used to mean all pulses which do not arise directly from the bombardment of \( \text{Be}^9 \) with deuterons. Some of these pulses are due to the detection of background \( \gamma \)-radiation. It is this component which increases during a run.
Since the noise level after a run was always considerably higher than before it, it was decided that the six individual parts of the spectrum should be observed on different days. It is a tribute to the long term stability of all the apparatus, that no changes of gain were noticed during the 6 days in which the data for the spectrum were obtained.

Each of the individual parts of the spectrum was corrected for noise (i.e. the estimated contribution from background pulses was subtracted from the observed pulse-height distribution, the shape of the noise spectrum being determined from the 1 hour's observation carried out before each run and the noise intensity from the 15 minute count carried out after each run); the lowest energy portion of the spectrum was also corrected for counting losses caused by the 30-channel analyser's 380 μsec. dead time. The six parts of the spectrum were fitted together, the positions of peaks in the overlapping parts of the spectrum being used to indicate the amount of overlap which would make the parts fit together correctly. Since the energy associated with each of the peaks was known, it was possible to associate an energy with each point of the spectrum. Fig. 49 shows the observed points (circled) plotted in terms of their associated energy. The line shapes appropriate to γ-rays of energy 0.72, 1.02, 1.43, 2.15, 2.86, 3.37 and 3.58 MeV were drawn (dotted curves in Fig. 49) using the interpolation curves of Fig. 48 and their intensities were adjusted until the curve obtained by adding them together (full line in Fig. 49) agreed as well as possible with the observed points. While the pulse-height distribution
The Spectrum of γ-rays of energy greater than 0.5 MeV from Be\(^9\)(d, n)B\(^{10}\).
indicated by the observed points looks very much the same as that obtained by Galloway and Sillitto, it can be seen that in this experiment the agreement in the valley near 1.3 MeV is as good as at any other part of the spectrum, so the discrepancy of Galloway and Sillitto's experiment appears to result from the use of inaccurate line shapes, rather than from the presence of a 1.3 MeV \( \gamma \)-ray.

The lower-energy part of the \( \gamma \)-ray spectrum (0.3 - 0.8 MeV) was investigated in a similar way, the gain of the type 1008 amplifier being increased by 8 db so that the required energy range could be covered in two steps. The \( \gamma \)-rays which appear in this low energy part of the spectrum have energies of 0.41, 0.48 and 0.72 MeV. Line shapes appropriate to these energies were estimated from the pulse-height distributions for 0.66 MeV \( \gamma \)-rays (from Cs\(^{137} \)) and 0.51 MeV \( \gamma \)-rays (annihilation radiation following \( \text{N}^{13}(p+)\text{C}^{13} \)) which are shown in Figs. 50 and 51. (This method has to be used for the lower-energy part of the spectrum because the interpolation curves do not cover this energy range). The low-energy part of the \( \text{Be}^9(d, n)\text{Be}^{10} \) \( \gamma \)-ray spectrum is shown in Fig. 52. The observed points are circled, the line shapes for individual \( \gamma \)-rays are dotted and the solid line gives the sum of the individual contributions.

11.1 The \( \text{Be}^{10} \) Decay Scheme

The spectra of Figs. 49 and 52 show all the expected \( \gamma \)-rays from \( \text{Be}^{10} \) (viz. 0.41, 0.72, 1.02, 1.43, 2.15, 2.86 and 3.58 MeV); in addition Fig. 52 shows the 0.48 MeV \( \gamma \)-ray from \( \text{Be}^9(d, \alpha)\text{Li}^{7} \) and Fig. 49 shows the 3.37 MeV \( \gamma \)-ray from \( \text{Be}^9(d, p)\text{Be}^{10} \).
Fig. 50. The Line Shape for 0.51 MeV γ-rays from $^{13}(\beta^+)^{13}$. 
Fig. 51. The Line Shape for 0.66 MeV $\gamma$-rays from Cs$^{137}$. 
Fig. 52. The Spectrum of $\gamma$-rays of Energy less than 0.8 MeV from Be$^9$(d, n)B$^{10}$. 

Number of counts $\leq 1000$

Observed Points
Single $\gamma$-Ray Line Shapes
Synthesised Spectrum

Combined effect due to $\gamma$-rays of energy $> 0.8$ MeV
The relative intensities of the $\gamma$-rays were found by measuring the area under the full energy peak for each of the $B^{10}$ $\gamma$-rays and correcting for the variation of the scintillation counter's detection efficiency with $\gamma$-ray energy, using photo-peak efficiencies interpolated from the data given by Miller and Snow (39) for a NaI crystal 1 inch in diameter and 1 inch long 10 cm. from the source, and by Lasar et al (40) for a 1$\frac{1}{2}$ inches by 1 inch crystal 7 cm. from the source. (As has been mentioned, the crystal used in the present experiment is 1$\frac{1}{2}$ inches by 1 inch and was about 8 cm. from the target). Fig. 53 shows the variation of photo-peak efficiency with $\gamma$-ray energy.

The relative intensities of the $\gamma$-rays from $B^{10}$ as observed in this experiment are given in the second column of the table shown below; they can be compared with the relative intensities calculated by Galloway and Sillitto, which are given in the fourth column of the table, and with the relative intensities from their proposed decay scheme, which are given in the fifth column. The third column of the table gives the relative intensities in a decay scheme proposed as a result of the present experimental investigation.

<table>
<thead>
<tr>
<th>$\gamma$-ray Energy MeV</th>
<th>Relative Intensity %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed (Present Experiment)</td>
</tr>
<tr>
<td>3.58</td>
<td>$3 \pm 1$</td>
</tr>
<tr>
<td>2.86</td>
<td>$11 \pm 2$</td>
</tr>
<tr>
<td>2.15</td>
<td>$6 \pm 1$</td>
</tr>
<tr>
<td>1.83</td>
<td>$5 \pm 1$</td>
</tr>
<tr>
<td>1.02</td>
<td>$14 \pm 2$</td>
</tr>
<tr>
<td>0.72</td>
<td>$57 \pm 8$</td>
</tr>
<tr>
<td>0.41</td>
<td>$5 \pm 1$</td>
</tr>
</tbody>
</table>
Fig. 53. Photo-peak Efficiencies in a NaI Crystal.
Comparison of these results shows them to be in good agreement except about the intensity of the 1.43 MeV and 0.41 MeV \(\gamma\)-rays. The present investigation indicates that these should be less intense than was thought by Galloway and Sillitto.

If line-shapes similar to the ones employed in the present experiment were used to analyse Galloway and Sillitto's coincidence spectra, one would expect to obtain relative intensities which agree broadly with the values which they quote, except perhaps for the 0.41 MeV \(\gamma\)-ray in the spectrum in coincidence with 0.72 MeV \(\gamma\)-rays. A relative intensity of about 20\(\pm\)10\% might be expected for this \(\gamma\)-ray, rather than the 26\(\pm\)13\% quoted by Galloway and Sillitto, since the effect of the rising low energy tail from higher-energy \(\gamma\)-rays would be most noticeable in this region of the spectrum. The value of 9\% for the relative intensity of the 0.41 MeV \(\gamma\)-rays in their decay scheme was chosen by Galloway and Sillitto to agree with the observed 26\% relative intensity in their coincidence spectrum. The present experiment indicates a maximum value of about 6\% for the relative intensity of the 0.41 MeV \(\gamma\)-ray in an ungated spectrum, which would lead to a relative intensity of about 18\% in the spectrum in coincidence with 0.72 MeV \(\gamma\)-rays; this is in good agreement with the 20\% suggested above.

While a detailed discussion of a decay scheme cannot be undertaken on the basis of the present experimental results, there are some points which can be discussed. The branching ratio for the decay of the 2.15 MeV level has been measured by Sprenkel and Daughtry\(^{41}\). They give the relative intensities of the 2.15, 1.43 and 0.41 MeV \(\gamma\)-rays from the decay of this level as
16%, 29% and 55% respectively. Since all the observed 0.41 MeV γ-rays must arise from transitions from the 2.15 MeV level to the 1.74 MeV level, this branching ratio indicates what fractions of the 2.15 MeV and 1.43 MeV γ-rays arise from the decay of the 2.15 MeV level. As about 6% of the observed γ-rays have 0.41 MeV energy, the relative intensity of 2.15 MeV γ-rays from the decay of this level is about 2% and of the 1.43 MeV γ-rays is about 3%, showing that about half the 1.43 MeV γ-rays must arise from transitions from the 3.58 MeV level to the 2.15 MeV level and about three fifths of the 2.15 MeV γ-rays cannot be associated with the decay of the 2.15 MeV level. The 2.15 MeV γ-rays can only be fitted into the decay scheme if a level at 2.86 MeV exists; they can then arise from transitions from the 2.86 MeV level to the level at 0.72 MeV.

Having established that a 2.86 MeV level must exist, the question now arises of how to divide the observed 2.86 MeV γ-rays between their two possible sources (transitions from the 2.86 MeV level to the ground state and transitions from the 3.58 MeV level to the level at 0.72 MeV). As Galloway and Sillitto's experiment is the only one which gives information on this point, the manner in which they divide the 2.86 MeV γ-rays between these two sources is followed. The decay scheme which results is shown in Fig. 54a, while the decay scheme proposed by Galloway and Sillitto appears in Fig. 54b.

The validity of the arguments used by Galloway and Sillitto in support of a 2.86 MeV level in $^3$H is unaltered by the fairly minor modifications indicated by the present experiment, and if the branching ratio for the decay of the 2.15 MeV level, as measured by Sprenkel and Daughtry, is to be believed, the present
Fig. 54. $^8$B$^10$ Decay Scheme

(a) from the Present Experiment.

(b) from Galloway and Sillitto's Experiment.
experimental results can only be interpreted in terms of a $^{10}$B decay scheme which includes a level at 2.86 MeV.

11.2 Suggestions for further experiments on $^{9}$(d, n)$^{10}$B

The most direct evidence for or against a 2.86 MeV level in $^{10}$B is to be obtained from the neutron spectrum from this reaction. The neutron spectra which gave the original evidence in favour of this level all suffered from rather poor statistics. It would appear that a neutron spectrum with good resolution and of much better statistical significance than those of Genin (33), Dyer and Bird (35) or Reid (36) is desirable. At the moment the preliminary work on an experiment to obtain a good neutron spectrum, using a time-of-flight technique to measure the neutron energies, is in progress. If this experiment is successful, n - γ coincidence experiments may be attempted to determine the branching ratio for the decay of the 3.58 MeV level and also the 2.86 MeV level, should this level be observed.
A PROPOSED INVESTIGATION OF THE PROPERTIES
OF THE 8.98 MeV LEVEL IN CARBON 11

A level in C¹¹ at about 8.98 MeV has been reported by
Johnson (42), by Cerineo (43) and by Graue and Trumpy (44) after
studying the neutron groups from B¹⁰(d, n)C¹¹. Nothing is known
of the properties of this level and there is no report of any
attempt to look for a proton resonance corresponding to the
formation of the level when B¹⁰ is bombarded with protons.

It is proposed to look for the proton resonance, which should
occur at a proton energy of about 310 KeV, and if the resonance
is observed, to investigate the decay of the 8.98 MeV level of C¹¹.
The level could decay by γ-ray emission either directly to the
ground state or through lower lying levels in C¹¹, or it could
decay by the emission of an α-particle to form Be⁷ either in
its ground state or first excited state.

If the resonance is observed and the 8.98 MeV level of C¹¹
decays by γ-ray emission, the γ-ray spectrum could cover an
energy-range of about 9 MeV and so would have to be investigated
with a large NaI scintillator and examined in several parts by
the 30-channel analyser. In order to obtain the data for all
the parts at the same time, and so under the same conditions, the
pulses from the scintillation counter could be recorded on magnetic
tape using the laboratory’s Marshall Type MFR 203 tape recorder,
and then played back into the 30-channel analyser several times
to enable the analysis to cover the complete energy-range. The
MFR 203 tape recorder has two channels and so could also be of
use if coincidence techniques are required to gain information about the way in which the level decays.

If the level decays by $\alpha$-emission semiconductor detectors might be used to investigate the $\alpha$-particle spectrum.

Before attempting an experiment of this kind a few technical problems have to be solved. At the moment the H.T. set does not supply a sufficiently stable voltage to keep the proton energy constant at the resonance level, but a stabilising unit is due to be fitted in the near future. Also the use of the tape recorder is not quite straightforward, as it requires negative input pulses with rise times of about 2\,\text{usec}, whereas the type 1008 amplifiers are intended to give positive output pulses which normally have rise times of less than 1\,\text{usec}. Feeding pulses from the tape recorder to the analyser also presents a problem, as the output pulses from the tape recorder are negative and have rise times between 2 and 5\,\text{usec}, depending on their size. The analyser is designed to accept positive pulses and the gate at the input to the analyser remains open for only about 2\,\text{usec} after accepting a pulse, so even if the sign of the pulses from the tape recorder were changed only part of each pulse would be accepted by the analyser before the gate closed.

The work described in this thesis has been of two types, transistor electronics and nuclear physics. This outline of work planned for the future shows that it too can be divided into these two categories.
ACKNOWLEDGEMENTS

I wish to record my grateful thanks to Professor N. Feather F.R.S. for his interest and encouragement in this work, and to Mr. E. M. Sillitto for suggesting that the work should be undertaken and for his helpful and encouraging comments during its execution. I thank my colleague, Dr. R.B. Galloway, for his support and for the many exceptionally helpful discussions we had throughout this work.

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I thank Mr. W. B. Wilson for ordering the components needed for the construction of the analyser, and for dealing with a large amount of correspondence about their availability and delivery. My thanks go too to Mr. G. Moirna for lending me test equipment and ensuring that this equipment was always in good working order, and to Mr. H.J. Napier who assisted in many ways with the mechanical construction of the analyser and ensured that the finished instrument has aesthetic as well as functional qualities.
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APPENDIX

THE ACCURACY OF THE EXPERIMENT ON $\gamma$-RAYS FROM $\text{Be}^9(d,n)\text{B}^{10}$

The accuracy will be considered in two parts. Firstly the accuracy of measuring the relative intensities of the $\text{B}^{10}$ $\gamma$-rays will be considered and secondly the accuracy of interpreting these results in terms of a decay scheme will be discussed.

The Relative Intensities of the $\text{B}^{10}$ $\gamma$-rays

The first factor which affects the measurement of the relative intensities of the $\gamma$-rays is the statistical accuracy of the actual observations; the second factor is the accuracy with which the contribution from background pulses (noise) can be assessed. Since the intensity of the background contribution increased during a run its magnitude cannot be estimated very accurately; errors of about 25% of the estimated background intensity are possible. The error bars on figs. 49 and 52 indicate the accuracy of the observed points after the background correction has been made.

The next point to be considered is the accuracy of the synthesis carried out on the spectra in figs. 49 and 52. For the moment it will be assumed that the line shapes for monochromatic $\gamma$-rays are accurately known. The synthesis is performed by fitting each photo-peak in turn, starting at the high energy end of the spectrum, so the accuracy of the height of each photo-peak is determined by combining the uncertainty in the number of counts in the neighbourhood of the peak concerned with the uncertainty in the magnitude of the contribution from higher energy $\gamma$-rays. The heights of the photo-peaks of the various $\gamma$-rays are shown in the second column of the table on page (ii).
<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Hioto-Peak Height</th>
<th>Are® under Photo-Beak</th>
<th>Photo-peak Efficiency</th>
<th>Mass Abs. Coeff. of Be (cm²/g)</th>
<th>Mass Abs. Coeff. of Cu (cm²/cm)</th>
<th>Corrected Relative Intensities</th>
<th>Observed Relative Intensities</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.58</td>
<td>2.86</td>
<td>2.15</td>
<td>1.02</td>
<td>0.72</td>
<td>0.48</td>
<td>0.22</td>
<td>1.43</td>
</tr>
<tr>
<td>5.98</td>
<td>6.00 ± 30</td>
<td>6.44 ± 71</td>
<td>8.64 ± 67</td>
<td>6.00 ± 70</td>
<td>6.00 ± 30</td>
<td>1500 ± 125</td>
<td>480 ± 35</td>
</tr>
<tr>
<td>1990 ± 130</td>
<td>1935 ± 85</td>
<td>225 ± 30</td>
<td>225 ± 30</td>
<td>225 ± 30</td>
<td>225 ± 30</td>
<td>1500 ± 125</td>
<td>480 ± 35</td>
</tr>
<tr>
<td>3460 ± 360</td>
<td>31430 ± 1000</td>
<td>2700 ± 310</td>
<td>2700 ± 310</td>
<td>2700 ± 310</td>
<td>2700 ± 310</td>
<td>1500 ± 125</td>
<td>480 ± 35</td>
</tr>
<tr>
<td>0.92</td>
<td>0.295 ± 0.030</td>
<td>0.085</td>
<td>0.085</td>
<td>0.085</td>
<td>0.085</td>
<td>0.085</td>
<td>0.085</td>
</tr>
<tr>
<td>67000 ± 6400</td>
<td>6000 ± 120</td>
<td>2750 ± 140</td>
<td>2750 ± 140</td>
<td>2750 ± 140</td>
<td>2750 ± 140</td>
<td>1500 ± 125</td>
<td>480 ± 35</td>
</tr>
<tr>
<td>0.241</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
</tr>
<tr>
<td>3 ± 7</td>
<td>3 ± 1</td>
<td>3 ± 1</td>
<td>3 ± 1</td>
<td>3 ± 1</td>
<td>3 ± 1</td>
<td>3 ± 1</td>
<td>3 ± 1</td>
</tr>
</tbody>
</table>
The intensity of a particular monoenergetic group of \(\gamma\)-rays is not determined simply from the height of the photo-peak, but rather from the area under it, since statistical fluctuations broaden the photo-peaks by different amounts for different \(\gamma\)-ray energies. The area under each photo-peak was measured to an accuracy of about 3%. This measuring accuracy combined with the possible variation of photo-peak height gives the accuracy of the area under each photo-peak. The results are shown in the third column of the table on page (ii).

To obtain the relative intensities of the observed \(\gamma\)-rays these areas have to be divided by the photo-peak efficiencies for the respective \(\gamma\)-ray energies. The photo-peak efficiencies are found from the graph in fig. 53; their accuracy, estimated from the "scatter" of the points about the line, is about 10%. The photo-peak efficiencies are given in the fourth column of the table and the relative intensities, found by dividing the area by the corresponding efficiencies, are given in the fifth column of the table.

The \(\gamma\)-rays from the reaction were observed in the forward direction, so before arriving at the counter they passed through the target and also through the walls of the target chamber. Absorption occurs as the \(\gamma\)-rays pass through these materials, the amount of absorption being greater for low energy \(\gamma\)-rays than for the higher energy radiation. The relative intensities of the \(^{10}\text{Be}\) \(\gamma\)-rays were adjusted to compensate for the variation of \(\gamma\)-ray absorption with energy. Mass absorption coefficients for Be and Cu (the absorption coefficient for copper applies fairly well for the brass target holder) were taken from the data compiled by White(50).
Fig 55. The Experimental Arrangement
The target thickness is about 1.5 mm, and the thickness of the wall of the target chamber is also about 1.5 mm. The corrected values of the relative intensities are given in column eight of the table.

Hitherto it has been assumed that the line shapes for monoenergetic $\gamma$-rays are accurately known. The line shapes were observed for a number of different $\gamma$-ray energies and the accuracy of these measurements is indicated by the error bars on figs. 33 to 47. On most of these curves the statistical accuracy of the points around the photo-peaks is about 1 or 2 per cent, so the line shapes which were actually observed can indeed be considered to be accurately known. Ideally all the line shapes should have been observed with the $\gamma$-ray sources inside the target holder and with the counter the same distance from the source as it would be from the target in the $^{10}$B experiment. Because of the variety of source strengths used, this could only be done with a few of the sources. The observed line shapes are therefore only approximations to the ones which ought to be used. Fig. 55 shows the experimental arrangement used to obtain the line shapes and also to perform the experiment on $^{10}$B; the positions at which the sources were placed are indicated on the drawing, and so is any material which might scatter the $\gamma$-rays.

The target holder has already been described in detail by Galloway (51) who also gave a detailed description of the scintillation spectrometer which was used in this experiment. It is estimated that the line shapes used in the analysis of the $^{10}$B $\gamma$-ray spectrum differ from the ones which ought ideally to be used by less than 5 per cent, for $\gamma$-rays with energy between 1.5 and 2.2 MeV and by less than 3 per cent, for the rest of the $\gamma$-rays. Allowance was
made for inaccuracies of about this size when the relative intensities of the $\text{Be}^{10}$ $\gamma$-rays were listed as percentages in column 9 of the table.

The $\text{Be}^{10}$ Decay Scheme

The observed $\gamma$-rays have energies which can be fitted into either a decay scheme which includes a 2.86 MeV level or one which does not include such a level. The key factor in deciding which decay scheme to adopt is the branching ratio for the decay of the 2.15 MeV level.

The $\gamma$-rays which can arise from the decay of this level have energies of 2.15, 1.43 and 0.41 MeV. The branching ratio quoted by Ajzenberg-Selove and Lauritsen in their review of the properties of light nuclei is 30:40:30, but the original work on which this is based is not mentioned. The only direct measurement of this branching ratio mentioned in the references given by Ajzenberg-Selove and Lauritsen is that carried out by Clegg, who studied the 330 KeV resonance in $\text{Be}^9(p,\gamma)\text{Be}^{10}$ which excites $\text{Be}^{10}$ to a level at 6.88 MeV. This level decays through various lower energy states, including the 2.15 MeV state, and the 2.15, 1.43 and 0.41 MeV $\gamma$-rays which were observed are all said to come from the decay of the 2.15 MeV level. The relative intensities of these $\gamma$-rays give the branching ratio for the decay of the level. It was found to be 32:28:30. If one were to accept either Clegg's branching ratio or that given by Ajzenberg-Selove and Lauritsen, the present experiment would indicate that all, or nearly all, of the 1.43 MeV $\gamma$-rays from $\text{Be}^9(d,n)\text{Be}^{10}$ arise from the decay of the 2.15 MeV state, a conclusion which is at variance with the experimental evidence provided by Shaffroth and Hanna and by
Galloway and Sillitto, that about half of the 1.43 MeV γ-rays arise from transitions between the 3.58 and 2.15 MeV states.

The more recent work by Sprenkel and Daughtry gave the branching ratio as 16:29:55. In their experiment the 7.56 MeV level of B\(^{10}\) was excited by bombarding Be\(^9\) with 1.08 MeV protons. The γ-ray spectrum in coincidence with the 5.41 MeV γ-rays which feed the 2.15 MeV level was observed and so the branching ratio for the decay of this level was found. Even more recently Grace et al. studying the γ-rays from proton bombardment of B\(^{10}\) found this branching ratio to be 20:28:52.

Although these are the only direct measurements of this branching ratio other recent work can be cited as supporting Sprenkel and Daughtry's measurement. The work of Singh on the γ-rays from the 7.19 and 7.48 MeV states of B\(^{10}\) indicates clearly that the 0.41 MeV γ-ray is much more intense than either of the other γ-rays from the decay of the 2.15 MeV level, and the decay scheme deduced by Galloway and Sillitto from their coincidence experiment also indicates this. Galloway and Sillitto deduce the branching ratio as 19:25:56. Theoretical calculation of the branching ratio carried out by Kurath using a shell model with a variable strength of spin-orbit coupling, also shows that the 0.41 MeV transition should be the strongest one. For one value of the intermediate coupling parameter the ratio is 71:35:57 which agrees fairly well with these recent experimental measurements.

The value of branching ratio which Sprenkel and Daughtry obtained is thought to be the best experimental value and it was
used to indicate that about three fifths of the 2.15 MeV $\gamma$-rays must arise from transitions other than those between the 2.15 MeV level and the ground state. This leads to the conclusion that a 2.86 MeV state exists in $^8B$.

In trying to assess the reliability of this conclusion one may wonder by what amount the branching ratio could be changed from that observed by Sprenkel and Daughtry and still lead to the same conclusion. The largest ratio of the intensities of the 0.41 and 2.15 MeV $\gamma$-rays consistent with the present experimental results is 1.2:1. This is therefore the largest value of this particular component of the 2.15 MeV state's branching ratio which could be consistent with all the observed 2.15 MeV $\gamma$-rays being associated with the decay of the 2.15 MeV state. Sprenkel and Daughtry found this component of the branching ratio to be 3.4:1 so changes of about a factor of three would have to be made before one could avoid concluding that the 2.86 MeV state exists. Sprenkel and Daughtry state that the standard deviations for the 2.15, 1.43 and 1.02$^\dagger$ MeV peak intensities in their experiments were 5.7%, 3.5% and 2.5% respectively (56) so it seems unlikely that the conclusion that a 2.86 MeV state exists can be avoided.

$^\dagger$ The 1.02 MeV $\gamma$-ray's intensity is the same as that of the 0.41 MeV $\gamma$-ray in Sprenkel and Daughtry's experiment.