THE STUDY OF REACTIONS IN LIGHT NUCLEI USING TECHNIQUES OF PULSE AMPLITUDE ANALYSIS

This work was carried out by the author under the supervision of his tutor, Dr. P. B. Treacy, who designed the detectors and target chambers used in the experiment. The assembly of these, the experimental observations and the interpretation of the results were carried out by the author. The method of calculating angular correlations was shown to the author by Dr. P. B. Treacy in a discussion between the author and Dr. A. V. Cohen.

This thesis is substantially the same as any other that has been submitted previously for the degree of Doctor of Philosophy.

This work is a thesis submitted for the degree of Doctor of Philosophy in the Australian National University.

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A. C. Riviere
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Two reactions in particular were investigated, \( \text{Li}^7(\text{p},\alpha)\text{Be}^8 \) and \( \text{Li}^7(d,\alpha)\text{He}^5(n)\text{He}^4 \). The \( \text{Li}^7 + p \) reaction was chosen for the information that could be obtained on the energy levels of \( \text{Be}^8 \) from a study of the alpha-particle energy spectrum. The \( \text{Li}^7 + d \) reaction was chosen in order to study the formation of the states of \( \text{He}^5 \) by this reaction in comparison with the properties of \( \text{He}^5 \) as observed in the scattering of neutrons in \( \text{He}^4 \).

Section I is concerned with the \( \text{Li}^7 + p \) reaction, and Sections II and III are concerned with the \( \text{Li}^7 + d \) reaction.

In each of the above reactions alpha-particles are emitted and the experimental observations were concerned with the measurement of the energy, direction of emission and rate of emission of these particles. Except in the work of the first part of Section I, the energy distribution and the directions of emission have been
INTRODUCTION

This thesis is based on a study of light nuclei (with $Z < 10$) and of the nuclear reactions in which they take part. The type of nuclear reactions considered are those which occur when a target containing the isotope of interest is bombarded with other light nuclei or nucleons which have been artificially accelerated with energies up to 1.0 Mev.

Two reactions in particular were investigated, $\text{Li}^7(p^8)\text{Be}^8(\alpha)\text{He}^4$ and $\text{Li}^7(d\alpha)\text{He}^5(n)\text{He}^4$. The $\text{Li}^7 + p$ reaction was chosen for the information that could be obtained on the energy levels of $\text{Be}^8$ from a study of the alpha-particle energy spectrum. The $\text{Li}^7 + d$ reaction was chosen in order to study the formation of the states of $\text{He}^5$ by this reaction in comparison with the properties of $\text{He}^5$ as observed in the scattering of neutrons in $\text{He}^4$.

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obtained by pulse amplitude analysis.

A large part of the work contained in this thesis has now been published:

"The design of a multiple-wire proportional counter and its use in the study of the alpha-particles from the reaction Li$^7 + p"$

A.C. Riviere and P.B. Treacy.

Australian Journal of Physics, 8, 408 (1955).

"The formation of He$^5$ by the deuteron bombardment of Li$^7$."

A.C. Riviere.

Nuclear Physics, 2, 81 (1956).

"The angular distribution of alpha-particles from Li$^7(d\alpha)He^5$."

A.C. Riviere and P.B. Treacy.

I. THE Li\textsuperscript{7}(p,\alpha)Be\textsuperscript{8}(\alpha)He\textsuperscript{4} REACTION AND THE NUCLEUS Be\textsuperscript{8}

(a) INTRODUCTION

The nucleus Be\textsuperscript{8} is an unstable configuration of nucleons which breaks up into two alpha-particles with an energy release of 0.096 Mev. Stability cannot be achieved by \( \beta \)-emission since Be\textsuperscript{8} has the lowest mass of the three isobars Li\textsuperscript{8}, Be\textsuperscript{8} and B\textsuperscript{8}, and neutron or proton emission is not possible except at much higher excitation energies. Only the break-up into two He\textsuperscript{4} nuclei is possible in the ground state.

The He\textsuperscript{4} nucleus has a binding energy per nucleon of 7.07 Mev which is large in comparison to the binding energies of the neighbouring nuclei T\textsuperscript{3} and He\textsuperscript{3}, of 2.83 and 2.57 Mev and Li\textsuperscript{5} and He\textsuperscript{5}, of -1.80 and -0.95 Mev respectively. One of the first models of the nucleus was based on the assumption that alpha-particles exist as rigid sub-units of all nuclei. This has since been shown to be untenable due to the high kinetic energy of each nucleon (about 20 Mev) within a nucleus. However, J.A. Wheeler\textsuperscript{(1)} put forward the idea of a "resonating group structure" as a possible nuclear model in which the most probable group would have the structure of an alpha-particle.

This bias towards an alpha-particle structure is suggested by the Pauli exclusion principle, which forbids

\begin{footnote}{J.A. Wheeler, Phys. Rev., 52, 1083 (1937)}
\end{footnote}
any two fundamental particles from occupying the same state. A proton and a neutron are considered as the two isotopic-spin states of a nucleon, and the "state" referred to above is defined by isotopic-spin, angular momentum and positional co-ordinates. The He4 nucleus contains the maximum number of nucleons which can have the same angular momentum and positional co-ordinates; there are two neutrons and two protons each.

In Wheeler's hypothesis the structure is only transitory in nature. Discussions and calculations on the alpha-particle model have been made by several authors (2, 3). In the limit, alpha-particle clusters are formed, although the exclusion principle tends to separate similar particles with their intrinsic spins anti-parallel to that of the other nucleon of the same type. In a heavy nucleus the Be8 nucleus contains the maximum number of nucleons which can exist for study in the present experiment. The Be8 nucleus is the lightest which can be simply pictured in terms of an alpha-particle structure, and a knowledge of the density levels of Be8 would enable a test to be made of the alpha-particle model. There is evidence, which has been summarised by F. Ajzenberg and T. Lauritsen (4), that the nucleus Be8 exists briefly in t. Lauritsen reaction.

The proton bombardment of Li7 leads to the following

(2) A. Herzenberg, Nuovo Cimento (10), I, 986, (1955)
(3) L. Rosenfeld, p. 269, Nuclear Forces, Amsterdam (1948)
(4) F. Ajzenberg and T. Lauritsen, Rev. Mod. Phys. 27, 77 (1955)
reactions:
\[ \text{Li}^7 + p \leftrightarrow \text{Be}^8 \leftrightarrow \text{Be}^8 + \gamma \]
\[ \text{Be}^8 \rightarrow \text{He}^4 + \text{He}^4. \quad \ldots \quad (i) \]
\[ \text{Li}^7 + p \rightarrow \text{Be}^8 \rightarrow \text{He}^4 + \text{He}^4. \quad (ii) \]

It is possible that \text{Be}^8 is not always formed in (ii) but that a direct transition occurs. However both reactions take place simultaneously in the proton bombardment of \text{Li}^7 and a study of reaction (i) must be made in the presence of \text{Li}^7 and \text{He}^4 particles from reaction (ii).

At a proton energy of 0.44 Mev there is a pronounced resonance for reaction (i) resulting in the formation of \text{Be}^8 in an excited state with an energy of 17.63 Mev. This state decays by the emission of gamma radiation. Burcham and Freeman \(^{(5)}\) have magnetically analysed the alpha-particles of energy up to 2.4 Mev and found that the ground and first excited states of \text{Be}^8 (0.096 Mev and 3.0 Mev above \text{He}^4 + \text{He}^4 respectively) are formed as intermediate stages in reaction (i). These levels are excited by gamma-ray transitions from the 17.63 Mev state\(^{(6)}\).

Reaction (ii) results in the emission of a single group of alpha-particles with an energy of 8.98 Mev\(^{(7)}\). This reaction is not resonant at 0.44 Mev but the yield

\(^{(5)}\) W.E. Burcham and J.M. Freeman, Phil.Mag., 41, 921 (1950)
\(^{(6)}\) E.K. Inall, Phil. Mag., 45, 768 (1954)
rises to a broad maximum at 3.0 Mev. (8).

Alpha-particles with energies between 2.4 and 8.98 Mev may be expected from (i) corresponding to the decay of other Be₈ levels. However, these particles may not be observed if the corresponding gamma-ray transitions are of high multi-polarity and therefore of relatively low intensity. It was the aim of the present experiment to study the alpha-particle energy spectrum in this region and hence to ascertain whether Be₈ levels other than the ground and first excited states are involved in (i).

Two methods have been used. Firstly the ranges of the alpha-particles were measured and the energy distribution obtained from the range distribution. Secondly, the ionisation produced by the particles in argon gas was measured and the energy distribution was obtained from the pulse height distribution. The results of both methods are discussed.

I (b). THE DIFFERENTIAL IONISATION CHAMBER

A fast charged particle loses energy when passing through matter by collision with the atomic electrons until it is brought to rest. For a given material the distance travelled by, or the "range" of a particle is uniquely determined by its initial energy except for a small straggling effect due to the statistical nature of the collision processes. The range is measured to the end

of the track of ionised matter, although the particle continues beyond this point until its energy is reduced to the thermal region by elastic collisions. For alpha-particles of given energy each individual track is slightly shorter or longer than the average. This is due to the statistical variation in the chance of a collision occurring. The ranges of many types of particles are known for a wide range of energies and a variety of absorbing materials. In the present work all information on the range-energy relationship for alpha-particles has been obtained from Bethe (9) and Segre (10). This information was used to convert the range distributions to energy distributions.

The ranges of the alpha-particles from the proton bombardment of Li$^7$ were determined by means of the differential ionisation chamber described by French and Treacy (11). A schematic drawing of the chamber and target box as used in the present observations is shown in Figure 1. Two shallow ionisation chambers (12) AC and CB were placed consecutively in the path of the particles. The electrodes A and B were made in the form of wire grids and electrode


(10) E. Segre, Experimental Nuclear Physics, Volume 1, John Wiley and Sons Inc., New York.


Figure 1. The differential ionisation chamber.
C was made of two thin gold foils. The potentials applied to A and B with respect to C were of opposite polarity so that when ions were formed in both chambers the charges collected on C cancelled out. If the ions were formed in AC only, that is, if the particle came to rest before entering CB, there was a net charge collected on C and the event was recorded. In this way, the point where the particle came to rest was determined. The density of ionisation increases as an alpha-particle is slowed down until a maximum is reached near the end of its range. The ionisation then falls to zero. If a particle came to rest at B there would be a small net charge collected on C of opposite sign to that of the wanted signal. To reduce this effect AC was made slightly deeper than CB so as to equalise the ionisation in each side. Only the electrons formed in the gas were collected since a high counting speed was required. This resulted in the use of only half the available signal voltage. An increase in the signal to noise ratio was obtained by increasing the thickness of electrode C.

The total range from an external source to the region AC was varied by changing the pressure in the air absorption cell D. Thin mica windows, W1 and W2, were used at each end of the absorption cell. For particles whose range was less than the total range of the system at zero pressure in D, W1 was removed and a series of aluminium foils $\alpha, \beta, \gamma, \delta$, placed in turn at E.
particles whose ranges were greater than could be accommodated by the system with a pressure of one atmosphere in D, an extra mica absorber (w) was introduced at E.

Argon of 99.8 per cent purity was used for the gas filling of the chamber at a pressure of 20 cm. Hg. The collecting voltages applied to the electrodes A and B were +120 and -120 volts respectively. This voltage was sufficient to ensure complete collection of the electrons formed in the gas. The signals appearing on electrode C were fed into a linear pulse amplifier. For the optimum signal to noise ratio, the rise and clipping time constants of the amplifier were set to 8 $\mu$ sec. each. This choice of time constants resulted in an increased sensitivity of the amplifier to mechanical vibrations. To avoid spurious effects due to the vibration of the accelerator tube, the amplifier unit was isolated mechanically from the chamber and mounted on sponge rubber pads.

Pulses from the amplifier were fed to a discriminator, and those large enough to overcome the discriminator bias were recorded by a scaling unit. The size of the signal from the chamber was dependent on the exact location of the end of the track of a particle so that the bias level of the discriminator determined the counting rate to a certain extent. However, no trouble was encountered during the experiment from changes in the gain of the system when a bias voltage of half the maximum pulse height was used.
Figure 2. The observation of alpha-particles from a thorium active deposit by the differential ionisation chamber when used for determining the air equivalent thickness of a mica absorber.
The pressure scale of the air absorption cell was calibrated by determining the effective length of the absorption cell and that of the chamber and mica windows, W1 and W2. These parameters were obtained by observing two groups of alpha-particles of known range. Thorium active deposit emits alpha-particles of energy 6.07 Mev. Mev. and 8.78 Mev. from ThC\textsuperscript{212} and ThC\textsuperscript{212'} respectively (13). These energies correspond to ranges in air of 4.73 cm. and 8.54 cm. respectively. The particles were observed by supporting a thin source at the target position T.

The differential chamber was also used with the Thorium source to calibrate other absorbers. For these measurements the chamber was detached from the target box, the mica window W1 removed, and the source supported on the moving arm of a height gauge. The heights were recorded at which the two alpha-particle groups were observed and from these readings a calibration was obtained of the local air at the time of the measurement. The absorber to be measured was then interposed between source and chamber and the height recorded at which the ThC\textsuperscript{212'} alpha-particles were detected. The air equivalent of the absorber was given by the difference between the two ThC\textsuperscript{212'} readings, when this difference had been corrected from local air to air at 760 mm. Hg. and 15° C.

A set of readings from the determination of the air equivalent of an absorber is shown in Figure 2.

The calibration of the absorption cell and of the various absorbers by the above method formed the basis for the energy scale of the observed particle distributions. The values obtained are listed in Table 1.

### TABLE 1

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of air cell</td>
<td>4.00 cm.</td>
</tr>
<tr>
<td>Air equivalent of W1</td>
<td>1.07 cm.</td>
</tr>
<tr>
<td>&quot; W2 + chamber</td>
<td>1.24 cm.</td>
</tr>
<tr>
<td>&quot; W</td>
<td>3.72 cm.</td>
</tr>
<tr>
<td>&quot; ( \lambda )</td>
<td>0.22 cm.</td>
</tr>
<tr>
<td>&quot; ( \lambda + \beta )</td>
<td>0.34 cm.</td>
</tr>
<tr>
<td>&quot; ( \lambda + \beta + \gamma )</td>
<td>0.54 cm.</td>
</tr>
<tr>
<td>&quot; ( \lambda + \beta + \gamma + \delta )</td>
<td>0.72 cm.</td>
</tr>
</tbody>
</table>

### I (c). EXPERIMENTAL OBSERVATIONS WITH THE DIFFERENTIAL IONISATION CHAMBER

The target box is shown with the differential chamber in Figure 1. The proton beam was collimated by a circular aperture, S, 0.25 in. in diameter, so that only the central portion of the target was bombarded. The target backing consisted of a 0.5 in. diameter polished brass button set at 45° to the beam. Natural lithium (92.5 per cent \( \text{Li}^7 \), 7.5 per cent \( \text{Li}^6 \) (14)), in the form of lithium aluminium hydride, was evaporated under vacuum directly on to the brass button. The thickness of the deposit was determined by measuring the width of the 0.44 Mev resonance in reaction (i) as
observed with this target. The width of the resonance which would be observed with an infinitely thin target is 12.2 Kev. (15). The thickness of the deposit was found to be 100 Kev. for protons with an energy of 0.5 Mev. This thickness is equivalent to 2 mm. of air. The target was maintained at a temperature of 100° C. to reduce the tendency for a layer of carbon to be formed on the target surface during bombardment.

Observations were made at 90° to the proton beam. The spread of angles about 90° at which particles were observed was defined by a 0.5 in. diameter aperture placed at E. The energy of a particle emitted at an angle θ with respect to the proton beam is given by the relation

\[ E = \frac{1}{2} m \left( V \cos \theta + \sqrt{V^2 - v^2(1+\cos^2 \theta)} \right) \]  

where V is the velocity of the particle in the centre of mass system, v is the velocity of the centre of mass and m the mass of the particle. The aperture introduced a spread of ±30 Kev in the observed energy of the alpha-particles.

A Geiger counter, shielded with 0.25 in. of lead, was used to monitor the gamma-ray yield from the target.

An energy of 0.47 Mev was chosen for the proton beam in the measurements on the alpha-particle spectrum. With protons of this energy the 0.44 Mev resonance was fully

Figure 3. The alpha-particle spectrum from the proton bombardment of Li$^7$ as observed with the differential ionisation chamber.
excited within the target layer. The number of particles detected was recorded at each absorption cell pressure for a total of $10^3$ gamma-ray monitor counts. Two complete sets of readings over the whole spectrum were taken and the mean of these is shown in Figure 3.

The peak in the spectrum at 8.8 Mev is due to the alpha-particles from reaction (ii). This peak has a "tail" on the low energy side down to 6 Mev. The presence of these particles of degraded energy was probably the result of scattering from the aperture at E and of unevenness in the windows due to the presence of fillets of wax formed when mounting the mica.

The rise at 2.7 Mev is due to He$^3$ particles from the reaction (16):

$$\text{Li}^6 + p \rightarrow \text{He}^4 + \text{He}^3 \quad \text{(iv)}$$

The He$^3$ particles are emitted with an energy of 2.53 Mev and have a range equal to that of an alpha-particle with an energy of 2.72 Mev. There are no peaks in the observed spectrum between 2.8 Mev and 8.7 Mev, although alpha-particles are present with all energies between these limits.

In all (6) studied the levels excited in Be$^8$ through reaction (i) by observing alpha-particles in coincidence with gamma-rays. He observed a level at an excitation of

7.5 Mev. The position and magnitude of the particle group arising from the excitation of this Be$^8$ level in the present observations are indicated by the dotted curve "a" in Figure 3.

La Vier et al. (17) have recently studied the alpha-particle spectrum from reaction (i) with a magnetic analyser. Their results indicate a broad level in the region of 10 Mev excitation. The position and magnitude of the particle group associated with this level is shown in Figure 3 as curve "b".

In all and La Vier et al. relate the intensity of "a" and "b" to the ground state transitions. In the present observations neither the ground nor the first excited states were seen, so that a relation between the intensities of "a" and "b" had to be found with respect to the particles from reaction (ii). To obtain this relation the following information was used: the known target thickness in the present observations, the yield curve for reaction (ii) as a function of energy from Heydenberg et al. (8) and the relation between the yield of gamma-rays from reaction (i) to the particles from reaction (ii) for a thick target as measured by Boyle (18).

Levels of Be$^8$ have been reported (19, 20) at excitation energies of 16.06 Mev and 16.72 Mev from the study


of other reactions. The width of the alpha-particle group observed from a radio-active source (Figure 2) is ± 125 Kev. The width of the alpha-particle group due to reaction (ii) (Figure 3) is ± 140 Kev. The increase in width can be accounted for by the spread due to the finite target thickness, ± 70 Kev, and the spread due to the finite aperture size, ± 30 Kev. Thus, it is concluded that alpha-particles from the excitation of the levels at 16.06 Mev. and 16.72 Mev are not present with an intensity greater than 10 per cent of that of reaction (ii).

I (d). THE WIDE-ANGLE MULTIPLE-WIRE PROPORTIONAL COUNTER

This counter was originally designed for use in a type of experiment (21) where it was necessary to detect alpha-particles from an external source over a wide range of angles. The counter was also required to determine the energy of the particles by measuring the ionisation formed in the counter gas, and to possess a response time of the order of 1.0 μsec. in order to reduce the pile-up of pulses at high counting rates and in order to be suitable for use in coincidence experiments.


A 'proportional' counter (12) was chosen. In this type of counter the number of ions formed in the gas is increased by gas multiplication, but the actual charge collected bears a definite relation to the initial ionisation. Restrictions were placed on the design of the counter for the following reasons: 1. The anode voltage was to be kept below 1000 volts to reduce the insulation problem, 2. The gas pressure had to be of the order of half an atmosphere due to the limited strength of the thin window through which particles entered the counter. 3. The size of the counter had to be such as to ensure that the range of an 8 Mev alpha-particle was contained within it.

In order to meet restrictions 2 and 3, the cathode diameter, $b$, had to be of the order of 20 cm. Restrictions 1 and 2 and the need for gas amplification limit the diameter, $a$, of the anode wire. Under these conditions the time required to collect all electrons from a track near the cathode is large. In coincidence experiments the difference in electron collection times from different points in the chamber must be kept small. The exact times involved cannot be calculated since the electron mobility in argon is very sensitive to the presence of impurities. However, in the present design, the electron collection delay time was reduced by dividing the sensitive region into a number of separate counters, each with its anode and cathode.

A schematic drawing of the counter is shown in Figure 4. The sensitive region was contained within a cube
Figure 4. The wide-angle multiple-wire proportional counter.
of side 8 in. in which there were 16 independent anode-cathode systems. Each anode wire, A, was located at the centre of a square array of 8 thicker wires, C, all earthed, which formed the cathode. The anode wires were of 0.0035 in. diameter beryllium-copper and were attached to two ebonite sheets mounted on a brass frame, F. This frame had large holes, H, drilled through it to expose the ebonite, E, around each anode wire and thus provide the necessary insulation. The anode wires were connected to a common lead which was fed through the wall of the chamber by means of a metal to glass seal. A spring contact allowed the top flange of the chamber to be lifted out of the enclosing cylinder with the frame attached to it and to be replaced with ease. The cathode wires were of 0.010 in. diameter copper and were attached directly to the frame. The total capacity between the anode system and the frame was 56 $\mu$F.

The outer chamber was constructed from a 12 in. diameter brass cylinder with rubber vacuum seals. It was evacuated and filled through a glass tube held by a semi-flexible O-ring seal. There were two other glass tube seals by means of which a side arm was attached to the chamber. This side arm contained metallic sodium and was used to purify the counter gas. When the sodium was heated the counter gas circulated through the arm by convection and the hot metal removed any oxygen or water vapour present.

The dotted lines in Figure 4 indicate the cone of
semi-angle 60° within which particles emitted from an external target, T, at the cone apex would be accepted by the counter. The particles entered the counter through a thin window, W. This window was constructed by attaching a piece of mica sheet with wax on to a brass grid. The thickness of the mica was equivalent to 0.62 cm. of air and the holes in the brass grid were countersunk to allow the wide-angle penetration of the counter.

The chamber was normally filled to a pressure of 38 cm. Hg. with argon of 99.8 per cent purity. The anode potential was 720 volts for this pressure. Under these conditions a gas multiplication factor of 4.7 was achieved. However, in spite of the use of the sodium purifier it was found that the gas multiplication drifted by as much as 10 per cent in 8 hours which was probably due to the presence of ebonite within the chamber. The counter was filled before each set of observations and since these were recorded in a short time no appreciable error was introduced. The pulse rise time due to positive ion motion away from the anode wire was measured by the method outlined by Gillespie (22) and found to be 2.4 μsec.

Pulses from the anode of the counter were fed into a linear amplifier with rise and clipping time constants of

(22) A. B. Gillespie, Signal, Noise and Resolution in Nuclear Counter Amplifiers, Pergamon Press Ltd., London.

0.16 μsec. and 1.6 μsec. respectively. These time constants were chosen for the optimum conditions of noise and resolution. The r.m.s. noise voltage at the first grid of the amplifier was equivalent to $2.7 \times 10^{14}$ ion pairs with the counter attached, and $7.8 \times 10^{3}$ ion pairs with the amplifier alone. The reduction in circuit and valve noise when the capacity of the counter was removed indicated that the main contribution to the noise was the shot effect in the first valve. This effect is sensitive to the capacity on the grid of the valve in which it is generated (22) and represents a limit to the number of anode wires which could be used in the design of the counter.

The energy lost in the formation of an ion pair by a fast charged particle in argon is independent of the energy of the particle (23). Thus, the height of the output pulse from the amplifier is proportional to the energy lost by the incident particle in the counter gas.

The pulse height spectrum was measured in the following way: The maximum height of each pulse was held by a diode pulse lengthener for 20 μsec. and this potential was applied to the Y deflection plates of an oscilloscope. A pulse generator was triggered by all pulses from the amplifier greater than 5 volts in height and the square waveform from this circuit was used to control the discharging of the diode pulse lengthener and the intensity

Figure 5. A typical example of recording film showing the pulse height distribution due to the observation of alpha-particles from a thorium active deposit.
Figure 6. The pulse height distribution recorded when alpha-particles from a thorium active deposit were observed by the multiple-wire proportional counter.
of the oscilloscope beam. The intensity of the beam was adjusted so that normally it could only just be seen. No X deflection was used. The pulses from the amplifier then appeared as bright dots above a faint zero position and these were recorded on slowly moving photographic film. When developed the film was placed in an enlarger and the pattern projected on to a piece of squared paper. The pulse height spectrum was determined by counting the number of dots in equal intervals above the zero line. The total number of times the pulse generator was triggered was recorded on a scaling unit so that the number of pulses recorded on the film was known.

The alpha-particles from a thorium source were observed with the counter. A reproduction of a one inch length of the recording film is shown in Figure 5, and the complete pulse height spectrum as obtained from the analysis of two feet of film is shown in Figure 6. The spread of each group at half height is ± 340 Kev. Amplifier noise contributes ± 150 Kev to this spread. The remainder of the spread in the groups was due to variations in gas amplification between the different anode-cathode systems, unevenness in the mica window and errors in reading the results from the recording film. No attempt was made in the present observations to obtain a better energy resolution with this counter.

I (e) EXPERIMENTAL OBSERVATIONS WITH THE WIDE-ANGLE PROPORTIONAL COUNTER

A schematic drawing of the target box with the
Figure 7. The experimental arrangement of the target box and the multiple-wire proportional counter.
Figure 8. The alpha-particle spectrum from the reaction Li$^7 + p$ as observed with the multiple-wire proportional counter when a circular aperture 0.63 in. in diameter was used.
wide-angle proportional counter attached is shown in Figure 7. The proton beam was collimated by a circular aperture, S, 0.19 in. in diameter, so that only the central portion of the target, T, was bombarded. The target backing and material were identical to those used in Section I (c). However, in this case, the thickness of the evaporated layer of lithium aluminium hydride was 50 KeV for 0.5 Mev protons. The alpha-particles were observed at 90° to the proton beam and the solid angle of acceptance of the counter was defined by an aperture placed at E. For the initial observations a circular aperture 0.63 in. in diameter was used. A pulse height spectrum was recorded at a proton energy of 0.47 Mev and this is shown in Figure 8. The group F is due to reaction (ii). There are five groups, A, B, C, D, E of lower energy than group F which were possibly due to the excitation of Be^8 levels by reaction (i). However, a second spectrum was recorded at a proton energy of 0.38 Mev and this contained groups of approximately the same magnitude and position as those in Figure 8. This indicated that the groups were not resonant at 0.44 Mev and hence were not due to reaction (i).

It was suspected that the groups A, B, C, D, E, resulted from the loss of energy by particles on striking the counter wires. The calculated solid angle presented to the target by the wires was half that required to account for the groups. The expected group
Figure 9. The alpha-particle spectra observed when two slits were used in place of the circular aperture. Full curve, spectrum taken at a proton energy of 0.47 Mev; circles, mean of spectra taken at proton energies of 0.40 and 0.54 Mev; broken curve, spectrum of Po$^{210}$ alpha-particles.
positions due to each layer of wire were calculated (24) and are indicated by arrows in Figure 8. There is a definite correlation between the observed groups and their expected positions. To confirm this explanation the circular aperture at E was removed for the next observation and two slits were used instead. The slits were arranged so that the chance of a particle striking a wire was reduced.

Pulse height spectra were recorded at three proton energies, 0.40, 0.47, and 0.54 Mev for a total of $5 \times 10^4$ alpha-particles in each. The results are shown in Figure 9 where all the spectra have been normalised to the same magnitude and position of group B. The spectrum recorded at 0.47 Mev is shown as a full curve and the circles are the mean of the results taken at 0.40 Mev and 0.54 Mev. The 0.44 Mev resonance for reaction (1) was fully excited in the 0.47 Mev spectrum but was not excited in the 0.40 Mev or 0.54 Mev spectra. The proportion of particles with energies below that of group B was halved by the introduction of the slits. An estimate of how much of the background was due to the counter was obtained by observing the spectrum of alpha-particles from a Po$^{210}$ source. For this measurement the gas pressure in the counter was reduced to 16 cm. Hg. and the anode voltage to 675 volts. Under these conditions the alpha-particles from Po$^{210}$ reached as far into the counter as the

(24) The calculation of the positions of the groups required a knowledge of the range energy relation for alpha-particles in argon. The derivation of this relation is given in Appendix I.
particles from reaction (ii) had in the previous observations and their pulse heights were the same. The low energy part of the $^{210}$Po spectrum is shown in Figure 9 by a dashed curve and it can be seen that this does not account for group A. However, Group A can be accounted for by assuming that alpha-particles from the reaction $^{18}$O + ^{7}\text{Be} \rightarrow ^{15}\text{N} + ^{4}\text{He}$, (25), were observed due to the presence of oxygen in the target layer.

The results of Inall (6) and La Vier et al. (17) are shown in Figure 9 by the dotted curves a and b respectively. The yields of a and b relative to the yield of the particles from reaction (ii) have been increased from those shown in Figure 3 since a thinner target was used in the present observations. Alpha-particles arising from transitions by reaction (i) to levels in Be$^8$ higher than 16 Mev (19, 20) would be masked here by the width of the group of particles from reaction (ii).

I(f) CONCLUSION

No well defined alpha-particle groups from reaction (i) were observed in the energy range, 2.8 Mev to 8.7 Mev. In the case of the ionisation chamber measurements (Figure 3) no further conclusions can be drawn. However it is possible in the case of the proportional counter measurements (Figure 9) to place an upper limit of 3 percent of the ground state transitions on the yield of

alpha-particles between 4.0 Mev and 8.0 Mev. This result is in disagreement with the intensity of 10 per cent for the background of alpha-particles observed by La Vier et al. (17) in the neighbourhood of 5.0 Mev. The figure of 10 per cent was obtained by integrating the relevant areas of the alpha-particle spectrum published by La Vier et al. and by using the ratio of 2:1 (26) for the intensity of the ground state transitions relative to that of the 3.0 Mev excited state transitions. There are two possible explanations for the difference in the observed intensities. Firstly, the data used here for calculating the intensity of the groups a and b in relation to the ground state transitions may be in error. Secondly, La Vier et al. may have observed scattered alpha-particles from reaction (ii). No narrow levels were observed in either case, but present evidence indicates the existence of a broad level in Be$^8$ with an excitation energy between 5.0 Mev. and 12.0 Mev.

II. FORMATION OF $\text{He}^5$ BY THE DEUTERON BOMBARDMENT OF $\text{Li}^7$

(a) **LOW LEVELS OF $\text{He}^5$**

The nucleus $\text{He}^5$ is unstable in its lowest state against dissociation into a neutron and an alpha-particle with an energy excess of 0.95 Mev. The Independent-Particle model of the nucleus indicates that the lowest state of $\text{He}^5$ should be a $2^P$ state, and the splitting between the two components, $P_1^2$ and $P_3^2$, would depend on the strength of the spin-orbit coupling of the nuclear interaction. These low energy levels have been observed in the scattering of neutrons in $\text{He}^4$. The total and differential scattering cross sections are known and have been summarised by Seagrave (27) for neutron energies up to 20 Mev. The total cross section has a resonance at a neutron energy of 1.15 Mev and phase shift analysis of the angular distributions show this to be the $P_3^2$ state of $\text{He}^5$. The phase shift analysis also indicates a broad $P_1^2$ level with a maximum cross section at 5.0 Mev. The possible existence of D states will not be considered here. The precise location of the $P_1^2$ level is not known and the width of the level (~2 Mev) is so great, hence lifetime so short, that it is doubtful whether the existence of a definite state should be

Figure 10. The low levels of He⁵.

(a) Cross section for neutron scattering in He⁴ due to the P states of He⁵.

(b) Be⁹ decay probability as calculated in ref. (39).

(c) Be⁹ decay probability as calculated by using equation (xi).
considered. However, the existence of a definite state will be assumed in the following discussion. The cross sections for the scattering of neutrons by $\text{He}_4^4$ due to the two $P$ states of $\text{He}_5^5$ are reproduced as the solid curves marked 'a' in Figure 10, up to a neutron energy of 6 Mev. These results were taken from Adair (28) and Seagrave (27).

The parameters associated with the neutron scattering in $\text{He}_4^4$ are similar to those for the scattering of protons in $\text{He}_4^4$ except for an energy difference between corresponding levels. The difference between the coulomb energy of $\text{Li}_5^5$ ($Z = 3$) and that of $\text{He}_5^5$ ($Z = 2$) accounts for the observed difference in energy. This supplies direct evidence for the charge-independence of nuclear forces.

Formation of $\text{He}_5^5$ has been observed in many nuclear reactions and a summary of these has been made by Ajzenberg and Lauritsen (4). One of these, the $\text{Li}_7^7 (d \alpha) \text{He}_5^5$ reaction, was the subject of the present experiment.

II (b) THE $\text{Li}_7^7 + d$ REACTIONS

The deuteron bombardment of $\text{Li}_7^7$ results in the production of two alpha-particles and a neutron with a total energy release of 15.11 Mev (29). The reaction can be considered to proceed via a compound nucleus state in $\text{Be}_9^9$ which then disintegrates by one of the


(29) Quoted by ref. (4), as calculated from the masses of the particles involved.
Figure 11. A velocity diagram representing a particular disintegration of Be$^9$. 

recoil direction of He$^5$
excitation energy $= 4.09$ Mev.

recoil direction of Be$^8$
excitation energy $= 14.7$ Mev.

recoil direction of He$^5$
excitation energy $= 1.0$ Mev.
following processes:

\[ \text{Be}^9 \rightarrow \text{He}^4 + \text{He}^5; \quad \text{He}^5 \rightarrow n + \text{He}^4 \quad (i) \]

\[ \text{Be}^9 \rightarrow n + \text{Be}^8; \quad \text{Be}^8 \rightarrow \text{He}^4 + \text{He}^4 \quad (ii) \]

\[ \text{Be}^9 \rightarrow n + \text{He}^4 + \text{He}^4 \quad (iii) \]

The present experiment has been concerned with the formation of \( \text{He}^5 \) by reaction (i) in comparison with its formation during the scattering of neutrons by \( \text{He}^4 \). It was first reported by Williams et al. (30) that reaction (i) occurred and that it was possible that the same state of \( \text{He}^5 \) was formed as was seen in the neutron scattering experiments. The information which was sought here was whether \( \text{He}^5 \) was also formed in the \( P_1 \) state. It was also expected to obtain information on the intermediate state in \( \text{Be}^9 \) and on the relative yields of reactions (ii) and (iii) in comparison with reaction (i).

A velocity diagram representing a particular disintegration of \( \text{Be}^9 \) is shown in Figure 11. The relative magnitude and direction of each vector were calculated on the following assumptions: that reaction (i) had occurred; that the compound nucleus state in \( \text{Be}^9 \) had disintegrated by the emission of an alpha-particle, \( \alpha_1 \), leaving \( \text{He}^5 \) with an excitation energy of 1.0 Mev; and that the nucleus \( \text{He}^5 \) had then decayed in flight to a neutron, \( n \), and an alpha-particle, \( \alpha_2 \).

at an angle $\theta$ of $60^\circ$ to the direction of recoil of $\text{He}^5$. The effect of the motion of the centre of mass has been neglected, but a vector has been drawn on the diagram to indicate the magnitude of this velocity.

There were three alternative ways in which $\text{Be}^9$ may have disintegrated and resulted in the same relative magnitude and direction for the vectors in Figure 11. Firstly, $\alpha_2$ may have been emitted first, leaving $\text{He}^5$ with an excitation of 4.09 Mev. The break-up of $\text{He}^5$ would have occurred at an angle $\omega$ of $29^\circ$ to the direction of recoil. Secondly, $\text{Be}^9$ may have disintegrated by the emission of a neutron, leaving $\text{Be}^8$ with an excitation of 14.7 Mev. The break-up of $\text{Be}^8$ would have occurred at an angle $\phi$ of $51^\circ$ to the direction of recoil. Thirdly, reaction (iii) may have occurred where $\text{Be}^9$ would have broken up into three particles. The study of a single disintegration leads to no information as to which way $\text{Be}^9$ has decayed. The fact that reactions (i) and (ii) do occur is deduced from the energy distribution of the particles which is obtained from the observation of a large number of disintegrations.

Let us assume that reaction (i) takes place. The energy $E_1$ of $\alpha_1$ (31) can be shown to be related to the excitation of $\text{He}^5$, $\text{Ex}(\text{He}^5)$, by the equation

$$E_1 = a_1 - a_2 \cdot \text{Ex}(\text{He}^5) \quad (iv)$$

(31) The particle $\alpha_1$ is that emitted by $\text{Be}^9$ and $\alpha_2$ is that arising from the break-up of $\text{He}^5$. This convention will be adhered to throughout the following discussion.
and the energy $E_2$ of $\alpha_2$ can be shown to be related to $E_1$ and $\Theta$ by the equation:

$$E_2 = b_1 + b_2 \cdot E_1 + b_3 \sqrt{b_4 \cdot E_1 - E_1^2} \cdot \cos \Theta,$$

where the $a$'s and $b$'s are constants which depend only on the energy released by the reaction and the energy of the incident deuteron.

Equation (iv) indicates that the energy distribution of $\alpha_1$ is directly related to the probability for the formation of He$^5$ with a given excitation. A group with a well defined energy has been observed (30) in the energy distribution of the alpha-particles arising from the deuteron bombardment of Li$^7$. This group could only have been due to the two-body break-up of Be$^9$ into He$^4$ and He$^5$ with a preferred value for $E_x(He^5)$, and it provided direct evidence for the occurrence of reaction (i). The observed energy of the group corresponds to the formation of He$^5$ with an excitation energy of 0.95 Mev above $n + He^4$. This was the same energy as that observed for the lowest state in He$^5$ in the scattering of neutrons by He$^4$.

From equation (v) it can be seen that $E_2$ depends only on $E_1$ and $\Theta$; that is, for a given $E_1$, there is a range of values for $E_2$ corresponding to all values of $\Theta$ between $0^\circ$ and $180^\circ$. It was pointed out by French and Treacy (11) that the angular correlation function, which relates the break-up of He$^5$ with the emission of $\alpha_1$, is identical in form to the energy distribution of $\alpha_2$ except
for a constant factor. Thus, if an $\alpha_1$ could be distinguished from an $\alpha_2$, the relative probability for the formation of He$^5$ with a given excitation and the angular correlation could both be determined from the energy distributions directly. In fact the actual alpha-particle energy distribution contains both $\alpha_1$ and $\alpha_2$, and their individual energy distributions are inseparable.

There is a larger proportion of $\alpha_1$ than $\alpha_2$ at the energy of the group due to the formation of He$^5$ in its ground state. In this experiment the energy distribution of one of the alpha particles was observed for a particular energy of the other. If this particular energy for one of the particles was chosen as that corresponding to the prominent $\alpha_1$ group, then the energy distribution observed in coincidence was largely due to $\alpha_2$, and was therefore an approximate form for the angular correlation function. The information obtained in this way on the angular correlation function enabled a comparison to be made between the formation of He$^5$ as a function of Ex(He$^5$) by reaction (i), and the formation of He$^5$ by the scattering of neutrons by He$^4$.

II (c) THE EXPERIMENTAL TECHNIQUE

The decay of the compound nucleus state in Be$^9$ yields two alpha-particles and a neutron. If one of the two alpha-particles is observed in a detector which narrowly defines the energy and direction of observation,
Figure 12. The target chamber and counter arrangement for the observations on the Li$^7 + d$ reaction.
the path of the second will lie within a cone whose axis is collinear with the direction of the first. (The effect of the motion of the centre of mass is neglected). The semi-angle of the cone is defined by the energy of the first particle. In the present experiment the energy and direction of observation of one of the two particles was fixed and the energy distribution of the second was measured in a detector with a wide angle of acceptance. The maximum semi-angle of the cone for these observations was $25^\circ$, and the second particle was directed away from the first.

A diagram of the target chamber indicating the position of the counters in relation to the target is shown in Figure 12. A peaked proportional counter (Counter I) was used to select the energy and direction of one of the particles. The wide-angled proportional counter (Counter II) which was described in Section I (d), was used to measure the energy of alpha-particles detected in coincidence with alpha-particles in counter I. Due to the motion of the centre of mass the two detectors were not directly in line; counter I was placed to observe alpha-particles at $81^\circ$ to the deuteron beam, so that the axis of the cone which defined the region of emission of the associated alpha-particles was symmetrically placed with respect to counter II.

A peaked proportional counter employs the increase in the density of ionisation at the end of an alpha-
particle's track. If a particle comes to rest in the counter the resulting pulse can be selected in the presence of smaller pulses due to particles which have passed right through. Counter I consisted of a short cylinder with a central anode wire. Alpha-particles entered through an aperture which subtended a cone of semi-angle $2^\circ$ at the target, and passed through the counter parallel to the anode. The gas filling consisted of 20 cm. Hg. of argon, and at this pressure the length of the sensitive region was equivalent to 2.5 mm. of air. Before entering the counter, the alpha-particles passed through an air absorption cell, D, which had thin mica windows at each end. One of the windows, $W_1$, is shown in Figure 12. An anode potential of 720 volts was used, and the counter pulses were amplified with equal rise and clipping time constants of $0.15 \mu$ sec. A discriminator at the output of the amplifier was adjusted so that only those particles which ended their range in the counter were recorded. This range was varied by changing the pressure in the air absorption cell. The absorption cell pressures were recorded at which alpha-particles from the reactions $\text{Li}^7 (p\alpha)\text{He}^4$ and $\text{Li}^6(d\alpha)\text{He}^4$ were observed. The energies and ranges of these particles were known, and from these two calibration points it was found that the total air equivalent of counter and windows at zero pressure was 5.5 cm. and that the length of the air cell was 14.6 cm.
The natural width of the groups was neglected and, on the assumption that the resolution of the counter was Gaussian in shape, the standard deviation was found to be 0.18 Mev for 9.0 Mev alpha-particles.

The full counter II aperture of ±60° was used for the present observations. The window was constructed by attaching aluminium foil to a perforated phosphor-bronze disc, 4.5 in. in diameter, with a dilute solution of Glyptal in amyl acetate. The disc was 0.025 in. thick, and had a symmetrical array of holes 0.078 in. in diameter drilled through it at 0.188 in. centres. The holes were centrally placed within an area 2.75 in. in diameter. The thickness of the aluminium foil was equivalent to 1.0 cm. of air. The space between the window and the sensitive region of the counter was equivalent to 0.5 cm. of air. This dead space and the foil together resulted in a total window thickness equivalent to 1.5 cm. of air. Due to the presence of the disc which supported the foil only 16 per cent of the alpha-particles reaching the window passed through it.

The counter was filled with argon to a pressure of 38 cm. Hg. and operated with an anode potential of 900 volts. Pulses from the counter were amplified with rise and clipping time constants of 0.32 μsec. and 3.2 μsec. respectively. The output pulses from the amplifier were recorded by a pulse height analyser (32)

(32) The pulse height analyser is described in Appendix B.
Figure 13. A block diagram of the electronic circuits used in recording coincidences between alpha-particles from the Li\(^7\) + d reaction.
only when particles were observed in both counters simultaneously.

A block diagram of the electronic circuits which were used in the experiment is shown in Figure 13. In the counter I channel, a blocking oscillator was triggered by the output from the discriminator and generated a negative pulse $2.25 \mu \text{sec.}$ long. In the counter II channel, a trigger circuit was used which was sensitive to all pulses greater than 3 volts, and this circuit generated negative pulses $1.20 \mu \text{sec.}$ long by means of a shorted delay line. A coincidence occurred when these two negative pulses overlapped in time. Thus the total resolving time was $3.45 \mu \text{sec.}$ A delay of $0.5 \mu \text{sec.}$ was inserted in the counter I channel to correct for the longer electron collection times in counter II. A check on the number of random events was obtained by using pulses from the counter I channel which had been delayed by $5.2 \mu \text{sec.}$, with pulses from the counter II channel in a second coincidence circuit. When a normal coincidence occurred the proportional pulses from counter II were allowed through a linear gate to the pulse height analyser. The linear gate was operated by a $10 \mu \text{sec.}$ pulse from the coincidence circuit. Random coincidence pulse height spectra were obtained by using artificially generated pulses in place of the output from counter I. The contribution to each pulse height spectrum due to random events was calculated from the recorded numbers of total and random coincidences.
The alpha-particles from the reaction $\text{Li}^7(p\alpha)\text{He}^4$ were observed in counter II in order to calibrate the energy scale of the pulse height analyser. A broad distribution resulted due to the wide range of angles with which the particles could traverse the window. In order to obtain a well defined group the pressure in the air cell was adjusted so that counter I would detect one of the alpha-particles, and the calibration was then achieved by means of a coincidence spectrum. Under these conditions, the angle of azimuth with respect to counter I at which the second particle traversed the window on counter II was constant and could be calculated. The standard deviation for the observed group was 0.37 Mev. The gas gain of counter II drifted by 4 per cent during the time required to record a pulse height spectrum from the $\text{Li}^7(d\alpha)\text{He}^5$ reaction. To correct for this drift a calibration spectrum was recorded before and after each run and the mean taken as the true calibration for that run.

The target, T, was made by evaporating lithium aluminium hydride onto an aluminium foil. The thickness of the foil was equivalent to 2 mm. of air. The alpha-particles detected in counter I were observed from the back of the target with little loss in energy. The thickness of the lithium aluminium hydride deposit was measured by observing the width of the 0.44 Mev. ($p\delta$) resonance in $\text{Li}^7$, and was found to be equivalent to
Figure 14. The distribution of alpha-particles from the Li$^7 + d$ reaction as observed by counter I at a deuteron energy of 0.9 Mev.
1 mm. of air. The plane of the target was set at 25° to
the beam. An elliptical aperture, S. 0.13. in. by 0.26 in.,
collimated the beam so that each counter saw an
approximately circular area of the target surface under
bombardment.

II (d) THE EXPERIMENTAL RESULTS

The energy distribution of the alpha-particles from
the reaction Li⁷ (dα)He⁵ was measured at a deuteron
energy of 0.9 Mev by using counter I. This distribution
is shown in Figure 14 where a smooth curve has been
drawn through the experimental points. The group
centred about 11.4 cm. Hg. was due to the emission of α₁
with an energy of 8.25 Mev leaving He⁵ with an excitation
of 0.95 Mev above n + He⁴. At 0cm. Hg. the energy of the
alpha-particles was 6.78 Mev and an α₁ emitted with
this energy would have left He⁵ at an excitation of 2.70
Mev above the ground state.

The neutron yield from the deuteron bombardment
of Li⁷ exhibits a resonance at a deuteron energy of
0.68 Mev and with a width of 0.25 Mev. The alpha-
particle energy distributions were also recorded at
deuteron energies of 0.3, 0.5, and 0.7 Mev. However
there was no evidence for a change in shape of the
distributions for the different bombarding energies.
Only alpha-particles with energies greater than 6.78
Mev were observed. No accurate measurement of the
deuteron beam current was possible with the existing
arrangement so a check on whether the total yield of
Figure 15. The pulse height distribution of alpha-particles detected in counter II in coincidence with alpha-particles of 8.20 Mev detected in counter I.
Figure 16. The pulse height distribution of alpha-particles detected in counter II in coincidence with alpha-particles of 6.78 Mev detected in counter I.
alpha-particles followed the resonance was not made.

Two energy distributions of the alpha-particles detected in counter II were measured at a deuteron energy of 0.9 Mev. The first was observed in coincidence with 8.20 Mev alpha-particles in counter I and the second with 6.78 Mev alpha-particles. The results are shown in Figure 15 and Figure 16 respectively. The curves drawn on these Figures are based on calculations which will be described later. The experimental points have been corrected for random coincidences and plotted with their probable errors. Both of the distributions were recorded the same number of disintegrations of Be$^9$ to within 5 per cent, as determined from the integrated beam current and also from the total number of particles detected in counter II. Each distribution is the sum of ten separate runs which have been normalised to a common energy scale. The time required for each run was approximately 30 minutes. The maximum beam current was limited to 0.1 $\mu$amp by the permissible counting rate in counter II. Due to the wide angle of acceptance, a large number of particles were detected in this counter, and the counting rate had to be kept low to avoid pulse pile-up.

A third energy distribution was recorded at a deuteron energy of 0.7 Mev under conditions corresponding to the formation of the ground state of He$^5$. This was found to be similar in shape to that obtained at 0.9 Mev, Figure 15.
II (e) THE INTERPRETATION OF THE EXPERIMENTAL RESULTS

The observed pulse height spectra represent energy distributions of particles detected in counter II. Each of these particles passed through the counter II window at a certain angle, and lost a corresponding fraction of its initial energy. Thus, the shape and energy of the distributions were altered by the presence of a window of finite thickness. With a minimum window thickness, \( d \), a given particle traversed a thickness \( d \cdot \sec \gamma \), where \( \gamma \) was the angle between the path of the particle and the normal to the window. The position of counter I was such that the axis of the cone containing the path of the particle detected in counter II was normal to the window. Referring to Figure 11, if \( \alpha_1 \) is assumed to have been detected in counter I, then the angle \( \gamma \) is that angle marked as such on the diagram. The effect of the centre of mass motion on \( \alpha_2 \) is neglected.

Each particle detected in counter II was recorded when in coincidence with the detection of another particle of known energy in counter I. If the initial energy of particles detected in counter II had also been known, then the angle \( \theta \) was defined by equation \( (v) \). It can be shown that

\[
\tan \gamma = \frac{\sin \theta}{\beta + \cos \theta} \quad (vi)
\]

where

\[
\beta = \frac{\text{velocity of } \text{He}^5 \text{ in the system with Be}^9 \text{ at rest}}{\text{velocity of } \alpha_2 \text{ in the system with He}^5 \text{ at rest}}
\]
Hence the angle $\theta$ could also be calculated when $E_1$ and $E_2$ were known. The energy lost by the particle was obtained from the range-energy relation.

There were two effects which distorted the shape of the distributions. Firstly, the angle $\theta$ was a function of particle energy, and changed from a maximum value at the centre of the distributions to zero at the high and low energy limits. Secondly, the energy lost by an alpha-particle in passing through a given thickness of material is a function of the initial energy of the particle. It can be shown that if $N(E_i)$ was the number of particles with initial energies between $E_i$ and $E_i + dE$, $N(E)$ was the number of particles observed with energies between $E$ and $E + dE$ and $\Delta(E_i)$ was the energy lost in the window by a particle of initial energy $E_i$, then

$$N(E) = N(E_i) \frac{1}{1 - \frac{d\Delta(E_i)}{dE_i}}.$$  \hspace{1cm} (vii)

The changes in the shape and energy of the distributions could be calculated by using equations (v), (vi) and (vii), if the initial energy distributions were known.

It may have been possible to have worked back from the observed to the initial distributions by a series of approximations. However, the initial energy distributions were calculated by making certain assumptions regarding reaction (i), and these were then compared.
with the experimental results. It was assumed that the \( \text{He}^5 \) states involved in reaction (i) were identical to those involved in the scattering of neutrons in \( \text{He}^4 \), that only a single compound nucleus level in \( \text{Be}^9 \) was involved, and that the Wigner and Eisenbud (33) resonance theory applied to this reaction.

The probability for the decay of \( \text{Be}^9 \) as a function of \( E_x(\text{He}^5) \)

The observed intensity for the formation of \( \text{He}^5 \) at a given \( E_x(\text{He}^5) \) in reaction (i) would be expected to differ from that observed in the scattering of neutrons in \( \text{He}^4 \), since a different incoming 'channel' is involved. Once \( \text{He}^5 \) is formed with a given excitation energy, the compound nucleus theory states that the mode of decay will be independent of the method of formation. The relation between the formation of \( \text{He}^5 \) by reaction (i) and by the scattering of neutrons in \( \text{He}^4 \) was obtained in the following manner.

The total scattering cross section for neutrons in \( \text{He}^4 \), where only one state of \( \text{He}^5 \) is considered, is given by

\[
\sigma_{n\alpha} = \frac{1}{k_n} \cdot \frac{(2J+1)}{(2S+1)(2L+i)} \cdot \frac{\sigma_n}{D(\text{He}^5)} \tag{viii}
\]

where \( k_n \) is the wave number associated with the relative

velocity in the n + He$_4$ system; J, s and l refer to
the total spin of He$_5$, the incoming channel spin and
the orbital angular momentum of the n + He$_4$ system
respectively; $\Gamma_n$ is the partial width for the transition
He$_5$ → n + He$_4$ and is defined by $\Gamma_n = \frac{K}{\tau_n}$,
where $\tau_n$ is the lifetime of the He$_5$ state against
decay into a neutron and He$_4$; and D(He$_5$) is the
resonance denominator associated with the particular
He$_5$ state. This cross section is shown for the P$_\frac{3}{2}$ and P$_\frac{1}{2}$
states, separately, as the 'a' curves in Figure 10.

We consider a limiting case where He$_5$ is formed in
a narrow stable state. The cross section for the
Li$_7$ (d α)He$_5$ reaction is then given by

$$\sigma = \frac{k_d^2}{(2s'+1)(2l'+1)} \cdot \frac{\Gamma_d}{\Gamma_d} \cdot \frac{\Gamma_f}{\Gamma_f} \cdot \frac{1}{D(\text{Be}_9)^2}$$

where $k_d$ is the wave number associated with the relative
velocity in the d + Li$_7$ system; J', s' and l' refer to
the total spin of Be$_9$, the incoming channel spin and
the orbital angular momentum of the d + Li$_7$ system
respectively; $\Gamma_d$ and $\Gamma_f$ are the partial widths for
the transitions Be$_9$ → Li$_7$ + d and Be$_9$ → He$_4$ + He$_5$
respectively; and D(Be$_9$) is the resonance denominator
associated with the compound nucleus state in Be$_9$.

If the lifetime of He$_5$ is now shortened, and thus the
level width broadened, the probability for the decay
of He$_5$ is unity but the choice of Ex(He$_5$) is determined
by \( \sqrt{\alpha} \), \( \sqrt{n} \) and \( D(\text{He}^5) \). The dependence of \( \sigma_d \alpha \) on \( \text{Ex(He}^5) \) must be written as

\[
\frac{d\sigma_d\alpha}{d\text{Ex(He}^5)} = \frac{1}{k_d^2} \frac{(2S'+1)}{(2S'+1)(2L'+1)} \frac{12\sqrt{\alpha}}{D(\text{Be}^9)^2} \frac{M \sqrt{n}}{D(\text{He}^5)^2}
\]

where \( M \) is a normalising factor defined by

\[
\int \frac{d\sigma_d\alpha}{d\text{Ex(He}^5)} \cdot d\text{Ex(He}^5) = \sigma_d\alpha
\]

in which the integration is performed for all possible \( \text{Ex(He}^5) \). The resonance denominator for \( \text{He}^5 \) is given by

\[
D(\text{He}^5)^2 = (E - E_r(\text{Ex(He}^5)))^2 + \frac{1}{4} \Gamma^2
\]

where \( \Gamma \) is the total width for the decay of \( \text{He}^5 \), and is in this case equal to \( \sqrt{n} \). By taking \( \sqrt{\alpha} \) as constant, a simple integration leads to the result that \( M = \frac{1}{2\pi} \).

By re-arranging the terms in equation (x), it can be written in the form

\[
\frac{d\sigma_d\alpha}{d\text{Ex(He}^5)} = \frac{1}{k_d^2} \frac{(2S'+1)}{(2S'+1)(2L'+1)} \frac{1}{D(\text{He}^5)^2} \frac{12\sqrt{\alpha}}{D(\text{Be}^9)^2} \frac{M \sqrt{n}}{(2S'+1)(2L'+1)}
\]

Since the observations in the present case were made at a fixed bombarding energy, the term \( \frac{1}{k_d^2} \frac{(2S'+1)}{(2S'+1)(2L'+1)} \frac{12\sqrt{\alpha}}{D(\text{Be}^9)^2} \frac{M \sqrt{n}}{(2S'+1)(2L'+1)} \) is a constant. Thus the probability for the decay of \( \text{Be}^9 \) as a function of \( \text{Ex(He}^5) \) is given by

\[
P[\text{Ex(He}^5)] = \sigma_n \alpha \cdot \frac{\sqrt{\alpha}}{\sqrt{n}} \cdot \frac{k_d^2}{k_n} \cdot \frac{(2S'+1)(2L'+1)}{(2S'+1)}
\]
The partial widths, $\Gamma$, can be written as the product of two factors

$$
\Gamma = \left\langle \frac{2k}{F_{e}^{2} + G_{e}^{2}} \cdot \gamma_{e}^{2} \right\rangle
$$

(xii)

The phase factors have been neglected in (xii) since only the total cross section is considered here. The first half of (xii), $\frac{2k}{F_{e}^{2} + G_{e}^{2}}$, defines the barrier penetrability and can be calculated by using the tables prepared by Bloch et al. (34). The term $\gamma_{e}^{2}$ is the reduced width for the transition and is independent of energy.

The partial width $\Gamma_{l}$ only involves neutrons with $l = 1$. There is however a different value of $\gamma^{2}$ for each of the He$^{5}$ states, P$_{3}^{2}$ and P$_{1}^{2}$. Adair (28) obtained the best fit to the neutron scattering results when $\gamma^{2}(P_{3}^{2}) = \gamma^{2}(P_{1}^{2}) = 17.6 \times 10^{-13}$ Mev. The analysis of all the available experimental results on neutron and proton scattering in He$^{4}$ by Dodder and Gammel (35) required that $\gamma^{2}(P_{1}^{2}) = 85 \times 10^{-13}$ Mev. The ratio $\frac{\gamma^{2}(P_{1}^{2})}{\gamma^{2}(P_{3}^{2})}$ will be referred to again in the discussion on the experimental results.

---


In order to calculate $I_2$, it was necessary to know the spin of the intermediate state in Be$^9$. A knowledge of this spin was obtained from the angular correlation between $\alpha_1$ and $\alpha_2$ in the following way.

The total spin of the intermediate state in Be$^9$

The known spins and parities of the states involved in the reaction Li$^7(d,\alpha)$He$^5$ were

<table>
<thead>
<tr>
<th>nucleus</th>
<th>spin</th>
<th>parity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li$^7$</td>
<td>$3/2$</td>
<td>$-$</td>
</tr>
<tr>
<td>d</td>
<td>$1$</td>
<td>$+$</td>
</tr>
<tr>
<td>He$^4$</td>
<td>$0$</td>
<td>$+$</td>
</tr>
<tr>
<td>He$^5$</td>
<td>$3/2$, $1/2$</td>
<td>$-$</td>
</tr>
<tr>
<td>n</td>
<td>$1/2$</td>
<td>$+$</td>
</tr>
<tr>
<td>He$^4$</td>
<td>$0$</td>
<td>$+$</td>
</tr>
</tbody>
</table>

The angular distribution of $\alpha_1$ was known to be isotropic with respect to the deuteron beam (36). This isotropy was taken as indicating the interaction of s-wave deuterons only. (There was also the possibility that if p-wave deuterons were involved there was a chance cancellation of terms in the angular distribution). Thus the possible values for the spin and parity of the Be$^9$ state were $1/2^-, 3/2^-$ and $5/2^-$, and the transition Be$^9 \rightarrow$ He$^4 +$ He$^5$ could have occurred with 0, 2 or 4 units of angular momentum.

(36) See Section III.
momentum in the formation of the $P_{\frac{3}{2}}$ state of $\text{He}_5$, and with 0 or 2 units in the formation of the $P_{\frac{1}{2}}$ state of $\text{He}_5$. With the assumption that only a single state of $\text{Be}_9$ was involved, there still remained the choice for the spin of that state from the three possibilities.

The calculation of angular correlations in nuclear reactions is now well understood, and the notation of Sharp et al. (37) has been adopted here. The angular correlation for a two stage process, particle in - particle out, defined by the quantum numbers $l_1, s_1, j_1, l_2, s_2$ is given by

$$W_{rr'}(\theta) = \sum_{k} (-1)^{s_1-s_2} Z(l_1, j_1, j_1', s_1, k) Z(l_2, j_2, j_2', s_2, k) P_k(\cos \theta).$$

(xiii)

The subscripts $r, r'$ refer to the possible intermediate states. The $Z$ transformation coefficients are tabulated (37) and $P_k \cos \theta$ is the Legendre polynomial of order $k$.

The $W_{rr'}(\theta)$ are related by

$$W(\theta) = \sum_{rr'} W_{rr'}(\theta) S_r^* S_{r'},$$

(xiv)

where $S_r$ and $S_{r'}$ are angle independent, but energy dependent, matrix elements defined by

$$S_r^* = \rho (1) \cdot \rho (2) = \int_0^{\frac{1}{2}} e^{i \xi(t)} (2l_1 + 1)^{\frac{1}{2}} \cdot \rho (2).$$

(xv)

The phase angle \( \theta_e(t) \) can be obtained from the tables of Coulomb functions tabulated by Bloch et al. The matrix element \( \beta(2) \) refers to the second stage and is of no interest in the present calculations since there is only one value of \( l_2 \) in the transition \( \text{He}^5 \rightarrow n + \text{He}^4 \).

The Li \(^7\)(d \( \alpha \))He \(^5\) reaction is a three stage process, but in the present experiment only the angular correlation between the second and third stages, that is, between \( \alpha_1 \) and \( \alpha_2 \), was observed. Thus the required correlation formula was that for a two stage process involving a particle out - particle out sequence. The form of the correlation for a similar sequence involving radiative transitions (38), gamma out - gamma out, shows that the summation again occurs over the possible intermediate states. From this it was inferred that equation (xiii) was applicable in the present case with the following notation:

\[
\text{Be}^9 \rightarrow \text{He}^4 + \text{He}^5 \rightarrow (\text{He}^4) + \text{He}^4 + n
\]

where \( s_1 \) had one of the values \( \frac{1}{2} \), \( \frac{3}{2} \) or \( \frac{5}{2} \); \( j \) was equal to either \( \frac{3}{2} \) or \( \frac{1}{2} \) - corresponding to the \( P_{3/2} \) and \( P_{1/2} \) states of \( \text{He}^5 \); and \( s_2 \) was equal to \( \frac{1}{2} \). By using equations (xiii) and (xiv) the following correlations were obtained:

\[ j = \frac{1}{2} - \quad s_1 = \frac{1}{2} - \quad \frac{3}{2} - \quad \text{or} \quad \frac{5}{2} - \quad : \quad W(\theta) = \text{const.} \]

\[ j = \frac{3}{2} - \]

\[ s_1 = \frac{1}{2} - \quad W(\theta) = 1 + 3 \cos^2 \theta \]

\[ s_1 = \frac{3}{2} - \quad W(\theta) = |S_0|^2 + |S_2|^2 + |S_0 S_2|^2 (3 \cos^2 \theta - 1) \]

\[ s_1 = \frac{5}{2} - \quad W(\theta) = \left\{ 38 |S_2|^2 - 8 \sqrt{56} |S_2 S_4| + 18 |S_4|^2 \right\} \]

\[ + \left\{ -30 |S_2|^2 + 24 \sqrt{6} |S_2 S_4| + 30 |S_4|^2 \right\} \cos^2 \theta. \]

It was expected that a comparison of these calculated correlations with the experimental results would indicate the correct assignment for the spin of the excited state in Be⁹.

It was pointed out in Section II(b) that the energy distribution observed at a counter 1 energy of 8.2 Mev was an approximate form for the angular correlation function between \( \alpha_1 \) and \( \alpha_2 \). This energy distribution is shown in Figure 15, and it corresponds to the form

\[ W(\theta) = 1 + A \sin^2 \theta \quad \text{where} \quad A > 10. \]

This could not be fitted by \( j = \frac{3}{2} - \), \( s_1 = \frac{1}{2} - \).

The calculated correlations for \( s_1 = \frac{3}{2} - \) and \( \frac{5}{2} - \) depend for their exact form on the ratio \( \frac{S_r}{S_r'} \). The experimental result was fitted by the use of equation (xv) and by calculating the maximum possible value.
for A consistent with real reduced widths. The radius of interaction for the $\text{Be}^9 \rightarrow \text{He}_4 + \text{He}_5$ transition was taken as $r = 1.3 \times 10^{-13} (4^{3} + 5^{3})$ cm. The phase angles, $\delta$, were obtained from Bloch et al., and the best fits to the experimental result were found to be

$$W(\theta) = 1 + 2.0 \sin^2 \theta, \quad \text{for } s_1 = \frac{3}{2}^-,$$

and

$$W(\theta) = 1 + 3.5 \sin^2 \theta, \quad \text{for } s_1 = \frac{5}{2}^-.$$

The calculated energy distributions

The probability for the decay of $\text{Be}^9$ as a function of $E_x(\text{He}_5)$ was calculated from equation (xi) with $s_1 = \frac{5}{2}^-$, and the results are shown as the 'c' curves in Figure 10. The 'b' curves correspond to the results which were published by the author (39) and were calculated by using a different form for equation (xi). The 'c' curves are now believed to be the correct results.

The ratios of the reduced widths $\frac{\gamma_n^+(P_{\pi})}{\gamma_n^+(P_{\pi}, l=2)}$ and $\frac{\gamma_d^+(P_{\pi}, l=2)}{\gamma_d^+(P_{\pi}, l=2)}$ were taken as unity in both cases. In presenting the

(39) A. C. Riviere, Nuclear Physics, 2, 81 (1956).
results, the 'b' and 'c' curves have been normalised to the same height as the maximum cross section of the 'a' curves at 1.0 Mev.

The energy distributions to be expected in the experimental observations were calculated on the basis of the 'b' curves and with the assumptions regarding the reduced widths outlined above. The angular correlation for the $P^{3}_{2}$ state formation was taken as of the form $W(\theta) = \sin^2 \theta$ over the whole range of $E_x(He^5)$ involved. The angular correlation for the formation of the $P^{1}_{2}$ state was isotropic at all energies. The calculated distributions are presented as the full curves on Figures 15 and 16, and those parts of each due only to the detection of $\alpha_1$ in counter II are shown as broken curves. The formation of the $P^{3}_{2}$ state is clearly revealed by the presence of the group at the high energy end of the distribution presented in Figure 16. The relative magnitudes of the two calculated distributions were determined by the kinetics of the break-up of $Be^9$ and by the value of $P[E_x(He^5)]$ for each state of $He^5$ at the two energies chosen for the observation of alpha-particles in counter I. The total area under the full curve in Figure 15 was made equal to the area under a smooth curve drawn through the experimental points. The finite resolution of both counter I and counter II, and the distortion of the distributions due to the window on counter II were taken into account. The centre of
mass motion due to the momentum of the incoming deuteron has been neglected in calculating the particle energies.

Although the calculated distributions were based on the incorrect 'b' curves, the use of the correct 'c' curves produces a negligible change in the results. The loss in intensity for the $P_{3/2}^2$ state at the higher excitation energies was matched by the increase in the intensity of the $P_{1/2}^2$ state. The $P_{1/2}^2$ state has a negligible influence on the distribution shown in Figure 15, but is required to explain the results shown in Figure 16.

The group at the low energy end of each spectrum was spurious and came about in the following way:- A small portion of the gating pulse from the coincidence circuit appeared at the output of the linear gate so that all smaller pulses from counter II were recorded as if of the same height as the spurious signal. The 'bumps' on the calculated curves represent the expected magnitude of this effect and were obtained from the known number of low energy particles in the calculated distributions. The discrepancy between the observed peak and expected 'bump' in Figure 15 was probably due to a higher proportion of low energy particles than expected.

There is a discrepancy of some 6 per cent in energy between the observed and calculated distributions. Each observed distribution was the sum of ten separate runs which were normalised to a standard energy scale. The error in making a number of such corrections for each
distribution could account for the discrepancy in energy.

If Be$^9$ had disintegrated through reaction (ii), the energies $E_1$ and $E_2$ of the alpha-particles and the excitation energy of Be$^8$, $\text{Ex}(\text{Be}^8)$, were related by

$$E_1 + E_2 = c_1 + c_2 \cdot \text{Ex}(\text{Be}^8),$$

(xvii)

where $c_1$ and $c_2$ were constants which depended only on the total energy released from the break-up of Be$^9$ and on the energy of the incident deuterons. Two neutron groups have been observed (40) which could only be due to the two-body break-up of Be$^9$ into a neutron and Be$^8$ with preferred values for $\text{Ex}(\text{Be}^8)$. The two groups corresponded to the ground state and 3 Mev level in Be$^8$. Alpha-particles from all $\text{Ex}(\text{Be}^8)$ between 9.5 Mev and 15.7 Mev would have been observed in the present energy distributions.

Since the spurious low energy groups appeared at the same energy in each of the measured distributions, they could not have been due to the formation of a narrow level in Be$^8$. Break-up of Be$^9$ through reaction (iii) would result in alpha-particles with continuous energy distributions. A broad level in Be$^8$ and particles from reaction (iii) could both have contributed to the observed energy distributions in the region where the $P_{1/2}$ state was used to fit the results. Physically, the separation of the break-up of Be$^9$ into three distinct channels (i), (ii) and (iii) in this region of very short lifetimes for the states is open to doubt, but this has

been assumed to be possible in the present calculations.

II (f) CONCLUSION

The mean deviation from the calculated curves of all the experimental points is approximately 20 per cent. If allowances are made for the discrepancy in the energy scales, this figure would be reduced to 10 per cent. Despite the uncertainty in energy, the overall agreement between the observed and calculated distributions indicates that the formation He$^5$ through reaction (i) can be interpreted in terms of the neutron scattering data in He$^4$, but leads to no new information.

The formation of He$^5$ has also been studied in the reactions T(tn)He$^5$ (41), T(He$^3$ p)He$^5$ (42), He$^4$(dp)He$^5$ (43), Li$^6$(nd)He$^5$ (44), Li$^7$(nt) He$^5$ (44) and Li$^6$(d He$^3$) He$^5$ (45). In all cases except the first the results are consistent with the neutron scattering experiments and lead to no new information. In the reaction T(tn)He$^5$ the P$_3$ state of He$^5$ appears to be split due to the observation of two close neutron groups, but the statistics were not good.

It is concluded that the decay of Be$^9$ through reactions (ii) and (iii) contributed less than one tenth of the disintegrations observed in the present experiment.

(41) W. T. Leland and H. M. Agnew, Phys. Rev., 82, 559 (1951)
III. THE ANGULAR DISTRIBUTION OF ALPHA-PARTICLES FROM \( \text{Li}^7(d\alpha)\text{He}^5 \)

(a) INTRODUCTION

In section II measurements were described which were made on the relationship between the two alpha-particles emitted in the reaction \( \text{Li}^7(d\alpha)\text{He}^5 \). The formation of \( \text{He}^5 \) by this reaction was compared with its formation by the scattering of neutrons in \( \text{He}^4 \). For the interpretation of the results use was made of the fact that the angular distribution of the alpha-particles contributing to the prominent group in the energy spectrum was isotropic with respect to the incoming deuteron beam. This angular distribution had been measured previously \((46)\) at a bombarding energy of 900 Kev and found to be isotropic to within 10 per cent. The purpose of the present observations was to obtain more accurate information at the same bombarding energy.

III (b) EXPERIMENTAL TECHNIQUE

In order to determine the required angular distribution the number of particles contained in a group at the high energy end of a continuous energy distribution had to be measured as a function of the angle between the direction of observation and the incoming deuteron beam. This required a measurement of the energy distribution at each angle of observation.

A schematic drawing of the equipment is shown in

\((46)\) P.B. Treacy, Ph.D., Thesis, Cambridge University (1951)
Figure 17. The target chamber and counter assembly for the measurement of the angular distribution of the alpha-particles from the reaction Li$^7$(d$\alpha$)He$^5$. 
Figure 17. Two identical proportional counters were mounted within a large cylindrical vacuum chamber with the target, T, at the centre. One counter (Counter I) could be set to observe particles emitted at any angle between 0° and 148° to the beam with an accuracy of ±0.5°. Counter II was fixed in position and detected particles emitted at 150° to the beam. Each counter consisted of a cylindrical cathode 3 in. in diameter with a 0.005 in. diameter tungsten wire supported axially for the anode. Particles entered the counters through thin aluminium windows equivalent to 4.0 cm. of air. The window apertures each subtended a solid angle of 0.0055 steradian at the centre of the target and were tapered at an angle of 10° to reduce small angle scattering of the accepted particles. The location of the windows on the cathode cylinders was such that the anode wire could not be seen from any part of the active target area; the axis of a ray drawn from the centre of the target through the centre of the window passed the anode wire at a distance of 0.375 in. This arrangement was used to avoid the loss of energy by particles in the wire. The gas amplification in a proportional counter occurs within a few wire diameters of the anode. If a particle passes within this region a reduction in the gas amplification occurs for that part of the track. These two effects cause a distortion
Figure 18. The circuit used to enable two pulse height distributions to be recorded simultaneously by the pulse height analyser.
of the observed energy distribution, but are easily avoided by the above method.

The gas filling consisted of a mixture of 97 per cent argon with 3 per cent of nitrogen. The gas pressure in the counters varied from 50 cm. to 100 cm. Hg; the actual pressure was chosen to suit the energy of the particles to be detected and to discriminate against pulses due to protons passing through the counters. For a gas pressure of 100 cm. Hg, an anode potential of 1500 volts was required and correspondingly lower potentials for the lower pressures.

The pulses from each counter were amplified by standard linear amplifiers with rise and clipping time constants of 1.6 μsec. and 10 μsec. respectively. In order to simplify the recording techniques the pulse height spectra from both counters were recorded on the same pulse height analyser (47). The display of both spectra on a single analyser was achieved by the use of a pedestal adding and pulse mixing unit, the circuit of which is shown in Figure 18. Output pulses from the counter II amplifier were increased in height by the addition of a fixed pedestal voltage which was greater than the maximum pulse size to be expected from the counter I amplifier. The two sets of pulses were then mixed and fed into the analyser. In the circuit, valves V2 and V3 formed a trigger circuit with a minimum bias of 5 volts. Valve VI acted as an amplifier and

(47) The pulse height analyser is described in Appendix B.
effectively reduced the bias to 1 volt. Valves V4, V5, V7 and V8 formed a linear gate which was controlled by the negative waveform from V3. Any pulses from the counter II amplifier less than 1 volt high had no effect on the potential of the point A; current was shared between the cathode of V4 and V7, and, until V7 was cut off, no effective change in the potential of A could occur. However, on the appearance of larger pulses the trigger circuit fired and cut off V5; the potential of the point A then rose to the cathode potential of V4. The output pulse from the counter II amplifier then appeared on the right hand grid of V6 with the addition of the potential difference between A and the cathode potential of V4. Under these conditions V4 acted as a cathode follower to drive the point A. The output from the counter I amplifier was applied to the left hand grid of V6 and both sets of pulses appeared on the cathode. The signals appearing on the cathode of V6 were fed to the analyser.

If two particles were detected simultaneously, one in each counter, then only the larger pulse on V6 was recorded. This pulse was in all cases that with the pedestal voltage added to it from the counter II amplifier. With the counting rates used in this experiment no significant errors were introduced by this preference.
A measure of the energy resolution of the detectors was obtained by observing the mono-energetic alpha-particle group from the reaction $\text{Li}^7(p\alpha)\text{He}^4$. The width at half height of the group as recorded by the pulse height analyser was three channels for each counter. This corresponded to a resolution of 10 per cent for particles leaving the target with an energy of 8.9 Mev or entering the counter with an energy of 6.0 Mev.

The targets were made by the electro-deposition of a thin layer of metallic $\text{Li}^7$ from a solution of the metal chloride in pyridine, and the metal was then allowed to oxidise in air. The lithium was deposited over a circle 0.5 in. in diameter. The target backing consisted of nickel foil equivalent in thickness to 2 mm. of air. The orientation of the target with respect to the beam was always such that alpha-particles detected in the counters were emitted at an angle which was less than 55° to the normal to the plane of the foil. The target holder could be rotated about a vertical axis. Provision was made for its withdrawal from the chamber without breaking the vacuum by means of the valve shown schematically in Figure 17. Changes in target thickness due to rotation of the target holder were compensated for by using counter II as a monitor.

The deuteron beam was defined by 0.25 in. diameter apertures S, S before entering the chamber, which ensured that the beam struck the centre of the target.
Figure 19. A typical pulse height analyser spectrum taken for $\theta = 34.5^\circ$. Curve A and curve B are due to the detection of particles in counter I and counter II respectively.
The two apertures, the target and the window on counter I were visually aligned to determine the zero error of the scale used to set the position of counter I. The beam was trapped by the Faraday cage F which was insulated from the chamber so that the target current could be recorded. The quartz window W allowed the beam to be seen when the target was lowered and permitted the visual alignment of beam and chamber.

III (c) EXPERIMENTAL RESULTS

Pulse height spectra from each counter were recorded at a series of angles which were spaced in approximately equal steps of \( \cos \theta \) from \( \theta = 0^\circ \) to \( 148^\circ \). Three runs were recorded and the spectra were repeated where a change was made from observing particles from the front of the target to observing particles from the back. A typical spectrum is shown in Figure 19. Curve A is that part due to the detection of particles in counter I and curve B is due to counter II. A pedestal voltage which was equivalent to 40 channels on the analyser was added to all pulses contributing to curve B. The general shape of each distribution is similar to that shown in Figure 14. The groups appearing at channels 18 and 55 are due to the emission of protons by an unresolved \((d, p)\) reaction. The protons had sufficient range to pass right through the counters.

The variation in yield of the main alpha-particle groups at channels 28 and 62 was deduced as a function
of the angle of observation in the following way:
The velocity of the centre of mass introduced a
variation in the observed energy of the alpha-particles
contributing to curve A as the angle of observation
was changed. Curve B remained constant. In a particular
run a curve B of average size was selected and all other
B curves of that run compared with it by superimposing
the graphs. The ratio \( R \) of the height of each B curve
to the height of the standard curve was recorded. The
A curves were analysed in the following way. Referring
to Figure 19, the extrapolated end point 'a' and the
centre of the peak 'b' were determined by inspection.
The distance \( X \) from the point 'a' to the ordinate at
'b' was measured and an ordinate 'c' drawn at a distance
of \( \frac{X}{2} \) from 'a'. The numerical sum of the numbers
of counts in the channels between 'a' and 'c' was then
used as a measure of the size of the group. This number
was normalised by using the ratio \( R \). These results
were then again normalised in such a way that the
mean of all runs for the angle \( \Theta = 150^\circ \) was unity; here,
\( 148^\circ \) was taken as being sufficiently close to \( 150^\circ \) to
normalise to the \( 148^\circ \) measurement. This method of
analysing the energy distributions is an arbitrary
one, but appeared to offer the least chance of
observer bias.

It can be shown that the centre of mass angle \( \Theta' \)
and the laboratory angle \( \Theta \) are related by the equation
Figure 20. The angular distribution of the alpha-particles from the reaction Li\textsuperscript{7}(d,\alpha)He\textsuperscript{5}; $\theta'$ is the angle between the deuteron beam and the direction of emission in the centre of mass system.
\[ \tan \theta = \frac{\sin \theta'}{\beta + \cos \theta'} \]

where \( \beta = \frac{\text{velocity of centre of mass}}{\text{velocity of particle in centre of mass system}} \)

The solid angle subtended by counter I at the target is a constant with respect to \( \theta \) but varies with respect to \( \theta' \).

We can write

\[ \frac{\Delta \Omega'}{\Delta \Omega}, \text{ solid angle in centre of mass system} \quad \frac{d\theta'}{d\theta} = \frac{d\Omega'}{d\Omega}, \text{ solid angle in laboratory system} \]

By using the relation between \( \theta \) and \( \theta' \) above we have

\[ \frac{d\theta'}{d\theta} = \frac{1 + 2 \beta \cos \theta' + \beta^2}{1 + \beta \cos \theta'} \]

In the present case \( \beta^2 \) and higher powers can be neglected and then we have

\[ \frac{d\theta'}{d\theta} = 1 + \beta \cos \theta' \]

The results were corrected for this variation in solid angle and are shown plotted as a function of \( \cos \theta' \) in Figure 20. A straight line has been drawn parallel to the abscissa to represent an isotropic distribution. The experimental points at the largest angles are seen to lie well below this line. At these angles the energy of the particles detected in counter I was low and the spectra were recorded with an increased gain in the counter I amplifier to spread...
the counts over a larger number of channels. This may have introduced an error. If these two points are ignored then the angular distribution is isotropic to within 2 per cent.

The results of Section II indicate that the intermediate state in Be$^9$ cannot have spin $\frac{1}{2}$. Also, the ground state of He$^5$ has spin $\frac{3}{2}$. Thus, the most likely explanation for the observed isotropy of the angular distribution is that predominantly s-wave deuterons are involved in the formation of the intermediate state in Be$^9$.

Other measurements on $(d,\alpha)$ angular distributions have been made (48, 49, 50) where the observed distributions could not simply be fitted on the basis of compound nucleus formation. It is possible that they could be explained in terms of direct transitions similar to those proposed for the $(d,n)$, $(d,p)$ and $(d,t)$ reactions. Measurements were made in the present experiment at a number of angles between $0^\circ$ and $50^\circ$ to investigate the possibility of direct transitions occurring in the Li$^7$(d,$\alpha$)He$^5$ reaction. However, these observations did not indicate any departure from isotropy to within an accuracy of 10 per cent.


(49) Freemantle, Gibson, Prowse and Rotblat, Phys.Rev., 92, 1268 (1953).

APPENDIX A

THE RANGE-ENERGY RELATION FOR ALPHA-PARTICLES IN ARGON.

Argon has certain properties which make it an ideal gas for use in counters in which particle energies are to be measured. Firstly, the average energy lost by a fast charged particle in forming an ion pair is independent of the particle energy. Hence, the total number of ion pairs formed is directly proportional to the energy lost by the particle in the gas. Secondly, the average energy lost per ion pair is 27.7 ev in comparison with 35.1 ev for hydrogen, 30.2 ev for helium and 36.2 ev for nitrogen, and hence a greater number of ion pairs will be formed in argon for the same expenditure of energy in each gas. Neon, krypton and xenon have similar properties to argon but are not as readily available in the same quantities. These factors have led to the use of argon in the counters employed in the present experiments.

A knowledge of the range-energy relation for argon is of use both in the initial design of a counter to detect particles of a given energy, and in the choice of

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(52) G. Stetter, Z. Physik, 120, 639 (1943).
the operating pressures in an existing counter. The range-energy relation for alpha-particles up to 8 Mev was needed in Section I (e) in order to determine the effect of the anode wires in the wide-angle proportional counter. This information was not available at the time so it was calculated by starting with the range-energy relation in air and assuming that the theory was sufficiently accurate to enable one to obtain a relation between the rate of energy loss in argon and that in air. It was not possible to calculate the absolute rate of energy loss, since at low energies where charge exchange occurs no satisfactory theory has been developed.

When a fast charged particle passes through matter it loses energy by collision with the atomic electrons. These collisions result in either excitation or ionisation of the atoms. If the velocity of the particle is greater than the orbital velocities of the atomic electrons, that is, if

\[ E > \frac{M}{m} E_{el}, \]

where \( E \) is the energy of the incident particle, \( E_{el} \) the ionisation potential of the electrons, and \( M \) and \( m \) the masses of the incident particle and electron respectively,

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\( ^{54} \) The calculations were based on the information in Section I, Part II, Vol. I, Segre, Experimental Nuclear Physics

\( ^{55} \) Only the non-relativistic region need be considered here.
then the rate of energy loss is given by

\[
\frac{\text{d}E}{\text{d}x} = -\frac{\hbar \pi e^4 z^2 NB}{m v^2},
\]

(ii)

where

\[
B = \frac{Z \log_2 mv^2}{I}.
\]

(iii)

\[v\text{ is the velocity and } z e \text{ the charge of the incident particle, } N \text{ the number of atoms per cc., } Z \text{ the nuclear charge and } I \text{ the average excitation potential of the atoms of the absorber. The alpha-particle energies corresponding to the right hand side of equation (i) are 2.95 Mev and 3.95 Mev for the K-shell electrons of nitrogen and oxygen respectively. For argon the corresponding energy is 23.7 Mev for the K-shell and 1.8 Mev for the L-shell. These figures show that equation (ii) is by no means an accurate representation of the rate of energy loss in the present case. Calculations have been made(56) however in the region where (i) does not hold. The term } B \text{ is then replaced by}
\]

\[
B = (Z-1-\frac{1}{2}f) \frac{l_0}{I'} 2mv^2 + B_k,
\]

(iv)

where \(f\) is the total oscillator strength of all optical transitions from the two states in the K-shell into the continuous spectrum, \(I'\) is the average ionisation potential for all electrons outside the K-shell, and \(B_k\) is the stopping number for the K-shell. The values of \(f\) and \(B_k\) were obtained from Table I, p.171, and Figure 1(a),

(56) Pages 170 to 171, ref (54).
Figure 21. The calculated range energy relation for alpha-particles in argon. The curve for air is taken from ref. (57) and the experimental points are from ref. (58).
p. 172, Segre, respectively. The following parameters were adopted in the calculations:

- **argon**
  - \( Z = 18 \)
  - \( f = 1.44 \)
  - \( \gamma' = 151.4 \text{ ev} \)
- **air**
  - \( Z = 7.22 \)
  - \( f = 1.79 \)
  - \( \gamma' = 40.37 \text{ ev} \)

The rate of energy loss for argon was obtained from that for air by the following relation

\[
\frac{dE}{dx} \text{(argon)} = \frac{dE}{dx} \text{(air)} \cdot \frac{B \text{(argon)}}{2B \text{(air)}}
\]

The rate of energy loss in air, \( \frac{dE}{dx} \text{(air)} \) was obtained by differentiating Figure 3, Bethe(57). The calculated values of \( \frac{dE}{dx} \text{(argon)} \) were graphically integrated. The final range-energy relation is shown in Figure 21(a) in conjunction with the corresponding relation for air. Since these calculations were made experimental measurements have been reported(58) of the range of alpha-particles of known energy in argon. Results are shown as circles on Figure 21(b) which is an enlarged section of Figure 21(a).

Although the agreement is not good both the calculated

(57) H.A. Bethe, Rev. Mod. Phys., 22, 213 (1950)
curve and the experimental results indicate a greater range in argon than in air for a particle of given energy. The difference between the calculated and experimental results could be due to the finite size of the steps used in the graphical integration of \( \frac{dE}{dx} \)(argon). Argon has a nuclear charge greater than twice that for air, however due to the monatomic character of argon and the diatomic character of air, the electron density in argon is only slightly greater. This should result in a shorter range in argon, but the average binding energy per electron is much higher than that of air so that the range is slightly longer at these energies, as in fact it has been found to be.

Following is a description of the instrument which includes the reasons for the choice of this particular design, and details of the electronic circuits. It has been included in this thesis as an operator's manual and as a source book for pulse handling circuits.

Pulse height analysis

When a fast charged particle is detected by an argon-filled proportional counter, the output pulse is proportional to the energy expended by the particle in the counter gas. The energy distribution of a beam of such particles entering the counter can be obtained by measuring the pulse height distribution and then

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(99) G.W. Hutchinson and G.G. Scarrott, Phil. Mag., 42, 792 (1951).
APPENDIX B

THE MULTI-CHANNEL PULSE HEIGHT ANALYSER

Introduction

The pulse height analyser which is described in this appendix was constructed and brought into operation by the author during the first year of the Ph.D. course. The analyser was used in carrying out the experiments described in Sections II and III. The design was not original, but was a copy of the analyser constructed at the Cavendish Laboratory, Cambridge(59). Two minor alterations were made to the original design in order to obtain an improvement in performance. The following is a description of the instrument which includes the reasons for the choice of this particular design, and details of the electronic circuits. It has been included in this thesis as an operator's manual and as a source book for pulse handling circuits.

Pulse height analysis

When a fast charged particle is detected by an argon-filled proportional counter, the output pulse is proportional to the energy expended by the particle in the counter gas. The energy distribution of a beam of such particles entering the counter can be obtained by measuring the pulse height distribution and then

(59) G.W. Hutchinson and G.G. Scarrott, Phil. Mag., 42, 792 (1951).
calibrating the energy scale of this distribution by means of particles whose energy is known. Methods for obtaining pulse height distributions have been fully discussed by several authors (60), (61), (62). The simplest method is to use a single discriminator which detects all pulses whose heights are greater than a predetermined bias voltage. The number of pulses detected by the discriminator is recorded for a series of bias voltages taken in equal steps across the range of pulse heights. A graph of number against bias obtained in this way is an integral bias curve, and the pulse height distribution can be obtained from it by differentiation. This method has poor statistical merit since each point on the differential curve is obtained by the subtraction of two larger numbers. The differential distribution can be obtained directly by the use of two discriminators with slightly different biases. Only pulses which trigger the lower discriminator are recorded; pulses which exceed both biases are disallowed by a cancelling circuit. The bias difference is kept constant, and the pulse height distribution is obtained by scanning with the single "channel" over the whole range of biases. This method gives an improvement in


(61) A.B. Van Rennes, Nucleonics, 10, 7, 20; 10, 8, 22; 10, 9, 32; 10, 10, 50 (1952).

statistical merit since the errors are related only to the actual numbers recorded. In both of these methods the pulse height distribution is obtained by making step by step observations across the required range of pulse heights; each observation is related to a monitor count. In general the pulse arrival rate is not constant but varies with time due to accelerator beam current fluctuations. A pulse height analyser with a large number of channels which will analyse the whole range of pulses at the same time is the ideal instrument.

At the time that the construction of a multi-channel analyser was first considered a number of designs were available (59, 60, 63). The analyser described by Johnston (63) consists of a number of discriminator circuits which are so arranged that the bias on each one differs by a channel width from the previous one. The great advantage of this type of analyser is the speed of operation. Only 4 μsec. are required to analyse a pulse. There is the disadvantage that each discriminator bias must be individually adjusted. A large volume of electronics is required since each channel has discriminator, cancelling and scaling circuits. The analyser described by Wilkinson (60) overcomes the disadvantage of individual channel adjustment by using the same circuit element to determine the height of all pulses. Each incoming pulse is used

(63) C. W. Johnston, Nucleonics, 11, 1, 36 (1953).
to generate another whose length is proportional to the height of the original. This time pulse is used to gate an oscillator and the number of cycles allowed gives a measure of the pulse height. A scaling circuit is then used to count the cycles, the final state of which selects the recording register for the corresponding channel. The time required to analyse a pulse is 0.1 sec., which is the time required to operate a mechanical register. This low speed is a disadvantage, but the analyser possesses simplicity and reliability. The instrument described by Hutchinson and Scarrott (59) employs the same principle of voltage-time conversion as the Wilkinson design. The time required to analyse a pulse is reduced to 700 $\mu$ sec. by the use of an electronic memory. The Hutchinson-Scarrott design was considered the most suitable and chosen for construction by the laboratory.

**The Hutchinson-Scarrott analyser**

The conversion of pulse height into an interval of time is achieved by comparing each input pulse with a continuously generated linear sweep waveform. The instant is recorded at which the voltage of the linear sweep is equal to the maximum voltage of the pulse. This instant occurs at a definite time after the start of the sweep "run-down" and this time is characteristic of a given pulse height. A delay line memory is used to store the information on the pulse heights. A pulse transmitted into the delay line reappears after the delay period and is then re-transmitted. Thus, the pulse
Figure 22. The main circuit elements of the pulse height analyser; the arrows indicate direction of flow of information.
is continuously circulated and stored. The pulses in
the memory are synchronised to the linear sweep waveform;
time position in the delay line corresponds to time after
the start of the sweep, and therefore to pulse height.
The channel boundaries are defined by an oscillator which
is turned on during the sweep period. The frequency
stability of an oscillator can be kept at ±0.5 per cent
with a simple circuit using regulated supplies. If the
sweep is linear, then the relative size of each channel
is constant and they are all equal to within 0.5 per cent.
The length and position of the pulses in the memory are
defined by a second oscillator whose frequency is a high
multiple of the channel frequency. This oscillator is
also switched on during the sweep period and is syn-
chronised to the channel oscillator. Since a pulse can
only be considered as there or not there in the memory
the numbering system is in binary form. The actual
pulses present in the memory are indicated on an
oscilloscope. The arrival of pulses to be analysed is
random in time but the linear sweep is a recurrent
waveform, so that each pulse has to be lengthened until
comparison with the linear sweep occurs. All other
pulses which arrive during the waiting time are excluded
from the analyser by a gate circuit. A pulse generator,
an amplifier, bias and limiting circuits complete the
analyser.

A block diagram of the circuit elements is shown in
Figure 23. The amplifier and bias circuits.
Figure 22, and the circuit diagrams are shown in Figures 23 to 31. The power supply circuit is not included as it is relatively conventional.

**The amplifier circuits**

The analyser is designed to accept positive pulses with amplitudes of up to 50 volts, since this is the output level of most conventional pulse amplifiers. A pre-amplifier stage forms the first circuit element, and it has a gain of 4 which raises the pulse height level to a maximum of 200 volts. The pre-amplifier consists of valves V6 and V7 in Figure 23. Negative feedback is employed from the anode of V7 to the cathode of V6 in order to stabilise the gain. The next circuit element is a biased cathode follower stage which is used to remove the lower portion of the pulse height distribution when it is not required. The bias is variable from 0 to 200 volts. The valves V8, V9 and V10 form the cathode follower in which V8 forms the cathode load of V9 and V10. Bias is applied to the grid of V9. With a signal applied, no change occurs in the cathode potential of V9 until its grid has been raised above the grid potential of V10. The use of the constant current generator, V8, in place of a cathode resistor makes the stage gain more nearly unity. With a constant current in V9, the grid to cathode potential does not alter, hence, for that part of the signal above the bias the cathode voltage change is identical to the grid voltage change. A faster response is also obtained with this type
Figure 24. The gate, lower limit and count control circuits.
of circuit for negative going signals.

An amplifier stage of variable gain follows the biased cathode follower, and this is used to expand a portion or all of the pulse height distribution which exceeds the bias. With a suitable combination of amplifier gain and bias, any part of the original distribution can be selected for analysis. The main amplifier, consisting of valves V11, V12, V13 and V14 in Figure 23, is direct coupled throughout and has negative feedback from the anode of V14 to the grid of V11. With very large pulses, V13 may be cut off. To prevent V14 from drawing excessive grid current, V80 and V90 are introduced as a d.c. limiting circuit. The amplifier inverts the positive input pulses to give negative pulses for the analyser and it is capable of handling these linearly up to 250 volts in height.

The gate circuits

The gating circuit is designed to exclude all signals from the comparison circuits after a pulse has been accepted, and to remain closed until the analysis is completed. A pulse is "accepted" when it exceeds the lower limit of 2 volts but does not exceed the upper limit of 200 volts. The gate consists of V15, V16 and V17 in Figure 24. Normally, V15 and V17 operate as a cathode follower with no current flowing in V16. When the gate is closed the current is transferred from V15 to V16, and pulses applied to the grid of V15 then produce no change in the cathode potential.
Figure 25. The upper limit, master trigger pair and pulse lengthener circuits; the dotted line indicates the specially insulated parts of the pulse lengthener circuit.
The signal on the cathode of V15 is passed to the lower limit. This is a trigger circuit, consisting of V21 and V23, with a threshold of 2 volts. When the input exceeds this voltage, a positive pulse is generated at the left hand anode of V21, and is passed to the count control valve V18 in Figure 24 and to the master trigger pair V24 and V26 in Figure 25.

The master trigger pair is a bi-stable circuit, and is triggered into its second state by the lower limit pulse. The change of state produces a positive waveform on the right hand anode of V24 which is passed to the right hand grid of V18. The presence of the lower limit pulse on the left hand grid of V18 prevents the master trigger pair waveform from immediately switching the current in this valve. The lower limit returns to its normal state as soon as the input pulse has fallen to zero. When this occurs the master trigger pair waveform switches the current in V18, which closes the gate. Thus, the gate is not closed until after the input pulse has gone, but then remains closed until the master trigger pair is reset.

The pulse lengthener

The pulse lengthener "holds" the maximum voltage reached by the input pulse until a comparison is made with the linear sweep waveform. The input pulse charges a 100 $\mu F$ condenser through the diode V31. The charge on the condenser corresponds to the peak
voltage of the pulse, and is retained by the condenser after the pulse has gone. Normally this condenser is maintained in a discharged condition by current flowing through V89. When the master trigger pair is switched to its second state, this discharging current is cut off. The control is made via V28, V87 and V29.

For the pulse lengthener to be effective the leakage from the condenser must be small. The linear sweep period is approximately 1300 μsec. The maximum pulse size is 200 volts, and this is the maximum voltage to be retained on the condenser. The maximum number of channels is 120. Thus, in 1300 μsec the potential must fall less than 1.66 volts from 200 volts, and this requires a time constant of 0.144 sec. The storage condenser cannot be made too large as it represents a direct load across the input. (The impedance of a 100 μF condenser is 1600 ohms at 1 mc/s.) Thus, the insulation resistance of the charged plate of the condenser and its associated wiring must be better than $2 \times 10^9$ ohms. The circuit is built on a perspex panel, and an isolation transformer is used to supply the heater of V89, since the normal heater-cathode leakage is of the order of $10^6$ ohms. In the original circuit V31 and V47 were combined in a single envelope as a double triode, type 12AT7. The insulation resistance of this valve was only of the order of $10^8$ ohms. The present circuit employs an EA50 for the charging diode and an EF37 pentode for V47.
The EF37 has a top-cap grid connection with excellent insulation properties. With these modifications no further leakage troubles were experienced with the pulse lengthener.

The cathode follower, V47 and V30, transmits the pulse lengthener potential to the comparison circuits and to the upper limit V22. When the signal voltage is greater than the grid bias on the right hand half of V22, this valve draws current and prevents the master trigger pair from being switched to its second state. This requires a pulse height of over 200 volts. If a pulse is too large, the gate is not closed, and the pulse lengthener condenser not charged.

The height of the input pulse has now been recorded by the pulse lengthener and the gate closed. The next step is the comparison of the pulse lengthener potential and the linear sweep waveform.

**The linear sweep**

The sweep waveform must be a linear relation between voltage and time if channel position is to be proportional to pulse height and if each channel is to be of a standard width. A Miller time base circuit is used to generate the waveform. The Miller valve is V60 in Figure 26. The time constant of the sweep "run-down" is determined by the 1.4 Megohm resistor and potentiometer RV2 in the grid circuit, and the 2500 μF condenser between the anode and grid circuits. The right hand
Figure 26. The linear sweep, channel oscillator and digit oscillator circuits.
half of V59 is introduced in the anode circuit to facilitate the discharge of the condenser and hence speed up the flyback. The starting and finishing voltages of the sweep run-down are defined by the 0 and -200 volt supply lines through the diode connected left hand half of V59 and the left hand half of V61 respectively. It was found that the actual variation of sweep period during operation was of the order of 0.1 per cent, and the variation of the supply lines was of the same order. The sweep waveform from a Miller time base has a slight non-linearity due to the finite grid base of the Miller valve. In the present circuit an antiphase signal is introduced at the top of RV2 from the right hand anode of V59 to correct this non-linearity. The amount of antiphase signal can be controlled by RV3 until a linear waveform is obtained.

The sweep circuit is normally free running with a waiting period which is longer than required. The actual repetition rate is controlled by synchronising pulses from the memory which are applied to the sweep circuit through the trigger valve V88 and cathode follower V85. The period of the sweep run-down is 1200 μsec.

The channel oscillator

The channel oscillator has three possible frequencies of 50 kc/s, 66.6 kc/s and 100 kc/s which can be selected by SW1. These frequencies give 20, 15 and 10 μsec. for
Figure 27. The comparison and channel coincidence circuits.
each channel, and 60, 80 and 120 channels respectively. The oscillator is of conventional design with an LC tuned circuit using iron dust cored coils. The left hand half of V64 forms the oscillator section, and this is cathode coupled to the right hand half. The output from V64 drives a blocking oscillator, V65, which produces a 0.5 μsec pulse at the start of each channel oscillator cycle. These pulses define the channel boundaries in terms of time intervals from the start of the sweep run-down.

The comparison circuit

The comparison circuit is shown in Figure 27. The pulse lengthener potential is applied to the left hand grid of V33, and the linear sweep waveform is applied to the right hand grid. The left hand triode is normally conducting so that the sweep signal produces no change in the anode currents. When a lengthened pulse is applied, the current exchanges either immediately if the signal is greater than the sweep voltage at that instant, or later when the flyback occurs. This first current exchange generates a positive voltage step on the left hand anode of V33 and this fires the trigger circuit V35 and V36. When the sweep run-down potential matches the pulse lengthener potential, the current in V33 is returned to the normal path, a negative voltage step is generated and the trigger circuit is
returned to normal. This trigger circuit generates a positive pulse on the right hand anode of V35, the trailing edge of which corresponds to the instant of comparison. The pulse is transmitted to the coincidence valve V40 via the cathode follower V38.

The recording of slow pulses which are too large is prevented by V39. No positive or negative signal can reach V40 unless V39 has been cut off. This is done by a negative "count now" pulse from the count control valve V18 in Figure 24, which coincides with the closing of the gate. The negative signal applied to V40 from the trigger circuit remains until V39 is released.

Negative channel pulses from the blocking oscillator are applied to the right hand grid of V40. When the next channel pulse arrives after comparison a coincidence occurs and a positive pulse is then generated at the anodes of V40. This positive pulse serves two purposes. Firstly, it is passed to the adding gate and thence to the memory for storage, since this coincidence pulse occurs on the next channel pulse after comparison and occupies a position on the sweep cycle which is related to the input pulse height. Secondly, the pulse is passed to V32 in Figure 25 where it returns the master trigger pair to its normal state. The gate is then opened, the count now pulse removed from V39 and the pulse lengthener condenser discharged.
Figure 28. The memory receiver and transmitter circuits.
The memory

The delay line memory circuit consists of 21.3 feet of hard drawn nickel wire 0.006 in. in diameter. A small coil of 1000 turns is placed at each end with the nickel wire passing through the centre. The transmitter valve, V56 in Figure 28, passes a pulse of current through one of the coils, and magnetostriction of the wire by the magnetic field at the centre of the coil produces a mechanical shock in the wire. This vibration travels down the wire and induces a signal in the second coil. The nickel wire must be magnetised where it passes through this coil. The line is protected by a polythene tube of 3 mm. bore, and the whole is wound into a coil 12 in. in diameter. A loss in intensity of about 60 db occurs in the nickel wire, and an amplifier is used to restore the signals to their original strength. This amplifier consists of valves V41, V42 and V43 in Figure 28. The output signal fires a trigger circuit, V45, which produces pulses of standard size. The small pulses on the cathode of V45 are rectified, integrated and applied as an automatic gain control voltage on the grids of V41 and V42. The standardised pulses are passed to the adding gate and thence to the transmitter for re-circulation.

The digit oscillator

We have seen that each channel occupies a certain interval of time in the memory cycle; for 120 channels this interval is 10 $\mu$-sec long, and is required for
storing the number of counts in that channel. The interval associated with a given channel occurs after the channel oscillator pulse. The maximum number of pulses which can be accommodated in each interval is limited by the speed of the electronic circuits, and a practical figure of one pulse per microsecond is adopted in the analyser. This allows ten pulses per channel and in the binary system the highest number that can be written with ten digits is $2^{10} - 1$ when all places are filled. In the 60 and 80 channel cases the totals are $2^{15} - 1$ and $2^{20} - 1$ respectively. The timing and position of the digit pulses is controlled by a 1 mc/s oscillator which is synchronised to the channel oscillator and only allowed to run during the sweep run-down. The left hand half of V68 is the oscillator valve. The right hand half is switched on each cycle and supplies 0.5 μsec pulses of current to the adding gate. The control from the sweep circuit and synchronisation with the channel oscillator are applied through V67.

**The adding gate**

The binary adding gate accepts pulses from the channel coincidence circuit and from the memory, adds them together and passes the sum to the transmitter. The circuit consists of the valves V49, V50, V51 and V96 in Figure 29. Since the current through the valves is controlled by the 1 mc/s oscillator, the gate can only operate during the synchronised periods. Current
Figure 29. The adding gate circuit.
normally flows through the left hand side of V49 and from there through the right hand side of V50. A pulse coming from the memory is applied to the left hand grids of V50 and V51, and in the absence of further information the current is switched from the right to the left in V50. This sends a pulse through T5 to the transmitter. When a channel coincidence pulse is applied to the right hand grid of V49, the current is switched to V51. If there is no pulse coming from the memory at this time, the current flows through the right hand half of V51, through T5 and thence to the transmitter. In this way the comparison pulse is inserted into the memory.

If there is a pulse from the memory at the instant when a channel coincidence pulse arrives, then the current flows through the left hand half of V51 and a pulse is passed into the 1 \( \mu \text{sec} \) delay line DL1. No pulse is transmitted. The delayed or "carry one" pulse is applied to the left hand grid of V49, which switches the current to V51 again. Due to the 1 \( \mu \text{sec} \) delay this switching action occurs in the second digit position. If there is no pulse from the memory at this time, a pulse is transmitted. If there is a pulse the "carry one" pulse is again generated and the cycle repeated. This process continues until a blank space is reached and this is then filled. All the previously filled spaces are cancelled. The result is that, if the number in the channel is 11111 = 2^4 + 2^3 + 2^2 + 2^1 + 2^0 = 2^5 - 1, and
one more is added, then the answer is $100000 = 2^6 + 0 + 0 + 0 + 0 + 0 = 2^6$, where 1 and 0 represent pulse and no pulse respectively.

**Synchronisation**

In order to ensure that the memory pulses remain in synchronisation with the two oscillators, a group of initial pulses are generated at the start of the sweep and transmitted into the memory. These pulses appear at the receiver during the next waiting period of the sweep. They then re-start the sweep generator through the trigger valve V88. The bias on V88 is used as a fine synchronisation control between incoming pulses from the memory and the digit oscillator current pulses. This time control is possible since the leading edge of the first initial pulse has a finite slope. A variable delay of about $0.5 \mu$ sec is also introduced between receiver and adding gate by the delay line, DL2. This delay is required to compensate for the finite time taken by the sweep generator to start and release the oscillators.

The first two sections of DL2 lengthen the incoming pulses so that they overlap the digit oscillator current pulses. The adding gate does not function correctly unless all signals applied to the control grids are wider than $0.5 \mu$ sec so that each current pulse follows one and only one path. The trigger valve V96 was added to the original circuit in order to standardise the
Figure 30. The display circuits.
height and increase the width of the "carry one" pulses.

The display circuits

A cathode ray oscilloscope displays the pulses which are stored in the memory. The X deflection is supplied by the linear sweep circuit and corresponds to pulse height. For the Y deflection, a sweep generator which consists of valves V69, V70, V71 and V72 in Figure 30 provides a vertical sweep for each channel. A just visible spot occurs for each digit oscillator pulse and a bright spot occurs for each pulse in the memory. The result is a rectangular array of spots, and for 120 channels there are 120 vertical columns with 10 spots in each. The binary digits are read upwards with the first spot corresponding to $2^0 = 1$. When a pulse height distribution has been recorded, the general shape can be seen on the screen. The total count in a given channel is obtained from the number and position of the bright spots in the corresponding column.

The test pulse generator

The circuit of the test pulse generator which is included in the analyser is shown in Figure 31. A multivibrator VI supplies positive pulses to a current switching valve V5. The current in V5 is controlled by the constant current valve V4. The grid bias on V4 is obtained from a 67.5 volt dry cell, and changes in the grid to cathode contact potential are corrected.
Figure 31. The test pulse generator circuit.
by a slave valve V3 in the grid circuit. Current normally flows through the right hand half of V5, and is adjusted to 2.00 mA. The anode load of V5 is a resistance of high stability and known value. When the current is switched by pulses from the multivibrator to the left hand half of V5, a positive pulse is generated at the right hand anode whose height is defined in terms of the known current and resistance.

**Operation of the analyser**

Once the initial troubles were cured, most of the recurring faults developed in the memory and synchronising circuits. Trouble-free operation was obtained over a period of a month on several occasions. Linearity was checked by the test pulse generator and found to be correct to within half a channel in the 60 channel case. Pulses shorter than a microsecond were not reliably analysed. This was probably due to the finite time required for the lower limit and master trigger pair to switch over and release the pulse lengthener.

A study of channel drift with time was not made since the drift in the gas gain of the proportional counters used in the experiments was a much greater problem.

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