THE RICE INSTITUTE

THE USE OF A NEUTRON SPECTROMETER IN AN INVESTIGATION OF THE Li$^6$(n,d)He$^5$ REACTION

by

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INTRODUCTION

The $^6\text{Li}(n,d)^5\text{He}$ reaction was to be investigated with bombardment by 15 Mev. neutrons. This entailed the detection of low energy (about 6 Mev.) deuterons in the presence of high energy (15-17 Mev.) background. The related detection of low energy neutron groups from $(d,n)$ reactions was also scheduled. The spectrometer used by Risser, Price, and Class, and improved by W.L. Anderson was to be employed in the experiments. Before this purpose could be realized, however, several problems left unresolved by Anderson had to be studied further, the major one of which was that of the central wire size. This problem involved consideration of ion movement, ion collection, and gas amplification.

The present work attempts to treat these problems and gives the experimental determination of some of the factors involved, plus the results of investigations of the background counting rate.

The work on the $^6\text{Li}(n,d)^5\text{He}$ reaction consisted of angular distribution measurements at different neutron energies, and was done in collaboration with Mr. R.L. Steele.
PART I

The apparatus to be used in detecting low energy deuterons from the $^6\text{Li}(n,d)^5\text{He}$ reaction is a coincidence counter, a schematic diagram of which is given in Fig. 1 and which is described elsewhere in the literature. It consists essentially of a polyethylene radiator for producing recoil protons when bombarded by neutrons, and a gas proportional counter operating in coincidence with a CsI crystal scintillation counter. The coincidence pulse operates a gate circuit, which allows the linearly amplified pulse from the crystal to be recorded. The counter is filled with a mixture of 95% argon and 5% CO₂ at one atmosphere pressure. The ions formed by collisions between recoil protons and gas atoms move under the influence of the large potential difference between the central electrode and the counter wall, forming the gas pulse. The scintillation pulse occurs when the protons strike the crystal, a distance of 10 cm. from the radiator.

The light collection in the scintillation crystal, and hence the scintillation pulse, rises in a few tenths of a microsecond, while the gas pulse requires longer, the time for ion collection depending on ion movement and position. In order to obtain resolving times of a few tenth microseconds, only the first few tenth microseconds of the gas pulse may be used. It will be noted that the criteria usually applied to gas proportional counters—large electric field
Fig. 1. A schematic diagram of the neutron spectrometer used in the investigation of the Li\(^6\)(n,d)He reaction.
at the periphery to attract all the ions, and a relatively long rise time of the pulse—do not apply here. Moreover, the recoil protons from the radiator all pass within several centimeters of the central wire. Therefore, a very strong electric field at the center of the gas counter seems indicated, from a consideration of the motion of the ions. The following sections deal with these problems.

I. PRIMARY IONIZATION AND GAS MULTIPLICATION:

The shape of the pulse arising from the gas counter is proportional to the number of primary ions, the gas multiplication, and a factor due to ion motion. Anderson suggested that a smaller central electrode could be used to obtain a larger initial rise of the pulse. His suggestion was based mainly on considerations of the ion movement factor. A conclusion about the wire size can be reached only after it is understood how to include considerations of gas multiplication.

Theory of Gas Multiplication:

Consider the gas multiplication factor $M$ to be defined thus (in a small region around the central wire):

$$M = \frac{n}{n_0},$$

where $n$ is the number of ions reaching the wire (electrons in this case, since the wire has a positive potential), and $n_0$ is the number of primary electrons from the initial ionization.

The electric field $E(r)$ due to the wire, at distance $r$, 

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is

\[ E(r) = \frac{V}{\ln b/a} \frac{1}{r} \]

where \( V \) is the voltage between the electrodes, \( b \) is the radius of the inner wall of the counter, and \( a \) is the radius of the central wire. In this field, an electron will not acquire enough energy while moving in a mean free path \( \lambda \) to ionize a gas atom unless its distance from the wire is less than the distance \( r_c \), given by

\[ I = \lambda E(r_c) = \frac{\lambda V}{\ln b/a} \frac{1}{r_c} \]

where \( I \) is the ionization potential of the gas.

\( \lambda \) can be given in terms of the number of atoms \( N_a \) and the collision cross-section \( \sigma_b \), thus:

\[ \lambda = \frac{1}{N_b \sigma_b} \approx \frac{5 \times 10^{-4}}{\frac{p}{76}} \]

with

\[ \frac{p}{76} = \frac{N_a}{22400} \times 10^{23} \]

\[ \sigma_b \approx 0.75 \times 10^{-16} \text{ cm}^2 \]

where \( p \) is the pressure of the gas in cm. of Hg (in this case, 76 cm. of Hg).

Thus

\[ r_c = \frac{V}{I \ln b/a} \frac{5 \times 10^{-4}}{\frac{p}{76}} \]

Now the number of ionizing collisions per drifting electron in a path length \( dr \) is \( dr/\lambda \), for \( a \leq r \leq r_c \). Then the number of electrons resulting from these secondary ionizations is

\[ dn = -n \frac{dr}{\lambda} \]

where \( n \) is the number of electrons present, the minus sign indicating that \( dn \) increases with a decrease in \( r \).
Integrating (6),

\[ \frac{n}{n_0} = e^{\left(\frac{r_0 - r}{\lambda}\right)} \]

taking \( n = n_0 \) at \( r = r_0 \). Substituting \( r_0 \) from (5) and \( \lambda \) from (4), and taking \( M = n/n_0 \) at \( r = a \), the following expression is obtained:

\[ M = e^{\left(\frac{V}{I \ln b/a} - \frac{a_p x 10^{-4}}{380}\right)} \]

(7)

The threshold for gas multiplication occurs when

\[ \frac{V}{I \ln b/a} = \frac{a_p x 10^{-4}}{380} \]

and

(8) \[ V_{th} = \frac{a_p x 10^{-4}}{380} I \ln b/a \]

**Measurement of Gas Multiplication:**

The first factor in equation (7), that is, \( e^{\left(\frac{V}{I \ln b/a}\right)} \), was determined for the present counter as follows. The pulses from the gas counter alone were fed from the gate into four channels of a five-channel analyzer with variable lower biases. Counts were taken at gas voltages of 2700 v., 2800 v., 2900 v., and 3000 v., with gas amplifier gain settings of 64, 64, 32, and 16, respectively. A typical distribution in the channels is shown in Fig. 6 (gas voltage = 2700 v.).

The channel voltage at which the number of counts reached a maximum was approximated each time, and this voltage was multiplied by the factor by which the gain was lowered from that of the preceding gas voltage (assuming that this factor is proportional to the gas multiplication) to give the rel-
ative multiplication factor $M$. Fig. 2 shows $M$ plotted as a function of gas voltage.

The ionization potential $I$ of argon can be calculated from the graph, since

$$\Delta \ln M = \frac{\Delta V}{I \ln b/a} .$$

With $b = 3.65$ cm. and $a = .0127$ cm. (10 mil wire),

$I = 33$ volts.

It is seen from equation (7) that the gas multiplication becomes larger as $V$ is increased or as $a$ is made smaller. However, as $a$ decreases, by equation (8) $V_{th}$ decreases.

Rough calculation of pulse sizes indicates that under present operational conditions $M$ is about 250 and $V$ is therefore about 800 volts above threshold. Hence a decrease in $a$ will, by lowering the threshold, allow the counter to operate at a lower voltage. This lower voltage has to be taken into account before applying the theory to the ion movement factor.

These changes arising from considerations of gas multiplication will have an effect on the pulse shape which is associated with the motion of the ions through the gas.

II. ION MOVEMENT IN THE GAS PROPORTIONAL COUNTER:

The gas counter pulse depends on the voltage induced at the central electrode by positive ions formed there. This voltage will vary depending on the location of the ions, increasing as the ions move farther from the wire (the electrons formed simultaneously with the positive ions move toward the wire).
Fig. 2. The relative gas multiplication factor $M$ is shown as a function of the gas counter voltage. $M$ is plotted on a logarithmic scale.
Theoretical Considerations:

It can be shown that the voltage induced at the central electrode by a positive ion has the form

\[ V(t) = \frac{-e n_0}{2C \ln b/a} \ln \left( \frac{2Kv_t}{a^2 \ln b/a} + 1 \right), \]

where \( e \) is the electronic charge, \( M \) is the gas multiplication factor, \( n_0 \) is the number of original ions, \( C \) is the capacitance of the chamber and input to the amplifier, \( K \) is the heavy ion mobility, \( b \) and \( a \) are the two radii mentioned above, and \( t \) is the time. A plot of \( V(t) \) vs. \( t \) for this counter is shown as curve I, Fig. 3, with \( M \) taken equal to 250, \( n_0 \) 3000, \( C = 10 \mu \text{fd} \), \( K = 7.5 \), \( e = 1.6 \times 10^{-19} \text{ coul.} \), \( b = 3.65 \text{ cm} \), \( a = 0.127 \text{ cm} \), and \( V = 2800 \text{ volts} \) (gas counter high voltage).

From equation (9) it is seen that \( V(t) \) would increase if \( M \) were increased, all the other factors remaining the same. However, in general \( M \) cannot be changed at will, so another quantity must be varied. In the discussion of gas multiplication, it was pointed out that a decrease in \( a \) at the same \( V \) is equivalent to an increase in \( M \), or, if \( M \) is to remain the same, such a decrease lowers the operating voltage \( V \).

Taking \( a = 0.00635 \text{ cm} \) (5 mil wire) (which would be expected to lower \( V_{th} \) to roughly 1000 volts), and hence \( V = 1800 \text{ volts} \), and with all the other quantities retaining their former values, a second curve of \( V(t) \) vs. \( t \) is obtained (Fig. 3, curve II). It is seen that the pulse has a more rapid initial rise in the second case; the new conditions would give a more effective counter operation. As time passes the curves level off, reaching a constant value of \( V = -en_0/C \) at \( t = \frac{(b^2 - a^2) \ln b/a}{2Kv} \), which occurs at 1796\( \mu \text{sec.} \) after
Fig. 3. The calculated potential $V(t)$ induced at the central electrode by the motion of the positive ions formed in the region of the wire, is shown as a function of the time since the initial ionization. Curve I results from using a 10 mil wire ($a=0.0127$ cm.) in eq. (9); with $a=0.00635$ cm. (5 mil), curve II is obtained.
the initial ionization for curve I and $31400 \mu \text{sec.}$ for II. However, as mentioned above, timing requires the use of only the first few tenth microseconds of the pulse, so attention must now be directed to the motion of the ions during this time.

Taking into account the rate of arrival of electrons at the central wire (assuming a mobility of $4 \times 10^6 \text{ cm./sec.}$ for the entire region within a few centimeters of the wire) and the heavy ion movement near the wire, a numerical calculation for the pulse shape in approximately the first half microsecond was done for two extreme positions of the primary ion track, shown diagramatically below.

The track at $r_0 = 1.2 \text{ cm.}$ represents approximately the farthest distance from the wire a track under consideration can be, since the radiator and the crystal are about one inch in diameter. Curves A and B, Fig. 4, show the pulse as a function of time for ion tracks at $r_0 = 0$ and $r_0 = 1.2 \text{ cm.}$, respectively, with $a = .0127 \text{ cm.}$ and $V = 2800 \text{ volts}$. When a smaller wire size ($a = .00635 \text{ cm.}$ and $V = 1800 \text{ volts}$) is used in the calculations, curves C and D result. Experience with the calculations shows that the electrons come from small distances and that we do actually use the first few tenth microseconds of the pulse. It is seen from Fig. 4 that at a given time the pulse from the counter with the
Fig. 4. The development of the gas counter pulse in the first few tenth microseconds after the primary ionization. The curves result from numerical calculations considering ion tracks shown on page 8; $a=0.0127$ cm. gives A and B; $a=0.00635$ cm. gives curves C and D.
smaller wire is larger. A smaller wire, then, would allow the pulse to be clipped earlier for a given pulse size. It is reasonable to assume that a still smaller wire would give curves with still greater slopes and would allow still earlier clipping. The non-linear portion of curves A and C is due to the non-homogeneity of the electric field close to the wire; for the larger wire this part of the field extends farther and hence diminishes at a later time than for the smaller wire. This portion of the curve would straighten out more and more as smaller wire sizes were used in the calculations. The actual use of smaller wires in the gas counter involves the mechanical problem of supporting the wire. A possible solution would be to have the ends held by conducting tubes extending into the counter from the top and bottom. This would further restrict the ion movement and would allow the volume of the counter to be reduced.

**Measurement of Rise Time:**

The gas pulses were clipped at different heights by different lengths of delay line in the amplifier. The gain was increased each time until a maximum number of 14 Mev. neutrons was counted. It was found that all the neutrons were counted with a clipping time of about .4 μsec., which is another indication that only the first few tenth microseconds are used.
PART II

The use of high energy neutrons for investigating the \( \text{Li}^6(n,d)\text{He}^5 \) reaction would naturally produce high energy background. The background, then, deserved some attention, and was treated in the following way.

I. TESTS ON BACKGROUND:

Coincidence pulses from 14 Mev, neutrons (produced by the \( T(d,n)\text{He}^4 \) reaction) were recorded in a five channel analyzer of variable bias, for various deuteron beam intensities. Counts were taken with and without the polyethylene radiator, to locate the neutrons.

The background count (that is, counts taken without the radiator) was found to be unusually high in the region of the neutrons (the 30 and 40 volt channels). Much time was spent attempting to discover the cause of this high background before it was decided to replace the CsI with a NaI crystal.

The background count with the NaI showed no build-up in the neutron region. Furthermore, the NaI pulses were found to have a faster rise time than those from CsI, as is shown in Fig. 7. The experimental procedure for measuring the rise times was the same as that used for the gas pulses (see page 9). The contribution of the accidental counts (i.e., causally unrelated events in the counter) to the background, with the NaI crystal, was computed from the following
relation:

\[ \text{No. accidentals} = 2 \tau n_1 n_2 t, \]

where \( \tau \) is the resolving time of the counter (in this case, \(0.8 \mu \text{sec.}\)), \( n_1 \) and \( n_2 \) are the gas and NaI singles rates, respectively, and \( t \) is the time during which the counts were taken. The total background and accidental distributions in the channels is given in Fig. 5.

The difference in the background count with the two crystals might be explained by the existence of large CsI pulses in the neutron energy region. This could be due to an \((n,p)\) process occurring in the CsI with higher cross-section and greater probability than in NaI. Indeed, from the masses of the reactants\(^7\), the Q-value for the Cs\((n,p)\) reaction is +.4 Mev., while those for Na\((n,p)\) and I\((n,p)\) are -4 Mev. and -18 Kev., respectively. This could account for the above effect; however the problem is not completely resolved at the present time.

Raising the NaI discriminator bias from 60 volts to 100 volts was found to eliminate the singles from the channels below 35 volts. The accidental and background rates could thus both be reduced by maintaining a high discriminator bias in the scintillation counter.

It was observed that the NaI discriminator singles were proportional to the beam intensity and not to the integrator as would be expected. This was concluded to be due to some electronic factors in the amplifier, rather than to some possible radioactive process. If the latter were occur-
Fig. 5. Total background and accidental count distribution in coincidence counter, with NaI scintillator. The background contribution is seen to be low in the region of maximum neutron counts.

Fig. 6. Gas counter singles distribution; gas voltage, 2700 volts.
Fig. 7. Pulse height vs. clipping time for NaI and CsI. Arrows indicate rise times by this rough measurement. Horizontal line in CsI case was the pulse height obtained with no delay line (infinite clipping time), hence no experimental points on this line.
ring the number of singles counts should still be proportional to the integrator counts: radioactivity with a short period would be counted like any other prompt count, while that with a long period would give a smaller counting rate (requiring a longer time for the pulses to be counted) and roughly the same number of counts.

In connection with the work on the background it was found that the gas singles rate decayed with time after the beam was turned off. The decay is shown in Fig. 8. Various processes seem to be occurring. A possible $\beta^+$-decay of copper (10 min. half-life) resulting from the $\text{Cu}(n,2n)$ reaction at 14 Mev., is indicated by the straight line. The contribution of this decay to the overall counting rate is negligible (only about 130 counts/sec.).

During the $\text{Li}^6(n,d)\text{He}^5$ experiment (see below), it was noted that the background count decreased as the counter was rotated slightly to take angular distributions. Since this rotation placed the Li target and the NaI crystal out of alignment, it would appear that the background is dependent on the relative positions of the radiator and the crystal.
Fig. 8. Decay of gas counter pulses with time after ceasing neutron bombardment. Counts were taken for 30-sec. intervals. The straight line indicates the contribution of possible $\beta^+$-decay of copper resulting from the Cu(n,2n) reaction with 14 Mev. neutrons.
SUMMARY OF CONCLUSIONS REGARDING NEUTRON SPECTROMETER:

The arguments advanced in the preceding sections concerning the most favorable operation of the counter may be summarized as follows:

1. A smaller central electrode in the gas proportional counter appears desirable in order to give a greater rise to the early part of the gas counter pulse, thereby obtaining better resolving time at the same gas multiplication.

2. Since calculations show that the early part of the gas pulse is due only to ions within about 1 cm. of the wire, it would seem advantageous to reduce the volume of the gas counter.

3. The background is due mainly to coincidences and not accidentals; the use of NaI scintillator reduces the background.
PART III

USE OF THE SPECTROMETER IN THE Li$^6$(n,d)He$^5$ EXPERIMENT:

In order to detect the 6 Mev. deuterons produced by high energy neutron bombardment of Li, a different set of operating conditions were used than for counting high energy protons. From the range-energy and energy loss curves, it was seen that the deuterons would produce a pulse 3 times that from the protons. The gas gain was therefore reduced by a factor of 3 and slight changes made in the differentiating and delay lines at the coincidence input to obtain a maximum counting rate.

The counter was rotated so as to detect deuterons emerging at different angles with the incident neutrons. The experiment was performed at several neutron energies.

Results:

A typical angular distribution is shown in Fig. 9. The experimental points give a very good fit to the theoretical curve. This fit is probably due to the ease with which the background can be subtracted, by taking counts with and without the radiator (the background was lower in this experiment, besides, because of the lower gas gain).
Fig. 9. Angular distribution of $\text{Li}^6(n,d)\text{He}^5$ reaction at neutron energy of 15.5 Mev. The vertical lines indicate the statistical variation of the experimental points. The dashed line is a theoretical curve.
REFERENCES

5. Anderson, op. cit.
6. Ibid.
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