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A STUDY OF THE PROPERTIES OF BORON-8
BY THE $^6\text{Li}^3(\text{He}^3, n)^8\text{B}$ REACTION

by

Bobby Joe Farmer

A THESIS
SUBMITTED TO THE FACULTY
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Houston, Texas
September 1959
Dedicated

to the Memory of

My Father

Maurice L. Farmer
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INTRODUCTION

A few years ago, when helium-3 became available in quantity, the way
was opened to forming a number of light nuclei which had hitherto been
inaccessible at Van de Graaff energies utilizing the reaction processes
then available. Among these nuclei are the proton rich isobars of the
masses A = 4n, boron-8 and nitrogen-12, both of which can be readily made
by the (He\textsuperscript{3},n) reaction but about which relatively little has been known.
The T = 1 isobaric spin multiplets of these A = 4n groups are of some
special interest due to their exceptionally high energies of excitation
(approximately 15 MEV). At the outset of this work it was intended that
a thorough study be made of both B\textsuperscript{8} and N\textsuperscript{12}; however, as the work developed,
major interest focused almost exclusively on B\textsuperscript{8}, although in several
phases the study of N\textsuperscript{12} was included to some extent. Due to the variety
of measurements made and experimental procedures employed, the thesis has
been divided into five chapters for convenience of discussion.

Chapter I describes a study of the states of B\textsuperscript{8} by means of the
Li\textsuperscript{6}(He\textsuperscript{3},n)B\textsuperscript{8} reaction using the "counter ratio" method to detect the neu-
trons. This method not only made possible an accurate determination of
the bombarding energy at the threshold for forming B\textsuperscript{8} in its ground state
and thereby accurately establishing its mass, but it also permitted a
search for possible excited states.

In Chapter II a method is discussed by which the cross-section for
the Li\textsuperscript{6}(He\textsuperscript{3},n)B\textsuperscript{8} reaction was determined in the region between the thresh-
hold of the reaction (2.967 MEV) and 5.5 MEV. The reaction yield was
determined by observing the positrons from the decay of B\textsuperscript{8}. Since B\textsuperscript{8} is
unstable to proton emission only 138 KEV above its ground state, the
cross-section derived from the positron yield is for forming $\text{Be}^8$ in its ground state only without interference from other levels. This favorable circumstance, together with the simple energy dependence which the cross-section curve displayed, suggested an analysis based on a simple direct interaction theory. Satisfactory agreement with the experimental curve has been obtained by such an analysis over the entire range of the data.

Chapter III is concerned with the observation and theoretical analysis of the alpha spectra from the decay of $\text{Be}^8$ produced by the two following reaction processes: (1) $\text{Li}^7(d,p)\text{Li}^8(\beta^-)\text{Be}^8\beta^*$ and (2) $\text{Li}^6(\text{He}^3,n)\text{Be}^8(\beta^+)\text{Be}^8\beta^*$. The alpha spectra were found to be essentially identical, confirming the expected symmetry in the decays from $\text{Li}^8$ and $\text{Be}^8$. Reasonable agreement with the experimental spectra has been obtained using a modified Wheeler single level formula and evidence has been found for the population of not only the 2.9 MEV state in $\text{Be}^8$ but also the level at 11.6 MEV.

In Chapter IV a method is described by which the half-lives of $\text{Be}^8$ and $\text{N}^{12}$ have been measured. The method, which utilizes a multi-channel analyzer, is applicable over a range of half-lives of from several minutes to less than a millisecond. For comparison the well-known half-lives of $\text{Li}^8$ and $\text{B}^{12}$ were also measured.

Finally, in Chapter V we discuss a method used to obtain the high energy beta spectra accompanying the decays of $\text{B}^{12}$, $\text{N}^{12}$, $\text{Be}^8$, and $\text{Li}^8$ using a rather crude plastic scintillation spectrometer. These spectra were found to be strikingly similar to those obtained by magnetic analysis, when comparison spectra were available, in spite of the many distortion effects possible. The primary objective in obtaining the spectra was an attempt to test a theory of beta decay recently proposed by Gell-Mann\(^1\) which
predicts sizable distortions in the simple Fermi spectra of transitions for which $\Delta T = 1$, $\Delta J = 1$, and with no change of parity. This is the situation for the $\text{B}^{12}$ and $\text{N}^{12}$ cases. Since the $\text{B}^8$ and $\text{Li}^8$ transitions have $\Delta J, \pi = 0^+$, the effect should not be present, thus, giving a method of checking instrumental sensitivity. Although not conclusive at this time, results were obtained which indicate the validity of the theory.
CHAPTER I

A STUDY OF THE STATES IN BORON-8

Introduction

Before this work was begun no intensive study had been made of boron-8. The nucleus was first produced and studied by Alvarez\(^2\) in 1952 with the reactions \(\text{B}^{10}(p,t)\), \(\text{Be}^9(p,2n)\), and \(\text{C}^{12}(p,n)\), all of which require bombarding energies in excess of 18 MEV. Later, in 1952 the nucleus was produced by Sheline\(^3\) using the three reactions \(\text{B}^{10}(\gamma,2n)\), \(\text{B}^{11}(\gamma,3n)\), and \(\text{C}^{12}(\gamma,p3n)\). Because of the low yields, high backgrounds, and poor energy determination (if any) intrinsic in these methods, the information obtained suffered rather large uncertainties. For example, the half-life was established to only \(\pm 15\%\), the mass value was uncertain to \(\pm 430\) micro-mass units, and nothing was known of possible excited states.

To determine the feasibility of a possible study of \(\text{B}^8\) with the Rice Institute's 5.5 MEV Van de Graaff Accelerator using the \(\text{Li}^6(\text{He}^3,n)\) reaction, at least a rough estimate of the \(Q\)-value was necessary. Using the best available mass values\(^4\) such a calculation was made, yielding a \(Q\)-value of \(-1.6 \pm 0.4\) MEV which corresponds to a \(\text{He}^3\) bombarding energy of \(2.4 \pm 0.6\) MEV. This relatively low bombarding energy placed the reaction within the range of energies attainable with the accelerator and permitted the production of the nucleus at excitation energies in excess of 1.5 MEV.

The neutron counter ratio method\(^5\) presented itself as a suitable method by which states in \(\text{B}^8\) might be observed. The method permitted a precise energy determination of the threshold for forming \(\text{B}^8\) in its ground state and yielded information concerning possible excited states.
During the course of this work a similar study was published\textsuperscript{6}, the results of which are in general agreement with those of this work.

Experimental Method

The counter ratio method, which has been discussed at length in the literature\textsuperscript{7,8,9}, involves the use of two paraffin moderated BF\textsubscript{3} counters, 96\% enriched in B\textsuperscript{10}, which are operated in the proportional region to enable discrimination against pulses produced by betas and gammas. The method is dependent on the fact that the neutron detectors have different sensitivities which are determined by the amount of moderator placed around the counter tubes. One counter, termed the "modified long counter" is constructed by surrounding the 1-inch diameter counter tube by a cylinder of paraffin 5 inches in both length and diameter. With this arrangement the counter has a relatively uniform sensitivity for neutrons of energies between 200 KEV and 2.5 MEV. The sensitivity falls off sharply below 200 KEV due to the absorption of the slow neutrons in a cadmium sheet placed in front of the counter tube. The second detector, the "slow counter", is most sensitive to the slow neutrons occurring at a threshold, and the amount of moderator is selected in view of the energy of the neutrons at a threshold. For the Li\textsuperscript{6}(He\textsuperscript{3},n)B\textsuperscript{8} reaction the energy is 110 KEV at the ground state threshold. A layer of paraffin 3/4 inch thick and 2-1/2 inches long surrounding the counter tube produced optimum conditions, i.e., the counter maintained a high sensitivity well above the energy of the threshold neutrons and yet was relatively insensitive to neutrons with energies above 500 KEV. The relative sensitivities of the counters have been measured\textsuperscript{8}.
For the counter ratio measurements the counters are situated, as shown in Fig. 1, at zero degrees with respect to the incident beam at distances such that they subtend essentially equal solid angles at the target, the optimum solid angles being a function of the neutron dynamics of the reaction under study. At the threshold for the emission of a neutron, leaving the residual nucleus in its ground state or one of its excited states, the neutrons are emitted only in the forward direction with a laboratory velocity equal to that of the center of mass motion of the system. As the bombarding energy is increased beyond the threshold energy, the neutrons remain within a cone, the half-angle $^{10}$ of which is given by

$$\theta = \sin^{-1} \left[ \frac{M_1 M_2}{M_1 M_e} \frac{\Delta E}{E} \right]^{1/2} \tag{1}$$

where $E$ is the bombarding energy, $\Delta E$ the energy above threshold and $M_1$, $M_2$, $M_e$, and $M_T$ refer to the masses of the incident particle, the target nucleus, the emitted particle (the neutron), and the residual nucleus, respectively. For the accurate determination of a ground state threshold it is necessary that the total neutron yield pass through the counters for several kilovolts beyond the threshold energy. For the $Li^6(He^3,n)B^8$ ground state threshold determination the counters subtended a half-angle of $32^\circ$. With this arrangement and the threshold energy of 2.967 MEV the cone opened beyond the counters approximately 53 KEV above threshold. For this geometry the counter ratio decreased very slowly beyond threshold. For the observation of the entire excitation curve, where better "resolution" was required, the slow and modified long counters were moved back to 5 and 10 inches, respectively, from the target, corresponding to a half-angle of $14^\circ$ for which the cone opened 11 KEV above the ground state threshold.
SHADED AREAS ARE PARAFFIN

TOP VIEW

BEAM

INCHES:
0 1 2 3 4 5 6

MODIFIED LONG SLOW COUNTER

SIDE VIEW

CADMIUM

TUBES

BF$_3$ COUNTER

LI. OVEN

BEAM

RATIO COUNTERS

Fig. 1
The targets were prepared by evaporating a thin film of lithium metal, 96% enriched in Li$^6$, onto 20 mil thick tantalum blanks. The evaporating system, shown in Fig. 1, consisted of a stainless steel tube built into the target chamber and directed at the target. A small electric oven was placed around the tube to apply the necessary heat for evaporation. Targets were used which ranged in thickness from 10 to 60 Kev to a 3 MeV He$^3$ beam. The thicknesses were estimated from the rise of the counter ratio curve of the Li$^6$(He$^3$,n)B$^8$ reaction at the ground state threshold and checked with the values, when available, obtained from the Li$^7$(p,n) and Li$^7$(HH$^+$,n) threshold curves which were used to calibrate the energy scale.

The target room was especially designed for neutron experiments to reduce background due to scattered neutrons. The floor below the target area was covered with 1/4 inch thick aluminum sheets supported with aluminum sheets supported with aluminum I-beams, below which was a pit approximately 8 feet deep. The walls of the room were not less than 10 feet from the target. Background from the analyzing magnet was small, since it was over 20 feet from the target. As a further precaution, the tantalum beam defining slits were cleaned before each run to remove carbon deposits.

Three sets of tantalum slits were used to define the path of the beam to the target. One set was approximately 15 inches from the entrance to the accelerator's 90° analyzing magnet and the second the third were approximately 6 inches and 12 feet, respectively, from the exit of the magnet. During all the threshold measurements, and in any other part of the experiment where energy resolution was important, the widths of the slits were less than 2 millimeters. Under such conditions the beam spread (defined as E/$\delta$E where $\delta$E is the width at half maximum) of greater than 3000 has been measured.
The energy scale was determined by calibrating the accelerator's 90° analyzing magnet with reference to accurately know neutron thresholds. The magnetic field was measured with a resonance magnetometer, the probe of which, containing lithium hydride, was situated near the path of the accelerated ions. An absolute calibration of the energy scale in terms of the gyro-magnetic frequency of the Li\(^7\) nuclei was obtained at 1.8811 ± 0.0004 MEV, the threshold energy of the Li\(^7\)(p,n)Be\(^7\) reaction. This value for the threshold energy is obtained from a weighted mean of six high precision measurements\(^{10}\). The energy scale thus obtained was then corrected for relativistic and magnet saturation effects on the basis of a correction curve determined with a series of neutron threshold and Cl\(^{12}\)(α,n) resonances\(^{11}\). A detailed description of the energy calibration procedure is given in Appendix I. In the precise determination of the ground state threshold of the Li\(^6\)(He\(^3\),n)B\(^8\) reaction, the energy scale was checked using the Li\(^7\)(HH\(^+\),n)Be\(^7\) threshold. The magnetic field necessary to bend the molecular beam at the threshold energy of 3.7632 ± 0.0010 MEV was only 8% below that for the He\(^3\) particles at the Li\(^6\)(He\(^3\),n)B\(^8\) ground state threshold. The threshold value obtained with this check point agreed with the calibration value to within 1 KEV.

RESULTS AND DISCUSSIONS

Ground State Threshold Determination

The first measurement carried out was the precise determination of the threshold energy for forming B\(^8\) in its ground state. Fig. 2 shows the resulting curve of the ratio of the "slow" to "fast" neutron counts as a function of the He\(^3\) bombarding energy. To obtain adequate counting
Fig. 2
statistics a rather thick target (approximately 58 KEV to the 3 MEV He³ beam) was used. Upon following the customary procedure of using the straight line extrapolated value as the true threshold energy, a value of 2.976 ± 0.007 MEV was obtained. In observing the excitation function a number of times on the same target it was noted that the position of the ground state threshold moved up in energy as a function of bombarding time. Also the total neutron yield was found to increase with time. Both of these effects are consistent with the usual deposit of carbon found to accumulate on targets under bombardment. The magnitude of the shift in energy due to the carbon layer was determined by repeating the run over the threshold and observing the increase in energy at which the threshold occurred. On this basis, a correction to be applied to the above threshold value of 5 KEV was calculated.

Because of the target thickness and counter geometry used, a more careful analysis of the rise of the slow counter yield at threshold is possible in this case. Use can be made of the known forms for the cross-section in the neighborhood of a threshold. If compound nucleus formation is assumed, the cross-section for the production of neutrons is expected to increase approximately as $k_f^2$, the wave number of the outgoing channel assuming the most common case of s-wave neutron emission. The other energy dependent terms are slowly varying functions. For a direct interaction process the cross-section can be taken to increase as $k_f/k_i$ where $k_i$ is the wave number of the incident channel. Since the variation of $k_i$ is very small over the energy range of interest here (approximately 50 KEV), both assumptions lead to the same approximate result for the cross-section:

- 9 -
\[ \sigma \propto \text{const} \ (E - E_{th})^{1/2} \]  

(2)

where \( E \) and \( E_{th} \) are the bombarding and threshold energies, respectively. Rather strong support for this form of the cross-section comes also from the analysis of the total cross-section obtained by observing the positrons from the decay of \( B^8 \) (Chapter II). The yield produced by a thick target is then simply the integral of this expression over the target thickness. For the region just above threshold, before all the target is contributing and before the cone of neutrons opens beyond the counters, the yield of neutrons is expected to increase as

\[ Y \propto \text{const} \ (E - E_{th})^{3/2} \]  

(3)

The beam resolution function (assumed to be a triangle) was then folded into this expression by numerical integration; however, this effect was negligible for the target thickness in question. The theoretical expression was then normalized to the data as shown in Fig. 3. The true threshold energy is seen to lie approximately 8 KEV below the value obtained by the straight line extrapolation. A fit with this formula is somewhat rare because in most cases other resonances appear near the threshold which tend to distort the curve.

By taking into account the two corrections just discussed and making, in addition, a slight adjustment to the energies assigned to the \( \text{Li}^7(p,n) \) and \( \text{Li}^7(\text{He}^+,n) \) thresholds to allow for a small thick target effect\(^{13}\), we obtain, finally, a value for the threshold energy of

\[ E_{th} = 2.966 \pm 0.010 \text{ MEV} \]  

(4)
Fig. 3
The $\text{Li}^6(\text{He}^3,\text{n})\text{B}^8$ Excitation Curve

The $\text{Li}^6(\text{He}^3,\text{n})\text{B}^8$ excitation function was explored in the energy interval from threshold to 5 MEV during four different running periods and was swept two or three times each period. Fig. 4 shows the results of the final run which was made under conditions that were found to be optimum, i.e., as to target thickness and position of counters. The energy scale in Fig. 4 has been corrected for the carbon buildup mentioned earlier. One would not expect any fluctuations in the ratio curve due to the carbon deposit since no thresholds occur in the $^{12}\text{C}(\text{He}^3,\text{n})^{14}\text{N}$ reaction in the region under study. (The ground state and first excited state thresholds are at 1.450 and 6.99 MEV$^{14}$, respectively.) Other likely contaminates in the target were nitrogen, oxygen, and fluorine. In the case of N$^{14}$ no neutron thresholds occur in the region under study; however, as in the case of F$^{19}$ (for which the $(\text{He}^3,\text{n})$ Q-value is 7.60 MEV), N$^{14}$ is a possible source of fast neutrons which make up the background. On the other hand, the $^{16}\text{O}(\text{He}^3,\text{n})\text{Ne}^{18}$ ground state threshold is known to occur at 3.45 MEV. The ratio curve shows a slight anomaly at this point which may be the result of such contamination. The 4% Li$^7$ in the target is partially responsible for the yield of fast neutrons below the ground state threshold of the reaction under study. The Q-value for the Li$^7(\text{He}^3,\text{n})\text{B}^9$ reaction is 9.346 MEV.

The appearance of the excitation curve, Fig. 4, in addition to the obvious ground state threshold at 2.967 MEV, includes a broad peak at 4.20 MEV which is believed to correspond to the first excited state in B$^8$. To obtain the true resonant energy and width of such a state, it is necessary to consider the effect of the energy resolution of the neutron
Fig. 4
detectors on the resonant shape. Since the ground state is essentially a level of zero width, the shape of the ratio curve at the ground state threshold is exemplary of this resolution function (excluding the effect of the cross-section for the formation of the state). The resolution function shown in the inset of Fig. 5 was obtained from the ground state threshold curve by removing the "background" effects indicated by the dashed line as shown in Fig. 4. The curve has also been corrected for the decrease in target thickness at the higher bombarding energy and the decrease in the slow counter sensitivity due to the higher energy of the threshold neutrons. This curve was then integrated over Breit-Wigner resonance curves of various widths in 20 KEV steps and the results compared to the experimental resonant shape obtained by continuing the trend of the ratio curve under the resonance (the dotted line in Fig. 4) and subtracting this "background" from the data. The best fit to the data, shown in Fig. 5, was obtained with a width at half height, $\Gamma$, of approximately 100 KEV. The effect of the integration on the assumed theoretical shape was to broaden the resonance by about 50% and shift the peak toward higher energy by 50 KEV. The departure of the theoretical curve from the data on the high energy side of the peak is of little significance since it is in this region that the cross-section strongly affects the shape of the curve. No correction for this effect could be made since there was no information available for the cross-section for forming the excited state as a function of energy. The resolution function used, thus, automatically assumed the same energy dependence for the cross-section for forming this state as for the ground state. It is well to mention, however, that this
Fig. 5
has a negligible effect on the leading edge of the curve, which is influenced only by the width of the assumed level.

From the experimentally observed level width, the fractional part of the Wigner limit, \( \theta_l^2 \), to which the level width corresponds, has been calculated for nuclear radii of 3, 4, and 5 fermis assuming \( l = 0, 1, \) and \( 2 \) for the relative angular momentum of the proton and Be\(^7\) nucleus. The penetrabilities required for this calculation were obtained from the graphs of Coulomb functions of Sharp et al.\(^{15}\). The results are tabulated in Table I. From the intermediate coupling model\(^{16}\) the spin and parity of this level in B\(^8\) is predicted to be \( J, \pi = 1^+ \). Also experimental evidence confirms this assignment for the analogous level in Be\(^8\). On this basis, the most likely decay of this state in B\(^8\) is by p-wave proton emission.

<table>
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<tr>
<th>Radius (fermis)</th>
<th>Wigner Limit (MEV)</th>
<th>( \theta_0^2 )</th>
<th>( \theta_1^2 )</th>
<th>( \theta_2^2 )</th>
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<td>7.98</td>
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<td>4</td>
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<td>0.035</td>
<td>0.18</td>
<td>4.2</td>
</tr>
<tr>
<td>5</td>
<td>2.87</td>
<td>0.036</td>
<td>0.14</td>
<td>2.1</td>
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The other feature of the excitation curve worth comment is the slow rise beginning at 3.6 MEV. This rise is not believed to correspond to structure in $^{8}_{B}$, but rather to the yield of slow neutrons from one or both of the following mechanisms: the $^{6}_{Li}(^{3}_{He},p)^{8}_{Be}$ and $^{6}_{Li}(^{3}_{He},np)^{7}_{Be}$ reactions. In the case on the former, $^{8}_{Be}$ may be produced in one or more of its neutron unstable excited states, in particular the 18.9, 19.1, and 19.22 MEV levels. This offers a source of neutrons of energies less than 350 KEV for which the slow counter is still highly sensitive. In addition, the neutrons from the 18.9 MEV level would have energies of only a few kilovolts and, due to the cone effect, most or all of them would pass through the counters. Neutrons from the upper two levels are emitted with sufficient energy to be distributed isotropically and, hence, may not contribute strongly to the slow counter yield. On the other hand, the yield of neutrons from these states might be expected to increase with bombarding energy due to the increasing cross-section of the $(^{3}_{He},p)$ reaction$^{17}$. The second reaction which may conceivably contribute to the slow neutron yield, namely the three-body breakup resulting in $^{7}_{Be}$, a neutron, and a proton, is energetically possible above a bombarding energy of 3.168 MEV. The Coulomb barrier opposing the separation of the $^{7}_{Be}$ nucleus and the proton is 1.23 MEV assuming a nuclear interaction radius of 4.4 fermis. Since the barrier must be penetrated by the separating proton and $^{7}_{Be}$ nucleus, the neutron energy spectrum will be a maximum for low neutron energies. Also, on the basis of barrier penetration, the total probability for the breakup to occur will increase with bombarding energy, giving an increasing number of neutrons, most of which will have very low energies. This is consistent with the increase in the
counter ratio beginning at 3.6 MEV. We further observe that as the bombarding energy increases, the average neutron energy will increase until most of them are beyond the range of strong sensitivity of the slow counter. At this point, the ratio curve should level off and start to decrease. In Fig. 4 this is seen to occur at approximately 4.4 MEV. Trends in slow neutron yields similar to this have been observed for other reactions\textsuperscript{17} and have been interpreted on the basis of three-body dissociations.

The ratio curve of Dunning et al.\textsuperscript{6} is similar to the one obtained in this study; however, their curve shows a slight flattening at 4.0 MEV. On this basis, they tentatively attribute the rise in the ratio curve to a state in \( \text{B}^8 \) at 0.60 ± 0.1 MEV having a width of 200 KEV. There is nothing in our data to corroborate the existence of this state. Further, the analogue states in \( \text{Li}^8 \) and \( \text{Be}^8 \) have not been observed. On these grounds, it is felt that evidence for such a state is very weak.

The results of this study are summarized in Table II, and for comparison those of Dunning et al are included. In addition to the threshold obtained by counter ratio method, the result is also given from Chapter II for the threshold for the production of betas from the decay of \( \text{B}^8 \). The average of these values is taken as the threshold for the \( \text{Li}^6(\text{He}^3,\text{n})\text{B}^8 \) reaction. Table II also includes other relevant information which was calculated on the basis of the threshold energy.
TABLE II

Results of the study of the Li$^6$(He$^3$,n)B$^8$ reaction

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<td>Threshold Energy</td>
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<td>Counter Ratio</td>
<td>2.966 ± 0.010 MEV</td>
<td>2.9661 ± 0.0017 MEV</td>
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<td>Beta Yield</td>
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<td>2.969 ± 0.003 MEV</td>
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<td>Average</td>
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<td>2.9661 ± 0.0017 MEV</td>
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<tr>
<td>Q-value</td>
<td>-1.976 ± 0.005 MEV</td>
<td>-1.978 ± 0.002 MEV</td>
</tr>
<tr>
<td>Excited States</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy in B$^8$</td>
<td>not observed</td>
<td>0.6 ± 0.1 MEV</td>
</tr>
<tr>
<td>Width</td>
<td></td>
<td>0.2 ± 0.1 MEV</td>
</tr>
<tr>
<td>Energy in B$^8$</td>
<td>0.79 ± 0.02 MEV</td>
<td>0.80 ± 0.05 MEV</td>
</tr>
<tr>
<td>Width</td>
<td>0.067 ± 0.010</td>
<td>0.07 ± 0.04 MEV</td>
</tr>
<tr>
<td>Mass of B$^8$</td>
<td>8.027 156 ± 0.000 007 amu</td>
<td>8.027 157 ± 0.000 008 amu</td>
</tr>
<tr>
<td>Mass Excess of B$^8$</td>
<td>25.287 ± 0.007 MEV</td>
<td>25.288 ± 0.008 MEV</td>
</tr>
</tbody>
</table>

Discussion of the Isobaric Triad, Lithium-8, Beryllium-8, and Boron-8

The established mass of B$^8$ and the energy of its first excited state enables one to compare the position of these levels with the analogous levels which appear in the other two members of the triad, namely Be$^8$ and Li$^8$. This comparison is of interest because of the information it gives on the charge independence of nuclear forces and nuclear radii. The T = 1 states in this triad, as in others of the A = 4n group, are unusual
in that they occur at much higher energies of excitation of nuclear matter 
(approximately 15 MEV) than do those of the triads for which \( A = 4n + 2 \), 
giving, possibly, a more severe test to the theory. The test of the theory 
comes, in this case, in its ability to predict the energy of the \( T = 1 \) 
states in the \( T_z = 0 \) nucleus from information concerning the states in the 
\( T_z = \frac{1}{2} \) pair. To carry out this test, corrections to the experimental 
energies must be made to allow for the different Coulomb energies of these 
nuclei. Two of the methods to be considered for applying the Coulomb 
corrections are based on crude assumptions that (1) the nuclear charge is 
distributed homogeneously throughout the nuclear volume and (2) that the 
charges exist as discrete quantities uniformly distributed throughout the 
nucleus. The third method to be employed for comparing the energies of 
the isobaric states is due to Inglis\textsuperscript{18} and is based on the assumption that 
the difference in Coulomb energy is the same for different isobaric pairs 
of the same elements. Refinements of these theories on the basis of 
various nuclear models have been proposed\textsuperscript{19,20,21}; however, they will not 
be considered here.

Under the assumption of discrete charges distributed uniformly through- 
out the volume of the nucleus, one obtains for the total Coulomb energy

\[
E_C = \left[ \frac{3}{5} e^2 \right] \frac{Z(Z-1)}{r_o A^{1/3}}
\]

where the term in brackets has the value 0.865 x \( 10^{-13} \) MEV cm. and 
\( r_o A^{1/3} \) is the nuclear radius to be expressed in centimeters. On this 
basis, the Coulomb energy differency between isobars is

\[
\Delta E_C = \left[ \frac{3}{5} e^2 \right] \frac{Z(Z-1) - Z'(Z'-1)}{r_o A^{1/3}}
\]

- 17 -
where \( Z = Z' + 1 \). For the homogeneous charge distribution model the value of the total Coulomb energy of a nucleus is

\[
E_C = \left[ \frac{2}{5} \varepsilon^2 \right] \frac{Z^2}{r_o A^{1/3}}
\]

(7)

for which the Coulomb energy difference of isobars is

\[
\Delta E_C = \left[ \frac{2}{5} \varepsilon^2 \right] \frac{Z^2 - Z'^2}{r_o A^{1/3}}
\]

(8)

Under either assumption the total isobaric correction is

\[
E_I = E_C - (n-H)c^2
\]

(9)

where the appropriate value of \( \Delta E_C \) is used. The position of the first \( T = 1 \) level is then

\[
E = (M_Z - M_{Z'})c^2 - E_I
\]

(10)

Using the information from both the \( T_z = +1 \) and \( T_z = -1 \) nuclei, one obtains two equations for \( E \) which eliminates the need of assuming a radius of charge and which, in fact, allows a value of the radius common to all numbers of the triad to be calculated if the self-potential of the proton is allowed for. In this manner a value of \( r_o \) of \( 1.24 \times 10^{-13} \) cm. was obtained for the discrete model and \( 1.30 \times 10^{-13} \) cm. for the homogeneous model. By an analogous calculation in which the nuclear mass energies of the first excited states are substituted for the ground state values, the position of the second \( T = 1 \) level may be estimated. The results of these calculations are tabulated in Table III.

The Inglis method, which assumes the equivalence of the difference in Coulomb energies of isobaric pairs of the same elements, requires the knowledge of the masses of these neighboring nuclei. The total ground state energy of a nucleus may be written\(^{18}\) as

- 18 -
\[ E(Z,A) = E_0(Z,A) + E_c(Z,A) + (ZM_H + NM_n)c^2 \]  \hspace{1cm} (11)

where \( E_0 \) is the binding energy provided by the specific nuclear interactions, \( E_c \) is the Coulomb energy, and \( (ZM_H + NM_n)c^2 \) is the energy equivalent of the nucleons making up the nucleus. The ground state energy difference of the isobaric pair \( \text{Be}^8 \) and \( \text{Be}^8 \) is then

\[ \Delta_8 = E(5,8) - E(4,8) \]
\[ = E_0(5,8) - E_0(4,8) + E_c(5,8) - E_c(4,8) + (n - H)c^2 \]  \hspace{1cm} (12)
\[ = \Delta_{0,8} + \Delta_{c,8} + \Delta_{n,H} \]

where the new symbols are defined by the equation. An analogous equation may also be written for the neighboring isobaric pair \( \text{Be}^9 \) and \( \text{B}^9 \)

\[ \Delta_9 = \Delta_{0,9} + \Delta_{c,9} + \Delta_{n,H} \]  \hspace{1cm} (13)

The basic assumption of the method may now be stated as \( \Delta_{c,8} = \Delta_{c,9} \). The further assumption is made that specific nuclear interactions are symmetric for neutrons and protons which implies that \( \Delta_{0,9} = 0 \). Eqn. (5) minus Eqn. (6) then yields

\[ \Delta_{0,8} = \Delta_8 - \Delta_9 \]  \hspace{1cm} (14)

where \( \Delta_8 \) and \( \Delta_9 \) are experimentally determined numbers. If the charge-independence of specific nuclear interactions is now assumed, making the isotopic spin \( T \) a good quantum number, \( \Delta_{0,8} \) is then an estimate of the excitation energy of the first \( T = 1 \) state in \( \text{Be}^8 \). An analogous procedure using the known mass of \( \text{Li}^8 \) and the mass difference of \( \text{Li}^7 \) and \( \text{Be}^7 \) yields a second estimate for the position of the first \( T = 1 \) state in \( \text{Be}^8 \). The position of the second \( T = 1 \) state may be calculated using the total energy associated with \( \text{B}^8 \) and \( \text{Li}^8 \) nuclei in this first excited state.
in place of the ground state energies. This method yields values which are, in general, higher than the experimental values by approximately 200 KEV. The results of the calculations are summarized in Table III and compared to those of the other models and the actual experimentally determined level positions.

**TABLE III**

Theoretical estimates of the positions of the first two $T = 1$ states in Be$^8$ compared to the experimentally determined values.

<table>
<thead>
<tr>
<th></th>
<th>First $T=1$ State in Be$^8$ (MEV)</th>
<th>Second $T=1$ State in Be$^8$ (MEV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous Charge Model</td>
<td>$16.769 \pm 0.009$</td>
<td>$17.67 \pm 0.02$</td>
</tr>
<tr>
<td>Discrete Charge Model</td>
<td>$16.736 \pm 0.009$</td>
<td>$17.54 \pm 0.02$</td>
</tr>
<tr>
<td>Inglis Method Via Be$^8$</td>
<td>$16.906 \pm 0.013$</td>
<td>$17.70 \pm 0.02$</td>
</tr>
<tr>
<td></td>
<td>$16.864 \pm 0.010$</td>
<td>$17.84 \pm 0.02$</td>
</tr>
<tr>
<td>Experimental Value</td>
<td>$16.67$</td>
<td>$17.64$</td>
</tr>
</tbody>
</table>

In Fig. 6 the experimental energy level diagram of the members of the triad are shown on the left for comparison with the level diagram on the right in which the energies have been corrected for the Coulomb energy and $(n-H)$ mass difference using the results of the discrete charge distribution model which gave the best agreement with the experimental values.
EXPERIMENTAL LEVEL POSITIONS

LEVEL POSITIONS AFTER ISOBARIC CORRECTION USING THE DISCRETE CHARGE MODEL

ISOBARIC TRIAD $A=8$

Fig. 6
EXPERIMENTAL LEVEL POSITIONS

LEVEL POSITIONS AFTER ISOBARIC CORRECTION
USING THE DISCRETE CHARGE MODEL

ISOBARIC TRIAD A=8

Fig. 6
CHAPTER II

THE $^6\text{Li}^6$(He$^3$,n)$^8\text{B}$ EXCITATION FUNCTION

Introduction

The $^8\text{B}$ nucleus is unusual in that all of its excited states are particle unstable. As a result it is possible to determine the cross-section for forming $^8\text{B}$ in its ground state only simply by observing the yield of positrons from the decay of this state, the yield of positrons being proportional to the cross-section. In this manner, the cross-section has been obtained in the energy interval between threshold for the reaction (2.967 MEV) and 5.5 MEV. The measurement consisted of two parts: That of obtaining the relative yield of $^8\text{B}$ as a function of energy and the calibration of this curve by measuring the absolute cross-section at one energy.

Experimental Methods

$^6\text{Li}^6$(He$^3$n)$^8\text{B}$ Relative Yield Function

The relative yield of the reaction as a function of energy was measured by a delayed counting technique making use of the 0.79 second half-life of $^8\text{B}$. The Van de Graaff beam was periodically interrupted by a mechanical shutter, the cycle period of which was 10 seconds, the beam being on the target approximately 50% of the time. The $^8\text{B}$ decays were detected during the beam off portion of the cycle by observing the high energy positrons with a plastic scintillation spectrometer. The spectrometer crystal was 3 inches long and 3 inches in diameter and was situated 4.4 cm. from the target. The delayed counting eliminated background effects due to neutrons and prompt gamma rays produced in the target.

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Other background effects were greatly reduced by using pulse height discrimination to eliminate pulses corresponding to beta energies below about 5.5 MEV.

The energy scale for this curve was obtained just as that for the counter ratio excitation curve discussed in Chapter I; however, only the calibration point produced by the Li⁷(p,n) reaction was used. The energy of the threshold for the production of positrons was found to be

$$E_{\text{th}} = 2.969 \pm 0.012 \text{ MEV}$$  \hspace{1cm} (15)

This agrees with the value obtained by Dunning et al, Table II. The yield function is shown in Fig. 8, the characteristics of which will be discussed later.

The target used for this measurement was evaporated in place by the method discussed in Chapter I. Its thickness was determined by two independent methods: From the rise of the counter ratio curve of the Li⁷(p,n)Be⁷ reaction taken for energy calibration and by a comparison of the positron yield to that produced by the calibrated target to be discussed in the absolute cross-section measurement below. The latter measurement yielded only the amount of Li⁶ in the target. This was corrected to include the amount of oxygen known to combine with the lithium when evaporated under these conditions. A thickness of 63 ± 10 KEV to the 3 MEV He³ beam was obtained from an average of the two measurements.
Absolute Cross-Section

The same delayed counting technique as described above was used for the absolute cross-section determination. In terms of the measurable parameters the cross-section may be written as follows:

\[ \sigma = \frac{\lambda \mu T}{\eta_\Omega \rho (1 - e^{-\lambda T})(e^{-\lambda t_1} - e^{-\lambda t_2})} \]  

(16)

\( \eta_\Omega \) corresponds to the total number of \( \text{He}^3 \) ions which struck the target and was measured by conventional beam integration. \( \rho \) denotes the total number of positrons emitted by the target into the solid angle subtended by the counter. To obtain this number, it was necessary to increase the counts observed by the fraction of the total beta spectrum lost due to biasing. This biasing was the result of two effects: Energy loss in the material between the target and counter (target backing and air) and pulse height discrimination. The fraction of pulses lost was estimated making use of the known energy spectrum of the betas (See Chapter V).

The geometrical solid angle, \( \Omega \), was \( 2.01 \times 10^{-2} \) steradians measured at the face of the 3-inch diameter crystal which was situated 50 centimeters from the target. This number includes a 1% correction to allow for those betas which scattered from the crystal before suffering a sufficient energy loss to produce pulses greater than the electronic bias level (approximately 0.63 MEV). The target thickness is denoted by \( \rho \) and was experimentally determined from the yield of elastically scattered protons from a comparison target evaporated on a thin carbon foil which was placed next to the actual target during evaporation. Elastic protons were observed at 150° in the laboratory system; however, the only
available cross-section was for $^{164}\text{O}$. It is hoped that the cross-section does not change rapidly over this angular range. Apart from this uncertainty, the accuracy of the target thickness determination is $\pm 10\%$. The value of the half-life is $0.79 \pm 0.02$ seconds as determined by the method to be discussed in Chapter IV. This corresponds to a decay constant, $\lambda$, of $0.88 \pm 0.02$ sec.$^{-1}$. The times $T$, $t_1$, and $t_2$ refer to the bombardment time, the beam off to counter on time, and the beam off to counter off time, respectively. These were determined with reference to the calibrated sweep of a Techtronics oscilloscope. With the determination of these quantities, the total absolute cross-section at $4.01 \pm 0.02$ MEV bombarding energy was determined to be

$$\sigma = 10 \pm 3 \text{ millibarns}$$  \hspace{1cm} (17)

Analysis

As mentioned earlier, boron-8 is unstable to the emission of a proton only $138$ KEV above its ground state; thus, the yield of positrons corresponds to the production of $^8\text{B}$ in its ground state only. We have then the total cross-section corresponding to the formation of only one state measured over a range of $2.5$ MEV. Such experimental data are rare and are obtainable only for a very few nuclear reactions. This in itself makes the yield function interesting; however, this interest is prompted further by the simple energy dependence which the function displays. These facts suggest that a fit to the data might possibly be sought in terms of the dynamical factors involved in the reaction. Attempts were first made to fit the data in the region of threshold using the asymptotic form for the cross-section which is valid for all types of reaction processes.  

- 24 -
\[ \sigma = \text{const} \, k_f^{2\ell + 1} \]  

(18)

where \( k_f \) is the wave number of the outgoing channel and \( \ell \) is the angular momentum of relative motion in this channel. This is equivalent to

\[ \sigma = \text{const} \, (E - E_{th})^{\ell+1/2} \]  

(19)

where \( E \) and \( E_{th} \) are the bombarding and threshold energies, respectively. One expects this asymptotic expression to hold over an energy range determined by the condition that \( k_f R \ll 1 \), where \( R \) is the nuclear radius. For this reaction, this energy range is of the order of a hundred kilovolts. On comparing the data with Eqn. 19, assuming \( \ell = 0 \), and integrating the expression over the target thickness, excellent agreement was found for an interval of about 50 KEV above threshold. Also, the trend of the data up to 3.5 MEV was reproduced surprisingly well. This is shown by the long dashed lines in Fig. 7. Also shown for comparison is the same expression for zero target thickness, short dashed lines. It should be remarked here that the expressions are normalized to the data at 3.5 MEV.

To obtain a fit to the entire curve, it was necessary to consider the type of reaction process which might be involved in the interaction. The monotonically increasing form of the cross-section suggests that the reaction proceeds by a mechanism other than through the formation of a compound nucleus. If the compound nucleus, \( B^9 \), is formed, its excitation energy would be in excess of 18 MEV. With this in mind, a direct interaction process was considered. Such interactions have been used with much success in deuteron reactions and precedence for their application to \( \text{He}^3 \) reactions is provided by the success attained in fitting the
**Figure 7**

- **DATA**
- \( P_2 \int_{\text{TARGET}} K_F/K_1 \, dE \)
- \( \int_{\text{TARGET}} (E-E_{TH})^{1/2} \, dE \)
- \( (E-E_{TH})^{1/2} \)

**Axes:**
- **X-axis:** \( \text{He}^3 \) ENERGY (MEV)
- **Y-axis:** CROSS-SECTION (MB/Steradian)
Fig. 8
angular distribution curves of the \( ^{13}\text{He}^{3},\alpha^{12} \text{C} \) reaction under assumptions similar to those involved with the deuteron\(^{25}\). Also, in the case of the \( \text{Li}^{6}(\text{He}^{3},p)\text{Be}^{8} \) reaction, the angular distributions of the ground and first excited state protons suggest some sort of direct process\(^{17}\). For the \( \text{Li}^{6}(\text{He}^{3},n)\text{B}^{8} \) reaction, an analysis of this type would require the assumption that a di-proton is stripped from the \( \text{He}^{3} \) nucleus and captured into \( \text{Li}^{6} \).

Before further discussion, we must first consider the spins and parities involved in this reaction. The ground state of \( \text{B}^{8} \) is believed to have \( J,\pi = 2^{+} \), as suggested by that of the analogous ground state of \( \text{Li}^{8} \) and also on the basis of shell model calculations\(^{16}\). \( \text{He}^{3} \) and \( \text{Li}^{6} \) are known to have \( J,\pi = 1/2^{+} \) and \( 1^{+} \), respectively. We further observe that the ground state of the \( \text{He}^{3} \) nucleus is described as a mixture of singlet and triplet configuration for the protons, being 96% in the singlet state\(^{26}\). Thus, one would expect stripping of the di-proton in its singlet state to be the major contributing factor in the cross-section, requiring that the di-proton carry two units of angular momentum in forming \( \text{B}^{8} \).

The ground state of \( \text{B}^{8} \) is believed to be given by the coupling of 4 nucleons in the p-shell; hence, the capture of an \( \ell = 2 \) di-proton is reasonable since this would enable each proton to carry one unit of angular momentum when the di-proton "dissolves" into the framework of the \( \text{Li}^{6} \) nucleus to form \( \text{B}^{8} \).

The differential cross-section for stripping in the case of the deuteron is\(^{27}\)

\[
\frac{d\sigma}{d\Omega} = \text{const} \frac{k\ell}{k_{1}^{2}} |A_{i}|^{2}
\]

(20)
where \( k_f \) and \( k_i \) are the wave numbers in the final and initial channels, respectively; and \( A \) is the matrix element involving the interaction of the nucleons in the incident and target nuclei. It is assumed that in applying this expression to the \( \text{He}^3 \) problem that at least the forms of the terms will remain unchanged. This formula is customarily used for analysis of angular distributions. However, we shall try, in a tentative fashion, to apply the expression to the case of our excitation function, making use only of the principal energy dependent parts. In doing so, one obtains for the total cross-section

\[
\sigma = \text{const} \frac{k_f}{k_i} \begin{bmatrix} P_f & B \end{bmatrix}
\]

where \( P_f \) is the penetration factor for the di-proton getting into the \( \text{Li}^6 \) nucleus and \( B \) then contains the other energy dependent terms which are assumed to be slowly varying over the range of interest\(^{28}\). We thus obtain

\[
\sigma \sim \text{const} \frac{k_f}{k_i}
\]

(22)

Since we have seen that the most likely case is \( l = 2 \) for the di-proton, the only parameter at our disposal is the nuclear radius. Evidence along these lines from other reactions of this type suggests that a radius of the order of 4 or 5 fermis is to be expected\(^{29}\). Using a radius of 5.4 fermis, a reasonable fit to the entire range of the data was obtained with Eqn. 22, including target thickness effect, of course. This result is shown by the solid lines in Fig. 7 and Fig. 8. It is noted that the fit is not exact but gives approximately the right trend.
Possibly by making a more intensive study of the remaining energy dependent terms in Eqn. 21, a better fit might be achieved. The long dashed line of Fig. 8 shows the trend if the penetrability factor is considered to be 1. All the expressions were normalized to the data at 3.5 MEV. The penetrabilities were obtained from the graphs of Coulomb functions of Sharp et al.\textsuperscript{15}.

It was possible, also, to fit the data using values of \( P_l \) with \( R = 3.4f \); however, this possibility may be ruled out by the conservation of parity. On the other hand, to obtain a fit with \( \ell = 0 \), a nuclear radius of less than 2 fermis would be required which is unreasonably small.

While the nature of the reaction mechanism is not rendered unambiguously by these data, it is noteworthy that a rather good fit can be achieved with the simple assumptions in the framework of the direct interaction process. Compound nucleus formation, although not discussed here, appears a less desirable alternative because it can be shown that the assumptions necessary to achieve a fit are rather arbitrary and because that feature characteristic of compound nucleus formation, namely fluctuating cross-sections, does not appear although ample opportunity would seem to have existed in the energy interval examined. In addition, a similar, yet more detailed, analysis has been carried out along these same lines in an attempt to describe the energy dependence of the cross-section for the \( T(p,n)\text{He}^3 \) reaction with the use of certain direct interaction models\textsuperscript{36}.

If further work bears out the inference that the \( \text{Li}^6(\text{He}^3,n)\text{B}^8 \) reaction does occur as a direct interaction process, it will be one of the
first instances where measurements of total cross-section have been used for this purpose and may establish another method for distinguishing reaction mechanisms.
CHAPTER III

ALPHA SPECTRA FROM THE $^8\text{Be}^8(^8\beta^+)\text{Be}^8(\alpha)\text{He}^4$
AND $^7\text{Li}^8(\beta^-)\text{Be}^8(\alpha)\text{He}^4$ DECAYS

Introduction

The continuous alpha spectrum from $^8\text{Be}$ following the $^7\text{Li}^8$ beta decay is a classic problem and, thus, has been the subject of many investigations$^{31-37}$. Also a rather crude attempt has been made to establish the symmetry of the alpha spectra of the $^8\text{Li}^8 - ^8\text{Be}$ decays$^{38}$; however, due to the relatively small number of decays observed in this work, only tentative conclusions could be drawn. With the availability of $^8\text{Be}$ by means of the $^6\text{Li}^6(\text{He}^3,n)$ reaction it is possible to compare the spectra from the two decays with much improved accuracy. For this purpose, the use of crystal detectors and multi-channel pulse height analyzers is of great help. It is also of interest to take advantage of the improved information on the states in $^8\text{Be}$ to better interpret the results.

Experimental Procedures

The alpha spectra were obtained with a crystal spectrometer used in conjunction with a 256-channel pulse-height analyzer. The spectrometer consisted of a 5 mil thick CsI(Tl) crystal attached to a Dumont 6363 photomultiplier tube, the crystal being in the vacuum of the target chamber. Because of the high intensity of elastically scattered particles and reaction products, the observation of the alphas required the use of delayed counting, taking advantage of the 0.8-second half-lives of $^8\text{Be}$ and $^7\text{Li}^8$ (Chapter IV). The Van de Graaff
beam was pulsed at a frequency of 5 cycles per second, and counting occurred only while the beam was off the target. A variable frequency oscillator\textsuperscript{39} was used to drive square wave-forming circuits, the outputs of which performed the following operations:

(1) **Beam Deflection:** The Van de Graaff beam was pulsed at the target by an electrostatic deflector. The voltage on the plates of the deflector was controlled by a high voltage triode, the grid of which was operated by one of the square wave outputs of the oscillator. It was found necessary to deflect the charged part of the beam onto the target with approximately 2 KV in order to eliminate background due to the small neutral portion of the beam. Approximately three times this voltage was used to deflect the beam off the target and onto a tantalum beam stop for the counting portion of the cycle.

(2) **Counter Gate:** The second square wave output was used to control a gate circuit for the photomultiplier tube. This was phased with respect to the beam deflection such that counting commenced approximately 10 milliseconds after the beam was off the target and ended approximately 10 milliseconds before it was deflected back on. The photomultiplier tube switching was accomplished by reversing the voltage on the focus electrode with respect to the photo-cathode. This method, which has been discussed in the literature\textsuperscript{40}, served not only to inhibit counts during the beam-on portion of the cycle but also to prevent "fatiguing" of the photo-cathode and dynodes resulting from the
high intensity of particles, incident on the crystal during the "beam-on" period, which were elastically scattered from the beam by the target and thin carbon foil backing.

The background produced by delayed beta and gamma activity in the target was reduced by the use of a very thin (5 mil) CsI(Tl) crystal. The remaining background was allowed for by subtracting from the gross spectra the yield obtained when the alphas were screened out with a thin foil (15 mg/cm² of nickel) between the counter and crystal. For the case of the Be⁷⁸ spectrum, due to the lower yield of alphas, the background subtraction was more sensitive to the running conditions and not as complete as in the case of Li⁸. However, this difficulty introduced uncertainties in the spectrum only for alpha energies below 1.5 MEV.

The response of a CsI(Tl) crystal is not a linear function of alpha particle energy; thus, it was necessary to obtain a calibration curve. The points for this curve, giving pulse height as a function of alpha energy, shown in Fig. 9, were obtained in two ways:

1) Those at 5 MEV and less were obtained by elastically scattering alpha particles from a thin gold layer evaporated on a VYNS film.

2) The points at 6.05 and 8.78 MEV were obtained from a Th(B+C+C") source.

When the calibration curve was used subsequently to assign energies to the alphas from Be⁷⁸, the pulse height scale was normalized to the check points obtained with the thorium source only. The lines
RELATIVE PULSE HEIGHT
FOR ALPHA PARTICLES
IN A CdI₂(Crystals)

PULSE HEIGHT (ARBITRARY UNITS)

ALPHA ENERGY (MEV)

Fig. 9
used for normalization are shown in Fig. 10. The two additional peaks corresponding to 3.92 and 7.21 MEV were obtained by placing a 3.43 mg/cm² aluminum foil between the source and the crystal. The corresponding energy losses were then calculated from a set of theoretical tables. These four normalization points were taken between successive measurements of the Be⁴⁺ alpha spectra, and fluctuations in gain were found to be negligible over long periods of time.

The reactions used to produce the B⁴⁺ and Li⁵⁺ nuclei were Li⁶ (He³,n) and Li⁷(d,p), respectively. The target material for former reaction was 96% enriched Li⁶ and that for the Li⁷ target was natural lithium metal. The targets were prepared in identical fashions by evaporating the metal onto thin carbon foils while in place in the reaction chamber. Under the conditions of the evaporation, the lithium layers deposited were certainly partially oxidized. The thicknesses of the targets were measured using the elastic scattering of deuterons. The position of the peak produced by the deuterons scattered from the carbon foil was determined before evaporation. After evaporating the lithium, the target was oriented at 45° to the beam such that the lithium was on the back side of the foil with respect to the beam and facing the scintillation crystal, Fig. 11. Then the scattering was repeated and from the shift of the peak due to the absorption of energy by the lithium and/or lithium oxide layer, it was possible to calculate the thickness using the experimentally determined stopping power for deuterons. To check the result from this measurement, the thickness was also estimated from the yield of
elastically scattered deuterons from the lithium, assuming the Rutherford scattering cross-section. The values of the thicknesses obtained in this manner agreed satisfactorily with those obtained with the above method when the uncertainties involved in cross-section and the target composition are taken into account. The resulting values of the targets' thicknesses are $530 \pm 50 \mu \text{gm/cm}^2$ and $340 \pm 40 \mu \text{gm/cm}^2$ for the $\text{Li}^7$ and $\text{Li}^6$ targets, respectively (when oriented at $45^\circ$ to the beam).

A sketch indicating the counter geometry and target position used in obtaining the alpha spectra is given in Fig. 11. In early attempts to obtain the spectra, the targets were evaporated onto a thick tantalum backing with the lithium on the side facing the beam;

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![Target and Counter Geometry](image)

*Fig. 11*
however, due to the recoil velocities, the $^{8}$B and $^{8}$Li residual nuclei were driven into the backing several microns. This increased the amount of material through which the alphas had to pass before reaching the target, thus, causing an energy loss and an effective loss of resolution. This effect was greatly reduced by evaporating the target on a thin carbon foil and bombarding through the foil to the target layer.

The spectra from both the $^{8}$B and $^{8}$Li decay schemes are displayed in Fig. 12. These data have been corrected for the slight distortions which resulted from (1) the finite target thickness, (2) the dissociation of the $^{8}$Be nucleus in flight, the motion here resulting from the recoil momentum imparted by the beta and neutrino in the preceding decay, and (3) the effect of counter resolution. These corrections will be considered now in detail: The calculation of the effect of the target thickness was complicated by the above-mentioned penetration and distribution of the recoiling $^{8}$B and $^{8}$Li nuclei in the target layer. The relevant information concerning the dynamics of the recoil nuclei are given in Table IV.
Fig. 12
TABLE IV

Dynamics of Recoil Nuclei

<table>
<thead>
<tr>
<th></th>
<th>$^8B$</th>
<th>$^8Li$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bombarding Energy</td>
<td>4.5 MEV</td>
<td>2.0 MEV</td>
</tr>
<tr>
<td>For Producing the Nuclei</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Recoil Energy</td>
<td>1.45 MEV</td>
<td>0.57 MEV</td>
</tr>
<tr>
<td>Minimum Recoil Energy</td>
<td>1.22 MEV</td>
<td>0.22 MEV</td>
</tr>
<tr>
<td>Maximum Angle of Recoil</td>
<td>18°</td>
<td>45°</td>
</tr>
<tr>
<td>w.r.t. Beam Direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated Range of Recoil</td>
<td>420 $\mu$ gm/cm$^2$</td>
<td>150 $\mu$ gm/cm$^2$</td>
</tr>
<tr>
<td>Nuclei in Lithium$^{44}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Assuming Average Recoil Energy)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target Thickness at 45°</td>
<td>530 $\mu$ gm/cm$^2$</td>
<td>340 $\mu$ gm/cm$^2$</td>
</tr>
<tr>
<td>Estimated Average Thickness</td>
<td>130 $\mu$ gm/cm$^2$</td>
<td>130 $\mu$ gm/cm$^2$</td>
</tr>
<tr>
<td>Penetrated by Alphas</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As is seen from the last entry in the table, offsetting effects result in the same average penetration distance for the alphas in the two cases, enabling the use of the same corrections in both spectra. A correction was applied first to the alpha energy scale to account for the average energy loss of the alpha particles (calculated from an experimental stopping power curve extrapolated to low energies on the basis of other complete curves$^{43}$). Second, an estimate was made of the spread in the energy of the alphas due to their production at different depths in the target. This spread effectively reduced the counter resolution and was applied with the counter resolution correction. The magnitude of the target effects is indicated in Table V.
for various alpha particle energies. The broadening, ΔE, refers to
the width of the resolution function at half maximum in MeV.

The Li^8 and Be^8 nuclei are at rest when their beta decays occur;
however, the recoil momentum of the beta and neutrino sets the residual
Be^8 nucleus in motion. Due to the extremely short life-times of the
states in Be^8, the dissociation of the nucleus occurs while it is in
flight causing a slight shift in the energies of the alphas. The
resulting distortion to the spectrum has been calculated by Frost and
Hanna^37 and may be described in terms of a loss of energy resolution.
It was, thus, possible to include this effect also in the counter
resolution correction. The magnitude of this energy broadening is
given in Table V for several energies.

The true counter resolution was determined from the calibra-
tion points shown in Fig. 10. The resolution at the 8.78 MeV
peak is 3.7% and was found to follow closely the familiar E^{-1/2} energy
dependence observed with such crystal spectrometers. The magnitude
of this energy broadening is included in Table V for several ener-
gies. Also included in the table are the root-mean-square values
of all three broadening effects. The resolution correction was applied
by a method which involves the fitting of the experimental curve by
analytical expressions^45. The expression for the true undistorted
spectrum T(Eα) is then related to the experimental curve S(E'α) by
the following integral equation

\[ S(E'\alpha) = \int_0^\infty T(E\alpha) R(E\alpha, E'\alpha) dE\alpha \]  (23)
where $R(E\alpha,E'\alpha)$ is the resolution function. If the resolution function is assumed to be Gaussian, the corrected expression is given by

$$T(E\alpha) = S(E'\alpha) - \frac{E'\alpha \Delta E'\alpha}{4} \left[ \frac{\pi}{4 \ln 2} \right]^{1/2} \frac{d^2 S(E'\alpha)}{dE'^2\alpha}$$  \hspace{1cm} (24)$$

where $\Delta E'\alpha$ is the width of the resolution function at half maximum.

Although the uncertainties were considerable in estimating the magnitudes of the individual contributions to the energy broadening, the resulting correction to the spectrum shape was small, as is indicated in Table V. The corrected spectra from both the $\text{Li}^8$ and $\text{B}^8$ decays are shown in Fig. 12. Fig. 13 shows the results of the present work on $\text{Li}^8$, denoted by P, compared to those of Bonner et al.\textsuperscript{34} (S), Frost and Hanna\textsuperscript{37} (FH), and Rumbaugh et al.\textsuperscript{32} (R).

---

**TABLE V**  
Corrections to Alpha Spectra

<table>
<thead>
<tr>
<th>$E\alpha$ (MEV)</th>
<th>1.5</th>
<th>3.5</th>
<th>6.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Correction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Shift (MEV)</td>
<td>0.16</td>
<td>0.13</td>
<td>0.10</td>
</tr>
<tr>
<td>Energy Broadening (MEV)</td>
<td>0.13</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>Beta-Neutrino Broadening (MEV)</td>
<td>0.14</td>
<td>0.14</td>
<td>0.10</td>
</tr>
<tr>
<td>Counter Broadening (MEV)</td>
<td>0.13</td>
<td>0.20</td>
<td>0.27</td>
</tr>
<tr>
<td>$\Delta E$ (R.M.S. Energy Broadening in MEV)</td>
<td>0.23</td>
<td>0.22</td>
<td>0.30</td>
</tr>
<tr>
<td>Change in Ordinate, Eqn. (24)</td>
<td>+1.6%</td>
<td>-0.5%</td>
<td>-0.9%</td>
</tr>
</tbody>
</table>

---
Li$^8(\beta^-)$Be$^8(\alpha)$He$^4$

Fig. 13
Analysis

Under the assumption that the beta decay and alpha dissociation are two very close but separate events, i.e., as opposed to a four-body dissociation of two alphas, a beta, and a neutrino, the alpha spectrum resulting from the population of a single level in Be$^8$ has been derived by Wheeler$^{46}$ and modified by Bonner et al.$^{34}$ by the inclusion of a penetrability factor. The resulting expression for the number of alphas, N, as a function of dissociation energy $2E\alpha$ is

$$\frac{N(2E\alpha)}{P_f} = \frac{(\xi - 2E\alpha)^5}{(E - E_{gs} - E_0)^2 + 1/4\Gamma^2}$$  \hspace{1cm} (25)$$

where $\xi$ is the total energy difference between the ground state of Li$^8$ or B$^8$ and two alpha particles at infinity, $E_0$ is the energy of the level in Be$^8$, $E_{gs}$ is the excitation energy of the ground state of Be$^8$ (94 Kev), $\Gamma$ is the width of the level in Be$^8$ and $P_f$ is the penetrability of one alpha in the field of another.

The first step in the analysis of the spectra was a test of the $(\xi - 2E\alpha)^5$ dependence. Since the parameters in the denominator of Eqn. (25) and $P_f$ concern only Be$^8$, they will be the same for both the Li$^8$ and B$^8$ decay schemes, giving for the ratios of the spectra

$$\frac{N_{B^8}}{N_{Li8}} = \left[\frac{\xi_{B^8} - 2E\alpha}{\xi_{Li8} - 2E\alpha}\right]^5$$ \hspace{1cm} (26)$$

The test of this expression is displayed with the data in Fig. 12. The dots correspond to the Li$^8$ decay and the crosses to B$^8$. The lower
line represents the best line through the $\text{Li}^8$ data, while the upper line is the lower line times the ratio (26). It is seen that the expression seems valid over the entire range, at least to the accuracy of the counting statistics. Furthermore, these results confirm the expectation that, apart from such an energy dependent factor, the alpha spectra obtained from $\text{Be}^8$ and $\text{Li}^8$ should be identical.

Expression (25) was next calculated for the $\text{Li}^8$ decay assuming only the transition to the first excited state in $\text{Be}^8$. The parameters of the state which yielded the best fit are shown in Table VI under "Present Work". The results of this calculation are shown in Fig. 14 as the line composed of long dashes. This is to be compared with the heavy solid line representing the best line through the data. The fit is very good at low energies but shows significant departures above $2E\alpha = 6$ MEV. We assume that the departure results from transitions to a higher level in $\text{Be}^8$. The difference in the calculated and experimental curves as shown by the light solid line in Fig. 14 should then correspond to the transitions to this higher level. Finally, a calculation using Eqn. (25) was made with the values of $E_0$ and $\Gamma$ of the now firmly established second excited state in $\text{Be}^8$, Table VI. The results are shown as the light dashed line in Fig. 14. The spin and parity of this state are known to be $4^+$, which required the use of $P_4$ in the calculation. The best fit was obtained with an interaction radius of 5.7 fermis. The composite curve, calculated simply as the sum of the transitions to the two states, is shown as the short dashed lines in Fig. 14. A similar analysis of the $\text{Be}^8$ spectrum was made with
TABLE VI
Parameters of the First Two Levels in Be$^8$

<table>
<thead>
<tr>
<th>Level in Be$^8$</th>
<th>E$_0$ in Be$^8$ (MEV)</th>
<th>$\Gamma$ in Be$^8$ (MEV)</th>
<th>J$\pi$</th>
<th>Interaction Radius (fermi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Work</td>
<td>first 2.9</td>
<td>2.2</td>
<td>2$^+$</td>
<td>5.7</td>
</tr>
<tr>
<td></td>
<td>second 11.7</td>
<td>6.7</td>
<td>4$^+$</td>
<td>5.7</td>
</tr>
<tr>
<td>He$^4\alpha\alpha$He$^4$ Data</td>
<td>first 2.9</td>
<td>2.0</td>
<td>2$^+$</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>second 11.7</td>
<td>6.7</td>
<td>4$^+$</td>
<td>4.44</td>
</tr>
</tbody>
</table>

the same parameters as used for the Li$^3$ case. Although not shown, identical results were obtained. On the basis of the assumptions made above, the fractions of the transitions proceeding to the second excited state were found to be 8% and 10% for Li$^8$ and B$^8$, respectively. This is to be compared with 10% for the Li$^8$ case as calculated from the beta spectra obtained by magnetic analysis$^7$.

The spectra appear to be rather well accounted for by considering contributions from only the first two levels in Be$^8$. The discrepancies that are apparent might be accounted for by recognizing that beta decay to the second excited (spin 4) state in Be$^8$ is a $J = 2$(no) transition, which is second forbidden. This fact introduces the possibility that additional energy dependent factors need to be included in the numerator of Eqn. (25) which could bring agreement with the data. Further attention will be given to this point.
CHAPTER IV

HALF-LIFE DETERMINATION OF BORON-8 AND NITROGEN-12

Before \( {\text{He}}^3 \) was available for acceleration in Van de Graaff generators, \( {\text{B}}^8 \) and \( {\text{N}}^{12} \) could be produced only by high energy particle or \( \gamma \) ray bombardment in excess of 18 MEV. Because of the low yields and high backgrounds accompanying these methods, half-life determinations were difficult, the uncertainties in the quoted values being greater than 10%, making the half-lives of the least well known among the high energy beta emitters of the light nuclei. Using the \( \text{Li}^6(\text{He}^3,n){\text{B}}^8 \) and \( \text{B}^{10}(\text{He}^3,n){\text{N}}^{12} \) reactions, the Q-values of which are -1.976 and +1.46 MEV, respectively, the nuclei could be produced in abundance at relatively low bombarding energies. (Approximately 4.5 MEV was used in both cases.)

The accurately known half-lives of \( \text{Li}^8 \) and \( \text{B}^{12} \) were each measured during the same run and under identical conditions as their respective "mirror" nuclei \( \text{B}^8 \) and \( \text{N}^{12} \). Since the members of both mirror pairs were known to have at least comparable half-lives, the possibility of undetected instrumental errors was reduced. The comparison nuclei were produced with the \( \text{Li}^7(d,p)\text{Li}^8 \) and \( \text{B}^{11}(d,p)\text{B}^{12} \) reactions, the Q-values for both of which are positive. Sufficient yield from both reactions was obtained at a bombarding energy of 3 MEV.

Since the four nuclei are all high-energy beta emitters, the end-point energies being 14.06 MEV, 13.10 MEV, 15.44 MEV, and 13.30 MEV for \( \text{B}^8 \), \( \text{Li}^8 \), \( \text{N}^{12} \), respectively, it was possible to use the same instrument for the detection of all decays: A crude plastic
phosphor scintillation spectrometer, consisting of a Pilot B plastic scintillator 10 cm. long and 7.5 cm. in diameter mounted on a 6363 Dumont photomultiplier tube. By pulse height discrimination, all pulses corresponding to beta energies of less than approximately 5 MEV were excluded, thus, eliminating all background except that produced by cosmic rays and possibly fast neutrons produced by contaminations on the beam-defining slits and the beam stop which intercepted the beam during the counting period.

The lithium targets were made by evaporating a thick layer of the pure metal (natural lithium for the Li\textsuperscript{7} target and 96% enriched in Li\textsuperscript{6} for the Li\textsuperscript{6} target) onto 1-mil nickel foils. Possible reactions with the nickel in addition to the nitrogen, oxygen, and other impurities which combined with the targets during transfer to the target chamber were of no consequence since no nuclei could be produced which emit betas with energies above the discrimination level. The boron targets were also prepared on 1-mil-thick nickel foil backings. The metal (natural boron and 96% enriched boron-10 for the B\textsuperscript{11} and B\textsuperscript{10} targets, respectively), being in powder form, was placed on the foil and secured by allowing shellac thinned with acetone to diffuse through. As above, reactions with elements in the bonding agent could produce no interfering sources of betas. The thickness of the targets was of no particular importance; they were simply made as thick as it was conveniently possible in order to obtain adequate yield. Also, possible target inhomogeneities had no effect on the results of the measurements.
BLOCK DIAGRAM OF
HALF-LIFE MEASUREMENT APPARATUS

Fig. 15
The technique which was developed to measure the decay times is applicable over a broad range of half-lives: from several minutes to less than a millisecond. The rough data are of sufficient accuracy to yield a value better than 3%; and after applying two small corrections, an accuracy of a few tenths of a percent is attainable. The method was built around a 256-channel pulse height analyzer, the channels of which were made to correspond to a time scale instead of the usual energy scale. This was accomplished by introducing pulses of a constant amplitude to the analyzer while its base line was swept at a constant rate; thus, the distribution accumulated corresponded to the counting rate as a function of time. Since, for an exponential decay, the time origin is of no significance, it was possible to accumulate counts for any desired number of sweeps, thus reducing statistical uncertainties.

The base-line voltage was swept in the case of $^8\text{B}$ and $^8\text{Li}$ by a motor-driven variable voltage supply, the sweep rate being such that each channel corresponded to approximately 0.03 second. For the faster sweep required in the $^{12}\text{B}$ and $^{12}\text{N}$ measurements, the linear sweep output from a Tektronix 515 oscilloscope was used. The sweep rate for this case corresponded to approximately 0.3 millisecond per channel. The sweep rates were accurately calibrated by accumulating counts from a 1-kilocycle crystal controlled oscillator under conditions identical to those used in obtaining the data. A brief discussion of the base-line sweep circuit is given in Appendix II.

The pulses produced by the betas were prepared for the analyzer in the following manner, as shown in block diagram in Fig. 15:
From the cathode follower of the spectrometer, the pulses were amplified by a linear amplifier before entering a single channel analyzer which performed two important functions. It served as the pulse height discriminator to eliminate the low-energy background and it converted the pulses from the beta spectra into pulses of a constant amplitude. The output pulses from the single channel analyzer, being approximately 20 volts negative, were inverted and amplified to 60 volts by a simple one-tube amplifier. These pulses, satisfying the requirements of rise time and pulse length, were then fed into the analyzer.

It was, of course, necessary that the beam be gated during the counting portion of the cycle. This was accomplished for the $^8\text{Be}$ and $^7\text{Li}$ measurements by a mechanical shutter. For the faster pulsing times required with the $^{12}\text{N}$ and $^{12}\text{B}$ decays, an electrostatic deflector was used. Because of the neutral component of the beam which suffered no deflection by the electrostatic field, it was not possible to simply deflect the beam off the target; instead, it was found necessary to deflect onto the target with 2 to 3 kilovolts. Approximately twice that voltage was used to deflect the beam onto a tantalum beam stop.

For the $^7\text{Li}$ and $^8\text{Be}$ measurements, the various controls were synchronized in a semi-automatic fashion by a motor-driven cam assembly, while for $^{12}\text{N}$ and $^{12}\text{B}$ a completely automatic electronic control was used which utilized a variable frequency oscillator to drive two square wave-forming circuits, one of which controlled the electrostatic deflector and the other actuated a circuit which
gated the photomultiplier by reversing the voltage on the focus electrode with respect to the photocathode. The purpose of the gating was to prevent the accumulation of counts during the return of the base-line control voltage to its initial value in preparation for the next cycle. The operations controlled by the cam assembly and the oscillator were analogous and may best be described by a consideration of the sequence of events, displayed in Fig. 16, during one cycle, which was approximately 13 seconds for the $^8$Be, $^8$Li case and 0.2 seconds for $^12$N and $^12$B. We shall consider that $t = 0$ marked the beginning of bombardment. The control signal for "beam-on" also triggered the sweep of the base-line voltage control of the analyzer. After a bombardment of several half-lives (until saturation was reached in all cases), the beam was deflected off the target; and after a brief delay, the counter was turned on. Immediately after the counter was operating, the base-line voltage was such that the counts "entered" the channels. After the pulses had "swept" through the channels, the counter was gated off, the base-line voltage returned to its initial value, and the cycle was repeated. The process was allowed to run until adequate counting statistics were obtained.

To obtain an accuracy of better than 3%, two small corrections were necessary: One for the nonlinearity of the base-line voltage sweep and a second to allow for the dead time of the analyzer. The nonlinearity of the sweep not only caused a variation in channel width but it also resulted in a distortion of the time scale. The integrated number of counts per sweep from channel one to a given
CONTROL PHASING DIAGRAM

Fig. 16
channel gave the time to which that channel corresponded. Since the calibration oscillator frequency was 1 kilocycle per second, the time was given directly in milliseconds. The corrections for the error due to the variation in channel width resulting from the sweep nonlinearity and analyzer dead-time were obtained simultaneously. Counts were collected from a Co\(^{60}\) gamma source giving a constant counting rate. Such data were taken at several different counting rates and cross plots were made showing the percent of the counts lost in a given channel when counting at a given counting rate. This correction was small (less than 2.5\%) and although the errors in the correction were rather large, they introduced only a small uncertainty in the final result.

The data for the four half-life measurements are shown in semi-logarithmic plots in Fig. 17 and Fig. 18. A least-squares fit was made to all the data which were denoted by the solid lines in the figures. Table VII displays the results of the present study and is compared to the data quoted in the literature. Also shown in the table are the log ft values for the decays, calculated using the latest values of the end-point energies (Table VIII).
Li$^{8}$
$T_{1/2}=0.84$ SEC

B$^{8}$
$T_{1/2}=0.79$ SEC

TIME (SECONDS)

COUNTS PER UNIT TIME
<table>
<thead>
<tr>
<th></th>
<th>$^8\text{B}$</th>
<th>$^6\text{Li}$</th>
<th>$^{12}\text{N}$</th>
<th>$^{12}\text{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-Lives Present Work</td>
<td>0.79 ± 0.02 sec</td>
<td>0.84 ± 0.02 sec</td>
<td>11.47 ± 0.05 ms</td>
<td>20.35 ± 0.10 ms</td>
</tr>
<tr>
<td>Log ft</td>
<td>5.64</td>
<td>5.59</td>
<td>4.06</td>
<td>4.06</td>
</tr>
<tr>
<td>Half-Lives Values from Ayzenberg and Lauristen (1959)</td>
<td>0.77 ± 0.02 sec</td>
<td>0.84 ± 0.004 sec</td>
<td>11.43 ± 0.05 sec</td>
<td>20.34 ± 0.50 ms</td>
</tr>
<tr>
<td>Log ft</td>
<td>5.72</td>
<td>5.60</td>
<td>4.17</td>
<td>4.18</td>
</tr>
</tbody>
</table>
A TEST OF A THEORY OF THE VECTOR INTERACTION IN BETA DECAY USING THE BORON-12, NITROGEN-12, LITHIUM-8, AND BORON-8 BETA SPECTRA

Introduction

A theory has been recently advanced by Feynman and Gell-Mann concerning the vector interaction in beta decay. According to the theory "...analogous gamma and beta transitions in light nuclei have proportional matrix elements, as far as the vector interaction is concerned. In particular, the vector interaction gives rise to a 'weak magnetism' analogous to the magnetic effects that induce the emission of M1 photons. This 'weak magnetism' obeys Gamow-Teller selection rules and interferes with the axial-vector coupling, distorting the spectra of high-energy beta transitions with $\Delta J = 1$ (no)."\textsuperscript{1} The effect has also been discussed in later work by Morita\textsuperscript{48} and again by Gell-Mann\textsuperscript{49}.

An experiment has been suggested by Gell-Mann\textsuperscript{1} by which this theory may be tested. The experiment is based on the fact that the predicted distortion is found to change signs when going from neutron to positron emission. It is this important point which makes the experiment feasible. Gell-Mann suggests that the neutron and positron decays for analogous transitions in which $\Delta J = 1$ (no) be accurately measured. The best example of such decays is $^{12}$B and $^{12}$N. Then these spectra may be compared, thus, eliminating many systematic errors; and furthermore, in the comparison the effect is doubled. The comparison is made as follows: The difference in end-point energies is allowed for by factoring the Fermi spectra from the experimental distributions. Then the ratio of the spectra is taken as a function of beta energy. It is
in this ratio that the effect is to appear as a linearly increasing function of the energy, having a variation between 0 and 10 MEV of approximately 13%.

The betas associated with these decays have end-point energies in excess of 13 MEV as shown in Table VIII. This relative large energy corresponds to electron momenta of approximately 50,000 gauss-cm. Few magnetic beta spectrometers exist which are capable of bending such electrons and none at The Rice Institute. If this experiment was to be done here, the choice had to be made between building such a magnetic analyzer or attempting the measurements with a scintillation spectrometer. Because of the time element involved, it was decided to attempt the measurement with a simple scintillation spectrometer. At first sight, this seems a rather crude technique with which to attempt to confirm the Gell-Mann theory; however, in performing some of the experiments previously discussed in this thesis, it was desirable to obtain reasonably accurate beta spectra from the decays under study (Chapters II and IV). For this purpose a rather crude plastic scintillation spectrometer was employed with various collimating systems. The spectra thus obtained were strikingly similar to those obtained by magnetic analysis. The compensating feature in this method is that roughly the same distortions should appear in both the $^6$B and $^8$N spectra, since they may be obtained under identical circumstances. This is further enhanced by the fact that a similar analysis may be made using the $^6$B and $^7$Li spectra which have no Gell-Mann effect. Additional incentive is given by the fact that the confirmation or not, as the case may be, of this theory will shed more light on the nature of beta interactions; thus, it is worthy of considerable effort.

- 50 -
TABLE VIII

The Beta Decays and Their End-Point Energies

<table>
<thead>
<tr>
<th></th>
<th>B\textsuperscript{12}</th>
<th>N\textsuperscript{12}</th>
<th>Li\textsuperscript{8}</th>
<th>B\textsuperscript{8}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay</td>
<td>$\beta^-$</td>
<td>$\beta^+$</td>
<td>$\beta^-$</td>
<td>$\beta^+$</td>
</tr>
<tr>
<td>EPE (MEV) (Calculated from Masses)</td>
<td>13.38</td>
<td>16.44</td>
<td>13.10</td>
<td>14.06</td>
</tr>
</tbody>
</table>

Experimental Method

The scintillation crystal used to observe the betas was a Pilot B plastic phosphor 9 centimeters in length. This length was found necessary to absorb the total energy of the most energetic betas (16.44 MEV from N\textsuperscript{12}), the range of which was obtained from a table of theoretical ranges assuming a stopping power equivalent to that of lucite\textsuperscript{50}. A relatively large diameter crystal, 7.5 centimeters, was used; however, to minimize the effect of scattering from the crystal walls, the betas were collimated into a small area at the center of the crystal.

The energy scale for the spectra was obtained in terms of the maximum energy of Compton recoil electrons from gamma rays. Those gammas used were the 2.62 MEV gamma from the first excited state in C\textsuperscript{12} produced by a Pu-Be neutron source (the neutrons being moderated by placing approximately 6 inches of polyethylene between the source and detector.) To determine the actual point on the experimental Compton spectrum corresponding to the maximum Compton electron energy, the resolution function was graphically integrated over the theoretical Compton distribution and...
the fraction of the distance to the peak of the integrated distribution was obtained by a comparison with the theoretical expression. This point on the experimental distribution was taken as the maximum Compton energy. The fraction of the distance to the peak was found to be 0.75 and 0.70 for the thorium and Pu-Be gamma sources, respectively. The resolution used above was obtained by observing the internal conversion electrons from Bi\(^{207}\) and Cs\(^{137}\) sources, the energies of which are 0.973 and 0.662 MeV, respectively. Then assuming the usual \(E^{-1/2}\) dependence of the resolution on energy, with which these points agreed, the resolution was calculated for the desired energies, being 1.8% at 1 MeV.

Early work showed distortions of the energy scale at high electron energy. Investigations showed that this distortion was a function only of the size of the pulse from the photo-tube, being the result of saturation at the last few dynodes. The effect was eliminated by using a relatively low voltage (750 volts) on the photo-tube.

On the basis of the reproducibility of the apparent end-points of the spectra, it is estimated that the relative uncertainties in the energy scales between spectra are less than 2%, and it is believed that the absolute energy scale is better than 4%, as estimated from comparisons with published spectra.

Various types of collimating systems were tried during the course of this work. An early type utilizing polyethylene defining apertures is shown in Fig. 20b. The purpose behind using polyethylene was to have a low-Z material to intercept the particles, thus, reducing the yield of bremsstrahlung. However, due to the large surface of material
inside the collimator rings which is "visible" to the betas from the target, a relatively large number of betas suffered small angle scatterings into the crystal. This produced rather large distortions in the spectra at low energies. An improved collimator design is shown in Fig. 20a and is made of aluminum with a lead-lined aperture. The relative dimensions of the collimating systems are indicated by the scale. The quality of the spectra obtained using these collimators is indicated in Fig. 20 by the comparison of the \( B^{12} \) spectra thus obtained to that obtained with a magnetic analyzer by Hornyak and Lauritsen\(^4\).

With the large volume crystal, which was essential for this measurement, delayed counting (taking advantage of the half-lives of the nuclei) was necessary to eliminate background due to neutrons and prompt gammas produced in the target. The same counting procedure was involved here as discussed in Chapter III. The beam was deflected onto the target by an electrostatic deflector, the voltage on which was controlled by one of the two square wave outputs of a variable frequency oscillator. The second signal gated the photomultiplier tube so that counts were accumulated only while the beam was off the target. The cycle period for the \( B^{8} \)-Li\(^8\) spectra was 0.2 second while that for \( B^{12} \) and \( N^{12} \) was 0.02 second. The counting and bombarding periods were approximately equal.

The reactions used to produce the nuclei were (1) \( Li^{6}(He^{3},n)B^{8} \), (2) \( Li^{7}(d,p)Li^{8} \), (3) \( B^{10}(He,n)N^{12} \), and (4) \( B^{11}(d,p)B^{12} \). For the reactions involving lithium, the targets were made by evaporating lithium metal (96% enriched and natural for the \( Li^{6} \) and \( Li^{7} \) targets, respectively)
into thin wafers and supporting them on 0.5 mil nickel foil. The thicknesses were determined very roughly by a simple micrometer measurement from which the energy loss was calculated and found to be less than 25 KEV in all cases. The nickel foil backings were held against an O-ring to form the vacuum seal in such a way that no other material was needed for support between the target and crystal.

The first step in obtaining a beta spectrum was the normal alternating bombardment and counting periods. The yield thus obtained included the small background produced by delayed gamma and beta activity in the target and nickel backing plus the neutron background produced by reactions with contaminants on the tantalum beam stop. The largest component of this background, the gamma yield, was determined by repeating the process used to obtain the spectrum with a polyethylene cylinder between the target and crystal as indicated in Fig. 19a and Fig. 19b. This yield contributed about 10% of the counts in the spectra at 3 MEV and was negligible above 6 MEV. The subtraction was made by complementing the numbers composing the original spectrum while still in the memory of the 256-channel analyzer and adding the background to this complemented spectrum. At this point, the spectra still included the small component of low-energy betas produced in the target and nickel backing (including the 0.96 MEV C\textsuperscript{11} and 3.7 MEV Cu\textsuperscript{59} activities, for example). Although the energies of all such betas produced are below region of most importance for the comparison of the spectra, their contribution was removed by two additional steps. The target used above was replaced by the target of the other isotope, i.e., if the B\textsuperscript{8} spectra
had been observed, the Li$^6$ target would have been replaced by the Li$^7$ target which had been made in an identical fashion for the (d,p) reaction. The substituted target in all cases produced no beta activity except that from the small amount of original target isotope (which was of no consequence), yet it reproduced exactly the background effects of the target backing and possible target contaminations. With the memory of the analyzer still complemented, the contribution from the substitute target was added. Then the polyethylene absorber was put in place, the memory was uncomplemented and the contribution from the gammas in the preceding step was removed. The betas thus removed accounted for only 1% of the counts at 3 MeV and a negligible number above 5 MeV. The remaining spectrum was the desired beta yield plus the small residual gamma yield which was not completely subtracted due to absorption in the polyethylene.

Results

The B$^{12}$ spectra shown in Fig. 20 were obtained in the manner just discussed, and a comparison with the spectrum obtained with magnetic analysis included in the figure indicates the distortions involved; however, it is hoped that they will be approximately equal for corresponding energies of all spectra. In the actual comparison of the spectra, the only corrections applied were for energy loss in the material between the target and crystal (target layer, nickel backing and air, comprising approximately 150 keV). Possible distortion effects will be discussed later but no corrections were applied since in most cases, due to the lack of high-energy experimental data, the uncertainties involved were of the same order of magnitude as the effect itself.
The Fermi-Kurie plots of the four spectra, \( B^8 \), \( Li^8 \), \( N^{12} \), and \( B^{12} \), obtained with the improved collimator shown in Fig. 19a are given in Fig. 21. It was necessary to calculate the Fermi functions, \( f \), for these spectra since none were available for such high-energy transitions. The calculation was made using the expression\(^{52}\)

\[
f(Z, \eta) = \eta^{2+2S} e^{i\pi \delta} \left| \Gamma (1 + S + i\delta) \right|^2,
\]

where the \( ^* \) sign refers to negative or positrons, respectively,

\[
\eta = \text{electron momentum},
\]

\[
S = (1 - Z^2/137^2)^{1/2} - 1
\]

\( Z = \text{atomic number of product nucleus} \),

and

\[
\delta = \frac{Z(1 + \eta^2)^{1/2}}{137\eta}
\]

The deviations of the Fermi-Kurie plots from a straight line indicate the experimental distortions in the spectra of \( B^{12} \) and \( N^{12} \); however, a greater curvature is observed in the \( Li^8 - B^8 \) cases which results from the width of the 2.9 MEV state in Be\(^8\) to which the transitions proceed.

Comparison of Spectra

In the actual comparison of the spectra, as mentioned earlier, the different end-point energies were allowed for by factoring out the

\*The calculations were made with an I.B.M. 650 Computer used through the courtesy of the Shell Research Laboratory, Houston, Texas. The sub-routine for the \( \gamma \) function of the complex argument was supplied by Robert C. Young.
Fig. 21a

Fig. 21b
Fermi spectrum, the calculations of which were made with the use of the above-mentioned Fermi functions and the end-point energies given in Table VIII. The spectra thus resulting are shown in Fig. 22. The ratio of the residual $B^{12}$ to $N^{12}$ spectra were then taken as a function of electron energy. According to the Gell-Mann theory, this ratio should be proportional to $1 + (16/3)AE$ where $E$ is the electron energy and

$$A = (2.34 \pm 0.25)/M$$

(27)

with $M$ the proton mass. The constant is dependent on the width of the analogous gamma transition of $C^{12}$. An analogous comparison was made of the $Li^8$ and $B^8$ spectra and this ratio should in theory be a constant. The resulting ratios are shown in Fig. 23; and as is observed, both sets of spectra showed deviations in the direction predicted by the theory, which is denoted by the heavy solid line. However, the magnitude of the distortion is greater for the $B^{12} - N^{12}$ case. One may, however, assume that the observed variation in distortion magnitudes results from the Gell-Mann effect. The ratio of the observed distortion effects was then taken and is displayed as the dashed line in Fig. 22.

This line compares favorably with the theoretical estimate. The data obtained with the polyethylene collimator were similarly analyzed and equivalent results were observed. Thus, it appears that we have, in fact, observed the Gell-Mann effect. However, one cannot be certain that the observed distortion is not simply the result of the difference in end-point energies (which is greater for the $B^{12} - N^{12}$ case than for $Li^8$ and $B^8$) or possibly some other effect.
Fig. 22a

Fig. 22b
Possible Distortion Effects

We shall now discuss possible energy dependent effects which tend to distort the spectra and may, in fact, produce the observed result. Of the effects considered, the following are believed to be the most important:

(1) Collimator scattering: This effect may well produce some of the largest errors involved; however, the problems involved are tremendous, since it is not only necessary to calculate the magnitude of scattering but the energy spectrum produced. Such calculations, if carried out adequately to produce reliable results, would require Monte Carlo calculations and the use of a high-speed computer. The effect may, however, be observed rather crudely by a comparison of the crystal observed spectra in Fig. 20, since the only difference is the design of the collimator.

(2) Counter resolution distortion: The counter resolution was determined, as mentioned earlier, at 0.662 and 0.973 MEV by internal conversion electrons. Then on the assumption that the resolution follows the \( E^{-1/2} \) dependence, the spectral distortion was calculated using a process which involved the solution of the integral equation given in Eqn. (23) of Chapter III by matrix inversion.\textsuperscript{53} Based on the above estimate of the magnitude of the resolution broadening, the distortion effect was found to be negligible. Other unknown effects may enter, however, to harm the resolution

\*The matrix inversion was carried out with the above-mentioned I.B.M. 650 Computer.
at high energy where no resolution data are available. One would suspect this when observing the tailing effect of the $^{12}\text{B}$ Fermi-Kurie plot in Fig. 21a which did not exist in a similar plot of the spectrum obtained by magnetic analysis$^{17}$.

(3) Scattering from the crystal walls: A method has been discussed by which one may calculate the number of electrons remaining within a cone of a given angle after traveling a given distance in matter$^{51}$. This procedure was applied to calculate the complement of this result. Only tentative results were obtained, the order of magnitude of which indicated distortions of, at most, 2 or 3% to the spectra.

We shall now simply list the other possible distortion effects considered which, on the basis of rough calculations, indicated that distortions of a very few percent would be expected:

(4) Back scattering from the crystal face$^{54}$,

(5) Radiative losses in the crystal$^{51}$, and

(6) Positron annihilation within the crystal.

Conclusions

The possible distortion contribution of any one effect considered was found to be small; however, collectively they all may have a significant effect. Without a tedious and detailed analysis of all these problems, little more may be said. Thus, we conclude that in this experiment an effect identical to (although larger than) the predicted Gell-Mann effect was observed; however, more work is necessary before unambiguous results may be obtained.
APPENDIX I

ENERGY CALIBRATION

Precise energy measurements were made by calibrating the accelerator's 90° analyzing magnet with reference to the ground state threshold of the Li$^7$(p,n)B$^8$ reaction using both the atomic and molecular beams. The probe of a Pound magnetometer containing lithium hydride was situated near the accelerator vacuum tube between the pole pieces of the analyzing magnet. The field strength at this point was then measured very precisely in terms of the frequency of the Larmor precession of protons or Li$^7$ nuclei. The frequency of the oscillator was matched to the Larmor precession frequency by centering the absorption signal on the screen of an oscilloscope. The signal from the magnetometer oscillator unit was fed into a Hewlett-Packard electronic counter which continuously monitors the frequency.

In terms of the frequency of Larmor precession, $f$, the magnetic field, $H$, is

$$H = \frac{hf}{2\mu}$$  \hspace{1cm} (2)

where $h$ is Plank's constant and $\mu$ is the magnetic moment of the proton or Li$^7$ nucleus.

Upon equating the centrifugal and centripetal forces on the accelerated particles in the magnetic field we obtain

$$HeV = \frac{MV^2}{R}$$  \hspace{1cm} (3)

where $e$ is the electronic charge, $V$ and $M$ are the accelerated particles velocity and mass, respectively, and $R$ is the radius of curvature of the
particles in the magnetic field. \( R \) is determined by the beam defining slits. Solving for the momentum in Eqn. (3) we have

\[
P = MV = \text{He}R
\]

combining this result with Eqn. 2, we have

\[
P = \frac{\text{he}R}{2\mu} f
\]

The relativistically invariant relation between the energy and momentum is

\[
W^2 - c^2p^2 = (M_0c^2)^2
\]

where \( W \) is the total energy of the particle and \( M_0 \) is its rest mass. Now

\[
W = E_R + M_0c^2
\]

where \( E_R \) is the relativistic kinetic energy. From these relations we obtain

\[
(E_R + M_0c^2)^2 - (M_0c^2)^2 = c^2p^2
\]

\[
E_R^2 + 2M_0c^2E_R = c^2p^2
\]

or

\[
E_R\left[1 + \frac{E_R}{2M_0c^2}\right] = \frac{p^2}{2M_0}
\]

Then by combining Eqn. (5) and Eqn. (10) we obtain

\[
E_R\left[1 + \frac{E_R}{2M_0c^2}\right] = \frac{\hbar e^2R^2}{8\mu^2 M_0} f^2
\]

which is the relativistically correct relationship between the energy and the frequency. Since at Van de Graaff energies the term \( E_R/2M_0c^2 \) is very
much less than 1, it is possible to treat it as a correction term and calculate it in terms of the uncorrected energy, $E$. This eliminates the solution of the quadratic equation. For convenience we write

$$K = \frac{\hbar^2 e^2 R^2}{8\mu^2} \quad (12)$$

Upon calibrating with accurately known thresholds or resonances, one finds that at higher energies there is a discrepancy between the correct value and that obtained with Eqn. (11) when the constant has been determined by the Li$^7$(p,n) threshold$^{11}$. This divergence is believed to be due to a combination of effects:

(1) As the magnet reaches saturation the frenging field causes the particles to enter the beam defining slits at a slightly different angle and, thus, changes the radius of curvature.

(2) The probe of the magnetometer measured the magnetic field at only one point which is approximately 2 cm. from the path of the beam. Thus, the probe cannot be expected to see the average field experienced by the particles. Then, too, as higher magnetic fields are reached this difference is expected to become even greater. The relation between the variation in the energy with that of the magnetic field may be derived as follows:

$$(E_R + \Delta E)(1 + \frac{E + \Delta E}{2M_o c^2}) = \frac{K}{M_o}(E' + \Delta E')^2 \quad (13)$$

where we have replaced $E_R$ by $E$, the uncorrected energy in the second order terms. Since $\frac{\Delta E}{E}$ and $\frac{E}{2M_o c^2}$ are both small quantities at Van de Graaff energies, $\frac{\Delta E}{2M_o c^2}$ will be negligible. If we divide through by Eqn. (10) and neglect small terms we obtain

- iii -
\[(1 + \frac{AE}{E}) = (1 + \frac{\Delta f}{f})^2 \quad (14)\]

and since \(f\) is proportional to \(H\)

\[(1 + \frac{AE}{E}) = (1 + \frac{\Delta H}{H})^2 \quad (15)\]

We see, then, that the error in particle energy is a function only of the magnetic rigidity of the particle, that is, the correction \(\frac{AE}{E}\) will be the same for all particles bent through the magnet at the same field strength. A curve showing this correction as a function of the frequency of the \(\text{Li}^7\) Larmor precession is given in Fig. 1'. This curve was constructed from data obtained by R. A. Chapman\(^\text{11}\) using several accurately known neutron thresholds and \(\text{C}^{13}\) \((\alpha, n)\)\(^{16}\) resources.

Finally, we have for the corrected relativistic energy of a particle as a function of the frequency

\[E_R(1 + \frac{AE}{E})(1 + \frac{E}{2M_0c^2}) = \frac{Kf^2}{M_0} \quad (16)\]

where \(K\) is determined for the \(\text{Li}^7(p, n)\) threshold calibration point which is at \(1.8811 \pm .0004\) MEV\(^\text{10}\), making \(\frac{AE}{E} = 0\) at this value.

The uncertainty in the calibration is estimated to be less than 10 KEV for bombarding energies of less than 3.5 MEV and no greater than 20 KEV above this energy.
Fig. 1A

FREQUENCY OF Li\textsuperscript{7} SIGNAL (MEGACYCLES)

$\frac{\Delta E}{E}$ (%)
APPENDIX II

CONNECTION OF THE BASE-LINE VOLTAGE SWEEP
TO THE 256-CHANNEL ANALYZER

The discussion in the text concerning the method by which the base line of the pulse-height analyzer was swept was given in rather general terms, since the method is applicable to any type of multichannel analyzer. We shall include here, however, a brief discussion to describe the actual circuit employed for the $^B_12$ and $^N_12$ half-life measurements. (This arrangement is also applicable to the $^B_8$ and $^B_8$ measurements; however, it was developed after these half-lives had been measured.)

It was necessary that the constant-height input pulses from the beta counter "move" toward increasing channels because of the dead-time of the analyzer which increases linearly with channel (being $16 + n/2$ micro-seconds where $N$ is the channel number). To accomplish this the voltage controlling the base-line position must decrease from 140 to 0 volts during the sweep. However, the linear sweep (saw-tooth) output of the 515 Tektronix oscilloscope used for this voltage control varied from 0 to 140 volts. To obtain the proper voltage change, it was necessary to make the connection as shown in Fig. 2A. Here it is seen that the chassis of the scope was insulated from ground and connected to the analyzer's base-line adjustment circuit, where normally the base-line potentiometer (R-132 of the R.C.L. 256-channel analyzer) is connected. Then the saw-tooth output was connected through 240 volts of batteries to ground through the square wave signal input

- v -
BASE-LINE VOLTAGE CONTROL CIRCUIT

140 v (regulated)

open

base-line potentiometer

chassis ground

Tektronix 515 oscilloscope

saw-tooth output

batteries

control phasing generator

analyzer base-line adjustment circuit

scope input

Fig. 2A
cable from the phasing control generator. This square wave, used here to trigger the sweep also controls the voltage on the beam deflector plates.
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