GAMMA RADIATION FROM THE PROTON BOMBARDMENT OF LITHIUM SIX

by

Thomas Kennedy Alexander

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The reaction \( \text{Li}^6(p, \gamma)\text{Be}^7 \) has been investigated using 0.4 to 1 Mev. energy protons incident on isotopically separated \( \text{Li}^6 \) targets. Capture gamma radiation to the ground state and the 430 Kev. state in \( \text{Be}^7 \) has been observed; some 62% of the transitions go to the ground state. The ratio of intensities does not change significantly with energy, nor with angle of observation at \( E_p = 750 \) Kev. The differential cross section with the counter at 90° to the proton beam and \( E_p = 750 \) Kev. is about \( 2 \times 10^{-32} \text{cm}^2/\text{steradian} \). The combined angular distribution of the two gamma rays is
\[ 1 + (1.05 \pm 0.15) \cos^2 \theta \] at \( E_p = 750 \) Kev. The \( Q \) value for the reaction is \( 5.66 \pm 0.03 \) Mev. in fair agreement with that calculated from mass values.
ACKNOWLEDGEMENTS

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CHAPTER I

Introduction

The location and properties of the energy levels of light nuclei are known in some detail as illustrated by the recent compilation of Ajzenberg and Lauritsen (Ajzenberg, 1955). The increasing volume of new material on all aspects of nuclear structure (e.g., mass values, excitation functions, energy levels and spin values) brings nearer the prospect of discovering a suitable nuclear force hypothesis and the formulation of a theory of nuclear structure.

This thesis is a study of the $^{6}\text{Li}(p, \gamma)^{7}\text{Be}$ reaction which had not been observed before the present investigation.

If a proton is projected with energy less than 2 Mev. at the isotope $^{6}\text{Li}$, two reactions are energetically possible:

$$^{6}\text{Li} + p \rightarrow ^{3}\text{He} + ^{4}\text{He}$$
$$\rightarrow ^{7}\text{Be} + \gamma$$

The most probable reaction, $^{6}\text{Li}(p, \alpha)^{3}\text{He}$, $Q = 4.023 \pm 0.002$ Mev., has been observed and studied extensively by detecting the alpha particles and the recoil $^{3}\text{He}$ nuclei. The first investigation of the reaction with separated $^{6}\text{Li}$ targets was made by Oliphant et al. (Oliphant et al., 1934). A summary of the early investigations can be found in the articles by Oliphant et al., while more recent results are compared in the article by Bashkin and Richards (Bashkin, 1951). The yield of the $^{3}\text{He}$ nuclei showed a
broad low maximum for $E_p = 0.6$ to $0.9$ Mev. and a pronounced resonance at $E_p = 1.82 \pm 0.08$ Mev., where the differential cross section at $164^\circ$ is $\sim 8$ mbn/steradian. The elastically scattered protons also showed the pronounced resonance at $E_p = 1.75 \pm 0.1$ Mev. Curran and Strothers (Curran, 1939) attempted to find the competing reaction, $\text{Li}^6(p, \gamma)\text{Be}^7$, but failed and estimated that the thick target yield of capture radiation at $E_p = 0.95$ Mev. was less than $2.5 \times 10^{-10}$ gammas per proton. They tried to detect the $\text{Be}^7$ activity with a Geiger counter after a 200 $\mu$A.-hour bombardment.

Any prompt gamma radiation emitted when pure $\text{Li}^6$ is bombarded with protons is certain to be due to the radiative capture process, since there are no excited states in $\text{He}^3$. The counter used in the present investigation was sensitive enough to detect radiation with cross sections as small as $4 \times 10^{-32}$ cm$^2$. Hence detecting the prompt radiation with this scintillation counter presented a worthwhile method of investigating $\text{Li}^6(p, \gamma)\text{Be}^7$. Detection of the delayed 478 Kev. radiation from $\text{Be}^7(\epsilon)\text{Li}^7* \rightarrow \text{Li}^7 + h\gamma$ with a scintillation counter could be used as an alternative method of measuring the cross section of the radiative capture process. The second method is less sensitive than the first by several orders of magnitude, since the half life of $\text{Be}^7$ is $52.93 \pm 0.22$ days and the fraction of transitions to the 478 Kev. state is 0.12 (Ajzenberg, 1955)

A measurement of the angular distribution of the capture radiation would be needed to calculate the total cross
section. A knowledge of the angular distribution would also provide information concerning the spin values of the states involved, in particular the ground state of Be\textsuperscript{7}.

The location of the energy levels of Be\textsuperscript{7} would be studied by a careful measurement of the energy of the gamma radiations from Be\textsuperscript{7}. A measurement of the energy of the capture radiation provides the Q of the reaction and the mass of radioactive Be\textsuperscript{7}. 
Figure 1. The Energy Level Diagram of Be$^7$
CHAPTER II

The Gamma Radiation Expected from the Proton Bombardment of a Lithium Target

A. The Li$^6$(p,$\gamma$)Be$^7$ Reaction

Figure 1, the energy level diagram of Be$^7$, serves to summarize the methods of studying the energy levels of Be$^7$ and the properties associated with these levels. The only known gamma ray emitting state was the 430 Kev. state. This radiation has been observed in the $^7$Li$^10$(p,$\alpha\gamma$)Be$^7$ and Li$^6$(d,n $\gamma$)Be$^7$ reactions (Lauritsen, 1950). Capture radiation to the ground state and to the 430 Kev. state in Be$^7$ were expected to be the most intense transitions, however, cascades through the 4.6 Mev. state (Thomson, 1952) could occur. When bombarding at $E_p = 1.82$ Mev., 7.1 Mev. radiation from the 4th excited state would probably dominate the de-excitation process with little contribution from the broad state at 6.4 Mev. The decay of Be$^7$ would produce 478 Kev. radiation with a 53 day half-life.

B. The Li$^7$ + p Reactions

A prolific yield of 478 Kev. gamma radiation arises from the inelastic scattering of proton in Li$^7$. This reaction, Li$^7$(p, p' $\gamma$)Li$^7$, exhibits a sharp resonance at 1030 Kev., $\sigma = 41.6 \pm 3$ millibarns (Mozer et al., 1954). The reaction Li$^7$(p, $\gamma$)Be$^8$, $Q = 17.242$ Mev., with two components of hard gamma radiation, 17.2 Mev. and 14.4 Mev., is also a prolific reaction with resonances at 441 Kev., 1030 Kev., and 2.0 Mev.
proton energy. The cross-section at 441 Kev. is 6.6 millibarns. When bombarding at Ep = 2.38 Mev., i.e. 430 Kev. above the Li\(^7\)(p,n)Be\(^7\) threshold (Ep = 1.8814 ± 0.001 Mev.), prompt 430 Kev. radiation would result from the first excited state of Be\(^7\). The decay of radioactive Be\(^7\) would again produce 478 Kev. radiation from the first excited state of Li\(^7\). It is therefore unlikely that any gamma radiation from Li\(^6\)(p,\(\gamma\))Be\(^7\) would be observed above the background radiation from Li\(^7\)+p if natural lithium targets were bombarded. Hence isotopic Li\(^6\) targets were needed for the experiment. Since it would be impossible to get absolutely pure Li\(^6\) targets, a scintillation counter with energy resolution of at least 10% was needed to separate the 430 Kev. and 478 Kev. radiations expected.

C. Contaminants

There are two elements which are very likely to seriously contaminate a target. The first is carbon which comes from the vacuum pump oil and is "pumped" by the proton beam to the target. The other is fluorine which seems to be present in small quantities on gold even after etching.

The reaction C\(^{12}\)(p,\(\gamma\))N\(^{13}\) has two resonances. A strong resonance at Ep = 456 Kev. produces 2.37 Mev. radiation and a weaker resonance at Ep = 1.7 Mev. produces 3.5 Mev. radiation as well as the 2.37 Mev. cascade (Ajzenberg, 1955). The decay of N\(^{13}\) by positron emission (half-life = 10.05 ± 0.03 min.) would give rise to 0.511 Mev. annihilation radiation.

The reaction F\(^{19}\)(p,\(\alpha\)\(\gamma\))O\(^{16}\) exhibits strong resonances producing 6.13 Mev., 6.91 Mev. and 7.12 Mev. gamma radiations in the de-excitation of O\(^{16}\)\(^*\)(Ajzenberg, 1955). This radiation would
be particularly serious since 6 to 7 Mev. radiation was expected from Li$^6(p, \gamma)Be^7$.

The backing materials for the Li$^6$ targets were expected to give background radiation as well. Radiation from Coulomb excitation of the heavy backing materials (gold, tungsten, or platinum) would not be troublesome except in the study of the low energy region of the spectrum. Coulomb excitation of Pt 194 results in 328 Kev. radiation which is the highest energy gamma ray resulting from the backing materials chosen (Heydenberg, 1954).
Figure 2. The Target Chamber used for the proton bombardment of Li$^6$. 

GLASS

.1820-27 O-RING

GOLD

GOLD

COPPER

LEAD

BRASS

LUCITE

1820-21 O-RING

24 T.P.I.

WINDOW

INCHES
CHAPTER III

Apparatus

A. The Targets and Bombarding Chamber

The targets consisted of 250 μgm./cm²/thick isotopically separated Li⁶ (99.7% pure) deposited on foils of gold (0.005"), tungsten (0.005") and platinum (0.004" thick). The targets had been prepared in a magnetic separator at A.E.R.E., Harwell with the kind cooperation of Dr. M. L. Smith and were sent to U.B.C. in evacuated glass containers. To ensure that the lithium was kept metallic, the targets were transferred into the bombarding chamber in a dry box filled with argon; the purity of which was tested by not using it until a slice of freshly cut natural lithium maintained its metallic lustre for at least 24 hours.

The bombarding chamber designed for the experiment is shown in figure 2. The following necessary requirements were incorporated into the design:

1. Small diameter and thin walls to allow maximum flux of radiation from target.

2. Heating (or cooling) facilities on the target mount. The targets would be heated if it was found necessary to prevent build-up of carbonaceous material during bombardment, or cooled if the targets could not stand the heat dissipated by the beam.

3. Gold stops to minimize background radiation.

4. Isolating valve to ensure that calibration runs with F¹⁹(p,αγ)O¹⁶ would not contaminate the target.

5. Insulated target holder for beam current measurements.
Facing Page 8.
Figure 3. The Target, Counter and Shielding Arrangement
(6) Rotating target holder.
(7) Windows for inspection of the target in situ and for beam alignment.
(8) Convenient construction for disassembly and cleaning.

The target, counter and shielding arrangement is shown in figure 3. With this arrangement the counter was well shielded with approximately 5" of lead and was 1\frac{1}{4}" from the centre of the lithium target, therefore allowing maximum target sensitivity. The lead shielding completely surrounded both the counter and the target chamber. No annihilation radiation was expected from the lead since the flux of radiation inside the lead shielding was small.

Any carbonaceous material which tended to collect on the target during bombardment was driven off by steam heating the target support and collected in the liquid air trap immediately in front of the target chamber. However, the main source of carbonaceous material was the O-ring seals and the bombarding chamber which were baked at approximately 150°C for 24 hours before the lithium target was mounted in the chamber. After several micro-ampere hours of bombarding with protons, the target had become coated with only a slight amount of carbon. With this procedure the gamma radiation originating from C^{12}+p was not a serious problem. However, heating the target did accelerate the oxidation of the lithium, but not to a serious degree.
Figure 4. (a) The container for 2 inch long, 1\(\frac{3}{4}\) inch diameter phosphor

Figure 4. (b) The container for the 1 inch long, 1\(\frac{1}{2}\) inch diameter phosphor
B. The Scintillation Counters

Radiation from 430 keV to 6 Mev. energy was expected, as mentioned, from the proton capture by Li$^6$. Since energy resolution depends on the energy of the gamma ray and the size of the phosphor, two scintillation counters were prepared, one consisting of a cylindrical sodium iodide (Thallium activated) block 2" long and 1½" in diameter mounted on a Dumont 6292 (later RCA 6342) photomultiplier tube, the other being a 1" long and 1½" diameter NaI(TI) cylinder on a Dumont 6292 photomultiplier. The crystal containers are shown in figure 4. The procedure for mounting the large crystal in its protective container was essentially the method used by Azuma (Azuma, 1953) although some improved techniques were used (see appendix 1). The smaller crystal was mounted by Harshaw Co.

Since the gain of the photomultipliers was sensitive to magnetic fields, a mu-metal shield was placed around the tube to provide full shielding notably in the region between the photocathode and the first dynode. The counters suffered no noticeable gain shifts due to change (or re-orientation) in the field on the 90° analysing magnet.

Both head amplifiers for the counters consisted of 6J6 tubes wired as cathode followers in the manner shown in figure 5, which also shows the stable H.T. supply used. A block diagram of the entire electronic detecting and analysing system is shown in figure 6. The collector load on the photomultiplier and the decay
Facing Page 10.
2X2 2000 VOLT SUPPLY

PHOTOMULTIPLIER HEAD AMPLIFIER

Figure 5.
Figure 6. Block diagram of the Counter and Pulse Height Analysing Apparatus
time of the phosphor determine the time constants of the pulses. The collector resistor was chosen to give pulses approximately 6 \mu sec. long which were suitable for the kicksorter. The rise time of the pulses was approximately \frac{1}{3} \mu sec., i.e. the decay time of NaI(Tl). The voltage of the photomultiplier was determined by tests for linearity and stability. The voltages used were approximately 1,000 volts, the exact value determined by the gain required.

The resolution of the small counter; i.e. the width of the photo-peak at half height divided by the voltage of the photo-peak, was 9\% for 0.511 Mev. radiation. The 2" counter had an energy resolution of 7\% for 1.28 Mev. radiation and approximately 6\% for the 5.11 Mev. Pair-peak of the 6.13 Mev. gamma ray from F^{19}(p,\alpha\gamma)O^{16}. The large counter, which was used almost exclusively throughout the experiment, did not drift more than 2\% throughout a day of running.

C. The Efficiency of the Counter for 6 Mev. Radiation

The absolute efficiency of the 2 inch counter was not known exactly for the detection of 6 Mev. radiation. However, it was possible to estimate the efficiency empirically by two methods. The first method consisted of measuring the thick target yield from F^{19}(p,\alpha\gamma)O^{16} and comparing the flux obtained with the values given by Chao et al. (Chao et al., 1950). The other method consisted of calculating the efficiency using the total absorption coefficient for NaI.
In practice the number of counts in a pulse height distribution are not integrated from 0 to $E_\gamma$, but from some bias point, a fixed energy down from $E_\gamma$. Therefore the effective efficiency, $e'$, for practical purposes must be calculated,

\[ \frac{N(E_{\text{bias}} \text{ to } E_\gamma)}{N(0 \text{ to } E_\gamma)} \quad e = e' \]

(1) **Thick Target Yield Method**

A thick calcium fluoride crystal (approximately 3/16" thick) was bombarded with protons of energy 830 Kev. to 1.0 Mev., i.e. including the two resonances at $E_p = 873.5$ Kev. and 935 Kev. The absolute yield of 6 to 7 Mev. radiation is known for these resonances.

To prevent the surface of the crystal from charging, a grid of fine wire was stretched over its surface and soldered to the brass holder. The target holder was insulated and connected to the integrator through a +300 volt battery. Since the yield of radiation was extremely prolific, it was practical to run beams of approximately 0.1 $\mu$A with the counter at 50 cm. This arrangement permitted adequate target sensitivity. To ensure that secondary emission from the target stop did not give false measurement of the small beam current, a second stop was placed in front of it and held at +67 volts.
Figure 7. Efficiency Calibration.

The ordinate is the detected thick target yield of 6 to 7 Mev. radiation from $^{19}(p, \alpha \gamma)_{^{16}}$ at $\theta = 90^\circ$ integrated over $4\pi$ steradians.
The results are shown in figure 7 as the solid curve. The ordinate is the total yield detected and corrected for angular distribution (Ajzenberg, 1955), target chamber absorption (7.5%), and shadow area of the grid (7.1%). Figure 7 also presents the yield from a thick CaF$_2$ packed powder target. The following table summarizes the results, taking $E_{\text{bias}}$ on the pulse height distribution equivalent to 4 Mev.

<table>
<thead>
<tr>
<th>Resonance $E_p$(Kev.)</th>
<th>Measured Yield $\gamma/10^7$ protons</th>
<th>Chao et al.</th>
<th>$e'$</th>
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<tr>
<td>873.5</td>
<td>1.10</td>
<td>3.7</td>
<td>30%</td>
</tr>
<tr>
<td>935</td>
<td>0.64</td>
<td>2.0</td>
<td>32%</td>
</tr>
<tr>
<td>873.5</td>
<td>1.18</td>
<td>3.7</td>
<td>31%</td>
</tr>
<tr>
<td>935</td>
<td>0.60</td>
<td>2.0</td>
<td>30%</td>
</tr>
</tbody>
</table>

(2) **Total Absorption Coefficient Method**

Using the tables of absorption coefficients compiled by Davisson and Evans (Davisson, 1952), the absorption coefficients for NaI were calculated by interpolation from elements of $Z$ near Na and I using the relations:

- Compton Process $\sigma'_C = \sigma_C \left(\frac{Z'}{Z}\right)$
- Photo-electric Process $\tau' = \tau \left(\frac{Z'}{Z}\right)^{4.73}$
- Pair-Production $K' = K \left(\frac{Z'}{Z}\right)^2$
The value of \( u = \sigma_c + \sigma + \kappa \) for \( E_Y = 6 \text{ Mev.} \) was calculated and found to be 8.6 barns/molecule. Hence if we define the efficiency as \( e = 1 - \exp(-ux) \), where \( x \) is the length of the crystal, we obtain \( e = 0.47 \). The ratio \( e'/e \) was obtained by plotting a complete pulse height distribution of the 6.13 Mev. gamma ray from \( F^{19}(p, \alpha \gamma)O^{16} \). The fluorine pulse height distribution yielded a value, \( e'/e = 0.53 \), hence \( e' = 25\% \).

The total absorption coefficient is practically constant and does not vary by more than 2.5\% over the energy 5 Mev. to 7 Mev. so that the efficiency was assumed to be constant over this range. Since the first measurement of \( e' \) is considered the most reliable, the effective efficiency was taken to be \( 0.3 \pm 0.05 \).

D. The Current Integrator

The total number of protons incident on the lithium target during a run was measured with a current integrator (Edwards, 1951), which was calibrated in the manner described by Edwards. To ensure that false current measurement would not occur from secondary emission from the target, +300 volts were applied to the target holder. No secondary electron current from the stop system to the target was observable. The target support was insulated from the rest of the bombarding chamber by a lucite spacer (see figure 2). No detectable current leakage was present provided the surface of the lucite ring was
maintained dry. The steam generator for heating the target was insulated by supporting the whole assembly on wax.
The Compton Distribution of pulses from the scintillation counter was used to test the discriminators of the kicksorter. Curve A shows poor operation. Curve B shows proper operation.

Figure 8. Kicksorter Test.
CHAPTER IV

The Experimental Procedure and Results

A. General Procedure

Mono-energetic protons were available from the University of British Columbia Van de Graaff generator. The energy of the protons was measured with the accelerator's generating voltmeter which was calibrated with the well known $^{19}$F$(p, \alpha \gamma)^{16}$ resonances. The scintillation counter was calibrated before running with Na$^{22}(0.511, 1.28$ Mev.), Th$^{232}$(2.62 Mev.) sources and the 6.13 Mev. radiation from $^{19}$F$(p, \alpha \gamma)^{16}$ at $E_p = 873.5$ Kev. and was found to be accurately linear. A Co$^{60}$ source was used when an energy bracket was required. The stability of the electronics was tested occasionally by running a Th$^{232}$ or a fluorine spectrum on the kick-sorter.

The setting up and proper operation of the discriminators of the kicksorter were tested by not running until the "Compton tail" of the 1.28 Mev. gamma ray from Na$^{22}$ was "flat" within the statistics of the channel counts. Poor operation of the kicksorter can result in misleading trends and peaks in pulse height distributions peculiar to the kicksorter and not to the spectrum of pulses from the counter. Figure 8 presents the Compton distributions when the kicksorter was operating properly (curve B) and when it was not (curve A).

B. Background Runs

Figure 3 shows the experimental arrangement which was
the same as the set-up used for bombarding Li$^6$. Freshly etched tungsten and gold targets were bombarded with protons to determine the contribution of counts from the target backing when struck by protons and the generator background. The target blanks were steam heated to test the effectiveness of this method of eliminating carbon build-up on the target. The following results were obtained:

(1) Cosmic-ray background in the 6 Mev. region =

1 count/Mev./Min.

(2) The tungsten background was decreasing slightly from 3.5 Mev. to 7 Mev. and was 0.025 counts/Mev./μcoulomb when bombarding at 800 Kev.

(3) The gold background was also decreasing from 3.5 Mev. to 7 Mev. and was 0.01 counts/Mev./μcoulomb at Ep = 800 Kev.

(4) Some 6 Mev. radiation from $^{19}\text{F}(p, αγ)^{16}$ was present when bombarding the gold with 873 Kev. protons. There were 0.44 counts/Mev./μcoulomb.

(5) In addition it was found that a gamma ray of 1.45 Mev. was present and was not target sensitive. This radiation probably arises from radioactive $^{40}\text{K}$ in the concrete of the building. Therefore the entire target assembly was encased in lead reducing this radiation to less than 1 count/min. in the photopeak. The cosmic-ray background was
2.2 counts/min. in this region, and since an average run took approximately 1 hour, the 1.45 Mev. gamma ray was not troublesome.

**Sensitivity**

Assuming that 6 Mev. radiation is detectable if it is twice as intense as the background, the counter could detect

$$0.5 \times 10^6 \times 1.6 \times 10^{-19} = 8 \times 10^{-14} \text{ } \gamma/\text{proton}.$$ 

Therefore, if the counter was placed 1/4" from a 250 \(\mu\text{g}./\text{cm}^2\) target of Li\(^6\) the limit of detection would be

$$4 \times 10^{-32} \text{ cm}^2.$$ 

C. **Pulse Height Distribution from a Single Crystal Spectrometer**

In the analysis of a complex pulse height distribution resulting from several gamma ray groups, the spectrum of pulses from a mono-energetic group must be known for the particular scintillation counter employed. The shape of the spectrum, by virtue of the absorption coefficients of the phosphor, depends on the energy of the gamma radiation. This fundamental shape which results from the usual interactions of photons with matter (i.e. Photo-electric, Compton, and Pair-creating events) is greatly modified by secondary interactions within the crystal, wall effect and Bremsstrahlung losses. The effect is a function of the size of the crystal. Therefore it is difficult to calculate the exact shape of the pulse height distribution\(^x\), but one can obtain this shape empirically if a source of radiation of the desired energy is available.

---

\(^x\) See Azuma, 1953  
Griffiths, 1953  
Warshaw, 1950
Figure 9. Pulse Height Distribution of 6.13 MeV Gamma Radiation from \(^{19}\text{F}(p,\alpha\gamma)^{16}\) at 340 KeV resonance. The broken line curve is the theoretical Compton distribution.
When 340 Kev. protons are incident on fluorine, the resonant reaction $^{19}\text{F}(p,\alpha\gamma)^{16}\text{O}$ produces 6.13 Mev. gamma radiation (96%). A pulse height distribution resulting from this gamma radiation is shown in figure 9. The channel widths of the kicksorter were set at 1 volt and the gain was adjusted so that this width was equivalent to approximately 100 Kev. energy lost in the phosphor. The three peaks correspond to the energy of the gamma ray (6.13 Mev.), full energy minus one electron mass (6.13 - 0.511 Mev.), and full energy minus two electron masses (6.13 - 1.02 Mev.). The peaks are:

1. 6.13 Mev. - "Full energy peak", resulting from photo-electric process and enhanced by secondary events, particularly of Compton process.

2. 5.62 Mev. - "Pair - 1 peak", resulting from pair production process with the escape of one 0.511 Mev. gamma ray from positron annihilation in the phosphor.

3. 5.11 Mev. - "Pair - 2 Peak", resulting from pair production process with the loss of both 0.511 Mev. gamma rays from positron annihilation.

4. The Compton electron distribution, shown as the broken-line curve.

This example pulse height distribution was used in the interpretation of the radiation from Li$^6(p,\gamma)$Be$^7$, which was approximately the same energy.

D. Spectrum of Radiation from Lithium Targets

Figure 10 presents complete pulse height distributions taken at $E_p = 400$ Kev. and 800 Kev. with the counter at 90° to the proton beam. A serious contaminating element was $^{19}\text{F}$ which
SINGLE CRYSTAL PULSE HEIGHT DISTRIBUTION OF RADIATION FROM LITHIUM-6 TARGET.

FEATURE AT

RESULTS FROM

- 873 Kev  \(O^+ + p\)
- 2.28 Mev  \(C^2 + p\)
- 6 Mev REGION  \(Li^3 + p\)

Figure 10.
seemed to be present even after the deliberate precautions taken. However by choosing bombarding energies away from the $^{19}\text{F}(p,\alpha\gamma)^{16}\text{O}$ resonances, the nature of the 6 Mev. radiation from $\text{Li}^6(p,\gamma)\text{Be}^7$ could be studied. For example the yield for $^{19}\text{F} + p$ is smaller by a factor of approximately $10^3$ when the bombarding energy is 73 KeV. lower than the 873 KeV. resonance. From the lithium target 47 counts/µcoul. were observed at $E_p = 873$ KeV., hence less than 0.05 counts/µcoul. would be expected from $^{19}\text{F}(p,\alpha\gamma)^{16}\text{O}$ at $E_p = 800$ KeV. The total observed was 5.5 counts/µcoul. To distinguish the radiation in the 6 Mev. region of the spectrum from $^{19}\text{F}(p,\alpha\gamma)^{16}\text{O}$ radiation, successive runs were taken at $E_p = 400$ KeV. and 800 KeV. The results are shown in figure 10, from which it is clear that the energy of the gamma ray increased with increasing bombarding energy. This is certainly not a property of the 6.13 Mev. radiation from the sharply resonant $^{19}\text{F}(p,\alpha\gamma)^{16}\text{O}$ reaction.

1. **The 6 Mev. Radiation from Li$^6(p,\gamma)\text{Be}^7$**

The hard gamma radiation from Li$^6(p,\gamma)\text{Be}^7$ was made up of two components, capture radiation to the ground state and capture radiation to the 430 KeV. state of Be$^7$. The detailed pulse height distribution shown in figure 11 demonstrates this clearly. The counter was set at $\theta = 90^\circ$ and the bombarding energy was 800 KeV. The broken line curve indicates the distribution of the pure 6.13 Mev. radiation previously described. With this spectrum for comparison, the pertinent pulse height distribution was interpreted as follows: The feature at 4.75 Mev. is the pair-2 peak of the excited state transition ($\gamma_2$),
Figure 11. Pulse Height Distribution of High Energy Gamma Rays from Li\(^6(p,\gamma)\)Be\(^7\), \(E_p = 800\) keV.
the peak at 5.27 Mev. is the pair-1 distribution of $\gamma_2$, plus the pair-2 peak of the ground state radiation ($\gamma_1$) and the peaks at 5.75 Mev. and 6.3 Mev. are the pair-1 and full energy peaks of $\gamma_1$. Therefore the energy of $\gamma_1$ is 6.29 Mev. and the energy of $\gamma_2$ is 5.77 Mev. (See figure 16 for the analysis of this pulse height distribution). For the range of bombarding energies used the energies of the gamma rays were found to fit

$$E_{\gamma_1} = Q + 6/7(E_p - \frac{1}{2} \Delta E)$$
$$E_{\gamma_2} = Q + 6/7(E_p - \frac{1}{2} \Delta E) - 0.43$$
$$Q = 5.66 \pm 0.03 \text{ Mev.}$$

$\Delta E =$ target thickness

in the manner expected for capture radiation. There was no definite evidence for any other cascading transitions, although there were more counts in the region near 4 Mev. than can be accounted for by the "Compton" distribution of pulses from the high energy gamma rays.

2. Radiation from Contaminating Materials

Although considerable care was taken to keep the Li$^6$ targets in pure metallic form, contaminating materials such as fluorine and perhaps boron were found to be on the lithium in minute quantities. After bombarding for several hours, radiations from C$^{12}$ and O$^{16}$ were observed indicating that heating the targets was accelerating the oxidation of the lithium and not keeping the carbon off entirely.

(a) C$^{12}(p, \gamma)N^{13}$ radiation

The carbon gamma ray (figure 10) at 2.28 Mev. was identified by observing the increased yield
Figure 12. Capture Gamma Radiation from $^{16}(p,\gamma)^{17}$. 
near the resonance at 456 Kev. bombarding energy (Ajzenberg, 1955).

(b) $^{16}{\text{(p, }\gamma){F^{17}}}$ radiation

The photo-peak at 873 Kev. (figure 10) was believed due to $^{16}{\text{(p, }\gamma){F^{17}}}$. Figure 12 shows a detailed study of this photo-peak with the counter at 90° to the proton beam. The following data was available from these spectra:

1. The gamma ray energy increased with increased bombarding energy
2. The background run had a feature at the same energy (indicating tungsten backing was also oxidizing).
3. The yield was greater for the higher energy run.
4. The energy of the gamma ray was:
   (i) $E_p = 0.75$ Mev. $E_\gamma = 777$ Kev.
   (ii) $E_p = 1.0$ Mev. $E_\gamma = 1.00$ Kev.

This photo-peak disappeared at $\theta = 0^\circ$, indicating a strong $\sin^2\theta$ angular distribution. Although the energy of the gamma ray was not exactly what one expects for the capture radiation to the 478 Kev. state in $F^{17}$ (Warren et al., 1954), the data taken as a whole proved that radiation was from $^{16}{\text{O}}$ contamination.
Figure 13. Pulse Height Distribution of Low Energy Radiation.

Photo-peak at $435 \pm 10$ Kev. arises from $\text{Be}^{7*}(1\text{st level}) \rightarrow \text{Be}^{7+} \gamma$.

Photo-peak at $476 \pm 10$ Kev. arises from $\text{Li}^{7}(p,p')\text{Li}^{7*} \rightarrow \text{Li}^{7+} \gamma$. 

- $435 \pm 10$ Kev
- $476 \pm 10$ Kev
- $E_p = 1500$ Kev
- $E_p = 1250$ Kev
(c) The Low Energy Radiation

The structure of the spectrum of gamma radiation in the low energy region is shown in figure 13. Two photo-peaks were observed, one at 435 ± 10 Kev. and the other at 476 ± 10 Kev. The latter radiation was from inelastic scattering of protons exciting the 478 Kev. state of Li\(^7\). The 435 Kev. radiation is tentatively assigned to the \(B^{10}(p,\alpha\gamma)Be^{7}\) reaction.

1. The \(Li^{7}(p,p'\gamma)Li^{7}\) Radiation.

The amount of Li\(^7\) in the target was calculated from the yield of 478 Kev. radiation. The cross section at \(E_p = 800\) Kev. is 0.83 x 10\(^{-27}\) cm\(^2\) (Mozer et al., 1954; Kraus, 1954). The yield of the 478 Kev. radiation was 5.8 x 10\(^{-12}\) \(\gamma/\text{proton}/4\pi\) sterad. assuming the photo peak efficiency was 50%. Therefore the thickness of Li\(^7\) was 0.08 \(\mu\text{gm/cm}^2\). This estimate agreed with the observed yield of 14.4 Mev. and 17.2 Mev. radiation from Li\(^7(p,\gamma)Be^8\).

2. The 430 Kev. Radiation

The yield of the 430 Kev. radiation was greater than would be expected from the \(Li^6(p,\gamma)Be^7\) reaction; for example at \(E_p = 800\) Kev.:

\[
\text{Number of counts in 430 Kev. photo-peak} \times \text{efficiency (5.86 Mev.)} \\
\text{Number of counts due to 5.86 Mev. radiation} \times \text{efficiency (430 Kev.)}
\]

\[
= \frac{3.9 \times 10^3}{6 \times 10^5 \times 0.38} \times \frac{30\%}{50\%} \approx 10
\]
Figure 14. Curve A, yield of 430 KeV. Radiation. A yield curve for the reaction $^{10}\text{B}(p,\alpha\gamma)^7\text{Be}$ is shown for comparison.
Therefore the 430 Kev. radiation was approximately 10 times as intense as the cascading 5.36 Mev. radiation.

Curve A in figure 14 is the relative yield function of the 430 Kev. radiation which was obtained from spectra similar to those presented in figure 13. The 478 Kev. components and the backgrounds were subtracted graphically. A yield function for $B^{10}(p,\alpha\gamma)Be^7$ is plotted for comparison. The similarity of the two curves indicates that the large yield of 430 Kev. radiation was from $B^{10}(p,\alpha\gamma)Be^7$.

If $B^{10}$ had contaminated the target, then there would be even more $B^{11}$ since natural boron is 81% $B^{11}$. From the relative number of counts in the 430 and 478 Kev. peaks in figure 13, and from the known cross sections of $Li^7(p,p'\gamma)Li^7$ and $B^{10}(p,\alpha\gamma)Be^7$, the amount of $B^{11}$ present can be calculated:

at $Ep = 1500$ Kev. \[
\frac{\text{Yield (478 Kev.)}}{\text{Yield (430 Kev.)}} = 0.22
\]
\[
\frac{\sigma(478 \text{ Kev.})}{\sigma(430 \text{ Kev.})} = \frac{0.05 \text{ bns.}}{0.21 \text{ bns.}} = 0.238
\]

hence thickness ($B^{10}$) = \(\frac{0.238}{0.22} \times 0.8 = 0.086 \mu gm/cm^2\)

and therefore thickness ($B^{11}$) = \(\frac{81}{19} \times 0.086 = 0.37 \mu gm/cm^2\).

The reaction $B^{11}(p,\gamma)C^{12}$ results in a cascade transition with the emission of a 4.4 Mev. gamma ray. The cross section is \(\sim 48 \mu bn\). at $Ep = 800$ Kev. (Ajzenberg, 1955).
and since the cross section for Li$^6$(p, $\gamma$)Be$^7$ is
$\sim 0.3$ $\mu$bn., the 4.4 Mev. radiation would have been approximately 1/7 as intense as the 6 Mev. radiation from Li$^6$(p, $\gamma$)Be$^7$. Therefore the 430 Kev. radiation could have arisen from B$^{10}$(p, $\alpha$ $\gamma$)Be$^7$ and no radiation would have been observed from B$^{11}$(p, $\gamma$)C$^{12}$.
The cross section of B$^{10}$(p, $\alpha$ $\gamma$)Be$^7$ at $E_p = 1.52$ Mev. is 0.21 barns. Therefore a few parts in $10^6$ of B$^{10}$ on the Li$^6$ target is sufficient to obscure any 430 Kev. radiation from Li$^6$(p, $\gamma$)Be$^7$. It is possible that boron was evolved from the glass target containers when they were sealed off by heating.

E. The Cross Section

By using the direct method of measuring the yield of the captureradiation from the Li$^6$(p, $\gamma$)Be$^7$ reaction, the differential cross section with the counter at 90° to the proton beam and $E_p = 800$ Kev., 750 Kev. corrected for target thickness, was found to be $2 \times 10^{-32} \pm 50\%$ cm$^2$/steradian. This figure represents the total differential cross section for the reaction, since, as can be seen from the complete pulse height distribution (figure 10), the two capture gamma rays previously discussed represent the only transitions occurring with measurable intensity. From Weisskopf's formula (Weisskopf, 1951) for the probability of gamma emission, the transition to the 4.6 Mev. state would be $< 2\%$ of the ground state transition assuming the most favourable case of dipole emission.
Experimentally one measures the number of gamma rays emitted per incident proton, i.e.,

\[ Y(E) = \left( \frac{1}{4\pi n_{c}} N_{\gamma}(E) \right) \frac{1}{N_{p}} \text{gamma's/proton/Steradian.} \]

where: \( n \) = solid angle subtended by crystal in steradians.
\( e \) = efficiency of counter.
\( N_{\gamma}(E) \) = number of gamma rays detected /unit time.
\( N_{p} \) = number of incident protons /unit time.
\( E \) = bombarding energy in Kev.

In order to calculate the cross section, \( \sigma \), the target thickness and stopping power, \( \delta \), must be known since these quantities are related by:

\[ Y(E) = \int_{E}^{E} \frac{d\sigma(E)}{d\omega} \frac{d\omega}{\epsilon} = \frac{d\sigma(E-\frac{1}{2}\Delta E)}{d\omega} \frac{N_{0}\Delta x}{A} \text{ for small } \Delta E \]

so that:

\[ \frac{d\sigma(E-\frac{1}{2}\Delta E)}{d\omega} = \frac{1}{4\pi n_{c}} \frac{N_{\gamma}(E)}{N_{p}} \frac{A}{N_{0}\Delta x} \text{ cm}^2/\text{steradian} \]

where
\( A \) = Atomic number
\( N_{0} \) = Avogadro's number
\( \Delta x \) = Target thickness in gm/cm^2
\( \Delta E \) = Energy lost by proton in passing through the target.

The solid angle, \( \Omega \), was taken as the solid angle subtended as shown in the figure below, a spherical cap at the centre of the crystal. The target was at 45° to the beam and the counter so that minimum target absorption occurred.
Figure 15. The yield of 6 Mev. Gamma Radiation from \( \text{Li}^6(p, \gamma)\text{Be}^7 \) is shown as points referring to the right hand ordinate. The left hand ordinate refers to the particle yields from \( \text{Li}^6(p, \alpha)\text{He}^3 \).
The target thickness was 250 μg/cm². The stopping power of lithium for protons is given by Warters (Warters, 1953) from 200 to 1,300 Kev. proton energy. Using his values, 800 Kev. protons will lose 79 Kev. in passing through 250 μg/cm² of lithium. Since the target was at 45° to the beam, \( \Delta E = \sqrt{2} \times 79 = 105 \text{ Kev.} \)

The pulse height distributions from the counter were displayed on the kicksorter, and the counts were numerically integrated from a bias corresponding to an energy 2.1 Mev. less than the gamma ray energy, cf. effective efficiency. The background was obtained by bombarding the back of the target for the same number of integrator counts.

The yield was measured at \( E_p = 400, 530, 620, 710 \) and 800 Kev. These energies were chosen at the minima of the \( \text{F}^{19}(p,\alpha\gamma)\text{O}^{16} \) excitation curve. However, the experimental points did not fall on a smooth curve, figure 15, so that this data was not considered very reliable due to the fluorine on the target. The ordinates on the right hand side of the figure refer to \( \text{Li}^6(p,\gamma)\text{Be}^7 \) while the left hand scale refers to the \( \text{Li}^6(p,\alpha)\text{He}^3 \) reaction (Bashkin, 1951). The measurement at 800 Kev. was considered to be reliable to within 50% accuracy, where the differential cross section was \( 2 \times 10^{-32} \text{cm}^2/\text{sterad.} \)
Facing Page 27.
Figure 16. Spectrum of High Energy Radiation taken at \( E_p = 800 \) Kev. and Counter at \( 0^\circ \). Curve C is the background. Curves A and B add to give the experimental curve. Ratio of areas under curves indicates \( 65 \pm 5\% \) of transitions go to the ground state of \( \text{Be}^7 \).
The angular distribution of the total capture gamma radiation was measured at $E_p = 800$ Kev. At this bombarding energy the energy of the gamma rays were 6.29 Mev. and 5.86 Mev. Since it was impossible to separate the two groups, the first measurement was the ratio of the intensities as a function of the angle $\theta$ with respect to the proton beam. This measurement was independent of the number of incident protons and therefore no monitoring of the beam was necessary. It was also independent in first approximation to the geometry.

1. Ratio of Intensities

The lithium target was placed at $45^0$ to the proton beam with the back of the target facing the counter at each angle so that the radiation had to pass through approximately equal thicknesses of target and tungsten at each angle. The counter arrangement was the same as described before (see figure 3). The pulse height distribution was well "spread out" so that a fair analysis of the curves was feasible.

Figure 16 is the pulse height distribution of the resulting radiation with the counter at $0^0$. The background was approximated by bombarding the tungsten backing for an equal number of incident protons. This is shown in the figure as curve C. Curves A and B are the spectra of single gamma rays of energy 6.29 and 5.86 Mev. which add up to give the experimental curve. The analysis of the experimental curve was done in the following manner:
(1) The shape of the pulse height distribution resulting from a clean 6.13 Mev. gamma ray was obtained experimentally by bombarding Fl9 with 340 Kev. protons. At this resonance in Fl9(p,αγ)016, 96% 6.13 Mev. radiation occurs. (See figure 9)

(2) Knowing the exact shape of the 6.13 Mev. radiation, it was assumed that this shape did not change for 5.86 and 6.29 Mev. radiation.

(3) Because the separation of the two radiations is 430 Kev. the photo-peak of A(6.29 Mev. gamma ray) will be the correct size and the slope of the curve on the high energy side will give the slope of the pair-1 peak of A. Knowing this, a test curve was plotted and subtracted from the experimental one giving curve B corresponding to γ2.

(4) The analysis was considered correct if:

   a. The pair-1 and pair-2 peaks of B were at the correct energy.

   b. The separation of the two peaks was .51 Mev.

The counts under curve A and curve B were integrated from the bias points shown in the figure to their respective high energy cut offs. The ratio of the integrated counts, $N(\gamma_2)$ is equal to the ratio of the gamma ray intensities. But it involves large errors in both numerator and denominator due to the subtractions, so that a more accurate measure of the relative contributions is the ratio $\frac{N(\gamma_2)}{N(\gamma_1)+N(\gamma_2)}$ which involves subtraction error only in the numerator.

For $0^\circ$ $\frac{N(\gamma_2)}{N(\gamma_1)+N(\gamma_2)} = .35$
Figure 17. Spectrum of High Energy Radiation taken at $E_p = 800$ KeV. and Counter at $60^\circ$. Curve C is the background. Curves A and B add to give the experimental curve. Ratio of areas under curves again indicates $62 \pm 5\%$ of transitions go to the ground state of Be$^7$. Average of 5 measurements taken at $0^\circ$, $30^\circ$, $45^\circ$, $60^\circ$ & $90^\circ$ is $62 \pm 5\%$. 

\[ \text{Li}^6(p,\alpha)\text{Be}^7 \]
Figure 17 shows the same method of analysis for the pulse height distribution obtained with the counter at 60°. The following table contains a summary of the results obtained.

<table>
<thead>
<tr>
<th>( \theta )</th>
<th>( \frac{N(\gamma_2)}{N(\gamma_1) + N(\gamma_2)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>.35</td>
</tr>
<tr>
<td>30°</td>
<td>.40</td>
</tr>
<tr>
<td>45°</td>
<td>.43</td>
</tr>
<tr>
<td>60°</td>
<td>.38</td>
</tr>
<tr>
<td>90°</td>
<td>.36</td>
</tr>
</tbody>
</table>

Average = .38

It is seen from the table that the angular distribution of \( \gamma_1 \) and \( \gamma_2 \) are the same to within 10%, and that 38 ± 5% of the transitions are cascades through the first excited state of Be\(^7\).

It is to be noted that the tail of curve A in figure 16 is too large. This can be explained as either faulty analysis, i.e. not considering that gamma rays could be scattered into the counter from the lead shielding or counts from unknown radiation.

2. Combined Angular Distribution

In order to measure the angular distribution with accuracy, the counter was placed at 10.3 cm. from the centre of the target so that the counter subtended a 12° angle to the source of radiation. A constant distance from the centre was ensured by measuring with a fixed spacer before each run. The
intensity of the radiation was measured with the counter at 0°, 22.5°, 45°, 67.5°, and 90°, Ep = 800 Kev. The proton beam was monitored by counting the 430 Kev. radiation from $^{10}\text{B}(p,\alpha\gamma)^{7}\text{Be}$ and the 478 Kev. radiation from $^{7}\text{Li}(p,p'\gamma)^{7}\text{Li}$ with the same rotating counter. In this way no errors were introduced by uncertain geometry and low counting rate in a monitoring counter which would have had to be extremely close to the target source. Both the 430 Kev. (Chadwick, 1955) and 478 Kev. (Littauer, 1950) radiations have been measured and found to be isotropic.

The build up of activity of $^{7}\text{Be}$ could be neglected because of the long half-life, 53 days. Neglecting the effect of this build up activity over the bombarding time introduced less than 0.08% error. The monitoring system was checked by simultaneously counting the hard radiation from $^{7}\text{Li}(p,\gamma)^{8}\text{Be}$. The measured distribution (figure 18b) for this radiation agreed well with the distribution measured by Kraus (Kraus, 1954). The solid line in the figure is the previously measured distribution normalized to the present data at $\theta = 90°$.

The pulse height distribution of the radiation from $^{6}\text{Li}(p,\gamma)^{7}\text{Be}$ was displayed on the kicksorter attenuated sufficiently so that approximately six channels recorded only background on the high energy side of the distribution. In this manner a fair estimate could be made of the dependency of the background upon angle. This background was then subtracted when the counts were integrated to give a measure of the yield.
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Figure 18a. The Angular Distribution of the 6 MeV. radiation from $\text{Li}^6(p, \gamma)\text{Be}^7$ measured at $E_p = 800$ Kev. The curve is $1 + 1.01 \cos^2 \theta$.

Figure 18b. The Angular Distribution of hard Gamma Radiation from $\text{Li}^7(p, \gamma)\text{Be}^8$ measured at $E_p = 800$ Kev. The curve is the distribution measured by Kraus (Kraus, 1954).
The experimental distribution, corrected for attenuation of intensity by target back is shown in figure 18a. A Least Square fit to the points is \( 1 + (1.01 \pm 0.15) \cos^2 \theta \).

To obtain the true distribution it is necessary to make a geometrical correction to the error introduced by the finite solid angle subtended by the counter. The experimental \( N_\theta (\theta) \) is not the yield at angle \( \theta \) but the integrated yield of \( N_\phi (\phi) \) over the solid angle of the counter. After correcting for this effect (see appendix 2), the angular distribution was found to be represented by:

\[
1 + (1.05 \pm 0.15) \cos^2 \theta
\]
CHAPTER V

Discussion of Experimental Results

The Q value for the ground state transition is a source of information about the mass differences between the initial and final nuclei in the reaction.

From the average Q value measured, 5.66 ± 0.03 Mev., the mass of Be$^7$ was calculated assuming:

\[ \text{Li}^6 = 6.017021 \pm 22 \times 10^{-6} \text{ amu.} \]
\[ \text{H}^1 = 1.008142 \pm 3 \times 10^{-6} \text{ amu.} \]
\[ 1 \text{ amu.} = 931.12 \text{ Mev.} \]

(Bainbridge, 1954)

The formula,

\[ = (\text{Li}^6 + \text{H}^1 - \text{Be}^7)C^2 = E_\gamma - \frac{\text{Li}^6}{\text{Li}^6 + \text{H}^1} (E_{\text{lab}} - \frac{1}{2} \Delta E) \]

is accurate to within the accuracy of the measurement of $E_\gamma$. The measurements were made at 90° so that Doppler correction to $E_\gamma$ was unnecessary. The mass of Be$^7$ calculated was 7.01908 ± 0.00003 amu, which is in fair agreement with that listed by Bainbridge (7.019150 ± 26 x 10^{-6}).

The cross section in the energy range studied is believed to be of the non-resonant type. This can be explained as the effect of a broad capturing level in Be$^7$ at 6.35 Mev, corresponding to the broad low maximum in the yield curve of alpha particles from Li$^6(p, \alpha)\text{He}^3$ (Bashkin, 1951). An alternate explanation is that the process is direct radiative capture, i.e. the proton is captured directly into an excited $d$ state of Be$^7$. 
say, assuming the ground state to be $P^{3/2}$ state. Direct radiation capture has been observed in the $^{16}(p, \gamma)F^{17}$ and $^{12}(p, \gamma, p')C^{12}$ reactions (Warren et al., 1954, Woodbury et al., 1954). Qualitatively this process would not be expected because the Li$^6$ nucleus does not consist of closed alpha particle groups as $^{16}$ and $^{12}$ do. It is seen from the values of the cross sections, $3.10^{-27}$ cm$^2$ for $^{6}(p, \alpha)He^3$ and $3.3 \times 10^{-31}$ cm$^2$ for $^{6}(p, \gamma)Be^7$, that emission of the particle is well favoured. The mirror reactions, $^{6}(n, \alpha)He^3$ and $^{6}(n, \gamma)Li^7$, show the same effect; the latter reaction has not been observed, (Ajzenberg, 1955), while the former with a cross section of the order of barns. The value of the cross section for $^{6}(p, \gamma)Be^7$ measured by Bashkin and Carlson (Bashkin, 1955) is approximately a factor 8 larger than our measurements. His method of determining the cross section consisted of measuring the thick target yield of 430 Kev. radiation in the bombarding range 180 to 415 Kev.

The transitions from the capturing state occur 62% direct to the ground level of Be$^7(\gamma_1)$ and 38% to the first excited level (\(\gamma_2\)). The ground state transition is favoured, because of its higher energy, as predicted by Weisskopf (Weisskopf, 1951). Simplified expressions for the radiative transition probabilities for 2\(^l\)-pole electric and 2\(^l\)-pole magnetic radiation are:

$$T_E(l) = \frac{4\pi(l+1)}{l[(2l+1)]^2} \left(\frac{3}{l+3}\right)^2 \left(\frac{\hbar \omega}{197 \text{ Mev.}}\right)^{2l+1} \left(R \left[\text{in } 10^{-13} \text{ cm}\right]\right)^{2l} \frac{10^{-21}}{\text{Sec.}}$$

$$T_M(l) = \frac{19(l+1)}{l[(2l+1)]^2} \left(\frac{3}{l+3}\right)^2 \left(\frac{\hbar \omega}{197 \text{ Mev.}}\right)^{2l+4} \left(R \left[\text{in } 10^{-13} \text{ cm}\right]\right)^{2l-2} \frac{10^{-21}}{\text{Sec.}}$$
so that the more energetic transition will be favoured. Spin values may be measured directly or assigned on the basis of beta particle spectra, shell model predictions, or angular distributions. The experimental angular distribution data showed
\[ W(\theta) = W_1(\theta) + 0.62 W_2(\theta) = 1 + (1.05 \pm 0.15) \cos^2 \theta \]
and \[ W_2(\theta) = 0.62 \pm 0.1 \text{ for } \theta \text{ between } 0^\circ \text{ and } 90^\circ. \]

where \( W_1(\theta) \) represents the transition to the ground state and \( W_2(\theta) \) to the first level in Be\(^7\). Assuming that a compound nucleus is formed in a state with definite parity and angular momentum, this data can be used to assign spin values and parities to the levels involved. A representation of the reaction can be written:
\[
\text{Li}^6 + p \rightleftharpoons \text{Be}^7 \rightleftharpoons \text{Be}^7 + \gamma_1
\rightleftharpoons \text{Be}^7(\star) + \gamma_2 \rightleftharpoons \text{Be}^7 + \gamma_3(430 \text{ Kev}).
\]

The angular distribution of the radiation of multipole order \( I \) resulting from the decay of Be\(^7\)\(\star\), with angular momentum \( J^\star \), to the final state of Be\(^7\), with \( J_f \), will be of the form:
\[
W(\theta) = \sum_k (-1)^{S-J_f} Z(1_p J^\star 1_p' J^{\star'}; Sk)x Z_1(l J^\star l' J^{\star'}; J_f k) P_k(\cos \theta)
\]

where \( S_k \) is the incoming channel spin (Li\(^6\) + p) and \( 1_p \) is the angular momentum of the incoming proton (Sharp, 1954). The change of parity in the de-excitation process determines the
type of radiation; magnetic or electric according to the selection rules. Here, consider only pure multipole transitions as the accuracy of the data does not permit interference effects to show up. The angular distribution data enables a plausible assignment of $J$ and parity to the states involved.

Since the distribution was not isotropic, S wave protons were not responsible for the reaction, in contrast to the explanation (Bashkin, 1951, 1955) given for the broad low resonance in the $\text{Li}^6(p,\alpha)\text{He}^3$ reaction at $E_p = 600$ to $900$ Kev. under the assumption of compound nucleus formation. The spin of $\text{Li}^6$ is known to be 1 (King, 1954), and assuming (Ajzenberg, 1955) that the parity is even, the capturing state in $\text{Be}^7$ must be odd if $p$ wave protons are responsible for the reaction. Likewise its spin cannot be $\frac{1}{2}$, since this would give an isotropic distribution; therefore it may be $3/2(-)$ or $5/2(-)$. Now the ground state of $\text{Li}^7$ is $3/2(-)$, the spin value having been measured directly (Fox, 1935). Therefore a reasonable assumption is that the ground state of $\text{Be}^7$ is $3/2(-)$ or less likely $\frac{7}{2}(-)$ following shell model predictions and the mirror nature of $\text{Be}^7$ to $\text{Li}^7$. This assumption is supported by the super-allowed character of the beta decays $\text{Be}^7(\beta)\text{Li}^7$ and $\text{Be}^7(\beta)\text{Li}^7^*$. From the isotropic character of the 430 Kev. radiation and the angular correlation of the neutrons and gammas in the reaction $\text{Li}^6(d, n\gamma)\text{Be}^7$, (Nielsen, 1955), the first excited level in $\text{Be}^7$ is $\frac{3}{2}(-)$. The half-life of the 430 state is $1.4 \times 10^{-13}$ sec. (Ajzenberg, 1955) providing evidence that the
$J = \frac{1}{2}$ character of the level is responsible for the isotropy of the radiation. Again, the mirror argument suggests that the parity of 430 state is odd since the 478 KeV state in Li$^7$ is $\frac{1}{2}(-)$. The probable transitions from the capturing state are indicated below for $l_p = 1$.

<table>
<thead>
<tr>
<th>S</th>
<th>J$^X$</th>
<th>l</th>
<th>J$^\gamma$</th>
<th>Type</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1/2</td>
<td>1</td>
<td>3/2$^-$</td>
<td>M1</td>
<td>$1 + 0.75 \cos^2 \theta$</td>
</tr>
<tr>
<td>(b)</td>
<td>1/2</td>
<td>2</td>
<td>1/2$^-$</td>
<td>E2</td>
<td>$1 + \cos^2 \theta$</td>
</tr>
<tr>
<td>(c)</td>
<td>3/2</td>
<td>1</td>
<td>1/2$^-$</td>
<td>M1</td>
<td>$1 + 0.75 \cos^2 \theta$</td>
</tr>
</tbody>
</table>

Hence transition (a) in the above table could be taken as $W_1$ and (b) or (c) as $W_2$ without conflict with our data or the relative intensities of the two transitions.

There are some less probable possibilities which arise from considering $l = 2$ protons. In this case the capturing state will be 7/2, 5/2, or 3/2 and even parity. The most plausible distributions are listed below:

<table>
<thead>
<tr>
<th>S</th>
<th>J$^X$</th>
<th>l</th>
<th>J$^\gamma$</th>
<th>Type</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d)</td>
<td>1/2</td>
<td>1</td>
<td>3/2$^-$</td>
<td>E1</td>
<td>$1 + 0.75 \cos^2 \theta$</td>
</tr>
<tr>
<td>(e)</td>
<td>1/2</td>
<td>2</td>
<td>1/2$^-$</td>
<td>M2</td>
<td>$1 + \cos^2 \theta$</td>
</tr>
<tr>
<td>(f)</td>
<td>1/2</td>
<td>1</td>
<td>5/2$^-$</td>
<td>E1</td>
<td>$1 + 8/9 \cos^2 \theta$</td>
</tr>
</tbody>
</table>

Transition (f) seems unlikely for the ground state distribution, and is certainly not the other since $J^\gamma = \frac{1}{2}$. Hence, in order that the observed relative intensities be adhered
to, $W_1$ and $W_2$ would both have to be $e$, which would be incompatible with the mirror nature of the ground states of Be$^7$ and Li$^7$.

It is therefore concluded that the reaction is probably due to $p$ wave protons, the capturing state in Be$^7$ being $3/2^-$, and the assumption that $J_f = 3/2$ for the ground state of Be$^7$ is not incompatible with the data. The data is in agreement with $J_f = 1/2$ for the first excited state of Be$^7$. 
Appendix 1

Crystal Mounting

The technique for mounting deliquescent sodium iodide phosphors was developed in this laboratory by Azuma (Azuma, 1953). The procedure followed was essentially his technique with improvements to ensure tight containers and better diffuse white reflecting surfaces on the crystals; thereby providing longer mount life and greater light collection efficiency enhancing the energy resolution.

The crystal face next to the photomultiplier photocathode was polished with a blotter soaked in n-butyl alcohol. The alcohol action was arrested with xylene and mineral oil. The other surfaces were sand-papereed and well-dried magnesium oxide (baked 24 hours at 500° C.) was rubbed into the rough surface of the crystal ensuring good contact of the NaI with the MgO. The thin layer of silicon oil ($10^6$ centistokes) between the polished face and the glass window was placed under vacuum before using to remove trapped air bubbles. The best ultraviolet transmitting glass available (photographic plates and Corning 774-0) was used for the container window in contrast to the lucite windows used by Azuma which contain water. The glass was cemented to the aluminum container with hot setting Araldite rather than using rubber gaskets which were unreliable.

With the above procedure, the crystal front surface reamins clear and the reflecting surfaces white for nine months at least; so that the energy resolution of the counter remains good (7% for 1.28 Mev. radiation) permanently.

x The time to date since the 2" long crystal was mounted.
Figure 19. Solid Angle Correction.
Appendix 2

Solid Angle Correction

The true angular distribution can be obtained from the experimental measurements if one assumes the form of the distribution and calculates the expected experimental distribution. A comparison then gives the values of the coefficients. To make a proper correction the finite solid angle subtended by the counter and the effective efficiency of the crystal at each $\Delta W$ must be considered.

In the present case the distribution was assumed to be

$$N(\theta_c) \, dw = A (1 + B \cos^2 \theta_c) \, dw$$

Experimentally one measures:

$$N_c(\theta_c) \, dw = \int \epsilon N(\theta_c) \, dw$$

where $\epsilon$, the efficiency, may be a function of $\theta$ and $\phi$ since we have a finite crystal presenting a finite solid angle, $\Omega$. (See figure 16) Analytic integration over $\Omega$ is difficult, therefore the integral has been replaced by the double summation:

$$N_c(\theta_c) \approx \sum_i \sum_j \epsilon_{ij} N(\theta) \Delta W_{ij}$$

where

$$\Delta W_{ij} = \frac{a^2}{r_{ij}} = \frac{a^2}{\sqrt{\frac{a^2}{r_{ij}} + \left[\frac{D}{\cos(\theta_c - \theta)}\right]^2}}$$

$$\epsilon_{ij} = \text{matrix depending on size, type and shape of crystal}$$

$$l_{ij} = \text{effective length of crystal presented at (i,j)}$$

In the present case the face of the crystal was divided into 36 squares of length $a$, and
\[
\epsilon_{ij} = \begin{pmatrix}
0 & \frac{1}{2} \epsilon' & \epsilon' & \frac{1}{2} \epsilon' & 0 \\
\frac{1}{2} \epsilon' & \epsilon & \epsilon & \epsilon & \frac{1}{2} \epsilon' \\
\epsilon' & \epsilon & \epsilon & \epsilon & \epsilon' \\
\frac{1}{2} \epsilon' & \epsilon & \epsilon & \epsilon & \frac{1}{2} \epsilon' \\
0 & \frac{1}{2} \epsilon' & \epsilon' & \frac{1}{2} \epsilon' & 0
\end{pmatrix}
\]

with \( \epsilon = 1 - e^{-\mu l} = 0.477 \)

\( \epsilon' = 1 - e^{-\mu l'} = 0.243 \)

where \( l \) and \( l' \) were obtained from a graphical construction of the geometry.

By a simple geometrical relation \( \cos \Theta \) can be shown to be

\[
\cos \Theta = \cos(\theta_c - \theta) \left\{ \left[ R^2 + D^2 \right] \frac{1}{2} \cos(\theta_c - \theta) - \left[ R - \tan(\theta_c - \theta) \right] \sin \theta_c \right\}
\]

hence:

\[
\cos^2 \Theta = \left\{ \left[ R^2 + D^2 \right] \frac{1}{2} \cos(\theta_c - \theta) - \left[ R - a(1 - \frac{1}{2}) \right] \sin \theta_c \right\}^2 \frac{1}{D^2 + a^2(1 - \frac{1}{2})^2}
\]

And since the summation over \( j \) is symmetrical:

\[
N_c(\theta_c) = 2A \sum_{i = -2}^{3} \sum_{j = 1}^{3} (1 + \cos^2 \Theta) \in ij \triangle Wij
\]
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