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

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The reaction $Li^6(p,\gamma)Be^7$ has been investigated by using protons of energy 0.4 to 1 Mev incident on isotopically separated Li^6 targets. Capture gamma radiation to the ground state and the 430-kev state in 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° and $E_p=750$ kev is about 2×10^{-32} cm²/steradian. The combined angular distribution of the two gamma rays is $1+(1.05\pm0.15)\cos^2\theta$ at $E_p=750$ kev. The Q value for the reaction is 5.66 ± 0.03 Mev in agreement with that calculated from mass values.

INTRODUCTION

WHEN Li^6 is bombarded with protons a relatively prolific yield of He^3 and alpha particles is observed from the reaction $Li^6(p,\alpha)He^3$ which shows a broad low maximum for $E_p=0.6$ to 0.9 Mev and a pronounced resonance at $E_p=1.82\pm0.08$ Mev. The elastically scattered protons also show a pronounced resonance in the 1.82-Mev region. The relevant level scheme of Be^7 taken from Ajzenberg and Lauritsen[1] is shown in Fig. 1. We thought it would be of interest to try to detect capture gamma radiation from the reaction $Li^6(p,\gamma)Be^7$ in spite of the competition from the alpha process, using the relatively efficient scintillation counter as detector. Our preliminary results, reported at the 1954 Seattle meeting of the American Physical Society,[2] showed the existence of radiation which could be assigned to the capture process, but, as might be expected from the low cross section involved, also indicated the presence of impurities, in particular of boron, which resulted in an unexpectedly high yield of 430-kev radiation compared to the higher-energy components. These results have recently been confirmed by Bashkin and Carlson[3] working with protons of energies between 180 and 415 kev.

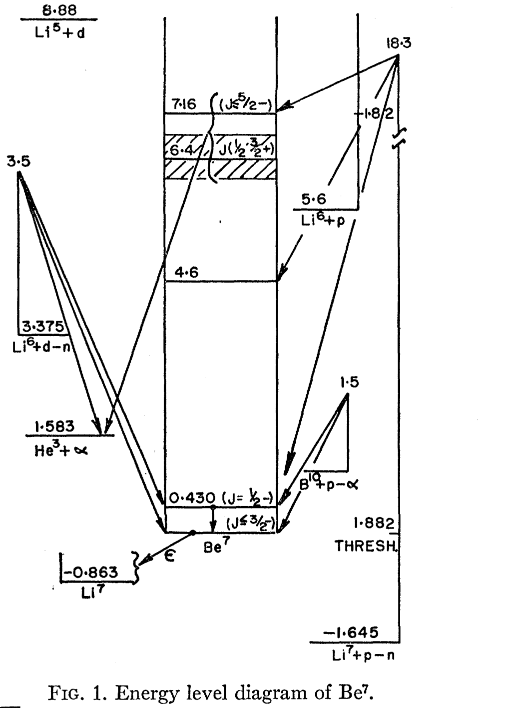

FIG. 1. Energy level diagram of Be^7.

EXPERIMENTAL

Targets of isotopically separated Li^6 (greater than 99.7%), of thickness 60 and 250 μg/cm² deposited on platinum, gold, and tungsten were supplied to us by Atomic Energy Research Establishment, Harwell with the kind cooperation of Dr. M. L. Smith. These were prepared in vacuo and sent to us in glass vacuum bottles. The targets were prepared from exceedingly pure lithium and great care was taken to avoid contamination. The targets were loaded into the bombardment chamber in a dry box filled with argon to just over one atmosphere. The purity of the argon gas in the box was ensured by not using it until a block of ordinary metallic lithium maintained its freshly cut metallic luster for 24 hours. Figure 2 shows the bombarding arrangement, the main features of which were to ensure that all surfaces which the beam might encounter were made of clean gold, and to provide large amounts of lead

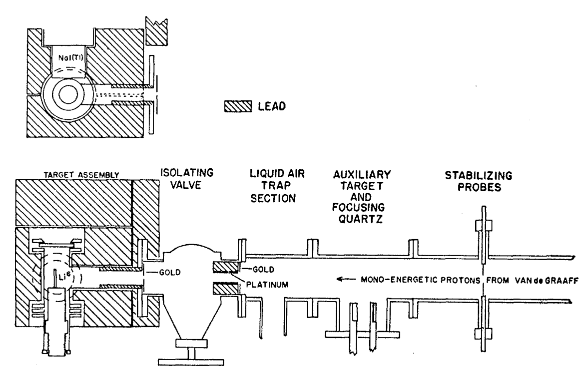

FIG. 2. Target, shielding, and counter arrangement.

[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 27, 77 (1955).
[2] Erdman, Warren, James, and Alexander, Phys. Rev. 96, 858(A) (1954).
[3] S. Bashkin and R. R. Carlson, Phys. Rev. 97, 1245 (1955).

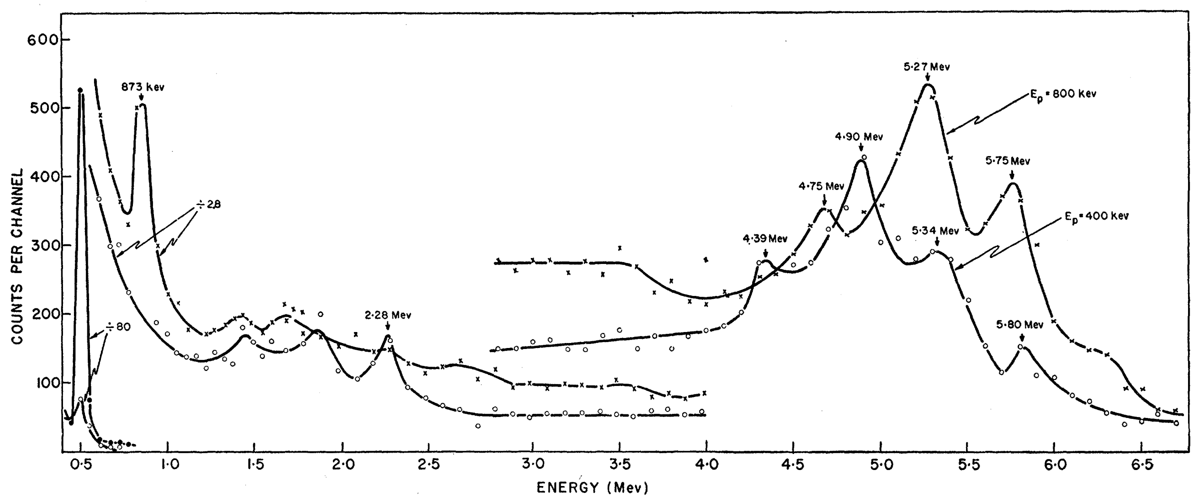

FIG. 3. Single-crystal pulse-height distribution of radiation from lithium-6 target. The peak at 873 kev results from $O^{16}+p$; that at 2.28 Mev from $C^{12}+p$; and the structure in the 6-Mev region results from Li^6+p.

in all directions to shield the counter from background radiations not emanating from the target. The targets were run warm by passing steam through the mount to reduce any build up of carbon. In addition considerable care was taken to avoid any grease on the 0 rings etc., which seems to be a major source of carbonaceous matter which gets onto targets, and to this end the whole assembly was baked at 150°C immediately prior to use. Also, an additional liquid air trap was mounted immediately in front of the target pot. The results showed that carbon was not a particularly awkward contaminant, even after many microampere hours of bombarding.

The University of British Columbia Van de Graaff generator supplied resolved beams of up to 10 μa on the target. The detectors used included, for the high-energy radiation, a 2 in. long$\times 1\frac{3}{4}$ in. diam activated sodium iodide block mounted on an R.C.A. 6342 or on a Dumont 6292 tube. Since these tubes suffer from gain drift at high counting rates, care was taken to keep the beam current at such a level that the low-energy components in the radiation did not cause gain shift while examining the high-energy spectrum. The pulse-height distributions were analyzed with a 30-channel kicksorter.

GAMMA-RAY SPECTRUM

Figure 3 shows complete pulse-height distributiosn taken at proton bombarding energies of 800 and 400 kev and normalized to an equal number of incident protons. The presence of 6-Mev radiation is quite obvious but the presence of a very small amount of fluorine contamination on the lithium, perhaps a residue from our sea air, was clearly shown by running over the well-known fluorine resonances. However, the fluorine contamination was small enough so that it only spoiled the results at the resonant energies and above $E_p\sim 1$ Mev; by working away from these resonances the nature of the 6 Mev radiation could be properly investigated. It is clear from Fig. 3 that the 6-Mev radiation from the Li^6 bombardment varies in energy with proton bombarding energy in the manner expected from the capture process. Figure 4 shows an enlarged version of this part of the spectrum taken at $E_p=800$ kev and for comparison a $F^{19}(p,\alpha\gamma)O^{16}$ spectrum taken at $E_p=340$ kev which gives practically pure 6.13-Mev radiation. It is also evident that there are two components present with an energy separation of about 430 kev, analysis (Fig. 5) showing that some $62\pm 5\%$ of the transitions go directly to the ground state and $38\pm 5\%$ to the first excited level of Be^7, 430 kev above the ground state. The relative proportions of these two components did not appear to change significantly over the energy range studied. (See Fig. 3.)

By using the gamma-ray energy measurements at various bombarding energies, a mean value for the Q of this reaction was found to be 5.66 ± 0.05 Mev corre-

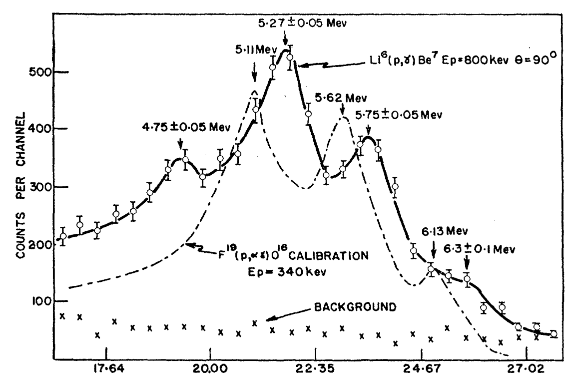

FIG. 4. Pulse-height distribution of high-energy gamma rays from $Li^6(p,\gamma)Be^7$, $E_p=800$ kev. Broken line indicates spectrum resulting from 6.13-Mev gamma radiation. The background from the tungsten target backing and cosmic rays is plotted *xxx*.

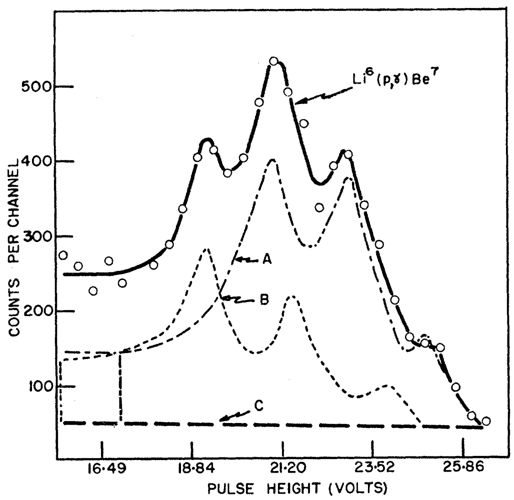

FIG. 5. Pulse-height distribution of high-energy radiation taken at $E_p=800$ kev and counter at $\theta=0°$. Curve C is the background. Curves A and B add to give the experimental curve. Ratio of areas under curves indicates that $65\pm5\%$ of transitions go to the ground state of Be^7. Average of five measurements was $62\pm5\%$.

sponding to a mean mass value for Be^7 of 7.01908 ±0.00003 amu, in fair accord with presently accepted value.[4]

The yield of this 6-Mev radiation showed no resonance behavior over the energy range investigated (400 kev to 1 Mev) and unfortunately at $E_p=1.82$ Mev the fluorine radiation was too large to measure properly any lithium capture radiation. The total differential cross section at 90° to the incident beam for this capture process was estimated at approximately 2×10^{-32} sq cm per steradian at $E_p=750$ kev, with an error considered to be within $\pm50\%$ of this figure and based on a counter efficiency of 30%, a figure we have not checked with any precision. The cross section appeared to increase slowly by a factor of about $1\frac{1}{2}$ from $E_p=400$ to 800 kev.

The most prominent feature of the spectrum was the low-energy photopeak arising from 430-kev radiation from $Be^{7*}\rightarrow Be^7+\gamma$ and from $Li^7(p,p')Li^{7*}\rightarrow Li^7+\gamma$ giving 478-kev radiation. A detailed pulse-height distribution of this region is shown in Fig. 6. The resolution of the counter was adequate to enable the proper subtraction of the 478-kev radiation and in this manner a yield curve of this 430-kev radiation was obtained. This is plotted in Fig. 7 together with a comparison yield curve for the 430-kev radiation from the $B^{10}(p,\alpha)Be^{7*}$ reaction. Obviously most of the observed 430-kev radiation arises from boron contamination and this swamps the contribution from the capture process. The origin of the boron is puzzling although, of course, a few parts per million would suffice. One possibility, yet to be investigated, is that the boron arises from the hot glass during the sealing off of the tube in which the target is prepared

[4] K. T. Bainbridge, *Experimental Nuclear Physics I*, edited by E. Segrè (John Wiley and Sons, Inc., New York, 1954), p. 745, part V.

The identity of the $C^{12}(p,\gamma)N^{13}$ feature in the spectrum was checked by its resonant behavior at $E_p=460$ kev. The peak at 873 kev although a little off the energy value,[5] appeared to be due to oxygen, since the distribution was strongly peaked at 90° to the incident direction.

There remains one other small rise which might be associated with transitions to the 4.6-Mev state in Be^7. Cascade transitions through this state would, from the energy available, be expected to be weak. Likewise there are rather more counts in the 3.5-Mev region in the spectra than would be expected in the Compton tail from 6-Mev radiation.

ANGULAR DISTRIBUTION OF 6-MEV CAPTURE RADIATION

Measurements made at $E_p=750$ kev at five different angles showed that the fraction of transitions direct to the ground state was independent of the angle of observation. The two gamma rays thus have the same angular distribution certainly to within 10%.

With this information it was then possible to measure the collective angular distribution of the whole 6-Mev radiation with better geometry. Owing to the weakness of the radiation a separate monitor counter was not used; instead, the incident protons were monitored by the yield of the 430-kev radiation from the $B^{10}(p,\alpha)Be^{7*}$

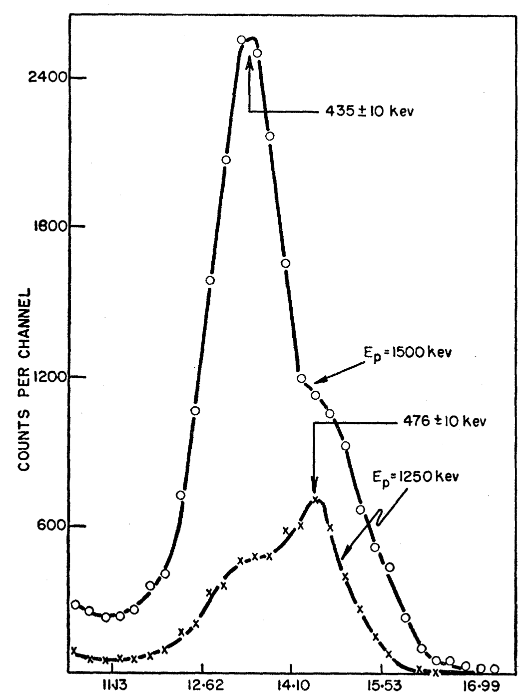

FIG. 6. Pulse-height distribution of low-energy radiation Photopeak at 435 ± 10 kev arises from Be^{7*} (first level) $\rightarrow Be^7+\gamma$. Photopeak at 476 ± 10 kev arises from $Li^7(p,p'\gamma)Li^7$.

[5] Warren, Laurie, James, and Erdman, Can. J. Phys. **32**, 563 (1954).

reaction and of the 478-kev radiation from $Li^7(p,p')Li^{7*}$. The isotropy of the 430-kev radiation has been established separately by the authors while that of the 478-kev radiation has been established by Littauer.[6] The dependability of this system of monitoring was checked simultaneously, and with the same counter, by measuring the known distribution of the hard gamma radiation[7] from $Li^7(p,\gamma)Be^8$. The results of our measurements at $E_p=800$ kev, after correcting for the solid angle effect, fit a distribution of the form

$$1+(1.05\pm0.15)\cos^2\theta.$$

DISCUSSION

From these results we believe that the reaction $Li^6(p,\gamma)Be^7$ proceeds with a differential cross section at 90° and $E_p=750$ kev of 2×10^{-32} cm² per steradian, about 10^{-5} of the cross section of the competing reaction $Li^6(p,\alpha)He^3$ of about 3×10^{-27} cm² per steradian. The transitions from the capturing state occur 62% direct to the ground level of Be^7 and 38% to the first excited level, 430 kev above the ground level. There is no real evidence from our data for any transitions to the second excited level of Be^7, 4.6 Mev above the ground level, although there was a small fluctuation in the gamma spectrum in about the right place.

If it is assumed that a compound nucleus is formed, so that the capturing state possesses a definite angular momentum and parity, then the angular distribution data enables a plausible assignment of J and parity to the levels involved. Since the distribution is not isotropic, s-wave proton capture is not responsible for the reaction, in contrast to the explanation[3,8] given for the broad low resonance in the $Li^6(p,\alpha)He^3$ reaction at $E_p=600$ to 900 kev. If p-wave protons are assumed then, since the parity of Li^6+p is even, the parity of the capturing state in Be^7 must be odd. Likewise its J value cannot be $\frac{1}{2}$, since this would give an isotropic distribution, but may be $\frac{3}{2}-$ or $5/2-$. From the isotropic character of the 430-kev radiation and the angular correlation of neutrons and gammas[9] in the reaction

TABLE I. Probable transitions from the capture state for $l_p=1$.

	Channel spin S for Li^6+p	J^*	l_γ	J final	Type	Distribution
(a)	$\frac{1}{2}+$	$\frac{3}{2}-$	1	$\frac{3}{2}-$	$M1$	$4P_0+1.6P_2$ i.e., $1+0.75\cos^2\theta$
(b)	$\frac{1}{2}+$	$\frac{3}{2}-$	2	$\frac{1}{2}-$	$E2$	$4P_0+2P_2$ i.e., $1+\cos^2\theta$
(c)	$\frac{3}{2}+$	$\frac{3}{2}-$	1	$\frac{1}{2}-$	$M1$	$4P_0+1.6P_2$ i.e., $1+0.75\cos^2\theta$

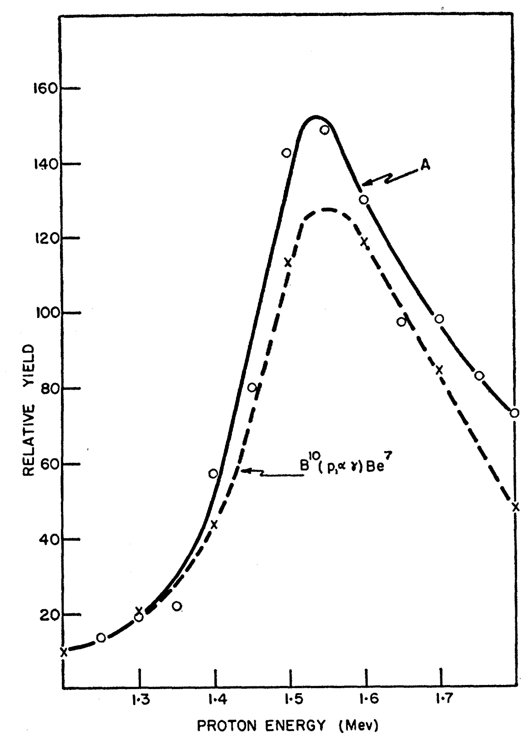

FIG. 7. Curve A, yield curve of 430-kev radiation. A yield curve for the reaction $B^{10}(p,\alpha\gamma)Be^7$ is shown for comparison.

$Li^6(d,n\gamma)Be^7$, the first excited level in Be^7 is $\frac{1}{2}-$. The probable transitions from the capture state are then indicated in Table I for $l_p=1$. The experimental data showed that

$$W(\theta)=W_1(\theta)+0.62W_2(\theta)=1+(1.05\pm0.15)\cos^2\theta,$$

and

$$W_2(\theta)/W(\theta)=0.62\pm0.1 \text{ for } \theta \text{ between } 0° \text{ and } 90°,$$

where W_1 represents the transition to the ground state and W_2 to first level in Be^7. 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. Possibilities which arise by considering $l=2$ protons are less plausible or incompatible with the data.

The process may, however, be one of direct capture; the low cross section and smooth variation with bombarding energy would suggest this.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the financial assistance provided by Atomic Energy of Canada Limited which has made this work possible; and two of us, T. K. Alexander and G. B. Chadwick, are grateful to the National Research Council of Canada for scholarships.

[6] R. M. Littauer, Proc. Roy. Soc. (London) A63, 294 (1950).
[7] A. A. Kraus, Jr., Phys. Rev. 93, 1308 (1954).
[8] S. Bashkin and H. T. Richards, Phys. Rev. 84, 1124 (1951).
[9] G. C. Neilson, Ph.D. Thesis, University of British Columbia, 1955 (unpublished).