$Li^7(d,p)Li^8$ Yield Curve*

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The absolute cross section for the $Li^7(d,p)Li^8$ reaction has been measured from 700 kev to 3.3 Mev. Previously reported resonances are located at 800 kev and 1.04 Mev, corresponding to states in Be^9 at 17.30 Mev and 17.49 Mev, respectively. A third resonance, indicated by the earlier work to be at 1.4 Mev, is not confirmed, from which it is concluded that Be^9 does not have the 17.8-Mev level for which that reported resonance was evidence. Above 1.8 Mev, the yield is relatively flat, perhaps indicating the influence of stripping, rather than compound nucleus formation.

INTRODUCTION

The $Li^7(d,p)Li^8$ yield has been previously studied by Bennett *et al.*[1] and by Baggett and Bame.[2] Both groups measured the number of Li^8 nuclei produced per incident deuteron by counting the energetic beta particles (end point near 13 Mev)[3] emitted from the short-lived (half-life = 0.89 sec)[4] Li^8.

These papers assumed that Li^8 was formed only in its ground state for all bombarding energies used.[5] The lifetime of this state is long enough for the Li^8 nuclei to become disoriented, and the emergent beta particles are consequently distributed isotropically in the laboratory system.

Bennett and his associates detected the betas with two Geiger counters in coincidence, the coincidence arrangement discriminating strongly against the background of neutron capture gamma rays. Baggett and Bame, using a single Geiger counter as the detector, obtained the absolute cross section for the reaction. Each of these groups found broad resonances in the Li^8 yield for bombarding energies of approximately 750 kev and 1.00 Mev, and obtained some evidence for a third resonance near 1.4 Mev. The 1.4-Mev resonance was indicated in the work of Baggett and Bame as a slight change in the slope of a steeply rising yield curve.

The present experiment has utilized a technique which allowed the determination of the beta yield in the presence of serious background effects. In addition, the range of bombarding energies has been extended beyond that of the previous work. At the highest energy used, a level[6] at 2.28 Mev in Li^8 might have been excited. However, it is assumed that neither this state nor the possible state[5] at 1 Mev affected this determination of the $Li^7(d,p)Li^8$ yield curve.

EXPERIMENTAL METHOD

The State University of Iowa Van de Graaff accelerator was used to accelerate monatomic deuterons to energies between 709 kev and 3.26 Mev. Beam energies were measured in terms of the magnet current required to deflect the beam into the target chamber. Three well-known gamma-ray resonances in the $F^{19}(p,\alpha)O^{16*}$ reaction, induced in thin CaF_2 targets by monatomic and diatomic proton beams, and the $Li(p,n)Be^7$ threshold obtained with the monatomic proton beam on thin lithium targets, served to calibrate the magnet current against energy. A reproducibility of ±0.5 percent in beam energy is inferred from the calibration data, and the absolute energy is believed known to ±1 percent over the range of this experiment.

Ordinary lithium was evaporated *in situ* on nickel backings 50 micro inches and 2 micro inches thick to provide targets 8 kev to 12 kev thick for 2-Mev protons. Target thicknesses were determined from the shape of the yield curve for the $Li^7(p,n)Be^7$ reaction just above the threshold, the detector being a shielded BF_3 long counter placed at zero degrees with respect to the incident beam. Frequent checks were made of the reproducibility of the beta yield at selected bombarding energies in order to guard against target deterioration. Very small beams, ranging from 0.03 to 0.1 microampere, were used to avoid target depreciation.

The target chamber, shown in Fig. 1, served as a Faraday cage. The collected charge was measured with a condenser-discharge type of current integrator circuit having a long time stability of ±0.5 percent and an absolute calibration known to ±1 percent. An electron repeller, shielded from the beam, was biased at 300 volts below ground to prevent secondary electrons from entering or leaving the target chamber.

A detecting system was designed to allow satisfactory measurements of the beta yield in the presence

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[1] Bennett, Bonner, Richards, and Watt, Phys. Rev. **71**, 11 (1947).

[2] L. M. Baggett and S. J. Bame, Jr., Phys. Rev. **85**, 434 (1952). We wish to thank Dr. Baggett for a private communication detailing the method used in this experiment.

[3] W. F. Hornyak and T. Lauritsen, Phys. Rev. **77**, 160 (1950).

[4] D. St. P. Bunbury, Phys. Rev. **90**, 1121 (1953).

[5] According to H. E. Gove and J. A. Harvey, Phys. Rev. **82**, 658 (1951), there is a doubtful state in Li^8 at 1 Mev. This level could have been excited for bombarding energies above 1.5 Mev. Beta or gamma-beta decays from this state would not affect the angular distribution of the betas, nor would the energy spectrum of the betas be significantly changed by direct beta emission from this level.

[6] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

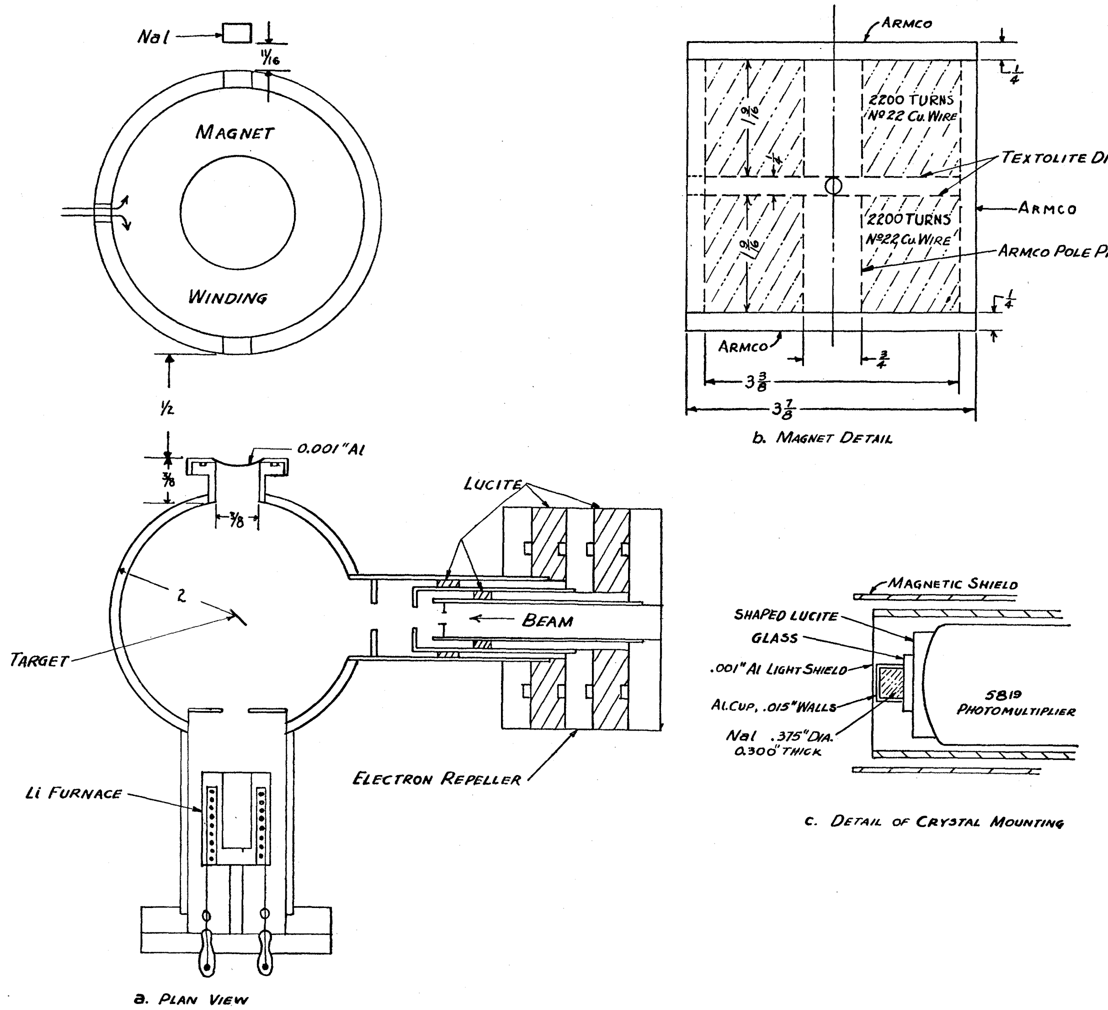

FIG. 1. Experimental arrangement for detection of betas from the $Li^7(d,p)Li^8$ reaction.

of a gamma-ray background which increased slowly with time and rapidly with bombarding energy. This background, which produced only one-tenth as many counts as did the betas at 709 kev, gave seven times the number of beta counts at 3.26 Mev. It appeared that neutron capture gamma rays contributed the major portion of the background. Large numbers of neutrons were created in the target proper via (d,n) reactions in Li^6 and Li^7. Moreover, semithick deuterium targets developed with time both in the target chamber due to the monatomic deuteron bombardment and elsewhere where the diatomic deuteron beam struck a beam stop. Despite the background, the number of betas was determined as follows, using the geometry illustrated in Fig. 1. Those betas which emerged through a small solid angle at 90° to the incident beam passed between the pole pieces of an electromagnet before entering a small NaI(Tl) crystal coupled to a 5819 photomultiplier. Sufficient current could be sent through the magnet coils to deflect all the betas away from the crystal. Thus, counts recorded with the field on were due solely to background, while "magnet off" data came from the background plus the betas. The difference between the two was attributed to the betas. This procedure had the great advantage over the use of absorbers, say, that the background could be measured without its being disturbed.

It is also worth mentioning that the frequently satisfactory method of using a blank target to determine background is inadequate in this experiment because the actual target contributes heavily to the neutron flux and, hence, to the flux of capture gamma rays.

The magnet was constructed to have a negligible external field, and tests showed that fields far higher than those actually employed in the experiment did not affect the operation of the photomultiplier. For this purpose, the radiations from Co^{60} and Cs^{137} were detected when the amplifier discriminator was so set that the counting rate changed rapidly with small

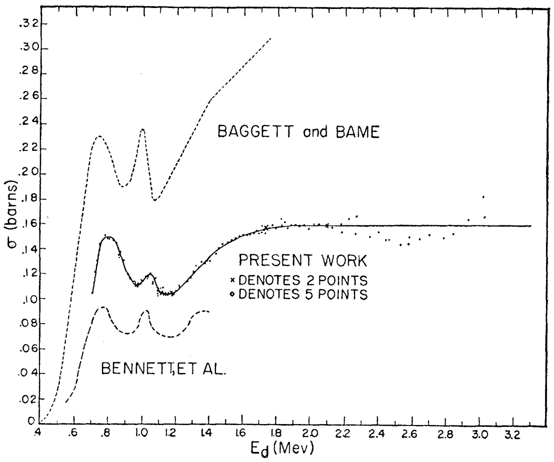

FIG. 2. Total cross section for the $Li^7(d,p)Li^8$ reaction.

changes in gain. Turning the magnet on and off had no observable effect on the counting rate. Further tests showed that the heating of the magnet by the magnet current did not affect the detector.

The magnet aperture and crystal were carefully aligned with the center of the $\frac{1}{8}$ in. high by $\frac{1}{16}$ in. wide target spot on the axis of the counting system. A mechanical stop on the target holder insured that every target occupied the same position when it was rotated into place.

Pulses due to betas of less than 2 Mev were rejected to avoid any background of neutron-induced beta activity. This bias setting was established by using a linear, single channel, pulse-height analyzer to take a pulse-height analysis of the Co^{60} and Cs^{137} gamma rays and extrapolating from their photopeak positions to 2 Mev. The crystal was too small to permit a good energy calibration, but that was unimportant since at most 2 percent of the Li^8 betas have such low energies.[3] The crystal itself had a beta stopping power of $\sim$4 Mev.

Data at each energy were acquired in a series of runs, the magnet being alternately on and off. This procedure enabled a check on the internal consistency of the data. Sufficient data were taken so that the statistical error, defined as $(N_{\text{off}}+N_{\text{on}})^{\frac{1}{2}}/(N_{\text{off}}-N_{\text{on}})$ was $\sim$0.01 for all points, N_{off} and N_{on} being the number of counts taken with the magnet off or on.

RESULTS AND DISCUSSION

The solid curve of Fig. 2 shows the excitation function for the $Li^7(d,p)Li^8$ reaction as obtained in this work. The dashed and dotted curves are, respectively, those of Bennett *et al.*[1] and Baggett and Bame.[2] The Bennett data have been arbitrarily plotted below the present curve since they show only relative cross sections. All three curves show two broad resonances which this experiment centers at 800 kev and 1.04 Mev, respectively. These resonances correspond to states in the compound nucleus Be^9 at 17.30 and 17.49 Mev, respectively.

However the current data do not substantiate the 1.4-Mev resonance indicated in the earlier findings. This resonance is listed[6] as the only evidence for an excited state in Be^9 at 17.8 Mev, and this level is therefore believed not to exist. It may be worth noting in this connection that the competing reaction, $Li^7(d,n)Be^8$, which also produces Be^9 as the compound nucleus, gives no indication[1,2] of a resonance at 1.4 Mev. Of course, the presence of a resonance in one process, and its absence in a competing reaction, may arise from differences in the characteristics of the final states involved. In fact, the 2.1-Mev resonance[2] in the $Li^7(d,n)Be^8$ reaction, which does not appear in the $Li^7(d,p)Li^8$ yield, might be due to such differences.

The lack of quantitative agreement between the present yield curve and the previous determinations can be accounted for in general terms. The results of Baggett and Bame are believed to be too high because of the inadequately corrected influence of background on their data. At the lower resonance, for example, where background in the present experiment was only 9 percent of the beta yield, the two cross sections are not inconsistent within the uncertainty in the present data and the assumption of a small uncertainty in the Baggett and Bame findings. At higher energies, the increasing deviation between their results and those of this experiment are in the correct direction to be explained by a steadily rising background contribution to their yield.

The coincidence counting of Bennett and his colleagues gave inherently good discrimination against background, and, indeed, the general shape of their curve is in good agreement with the present curve. It is possible that much of the differences which do exist come from dead time corrections required in that Geiger counter work.

For energies below 2.1 Mev, the relative yield is believed known to 10 percent, and the absolute cross section to 25 percent. Above 2.1 Mev, the data exhibit a very considerable scatter, making it difficult to assess the true variation of the cross section. The scatter derives from the fact that, at high energy, the background is large and the final data represent the small difference between two large numbers. At 3.26 Mev, for example, 1.2×10^6 counts were needed to obtain a net of 7.5×10^4 counts. The counting rate was kept down to $\sim$200 counts per second, by far the highest rate used in the entire experiment, so that quite a long running time was required to accumulate the data. Over this time, relatively small percentage fluctuations in the background had a disproportionately large effect on the net counts. The most reasonable conclusion to draw from the data is that the yield curve is substantially flat above 1.8 or 1.9 Mev. Perhaps this indicates that stripping, rather than compound nucleus formation, is the dominant feature of the reaction at high energies.

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Production of Cosmic Radiation at the Sun*

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A calculation is made of the average production rate of 4-Bv cosmic-ray particles at the sun. The calculation is based upon the recent experimental evidence that the frequently occurring small solar flares produce temporary increases of neutron intensity in suitably located neutron pile detectors. This production rate, averaged over the 11-year solar cycle, is somewhat in excess of the absorption rate of 4-Bv particles by bodies in the solar system. If the production at the sun is to account for most of the observed cosmic radiation intensity, a trapping magnetic field is required. Limits on the size of such a trapping volume are estimated by considering the limits of cosmic-ray lifetime; the requirement of a high degree of radiation isotropy at the earth is satisfied. The existence of high-energy particles in the cosmic radiation imposes the principal difficulty for any solar origin hypothesis.

I. INTRODUCTION

THE four large increases in cosmic-ray intensity which have been observed in association with large solar flares[1] indicate that the sun occasionally produces cosmic-ray particles. More recently it has been found that the smaller, but more frequent solar flares are also associated with increases in cosmic-ray intensity at the earth.[2] That these increases represent true cosmic-ray production on or near the sun is suggested by analogy with the large flare events, where the size of the increases clearly excludes the possibility of a modulation effect on pre-existent cosmic radiation.

The results on the small flare effect may be summarized as follows:[2] A neutron detector[3] at Climax, Colorado, recorded increases of $\sim$1 percent for flares of importance 1+ or greater during the period studied (May, 1951, to August, 1953), provided that the local solar time at Climax was 4 A.M.$\pm$2 hours. No observable effect, however, was found to accompany flares which occurred outside of this "impact zone" of local solar time. This local time dependence of the flare effect indicates that the particles which give rise to the intensity increase approach the vicinity of the earth from the direction of the sun. For both the large and small flare events increases were observed for flares near the limb of the sun as well as for those which occurred at the center of the visible solar disk. The distribution on the visible disk is shown in Fig. 1 for a group of flares which entered into the studies reported in reference 2. The indication is clear that the particles are emitted in a wide angle cone. An analysis of the cosmic-ray trajectories in the field of the earth's magnetic dipole shows that the particles from the sun which come in at Climax at 4 A.M. have a magnetic rigidity of 4 Bv.

The small flare effect appears to be a frequently occurring phenomenon; and if it represents production of cosmic rays on or near the sun, then the possibility arises that this effect has an important bearing on the question of the origin of cosmic rays. Before discussing any such implications, however, it is first necessary to obtain a numerical estimate of the production rate of (4-Bv) cosmic-ray particles at the sun. This is the main purpose of the present paper and is the subject of the following section. It should be emphasized that the calculation is based on the experimental data; we do not consider here the question of possible production mechanisms. In the remaining sections of the paper we discuss in a general way the implications of our result

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1 Forbush, Stinchcomb, and Schein, Phys. Rev. **79**, 501 (1950).

2 J. W. Firor, Phys. Rev. **94**, 1017 (1954).

3 See Simpson, Fonger, and Treiman, Phys. Rev. **90**, 934 (1953) for a description of the experimental apparatus. Neutron pile monitors *D*-1 and *D*-3 were used for the solar flare effect studies.