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Study of the Reaction $Li^6(d,n\gamma)Be^7$

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The angular correlation of the neutrons to the first excited state in Be^7 and the associated 430-kev gamma rays has been measured. Energy selection of the neutrons was made possible by a time-of-flight spectrometer. The angular correlations were predominantly isotropic at bombarding energies below 600 kev, while above this energy the correlations showed a strong peaking in the beam direction. Analysis using stripping theory shows that the 430-kev state is very probably a $J=\frac{1}{2}-$ state. The excitation function corrected for Coulomb penetration shows a resonance corresponding to an excited state in Be^8 at 22.6 Mev.

I. INTRODUCTION

The reactions resulting from the deuteron bombardment of lithium-6 have been investigated by many workers.[1,2] The reaction $Li^6(d,p\gamma)Li^7$ has been studied in some detail owing to the relative ease with which charged particle energies may be determined; and, from measurements of the angular distribution of the protons, of the associated gamma rays and of the correlation between them, it seems that the first excited level of Li^7 is a $J=\frac{1}{2}-$ state. For high deuteron energies, 8 and 14 Mev, the angular distribution of the protons shows that the reaction proceeds predominantly by a stripping process, the formation of the first excited state of Li^7 proceeding by the capture of a p-wave neutron.[3,4] Even with deuterons of only 1-Mev energy, it is apparent that stripping plays a significant part.[5]

The alternate reaction $Li^6(d,n\gamma)Be^7$, leading to the mirror nucleus, has been investigated in a less conclusive way owing to the experimental difficulty of distinguishing between the various neutron groups formed. Thus the total yield of neutrons as a function of deuteron energy has been determined,[6,7] but the excitation function so obtained corresponds to the total neutron yield from the three reactions:

$$Li^6+d\rightarrow Be^7+n, \qquad Q=3.375 \text{ Mev}, \qquad (a)$$

$$\rightarrow Be^7+n+\gamma, \qquad E_\gamma=429 \text{ kev}, \qquad (b)$$

$$\rightarrow He^4+He^3+n, \qquad Q=1.792 \text{ Mev}, \qquad (c)$$

or, where the Be^7 activity is used as a measure of the yield,[8] to the reaction (a) plus (b). With deuteron energies of 3.5 Mev, the neutron angular distributions[9] indicate that both reactions (a) and (b) are predominantly stripping in character proceeding by capture of p-wave protons.

The fast-neutron spectrometer technique developed at this laboratory[10] uses time-of-flight for energy sorting. In this device, the time-of-flight distributions are converted with a new type of time sorter into pulse-height distributions which can be analyzed by a conventional pulse-height analyzer. This energy-selecting neutron detector has made possible the study of the single neutron group corresponding to the second reaction listed above. It was hoped that, from the angular correlation data, the spin and parity assignment of the first excited level in Be^7 would be determined unequivocally and, in fact, the only assignment which satisfies all the data is $J=\frac{1}{2}-$ for this level, as one would expect from the mirror nature of the Li^7 and Be^7 nuclei. Again with the bombarding energy range available to us we have been able to study the onset of the stripping process in this reaction. The results show that a compound nucleus process is adequate to account for the angular data at a deuteron bombarding energy of 400 kev, but at 600 kev the stripping process has set in strongly and becomes the dominant mechanism at higher energies.

II. EXPERIMENTAL

Figure 1 shows the position of the two stilbene scintillation counters with respect to the Li^6 target. Figure 1 shows also the associated electronics in the form of a block diagram. The Li^6, kindly supplied to us by A.E.R.E. Harwell, was in the form of isotopically pure metal, about 60 micrograms/cm² thick, and deposited on a thin platinum backing. Precautions were taken in the mounting of the target to ensure that the Li^6 remained in a pure metallic form. The target was heated during bombardment in order to minimize buildup of carbon from organic vapors introduced by the oil-diffusion pumps.

Since the counting rate in the neutron counter was low, the background counting rate in it was reduced to

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[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

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

[3] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 1032 (1953).

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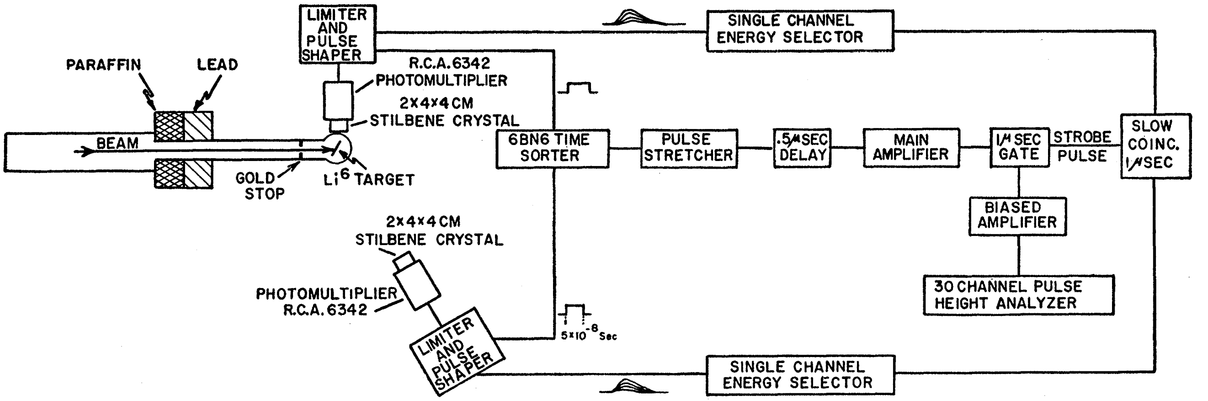

FIG. 1. Counter and target geometry and a block diagram of the electronics. The analyzed deuteron beam from the Van de Graaff generator is collimated by the gold stop in front of the Li^6 target. The two counters are free to rotate about the target in the plane of the paper. A detailed account of the time sorter and associated electronics has been published elsewhere.[10]

as low a level as possible by lead shielding. In order to check the effectiveness of the mu-metal shielding of the photomultipliers and the over-all symmetry of the arrangement, the well-known angular correlation of the two cascade gamma rays from a metallic Co^{60} source was measured. In these tests, the Co^{60} source was placed at the target position and the angular correlation was measured with the beam-analyzing magnet on and off. In both cases good agreement with the established correlation indicated that there was no major asymmetry and that the counters were insensitive to stray magnetic fields.

The response of a stilbene crystal to gamma rays is known to be linear to quite low energies, but, since the absorption is primarily by the Compton process [see Fig. 2(A)] in the medium-energy region, the side-channel discrimination is unfortunately not very selective as to gamma-ray energy. The neutron sensitivity of the stilbene counter was calibrated by using the neutrons from the $D(d,n)He^3$ and the $T(p,n)He^3$ reactions. Figure 3 shows the response of the 4×4×2 cm stilbene crystal for various neutron energies as compared to the response for gamma rays from a Na^{22} source, the 2-cm thickness being in the direction of the neutron beam. Figure 2(B) shows a typical proton-recoil spectrum.

III. DELAYED NEUTRON SPECTRUM FROM $Li^6(d,n\gamma)Be^7$

A typical spectrum of the delayed neutron–gamma-ray coincidences, taken in about half an hour at a deuteron bombarding energy of 600 kev and beam current of 2 μa, is shown in Fig. 4. In this case the gamma-ray counter was at an angle of −90° to the incident deuteron beam, i.e., in an anticlockwise direction as seen from above, and the neutron counter at +90° and at a distance of 52 cm from the target.

The delay time scale was calibrated by using the prompt coincidences between annihilation quanta from a Na^{22} source and inserting known lengths of cable between one detector and the time sorter. The velocity of pulses along this Telcon "AS48," 90-ohm, cable was

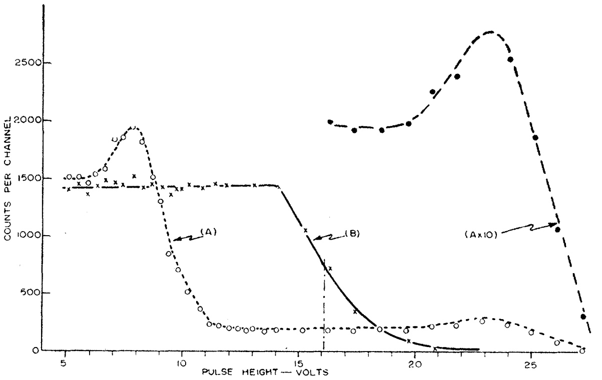

FIG. 2. Pulse spectra from a stilbene crystal. (A) Gamma rays from a Na^{22} source. The Compton peaks from the 0.51-Mev and 1.28-Mev gamma rays are indicated at 8 and 23 volts, respectively. (B) Proton knock-on spectrum for 2.67-Mev neutrons from the reaction $D(d,n)He^3$. (A) and (B) are taken under conditions of identical gain.

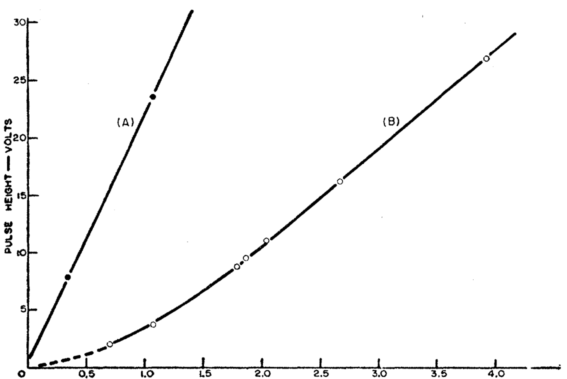

FIG. 3. Relative pulse heights from a stilbene crystal as a function of energy. (A) Gamma rays from a Na^{22} source. (B) Neutrons (pulse height corresponds to the maximum pulse height in the proton knock-on spectrum).

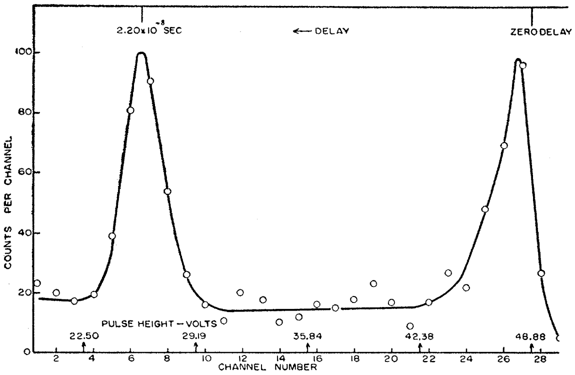

FIG. 4. Neutron spectrum from the reaction $Li^6(d,n\gamma)Be^7$.

measured to be $(2.39\pm0.02)\times10^{-8}$ meters per second. Thus the only neutron group seen at a delay time of 2.20×10^{-8} second has an energy of 2.9 Mev and clearly corresponds to the group leading to the first excited state of Be^7 which, according to the accepted Q value,[1] should have an energy of 2.95 Mev. No other groups were found and, since it is believed that any group of 10% of the intensity of this single main group would have been detected, to this degree of sensitivity there are no transitions to other states in Be^7 corresponding to energy levels from 300 to 2000 kev excitation above the ground state.

The zero-delay peak arose from events in which a neutron was detected in the "gamma" counter close to the target and a coincident gamma ray was detected in the distant "neutron" counter. The general background, about 15 counts per channel in Fig. 4, arose not from chance coincidences but from genuine coincident events such as neutron scattering between counters, competing $(d,n\gamma)$ processes from, for example, carbon in the magnet-box and on the target, detection of a slow neutron in the "gamma" counter and a coincident gamma in the "neutron" counter, double-scattering events from the surrounding shielding, walls, and so forth.

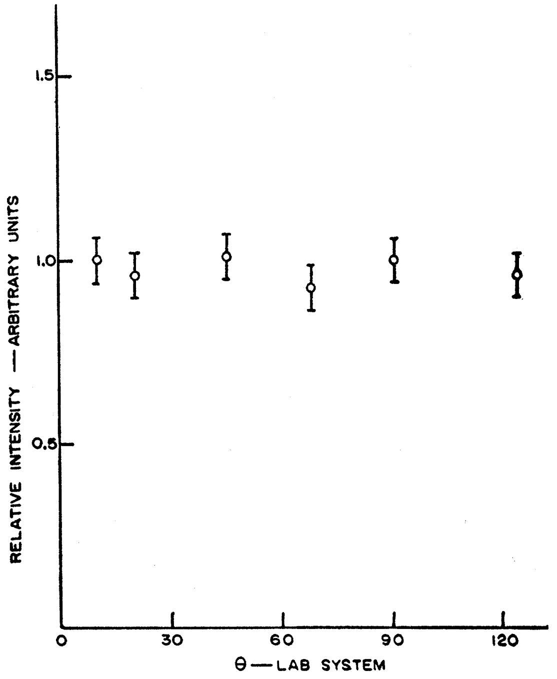

FIG. 5. $Li^6(d,n\gamma)Be^7$ angular correlation of neutrons and gamma rays. Neutron counter at a fixed angle.

IV. ANGULAR CORRELATION MEASUREMENTS

With one counter in a fixed position, the other counter was moved in the plane containing the deuteron beam and the fixed counter. The fixed counter served as monitor and the correlation was measured as the ratio of the coincident counts in the neutron group minus the background to the total number of counts recorded by the fixed counter. As a check on this method of normalization, the coincident counts were compared to the integrated deuteron beam current falling on the target in any particular run. These two methods were found to be in accord within the statistical error on each point, showing that the target did not deteriorate appreciably during bombardment.

(*a*) *Angular correlation with the neutron counter at a fixed angle.*—With this arrangement the correlation was isotropic within the experimental accuracy, and is to be compared with the isotropy found[11,12] with the mirror reaction $Li^6(d,p\gamma)Li^7$. A typical result taken at $E_d=600$ kev with the neutron counter 25 cm from the target and fixed at +45° is shown in Fig. 5. At this angle one might expect any influence of stripping to be noticed. This isotropy is also in accord with the measurement of Thirion[13] on (n,γ) coincidences in the reaction $Li^6(d,n\gamma)Be^7$.

(*b*) *Angular correlation with the gamma-ray counter at a fixed angle.*—A typical set of experimental curves

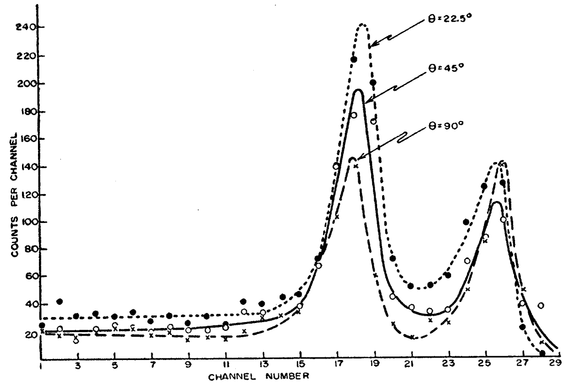

FIG. 6. $Li^6(d,n\gamma)Be^7$ typical spectra for neutron counter at various angles.

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[11] C. M. Class and S. S. Hanna, Phys. Rev. **87**, 247 (1952).
[12] Burke, Risser, and Phillips, Phys. Rev. **93**, 188 (1954).
[13] J. Thirion, Ann. Phys. **8**, 489 (1953).

taken at $E_d=600$ kev with the gamma-ray counter fixed at −90° and the neutron counter rotated at a radius of 25 cm from the target is shown in Fig. 6. From such data after normalization, the true angular correlation was obtained by making allowance for the change in energy of the neutron as the angle of observation changed. The number of counts in each peak, after normalization, was multiplied by a factor f:

$$f=\left(\frac{E_n(0^\circ)-E_n(b)}{E_n(\theta^\circ)-E_n(b)}\right)\frac{1}{\sigma(n,p)},$$

where $E_n(\theta)$ is the neutron energy at the laboratory angle θ and $E_n(b)$ is the energy of the recoil proton corresponding to the fixed bias level of the side channel discriminator in the neutron counter side of the coincidence unit. The $1/\sigma(n,p)$ factor takes into account the change in detector efficiency as a function of neutron energy. The other factor is based on the assumptions that the proton recoil spectrum has a rectangular shape and that the response of a stilbene scintillator to protons of energy greater than E_b, about 1.6-Mev recoil energy with the normal bias used, was approximately linear. These assumptions were checked experimentally as is shown in Figs. 2 and 3. Within the accuracy of this experimental check, 10%, the data are in accord with the results of Taylor *et al.*[14] and Fowler and Roos[15] on the scintillation response of stilbene to low-energy protons, though these results indicate a rather more linear response above 1.5 Mev than would be expected from the proton results.

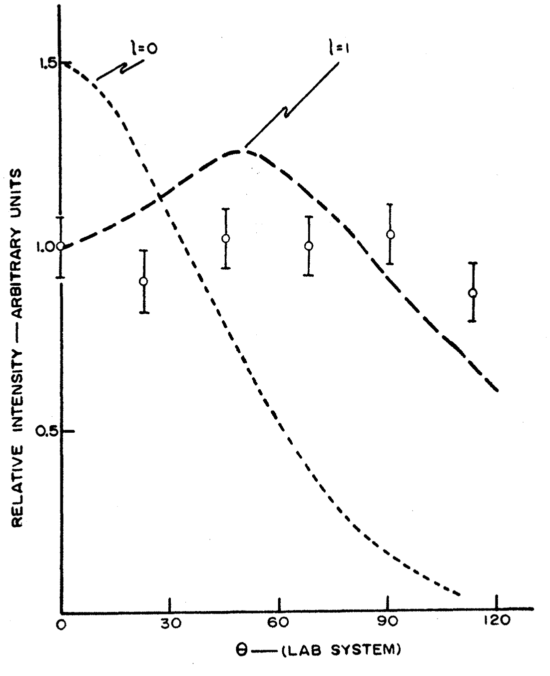

FIG. 7. $Li^6(d,n\gamma)Be^7$ angular correlation at 400 kev with the gamma-ray counter at a fixed angle.

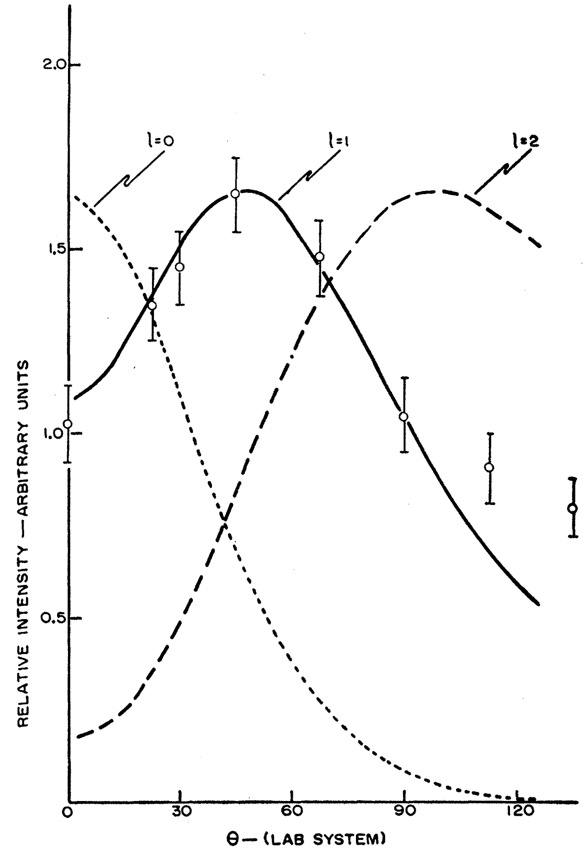

FIG. 8. $Li^6(d,n\gamma)Be^7$ angular correlation at 600 kev with the gamma-ray counter at a fixed angle.

In this manner the corrected angular distribution curves shown in Figs. 7, 8, and 9 were obtained at deuteron energies of 400, 600, and 1500 kev.

V. EXCITATION FUNCTION

With the gamma-ray detector fixed at −90° and the neutron detector at +45° and at a distance of 25 cm from the target, the relative intensity was measured as a function of deuteron bombarding energy from 300 to 1500 kev. Figure 10 shows the experimental yield curve corrected for the changing sensitivity of the neutron counter since the neutron energy changes with E_d.

It is estimated that, under these conditions, the absolute cross section was 2 millibarns per steradian at $E_d=600$ kev. This figure is only approximate, probably within a factor 3, because the absolute efficiency of the spectrometer has not been measured experimentally and the target thickness was not accurately known.

VI. INTERPRETATION OF THE RESULTS

The only reasonable way to explain all of the angular correlation data is to assume that the first excited state

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[14] Taylor, Jentschke, Remley, Elby, and Kruger, Phys. Rev. 84, 1034 (1951).

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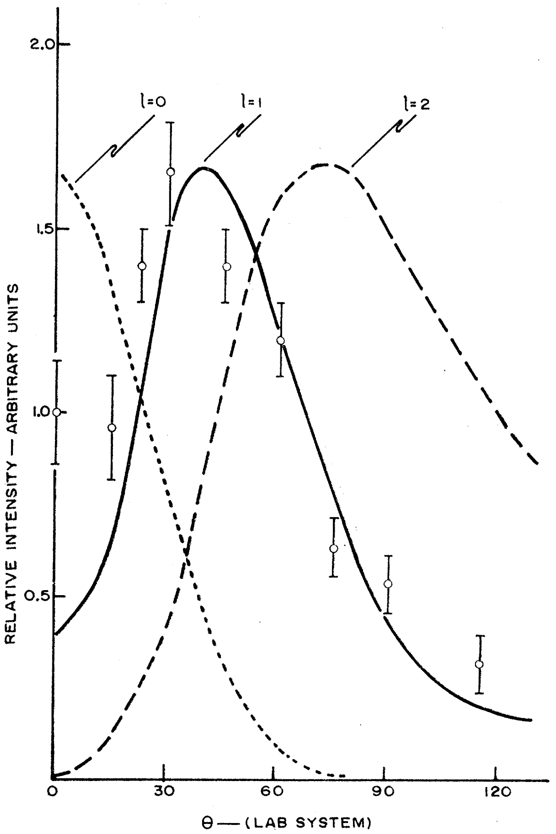

FIG. 9. $Li^6(d,n\gamma)Be^7$ angular correlation at 1500 kev with the gamma-ray counter at a fixed angle.

of Be^7 has a total angular momentum $J=\frac{1}{2}$ and odd parity. Thus the isotropy of the angular correlation taken at $E_d=600$ kev with the neutron counter fixed, Fig. 5, would be expected both on the basis of a compound nucleus formation[16] or a stripping process[17,18] if the excited state is a $J=\frac{1}{2}-$ state. On this assumption, the direction of emission of the gamma ray is independent of the direction of emission of the preceding neutron.

Consequently, when the neutron counter was rotated, the angular correlation which was measured was just the differential cross section for neutron emission. The sharp forward peaking of the distributions at bombarding energies of 600 and 1500 kev, Figs. 8 and 9, is characteristic of a stripping process. It is known, moreover, that at rather higher deuteron energies the alternate reaction $Li^6(d,p\gamma)Li^7$ proceeds via a stripping process.[3,4] Thus it is plausible to try to interpret Figs. 8 and 9 in terms of stripping theory, and the theoretical distributions drawn in those figures are for angular momenta of the ingoing proton of $l_p=0$, 1, and 2. These curves were computed from the theory of Bhatia *et al.*,[19] using a nuclear radius for Li^6 of 6.0×10^{-13} cm.[18] It is a little surprising that these computed curves agree so well with the experimental data, since Coulomb and other corrections might be expected to be appreciable at the low energies of the present work.[20,21] In this case agreement is good for *p*-wave proton capture, which would necessarily imply that the 430-kev state of Be^7 has odd parity if we assume even parity for Li^6. The capture of a *p*-wave proton together with the isotropic correlation of the gamma rays (Fig. 5) is sufficient to define the spin as $J=\frac{1}{2}$. This assignment is not only in accord with the value of the spin for the corresponding state in the mirror nucleus Li^7, but is also in accord with the isotropic angular distribution of the 430-kev gamma radiation.

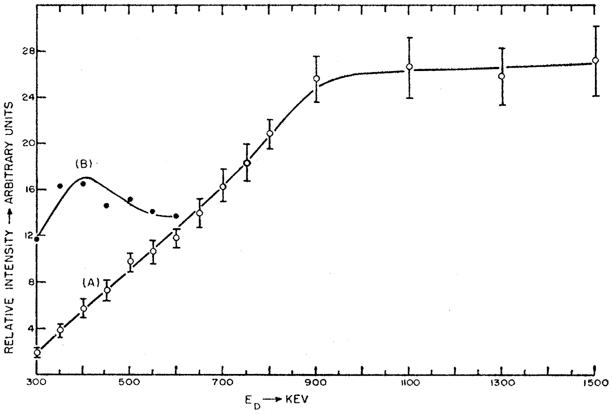

FIG. 10. (A) Experimental excitation curve. (B) Corrected for *s*-wave deuteron capture.

The isotropic character of the neutron-gamma correlation at $E_d=400$ kev can be explained by a compound nucleus formation with *s*-wave deuterons and it is clear that while the stripping process is dominant at the higher energies, there is in fact an isotropic contribution even at these higher energies. The relatively rapid rise in cross section of the stripping mechanism compared to the compound nuclear formation is striking but is to be expected from stripping theory.[22] In this case the cross-over occurs somewhere just above $E_d=400$ kev, a rather low value. It may be noted that the measurements by Whaling and Bonner[5] and by Krone, Hanna, and Inglis[23] of the angular distribution of the proton groups from $Li^6(d,p)Li^7$, Li^{7*} at low bombarding energies are similar to ours and might similarly be interpreted as arising from the onset of the stripping process at a deuteron bombarding energy of about 650 kev.

The excitation function is very similar to that for the alternate reaction $Li^6(d,p\gamma)Li^7$.[5] It also has the same

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[16] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

[17] G. R. Satchelor and J. A. Spiers, Proc. Phys. Soc. (London) **A65**, 980 (1952).

[18] R. Huby, *Progress in Nuclear Physics* (Pergamon Press, London, 1953).

[19] Bhatia, Huang, Huby, and Newns, Phil. Mag. **43**, 485 (1952).

[20] S. T. Butler and N. Austern, Phys. Rev. **93**, 355 (1954).

[21] W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).

[22] S. T. Butler (private communication).

[23] Krone, Hanna, and Inglis, Phys. Rev. **80**, 603 (1950).

general shape as that obtained by Baggett and Bame[7] who bombarded Li^6 with deuterons and detected all neutrons above 10 kev coming from the target with approximately equal efficiency using a boron trifluoride counter. It must be deduced, therefore, that either all three possible reactions have similar excitation functions, or that either or both of the other two reactions have a relatively smaller cross section. In order to determine the ratio of the intensities of neutrons resulting from reactions proceeding direct to the ground state of Be^7 to those to the first excited state, the spectrometer was used in a different way. The first, close-up, crystal was biased to accept protons recoiling from neutrons scattered in it which were then detected by the second counter. While it was not possible to resolve the two neutron groups adequately by this technique, it appeared that the transitions to the first excited state predominated at $E_d=600$ kev. This result is in contradiction to the results of Gibson and Green[24] using photoplate technique and working with $E_d=930$ kev.

If it is assumed that the isotropic character of the correlation at $E_d=400$ kev arises from the capture of *s*-wave deuterons, then the excitation curve may be corrected for the Coulomb penetrability at the low-energy end. This leads to the resonance shown in curve *B* of Fig. 10 which would correspond to an excited state in Be^8 at 22.6 Mev in accord with previous work.[6,7]

ACKNOWLEDGMENTS

We are indebted to the Atomic Energy of Canada, Ltd., for financial support which made this work possible. One of us (G.C.N.) gratefully acknowledges the award of a National Research Council of Canada fellowship.

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Elastic and Inelastic Scattering of 31.5-Mev Alpha Particles by Light Nuclei*

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Using the 31.5-Mev alpha-particle beam of the Massachusetts Institute of Technology cyclotron, a study has been made of the angular distributions obtained in the (α,α) and (α,α') interactions on Li^6, C^{12}, and Mg^{24}. Separation of the alpha particles from other products of the alpha-induced reactions was accomplished by a dE/dx and E two-crystal technique developed at the cyclotron laboratory. The experimental inelastic angular distributions are shown to be in agreement with those predicted by the direct surface interaction theory. The experimental elastic angular distributions are compared with the diffraction of light by an opaque sphere. The probabilities of excitation of isotopic spin "forbidden" and "allowed" levels were also obtained for specified levels of Li^6 and N^{14}.

I. INTRODUCTION

It has long been recognized that a direct experimental study of the scattering of charged particles by atomic nuclei provides a valuable source of information concerning the force field of the nucleus. In recent years there has been a renewal of interest in the scattering of alpha particles, occasioned by the high energies to which they may be accelerated in the various types of particle accelerators. For the most part, these investigations have been confined to a study of elastic scattering phenomena,[1–4] and relatively little information[5,6] is available concerning the (α,α') interaction. The stable 31.5-Mev high intensity alpha-particle beam of the M.I.T. cyclotron, used in conjunction with a particle selection technique developed by Aschenbrenner,[7] has proven to be of great value in extending the scope of these investigations.

The primary object of this experiment was to obtain information concerning the (α,α') scattering process by a study of the inelastic angular distributions. Preliminary data disclosed a well-defined structure, asymmetric in the center-of-mass coordinate system and quite suggestive of the angular distributions predicted for a direct surface interaction.[8] The objective of comparing experimental data with this or any other theory imposed certain restrictions on the choice of target nuclei.

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† Lieutenant Commander, U. S. Navy, now on duty with Commander Joint Task Group 7.3.

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[8] Austern, Butler, and McManus, Phys. Rev. **92**, 350 (1953).