Study of the $Li^6(p,\alpha)He^3$ Reaction*

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The $Li^6(p,\alpha)He^3$ reaction has been studied in the energy range $0.6 \leq E_p \leq 2.9$ Mev by observing the magnetically analyzed He^3 and α particles at laboratory angles of 20° and 60°. By inferring the α yield in the backward direction from the He^3 yield observed at the corresponding forward angle, it was possible to construct the angular distributions of the α particles. Two resonances were found in the energy range studied, corresponding to a low-energy (≈ 1 Mev) s-wave state and a p-wave state near 1.85 Mev. A single-level resonance formula for a $J=5/2^-$, p-wave state plus a smoothly varying background has been fitted to the total cross-section curve in the region of the 1.85-Mev resonance and the following resonance parameters extracted: $E_\lambda=2.20$ Mev, $Be^{7*}=7.80$ Mev, $\theta_p^2=0.24$, $\theta_\alpha^2=0.048$. A similar analysis was made of the data of Blair and Holland on the mirror reaction, $Li^6(n,\alpha)H^3$, and the following parameters obtained: $E_\lambda=0.43$ Mev, $Li^{7*}=7.68$ Mev, $\theta_n^2=0.26$, $\theta_\alpha^2=0.0085$. The close agreement between the reduced proton and neutron widths obtained from these mirror reactions indicates that the Be^7 level at 7.80 Mev and the Li^7 level at 7.68 Mev are mirror states with $J=5/2^-$. This conclusion agrees with that previously reached by Bashkin and Richards. The α-particle angular distributions in the energy range $0.6 \leq E_p \leq 2.5$ Mev can be qualitatively explained on the basis of two interfering levels with $J=3/2^+$ (at $E_p \cong 1.0$ Mev) and $J=5/2^-$ (at $E_p \cong 1.85$ Mev). The angular distribution of the α particles from the $Li^6(p,\alpha)He^3$ reaction at $E_p=2.91$ Mev cannot be described in terms of s and p waves alone and suggests either that angular momenta greater than one are becoming effective in the formation of the compound nucleus at the higher bombarding energies or that a direct interaction process is taking place.

INTRODUCTION

THE regions of excitation energy near 6–8 Mev in Li^7 and Be^7 may be investigated by means of the mirror reactions, $Li^6(n,\alpha)H^3$ and $Li^6(p,\alpha)He^3$. The $Li^6(n,\alpha)H^3$ reaction has been studied by Blair and Holland[1] in the energy range $0.1 \leqslant E_n \leqslant 0.6$ Mev and has been discussed by Johnson, Willard, and Bair[2] in connection with the scattering of neutrons by Li^6. The $Li^6(p,\alpha)He^3$ reaction was investigated by Bashkin and Richards[3] in the energy range $0.4 \leqslant E_p \leqslant 3.6$ Mev. These experiments have disclosed what are apparently $J=5/2^-$ mirror levels in Li^7 and Be^7 near 7.7 Mev; the resonance parameters have been discussed by Bashkin and Richards. Furthermore, broad s-state structure in both nuclei near 6.5 Mev is indicated by the large zero-energy neutron scattering length[4] in Li^6+n and by the broad, low-energy resonance in the $Li^6(p,\alpha)He^3$ reaction.[3]

The analysis of the $Li^6(p,\alpha)He^3$ reaction by Bashkin and Richards[3] was based on data obtained only at one angle of observation. Since there is interference between the low-energy s state and the $J=5/2^-$ state (formed by p-wave protons) and since the angular distribution of the reaction products was not known, a more complete investigation of this reaction was warranted in order to obtain a more precise determination of the resonance parameters. Such parameters can be compared with those obtained from an analysis of the $Li^6(n,\alpha)H^3$ cross section; agreement between the two sets of data would strongly indicate that the levels are mirror states.

EXPERIMENTAL PROCEDURE

The target used for the study of the $Li^6(p,\alpha)He^3$ reaction was prepared by evaporating lithium metal enriched[5] to 96% Li^6 onto a thin copper foil. The lithium was then allowed to react with the air for several hours in order to form Li^6OH throughout the lithium layer. This target showed no deterioration during prolonged bombardments with 1 microampere of protons. The thickness of the material and of the copper backing were measured by magnetically analyzing the elastically scattered protons at a bombarding energy of 2 Mev. The momentum spectrum showed peaks due to copper, oxygen, and Li^6; no carbon was found on the freshly prepared target (lithium hydroxide converts to the carbonate if exposed to air for long periods) and therefore it was assumed that the target was entirely Li^6OH. At this bombarding energy the copper foil was found to be 60 ± 3 kev thick and the Li^6OH 6.2 ± 0.2 kev thick when the target was oriented at 45° with respect to the beam direction.

The number of Li^6 atoms per cm^2 was computed from the observed thickness and the stopping cross section of lithium hydroxide. The latter quantity was determined by adding the stopping cross sections at 2 Mev for lithium, hydrogen and oxygen.[6] The value for oxygen was found by multiplying the stopping cross section for air at 2 Mev by the ratio of the stopping

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[1] J. M. Blair and R. E. Holland in *Neutron Cross Sections*, compiled by D. J. Hughes and J. A. Harvey, Brookhaven National Laboratory Report BNL-325 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1955).
[2] Johnson, Willard, and Bair, Phys. Rev. **96**, 985 (1954).
[3] S. Bashkin and H. T. Richards, Phys. Rev. **84**, 1124 (1951).
[4] A. M. Lane, Atomic Energy Research Establishment Report T/R 1289, 1954 (unpublished).
[5] The enriched lithium metal was supplied by the Stable Isotopes Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
[6] R. Fuchs and W. Whaling (unpublished).

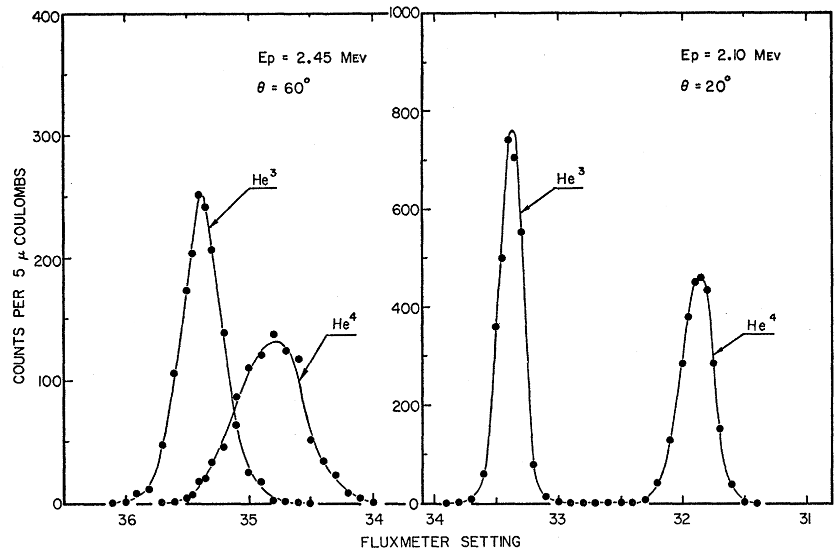


FIG. 1. Momentum profiles of the He^3 and α particles from the $Li^6(p,\alpha)He^3$ reaction at $\theta=60°$, $E_p=2.45$ Mev and at $\theta=20°$, $E_p=2.10$ Mev. Pulse-height analysis was necessary to separate the two groups at $\theta=60°$.

cross section of oxygen to that of air at 0.6 Mev. The stopping cross section of LiOH at 2 Mev computed in this manner was $6.04\pm0.60\times10^{-15}$ ev-cm², and hence the target presented $(0.98\pm0.10)\times10^{18}$ Li^6 atoms per cm² when oriented at 45° with respect to the beam direction.

It was desired to make the measurements on the $Li^6(p,\alpha)He^3$ reaction in the forward direction where the momenta of both the He^3 and α particles are greater than the momentum of protons elastically scattered from the copper foil. At observation angles up to about 80°, it is possible to measure the momentum profiles of the reaction products without interference from the large yield of scattered protons. In addition, by observing both the He^3 and α particles in the forward direction it is possible to infer the yield in the backward direction, thus making measurements in the backward hemisphere unnecessary. Observation angles of 20° and 60° were chosen to give data at approximately equal intervals in $\cos\theta$ when the transformation to the center of mass system is made.

Since He^3 and α particles lose energy quite rapidly when passing through matter, it was necessary, in order to make measurements in the forward direction, to mount the target in such a position that the proton beam passed through the copper foil before striking the Li^6OH target. With such an arrangement the reaction products underwent little straggling and good momentum profiles could be obtained. Figure 1 shows the He^3 and α-particle profiles taken at $E_p=2.45$ Mev, $\theta=60°$ and at $E_p=2.10$ Mev, $\theta=20°$. At $\theta=60°$, the He^3 and α particles have approximately the same momentum and pulse-height analysis was necessary to separate the two groups. This was easily accomplished since the pulse height of the He^3 particles in the CsI detector was about 1.5 times that of the α particles. At 20°, the two peaks were well separated in momentum at all bombarding energies investigated.

Since the target was bombarded by protons which had passed through the copper foil, it was necessary to correct the energy scale for the energy loss of the protons. This value was accurately known at 2 Mev from the scattering measurements described above. The energy loss at other bombarding energies was determined by using the stopping cross-section curve for copper given by Fuchs and Whaling.[6] There are no known or expected narrow resonances in the $Li^6(p,\alpha)He^3$ reaction, so that the spread in the bombarding energy introduced by the straggling of the protons in the copper foil is not important and has been neglected.

At each bombarding energy and angle of observation, complete momentum profiles similar to those in Fig. 1 were obtained for both the He^3- and α-particle groups with the Kellogg Laboratory's 16-in. double-focusing 180° magnetic spectrometer. The differential cross sections were calculated from the relation[7]:

$$\frac{d\sigma}{d\Omega}=\frac{R_c\times10^{12}}{2\pi q\Omega_c nt}\int\frac{N(I)}{I}dI \text{ barns/sterad,}$$

where R_c is the momentum resolution of the spectrometer ($p/\Delta p=226$), q is the amount of charge collected at the target in microcoulombs, Ω_c is the solid angle of the spectrometer (62.4×10^{-4} steradian), nt is the number of Li^6 atoms per cm², and $N(I)$ is the number of counts obtained at a fluxmeter setting I.

The uncertainty in the absolute cross-section measurements is compounded from the uncertainties in the target thickness (3%), the stopping cross section of LiOH (10%), the chemical composition of the target

[7] Snyder, Rubin, Fowler, and Lauritsen, Rev. Sci. Instr. **21**, 852 (1950).

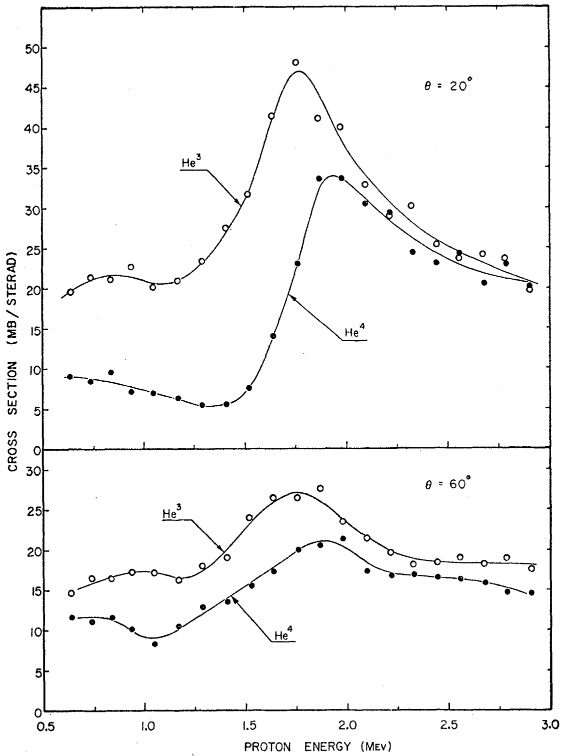


FIG. 2. Excitation curves of the He^3 and α particles from the $Li^6(p,\alpha)He^3$ reaction at $\theta=20°$ and 60°.

(estimated to be about 10%), the current integrator calibration (1%), the spectrometer constants (1.5%), and in obtaining the areas under the momentum profiles (in general about 4%). Therefore, the absolute cross sections are probably accurate to about 15%.

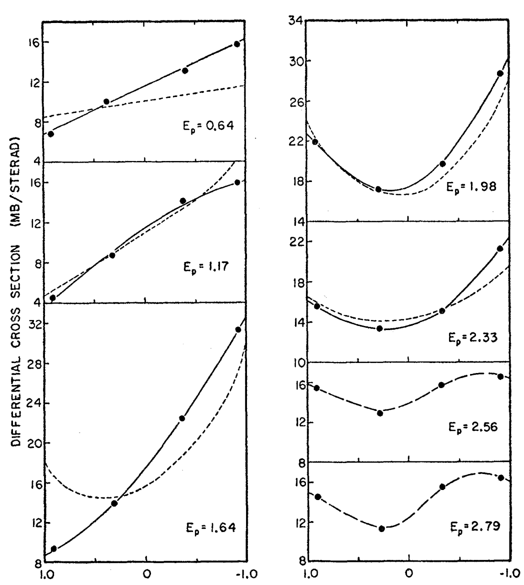


FIG. 3. Typical angular distributions of the α particles from the $Li^6(p,\alpha)He^3$ reaction at various bombarding energies. The solid curves were calculated from the coefficients listed in Table I. The broken curves represent those distributions which could not be fit with the $\cos^2\theta$ expansion. The dotted curves were derived theoretically from the assumption of two interfering levels with $J=3/2^+$ and $J=5/2^-$ at $E_p=1.0$ and 1.85 Mev, respectively.

RESULTS

The excitation curves for the He^3 and α particles obtained at $\theta=20°$ and 60° are shown in Fig. 2. The 20° curve for the α particles is very similar to that obtained by Bashkin and Richards[3] for the He^3 particles at $\theta=164°$. All of the curves show the resonance near 1.85 Mev and the broad maximum previously observed[3] at about 1 Mev. In view of the interference between these two levels which is apparent in the excitation curves, a total cross section for the reaction must be obtained before a single-level resonance formula can be fitted to the data. The total cross section was obtained in the following manner.

TABLE I. Total cross section and the coefficients of the expansion $\sigma(E,\theta)=a(E)+b(E)\cos\theta+c(E)\cos^2\theta$ for the α particles from the $Li^6(p,\alpha)He^3$ reaction.

E_p (Mev)	σ (mb)	$a(E)$ (mb)	$b(E)$ (mb)	$c(E)$ (mb)
0.64	126	10.0	−4.0	···
0.74	133	10.6	−5.5	···
0.84	134	10.6	−4.8	···
0.94	138	11.0	−6.7	0.3
1.05	133	10.8	−6.4	−0.7
1.17	137	11.4	−6.4	−1.4
1.29	154	13.3	−7.7	−3.0
1.41	164	13.7	−9.2	−1.9
1.52	197	16.7	−10.3	−2.8
1.64	234	17.5	−12.1	3.0
1.76	262	18.1	−10.5	8.3
1.87	272	18.8	−4.8	8.5
1.98	258	17.4	−3.6	9.5
2.10	215	15.1	−1.1	5.9
2.22	205	14.1	−1.2	6.6
2.33	196	13.5	−3.1	5.8
2.45	185	13.7	−1.6	3.0
2.56	187			
2.68	174			
2.79	179			
2.91	168			

At each bombarding energy the measured cross sections were converted to the center-of-mass system[8] and the He^3 cross section was used to infer the α-particle cross section at the corresponding center-of-mass angle in the backward hemisphere. In this manner, four-point angular distributions of the α particles were obtained at approximately 100-kev intervals from $E_p=0.6$ to 2.9 Mev. Some of these distributions, typical of the respective energy regions, are shown in Fig. 3. It was apparent from these angular distributions that up to a bombarding energy of about 2.5 Mev the distributions could be well represented in terms of only s and p waves. Consequently, a least-squares analysis

[8] J. B. Marion and A. S. Ginzberg, *Tables for the Transformation of Angular Distribution Data from the Laboratory System to the Center-of-Mass System* (Shell Development Company, Houston, 1955).

of the form $\sigma(E,\theta)=a(E)+b(E)\cos\theta+c(E)\cos^2\theta$ was made for $E_p \leqslant 2.45$ Mev. The coefficients and total cross sections obtained are given in Table I and the total cross section is also shown in Fig. 4. Above 2.45 Mev it was necessary to obtain the total cross section by graphical integration. The solid curves in Fig. 3 represent the least-squares fitted angular distributions, calculated from the coefficients listed in Table I. The broken curves represent the high-energy distributions which could not be described by the $\cos^2\theta$ expansion and are the curves used to obtain the total cross section by integration. The dotted curves are theoretical curves based on the interference between two levels with $J=3/2^+$ and $J=5/2^-$ and are discussed in the next section. Also shown in Fig. 4 are the low-energy data of Sawyer and Phillips[9]; these data are

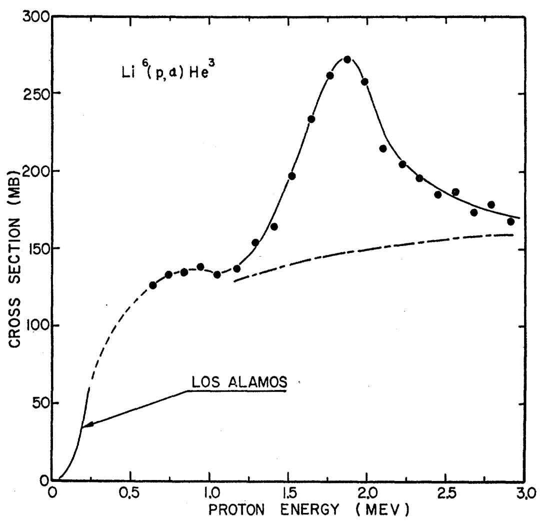


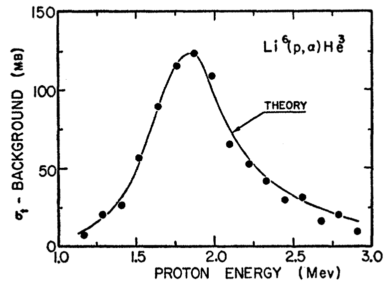
FIG. 4. Total cross section for the $Li^6(p,\alpha)He^3$ reaction. The low-energy Los Alamos measurements are due to Sawyer and Phillips (reference 9). The dashed curve is an extrapolation through the energy region in which total cross-section measurements are not available. The dot-dash curve is the background assumed in order to analyze the 1.8-Mev resonance.

accurate to about 15%. The broken curve between the results of these authors and the present work represents a reasonable extrapolation through the energy region for which no total cross-section measurements are available. The dot-dash curve in Fig. 4 represents the background under the resonance which was assumed in order to analyze the resonance portion of the total cross section.

The absolute cross sections which have been measured here are about a factor of 3 higher than those obtained by Bashkin and Richards[3]; however, the present results extrapolate well to the accurate low-energy measurements of Sawyer and Phillips[9] whereas a cross section 3 times smaller would be in definite disagreement. The

[9] G. S. Sawyer and J. A. Phillips, Los Alamos Scientific Laboratory Report No. 1578, 1953 (unpublished).

FIG. 5. Interpretation of the $Li^6(p,\alpha)He^3$ cross section above background in terms of a single $J=5/2^-$ level formed by p-wave protons. The curve was calculated from the single-level resonance formula with the parameters listed in Table II.



old (1938–39) measurements of Rumbaugh, Roberts, and Hafstad[10] and of Bowersox[11] also indicated smaller cross sections, but the values of Burcham and Freeman[12] are in fair agreement with the present results.

DISCUSSION

The total cross section of the $Li^6(p,\alpha)He^3$ reaction shown in Fig. 4 indicates a broad, low-energy peak and a pronounced resonance near 1.85 Mev. When a smoothly varying background (indicated by the dot-dash curve in Fig. 4) is subtracted from the total cross section, the resonance portion may be analyzed by fitting a single-level resonance formula[13] to the data.

The scattering of neutrons from Li^6 has established[2] the existence of a $J=5/2^-$ state near 7.7 Mev in Li^7 which is formed by p-wave neutrons. It is therefore reasonable (and in agreement with the conclusion of Bashkin and Richards[3]) that the pronounced resonance observed in the $Li^6(p,\alpha)He^3$ reaction corresponds to a p-wave, $J=5/2^-$ state in Be^7. The analysis of the present data has been made under this assumption. When the energy variation of the quantities Γ_p, Γ_α, $\Delta_{\lambda p}$,

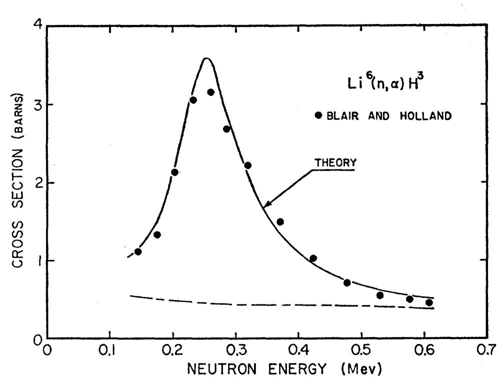


FIG. 6. Interpretation of the $Li^6(n,\alpha)H^3$ cross section in terms of a smoothly varying background (dot-dash curve) and a single $J=5/2^-$ level formed by p-wave neutrons. The experimental points are due to Blair and Holland (reference 1). The solid curve was calculated from the single-level resonance formula with the parameters listed in Table II.

[10] Rumbaugh, Roberts, and Hafstad, Phys. Rev. **54**, 657 (1938).
[11] R. B. Bowersox, Phys. Rev. **55**, 323 (1939).
[12] W. E. Burcham and J. M. Freeman, Phil. Mag. **41**, 921 (1950).
[13] E. P. Wigner and L. Eisenbud, Phys. Rev. **72**, 29 (1947); R. G. Thomas, Phys. Rev. **81**, 148 (1951).

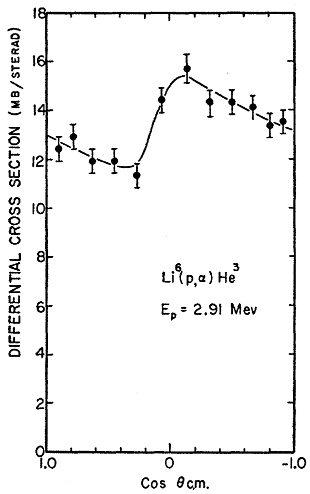


FIG. 7. Angular distribution of the α particles from the $Li^6(p,\alpha)He^3$ reaction at $E_p=2.91$ Mev. The points for $\cos\theta<0$ were inferred from the He^3 yield at the corresponding forward angle.

and $\Delta_{\lambda\alpha}$ are taken into account, the total cross section above background in the range $1.2\leqslant E_p\leqslant 2.9$ Mev can be adequately described by the single-level resonance formula with the parameters $E_\lambda=2.20$ Mev, $\gamma_p^2=0.42\times10^{-12}$ Mev-cm, $\gamma_\alpha^2=0.079\times10^{-12}$ Mev-cm, and $\Delta_\lambda(E_R)=-0.57$ Mev. The calculated curve and the experimental points (total cross section minus background) are shown in Fig. 5. Several sets of parameters were tried and the above values gave the most satisfactory fit. A change in the background of 5% would introduce changes in the resonance parameters of less than half this amount.

The mirror reaction $Li^6(n,\alpha)H^3$ has been studied by Blair and Holland[1] and analyzed by the Oak Ridge group.[2] The latter investigators used radii of interaction appreciably smaller than those used above in the analysis of the $Li^6(p,\alpha)He^3$ reaction and consequently their parameters cannot be compared directly with the present results. Therefore, the analysis of Blair and Holland's data was undertaken using the same channel radii as for the $Li^6(p,\alpha)He^3$ reaction. The experimental points are shown in Fig. 6; the dot-dash curve is the assumed nonresonant background. The solid curve is that obtained from the single-level formula with the parameters $E_\lambda=0.43$ Mev, $\gamma_n^2=0.46\times10^{-12}$ Mev-cm, $\gamma_\alpha^2=0.014\times10^{-12}$ Mev-cm, and $\Delta_\lambda(E_R)=-0.23$ Mev. The value of $\Gamma_n(E_R)(=0.114$ Mev) was chosen to be the same as that deduced from the analysis[2] of the neutron total cross section of Li^6. The values of γ_n^2 and γ_α^2 that were obtained agree with those determined by Johnson *et al.*,[2] when the effect of the different radii is taken into account.[14]

The resonance parameters obtained from the analysis of the mirror reactions $Li^6(n,\alpha)H^3$ and $Li^6(p,\alpha)He^3$ are compared in Table II. The close agreement between the

TABLE II. Comparison of resonance parameters for the $Li^6(n,\alpha)H^3$ and $Li^6(p,\alpha)He^3$ reactions. $a_s=R(Li^6+n)=R(Li^6+p)=4.08\times10^{-13}$ cm. $a_{s'}=R(H^3+\alpha)=R(He^3+\alpha)=4.39\times10^{-13}$ cm. All quantities refer to the center-of-mass system.

$Li^6(n,\alpha)H^3$	$Li^6(p,\alpha)He^3$
$E_\lambda=0.43$ Mev	$E_\lambda=2.20$ Mev
$Li^{7*}=Li^6+n-Li^7+E_\lambda=7.68$ Mev	$Be^{7*}=Li^6+p-Be^7+E_\lambda=7.80$ Mev
$\Delta_\lambda(E_R)=-0.23$ Mev	$\Delta_\lambda(E_R)=-0.57$ Mev
$\Gamma_n(E_R)=0.114$ Mev	$\Gamma_p(E_R)=0.67$ Mev
$\gamma_n^2=0.46\times10^{-12}$ Mev-cm	$\gamma_p^2=0.42\times10^{-12}$ Mev-cm
$\theta_n^2=\gamma_n^2\times(2\mu a_s/3\hbar^2)=0.26$	$\theta_p^2=\gamma_p^2\times(2\mu a_s/3\hbar^2)=0.24$
$\Gamma_\alpha(E_R)=0.064$ Mev	$\Gamma_\alpha(E_R)=0.05$ Mev
$\gamma_\alpha^2=0.014\times10^{-12}$ Mev-cm	$\gamma_\alpha^2=0.079\times10^{-12}$ Mev-cm
$\theta_\alpha^2=\gamma_\alpha^2\times(2\mu a_{s'}/3\hbar^2)=0.0085$	$\theta_\alpha^2=\gamma_\alpha^2\times(2\mu a_{s'}/3\hbar^2)=0.048$
$\Gamma(E_R)=0.18$ Mev	$\Gamma(E_R)=0.72$ Mev

reduced neutron and proton widths for the two levels leaves little doubt that these are mirror $J=5/2^-$ states formed by p-wave particles. The fact that the reduced α-particle widths differ by a factor of 6 probably does not contradict this conclusion, since similar differences are known[4] for other mirror levels. The reason for this difference is not fully understood.

A broad maximum in the $Li^6(p,\alpha)He^3$ total cross section (Fig. 4) is apparent near 1 Mev. In the energy region between this peak and the p-wave resonance the angular distributions contain large $\cos\theta$ terms indicating interference between states of opposite parity. Lane[4] has suggested that the energy region near 6–7 Mev in Li^7 and Be^7 should contain two broad s states with J values of $1/2^+$ and $3/2^+$. Since the $J=5/2^-$ state is formed with channel spin 3/2, only the s state with $J=3/2^+$ can interfere coherently with the $J=5/2^-$ state to produce the $\cos\theta$ terms. Therefore it seemed probable that the 1-Mev peak was due to a $J=3/2^+$ state and a theoretical calculation of the angular distributions expected from a $J=5/2^-$ state at $E_p=1.85$ Mev interfering with a $J=3/2^+$ state at 1.0 Mev was undertaken. This calculation utilized the resonance parameters of the $5/2^-$ state determined from the total cross-section analysis near 1.85 Mev. For the $3/2^+$ state the resonance parameters were determined from a rough fit of the low-energy total cross section. The results of this analysis, illustrated by the dotted curves of Fig. 3 indicate that both the magnitude and energy variation of the interference terms are qualitatively explained by the assumption of the $5/2^-$ and $3/2^+$ levels.

That the experimental situation is much more complex than assumed in this analysis is obvious when the total $Li^6(p,\alpha)$ cross section is studied in greater detail. No set of single-level s-wave resonance parameters can account for the total cross section with the 1.85-Mev resonance contribution removed. Therefore one or more additional compound nucleus states exist in this energy region, or a direct interaction process[15] is taking place.

[14] The ratio of the reduced widths $\gamma_n^2/\gamma_\alpha^2$, stated to be $\approx10^3$ in reference 2, should have read $\gamma_n^2/\gamma_\alpha^2=30$ [C. H. Johnson (private communication)]. This latter value is then in agreement with the present result for this ratio ($\gamma_n^2/\gamma_\alpha^2=33$).

[15] R. G. Thomas (unpublished).

Since the $Li^6(p,\gamma)Be^7$ angular distributions of Warren, Alexander, and Chadwick[16] near 1 Mev indicate the presence of a large $\cos^2\theta$ term, the situation can at best be only partially helped by the inclusion of the s-wave $J=1/2^+$ state suggested by Lane.[4] Thus the theoretical situation leaves room for further experimental studies in this energy region. A fruitful experimental approach would seem to be a study of the elastic scattering of protons by Li^6.

At the highest bombarding energies investigated the angular distributions could not be explained in terms of s and p waves alone. In order to obtain an angular distribution more accurate than the four-point distributions which were adequate at the lower energies, measurements were made at 3 additional angles at 2.91 Mev. The angular distribution obtained is shown in Fig. 7. The form of this curve suggests that either angular momenta greater than one are becoming effective in the formation of compound nucleus states or that some sort of a direct interaction process is taking place.[15] Measurements at higher bombarding energies will be necessary in order to clarify this point.

[16] Warren, Alexander, and Chadwick, Phys. Rev. **101**, 242 (1956).

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Gamma Radiation from Co^{56} and Co^{58}

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The gamma rays following the decay of Co^{56} and Co^{58} have been observed by means of a large NaI(Tl) crystal scintillation spectrometer. Relative intensities of the Co^{56} gamma radiation are presented as well as ratios of orbital electron capture to positron emission for both Co^{56} and Co^{58}.

INTRODUCTION

THE availability of large NaI(Tl) crystals has made possible the measurement of gamma-ray spectra from sources too weak to produce statistically significant results in other spectrometers. As long as very good resolution is not required, measurement of the area of the full-energy peak, with appropriate corrections, gives a good measure of the gamma-ray intensity[1,2] relative to other gamma rays in the same spectrum.

In the current measurements a cylindrically-shaped NaI(Tl) crystal, four inches high and four inches in diameter, and a DuMont type-6364 photomultiplier tube were used to observe the gamma radiation. The resulting pulse-height distribution was recorded on a Bell-Kelly type 20-channel analyzer, operated so that the spectrum covered a total of 100 channels.

The sources were placed exterior to a lead housing surrounding the crystal-photomultiplier system and observed by the crystal through a collimating aperture $\frac{1}{2}$ inch in diameter and 8 inches long.

COBALT-56

Source Preparation

Two different sources of Co^{56} were used for this experiment. One was prepared in the University of Washington cyclotron by the $Fe^{56}(p,n)Co^{56}$ reaction on a stainless steel foil used by the Seattle group as exit window for their cyclotron.[3] The other was prepared by the same reaction in the University of California 60-in. cyclotron.[4]

The sources were encapsulated in the end of either a glass or brass container in a space adequately small so that they could be considered point sources. The brass capsule was made especially for this purpose with walls just thick enough to stop all positrons. Thus, the full-energy peak from the annihilation radiation may be used to determine positron intensity.

Analysis of Data

The pulse-height distribution from one of the Co^{56} sources is shown in the lower histogram of Fig. 1. It is a spectrum typical of either source. The upper distribution is the statistical error for this particular set of data. Analysis of relative intensities has been made by a series of successive subtractions of normalized spectral shapes, as indicated in Fig. 2, these shapes having been determined experimentally for a series of monoenergetic gamma rays from Cs^{137}, Nb^{95}, Zn^{65}, K^{42}, and Na^{24}. For the lower energy radiations, a high-gain set of data (Fig. 3) was obtained and analyzed in the same manner. This distribution was used to determine the relative

[1] R. S. Foote and H. W. Koch, Rev. Sci. Instr. **25**, 736 (1954).
[2] G. M. Griffiths, Can. J. Phys. **33**, 209 (1955).
[3] This source was obtained from Dr. D. J. Farmer, who had the required chemistry performed to extract the cobalt fraction.
[4] This source was obtained from Dr. C. D. Jeffries, who initially prepared the source for studies of the paramagnetic resonance fine structure of Co^{56}; see Jones, Dobrowski, and Jeffries, Phys. Rev. **102**, 738 (1956).