# Proton Bombardment of the Lithium Isotopes*

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Thin targets of ordinary lithium have been bombarded by protons over the energy range 0.4 Mev to 3.6 Mev. Observations of the magnetically analyzed reaction and scattered particles were made at 164° to the incident beam. Differential cross-section curves were obtained for protons scattered elastically and inelastically from $Li^7$, elastically from $Li^6$, and for the $He^4$ and $He^3$ particles from the $Li^6(p, \alpha)He^3$ reaction. The $Li^6$ data show an excited state in $Be^7$ at about 7.2 Mev and also a lower and very broad state. Possible correspondence to levels in the mirror nucleus $Li^7$ is discussed. The protons scattered inelastically from $Li^7$ do not show any resonances above $E_p = 1.5$ Mev. The $Li^7$ elastic scattering cross section has maxima at proton energies of 1.05 Mev, 1.88 Mev, and 2.06 Mev.

## INTRODUCTION

WHEN $Li^6$ is struck by protons, the compound nucleus, $Be^7$, is formed with an excitation energy of 5.60 Mev$+6E_p/7$, where $E_p$ is the proton energy in laboratory coordinates. The two most probable modes of decay of these virtual states are

$$Li^6+p \rightarrow (Be^7)^* \rightarrow Li^6+p \quad (1)$$

$$\searrow He^4+He^3+4.024\pm0.005 \text{ Mev.}^1 \quad (2)$$

In the present experiment, the excitation functions of the above reactions have been studied for incident protons up to 3.6-Mev energy. It was hoped to find the location and character of the states of $Be^7$ which lie between 6- and 9-Mev excitation energy. In particular, it was hoped to locate the state in $Be^7$ which should mirror the 7.5-Mev level in $Li^7$ which was observed by Blair[2] as a resonance in the $Li^6(n, \alpha)H^3$ reaction for 250-kev neutrons. Gove and Harvey[3] have seen this level (7.50±0.17 Mev) in the $Be^9(d, \alpha)Li^7$ reaction and also report a level in $Li^7$ at 4.77±0.10 Mev.

At the same time that the virtual levels of $Be^7$ were being investigated, it proved convenient to study the elastic and inelastic scattering of protons by $Li^7$. These data provide information concerning very highly excited states of the compound nucleus, $Be^8$.

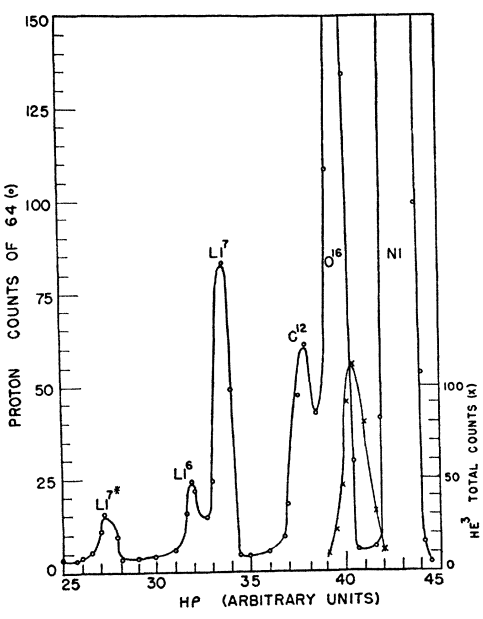


FIG. 1. Momentum spectrum at laboratory angle 164±5 degrees of the protons scattered by the Li target, the 1000A nickel foil backing and by carbon and oxygen contaminants. The group at about 40 Hp units are $He^3$ reaction products and were separated from the scattered protons by pulse-height discrimination. The incident proton energy was 1.91 Mev.

## PROCEDURE

Targets of ordinary lithium metal (92.5 percent $Li^7$) were prepared by evaporation upon thin nickel foil.[4] These backings were only 500A thick for some of the work. The lithium targets were about 10-kev thick for 2-Mev protons. The targets were placed on a heated support at one focus of a 90° magnetic analyzer[5] and struck by protons monoergic to 0.1 percent. Particles which emerged from the target at an angle of 164±5° to the incident beam and which had the proper momentum to charge ratio were directed by the analyzer's magnetic field through a conjugate focus and detected by a proportional counter. The counter window prevented detection of protons of energy less than 320 kev. A schematic diagram of a similar experimental arrangement is shown in Fig. 1 of reference 5. The resolution of particle groups of different momentum to charge ratio and of different specific ionization is illustrated in Fig. 1. Pulse-height discrimination in the proportional counter allowed a clean separation of the $He^3$ particles from protons. The $He^4$ particles could also have been distinguished by pulse-height analysis, but were actually

* Work supported by the AEC and the Wisconsin Alumni Research Foundation.
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1 Williamson, Browne, Craig, and Donahue, Phys. Rev. 84, 731 (1951).

2 J. M. Blair, private communication. Older cross-section data are shown in Adair's summary article, Revs. Modern Phys. 22, 249 (1950).
3 H. E. Gove and J. A. Harvey, Phys. Rev. 82, 658 (1951).
4 S. Bashkin and G. Goldhaber, Rev. Sci. Instr. 22, 112 (1951).
5 Shoemaker, Faulkner, Bouricius, Kaufmann, and Mooring, Phys. Rev. 83, 1011 (1951).

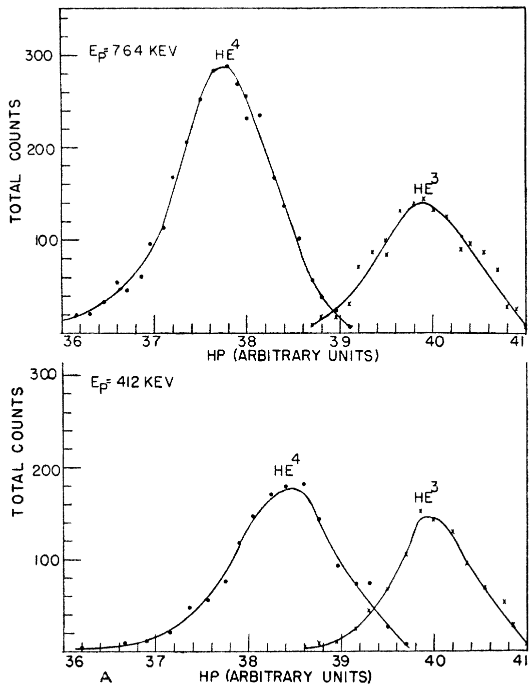


FIG. 2. Typical momentum spectrum of reaction products from $Li^6(p, He^4)He^3$ at low incident proton energies. The rapid variation of $He^4/He^3$ yield with proton energy is apparent.

studied only in an energy region where the magnetic field separated them from the other particles (see Fig. 2).

The yields of some of the well-resolved particle groups were followed as a function of the bombarding energy. At each energy the magnetic field was varied until the greatest number of counts per incident charge was found. The excitation functions presented in this paper show how those maxima varied with energy. For large enough exit slits to the analyzer, the maxima should be flat-topped and proportional to the total number of particles. For reasonable target thicknesses and for resolution sufficient to separate protons scattered from $Li^6$ and from $Li^7$, the flat-topped portion in many cases disappeared. Hence, there is some question concerning the exact proportionality to differential cross section of some of the yield curves here reported. This questionable proportionality was checked over part of the momentum range by comparing the total number of particles entering the analyzer as determined from the maximum yield with the number calculated from $\int N(p)dp/p$, where $N(p)$ is the number of particles observed for a given setting of the magnetic field and $dp/p$ is given by the momentum resolution of the analyzer. The agreement was within 10 percent for the points so checked.

The lithium content of one target was found by measuring the neutron yield from the $Li^7(p, n)Be^7$ reaction. A flat-response long counter,[6] calibrated with a radium-beryllium source of known neutron strength, was used as a detector. Taschek and Hemmendinger's data[7] on the absolute differential cross section of the $Li^7(p, n)Be^7$ reaction were used to compute the lithium content of the target. The uncertainty in the lithium thickness is probably about 15 percent and the uncertainty in the absolute differential cross sections reported in this paper is at least 20 percent.

## RESULTS AND DISCUSSION

### $Li^6+p$

Figure 3 shows the yield of protons scattered elastically from $Li^6$ for bombarding energies between 1.2 and 3.1 Mev. The scattering yield above background outside of this energy interval was too small to permit a reliable extension of the curve. The maximum in the curve at 1.75±0.1 Mev indicates a virtual level of $Be^7$. The $He^3$ yield curve, Fig. 4, also shows a similar maximum, but at $E_p=1.82\pm0.08$ Mev. This latter energy may be used to locate the resonance energy as (6/7)(1.82) Mev above the dissociation energy of $Be^7$ or as 7.16 ±0.08 Mev above the ground state of $Be^7$.

There are reasons for identifying this state of $Be^7$ as the mirror level to one observed in $Li^7$ at 7.46±0.03 Mev.[2,3] The similarity in resonance energy (7.16 *vs* 7.46 Mev) and the paucity of other levels points strongly to this identification. A few hundred kilovolt shift of the mirror levels at this excitation energy is not unexpected. It could presumably result from the combined effects of, (1) a differential reduction in coulomb energies as the radii increase with excitation energies, (2) a difference in electromagnetic spin-orbit interaction for the odd neutron and proton, and (3) a difference in boundary conditions at the nuclear surface for the neutron and proton wave functions. (Table I shows that the difference in level shift probably accounts for ~70 kev of the discrepancy in excitation energy.)

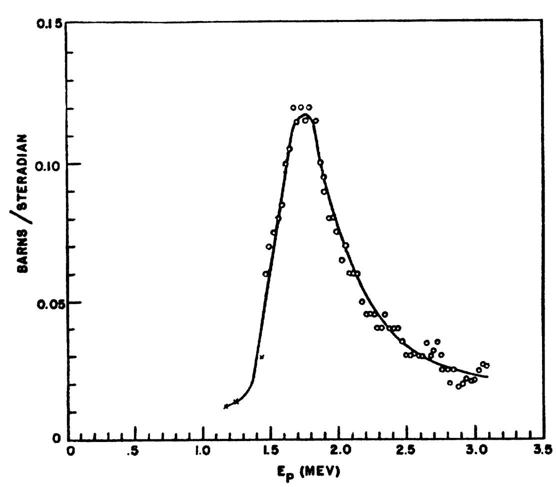


FIG. 3. Differential cross section (barns/steradian) at laboratory angle of 164° for protons scattered elastically from $Li^6$.

[6] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

[7] R. F. Taschek and A. Hemmendinger, Phys. Rev. **74**, 373 (1948).

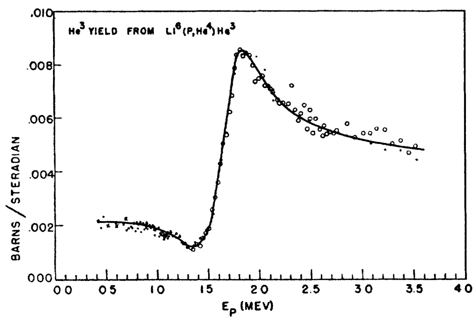


FIG. 4. Differential cross section (barns/steradian) at laboratory angle of 164° for the $He^3$ particles from $Li^6(p, He^3)He^4$.

Mirror levels should not only have corresponding excitation energies, but also the same $J$ values, parity, and reduced widths. This last condition may be used not only to support the mirror level identification, but also to fix the parity and give limits on the $J$ value of the level. Therefore, in Table I we have calculated the reduced widths of these levels in $Li^7$ and $Be^7$ for various assumptions regarding the angular momentum of the neutron or proton incident on $Li^6$. Six-sevenths of the experimental resonance width at half-maximum gives in each case the total width, $\Gamma$, of the level in gravicentric coordinates. The $(p, He^3)$ differential cross section is at resonance only 1/14 that of the elastic scattering (see Figs. 3 and 4). If one neglects effect of angular distribution on the ratio of total cross sections, then the partial width, $\Gamma_\alpha$, for alpha-emission is $\sim\Gamma/15=(6/7)(0.5/15)=0.03$ Mev. The proton width, $\Gamma_p=\Gamma-\Gamma_\alpha$, is therefore $\sim 0.40$ Mev. Since $\Gamma_\alpha \ll \Gamma_p$, the reduced proton width of $Be^7$ will be very insensitive to the exact value of $\Gamma_\alpha$ and hence our neglect of the unknown angular distribution is not serious. In the case of $Li^6+n$, it is the total $(n, \alpha)$ cross section which has been measured so $(2J+1)\Gamma_\alpha$ can be found by fitting a single level dispersion formula to the experimental cross section. Unless $\Gamma_\alpha \gg \Gamma_n$, the Wigner sum rule, $\gamma^2 \leq 3\hbar^2/mR$ excludes consideration of $l \geq 2$ neutrons and hence limits $J$ to values $\leq 5/2$. Experimentally,[2] the maximum in the $(n, \alpha)$ cross section is $\sim 3$ barns. This experimental value points to $J=5/2$ since the experimental cross-section value is almost the maximum theoretical absorption for $J=5/2$: $\sigma_{\max}=(2J+1)\pi\lambda^2/6$. If we therefore assume $J=5/2$ and $\Gamma_n > \Gamma_\alpha$ the experimental total cross section fixes $\Gamma_\alpha$ as $\sim 0.036$ Mev. This agreement with the $\Gamma_\alpha$ for the $Be^7$ level is gratifying evidence of the mirror character of the resonances; however, the agreement is perhaps fortuitous considering the unknown angular distribution of the alphas in the proton case and the uncertainties in the total cross-section measurements in the neutron case. The $\gamma_0^2=\Gamma_s A_l^2/2k$ in column three of Table I is the reduced width when the variation of level shift with energy can be neglected. $A_l^2$ for neutrons is the same as the $|v|^2$ of Feshbach, Peaslee, and Weisskopf,[8] while for protons $A_l^2=F_l^2+G_l^2$ (in the notation of Yost, Wheeler, and Breit[9]) and was evaluated with the use of Breit's coulomb wave-function tables.[9a] The fourth column, $\gamma^2=\gamma_0^2/(1-\gamma_0^2/R\cdot dg/dE)$ is the reduced width when account is taken of the variation of level shift with energy.[10] $R$ is the reaction radius and $g=d(\ln A_l)/d(\ln kR)$. The fifth column, $\Delta=-\gamma^2(g+l)/R$ gives the actual level shift at resonance and the last column corrects the observed resonance energy (as measured from the ground state of the nucleus) for the level shift $\Delta$.

Inspection of Table I shows that the reduced widths agree satisfactorily only if $l=1$ incident particles are involved in the resonance. Independent confirming evidence for this assignment in the case of the $Li^7$ level

TABLE I. Possible level parameters of the neutron (or proton) plus $Li^6$ resonance. An interaction radius $R=0.4\times10^{-12}$ cm (i.e., $\sim\frac{1}{2}(e^2/mc^2)(6^{\frac{1}{3}}+1^{\frac{1}{3}})$ was assumed.
The experimental total widths are (in center-of-mass coordinates)

$$\Gamma(Li^{7*})=(6/7)(0.1)\text{ Mev}=0.086\text{ Mev}$$
$$\Gamma(Be^{7*})=(6/7)(0.5)\text{ Mev}=0.43\text{ Mev.}$$

The partial widths $\Gamma_s=\Gamma-\Gamma_\alpha$ were taken as follows:

$$\Gamma_n=0.086-0.036=0.05\text{ Mev}$$
$$\Gamma_p=0.43-0.03=0.40\text{ Mev.}$$

| Orbital momentum of incident nucleon | Compound nucleus | Reduced nucleon width (×10¹² Mev-cm) $\gamma_0^2=\Gamma_s A_l^2/2k$ | $\gamma^2=\gamma_0^2/(1-\gamma_0^2/R\times dg/dE)$ | Level shift (Mev) $\Delta=-\gamma^2(g+l)/R$ | Energy of level (Mev above ground state) $E_\lambda=E_R-\Delta$ |
|---|---|---|---|---|---|
| $L=0$ | $Li^{7*}$ | 0.025 | 0.025 | 0 | 7.46 |
| | $Be^{7*}$ | 0.103 | 0.104 | +0.04 | 7.12 |
| $L=1$ | $Li^{7*}$ | 0.18 | 0.24 | −0.08 | 7.54 |
| | $Be^{7*}$ | 0.25 | 0.26 | −0.15 | 7.31 |
| $L=2$ | $Li^{7*}$ | 9.7 | (All values of $\gamma^2$ for $L\geq 2$ exceed $3\hbar^2/2mR\approx 1.8\times10^{-12}$.) | | |
| | $Be^{7*}$ | 2.1 | | | |

[8] Feshbach, Peaslee, and Weisskopf, Phys. Rev. **71**, 145 (1947).
[9] Yost, Wheeler, and Breit, Phys. Rev. **49**, 174 (1936).
[9a] Bloch, Hull, Broyles, Bouricius, Freeman, and Breit, Revs. Modern Phys. **23**, 147 (1951).
[10] R. G. Thomas, Phys. Rev. **81**, 148 (1951).

comes from the angular distribution[11] of the $Li^6(n, \alpha)H^3$ reaction at the 250-kev resonance.

We thus conclude that correspondence of mirror levels is indicated if $l=1$ neutrons or protons are assumed responsible for the resonances. Further, since $Li^6$ apparently has even parity, this would fix the parity of the $Li^7$ level as odd. The magnitude of the $(n, \alpha)$ cross section favors $J=5/2$. This level could therefore be one member of the low-lying $F$ doublet predicted on the quasi-atomic model.[12]

A noteworthy feature of the $He^3$ yield in both laboratory coordinates (Fig. 4) and in c.m. coordinates (Fig. 5) is the appearance of a broad yield maximum at low proton energies (0.6 to 0.9 Mev). Consideration was given to the possible influence on this maximum of alpha-particles from reactions of protons with the $Li^7$ isotope. The only $Li^7$ reaction giving alphas of the proper energy is the $(p, \gamma)$ reaction in which $Be^8$ is left in an excited state which decays by alpha-emission. The $(p, \gamma)$ cross section is apparently so small[14] that alphas from this reaction are difficult to detect. Furthermore, the 2-Mev half-width of the excited $Be^8$, plus the broadening in alpha-momentum because of the recoil from the preceding 14.5-Mev gamma-ray, would produce about twice the experimental momentum spread observed in the present experiment (Fig. 2). We therefore believe that reactions with the $Li^7$ isotope did not contribute significantly to the above low energy maximum.

This low energy maximum must then be associated with a very broad level in $Be^7$. It is tempting to assume that it is the mirror level to the one in $Li^7$ which must be postulated to account for the high thermal neutron cross section of $Li^6$. This identification is consistent with the fact that the great breadth of the low energy resonance requires that $s$-protons be responsible for the resonance. Higher momenta incident particles would give a reduced width exceeding the Wigner limit.

Figure 5 also shows a comparison of the present low energy $He^3$ and $He^4$ data with previous work by Rumbaugh, Roberts, and Hafstad,[13] Burcham and Freeman,[14] and Bowersox.[15] All data of Fig. 5 have been converted to cm coordinates and to differential cross sections to make comparisons more meaningful.

Our present data agree qualitatively in shape with the data of Rumbaugh, *et al.*,[13] and also with Burcham and Freeman.[14] The disagreement in absolute cross sections of the various experiments is marked. (The Burcham and Freeman cross section used in Fig. 5 is based on their comparison of the $(p, \alpha)$ yield of $Li^6$ and $B^{10}$. Were their other comparison to the $(p, \alpha)$ yield of $Be^9$ to be used, their cross-section values would be increased by a factor 1.7 and the disagreement would be even more marked.)

[11] Roberts, Darlington, and Haugness, Phys. Rev. **82**, 299 (1951).
[12] E. Feenberg and M. Phillips, Phys. Rev. **51**, 597 (1937).
[13] Rumbaugh, Roberts, and Hafstad, Phys. Rev. **54**, 657 (1938).
[14] Burcham and Freeman, Phil. Mag. **41**, 921 (1950).
[15] R. B. Bowersox, Phys. Rev. **55**, 323 (1939).

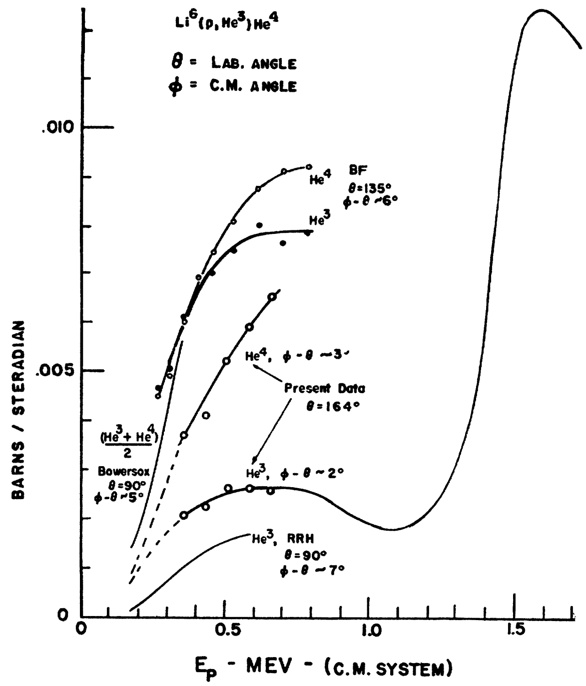


FIG. 5. Comparison (in gravicentric coordinates) with other measurements of the differential cross section of the $Li^6(p, He^4)He^3$ reaction. Note that the measurements have been made at several different angles. BF refers to Burcham and Freeman, reference 14; RRH to Rumbaugh, Roberts, and Hafstad, reference 13. Bowersox's data are from reference 15.

The larger yield of $He^4$ compared to that of $He^3$ is noteworthy, both in the 135 degree data of Burcham

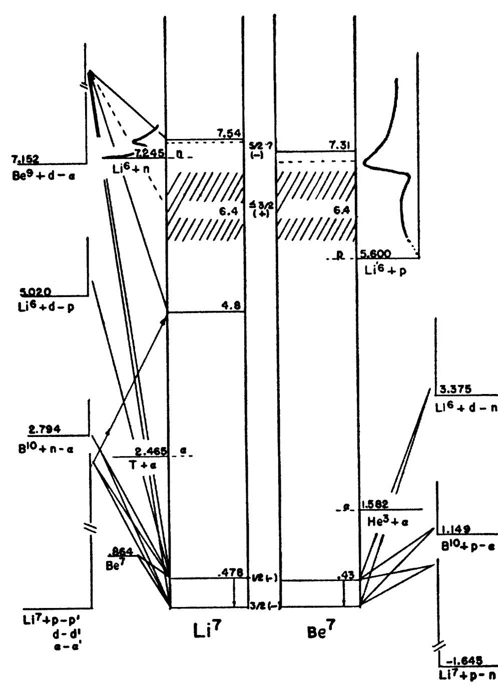


FIG. 6. Comparison of energy levels of the mirror nuclei $Li^7$ and $Be^7$.

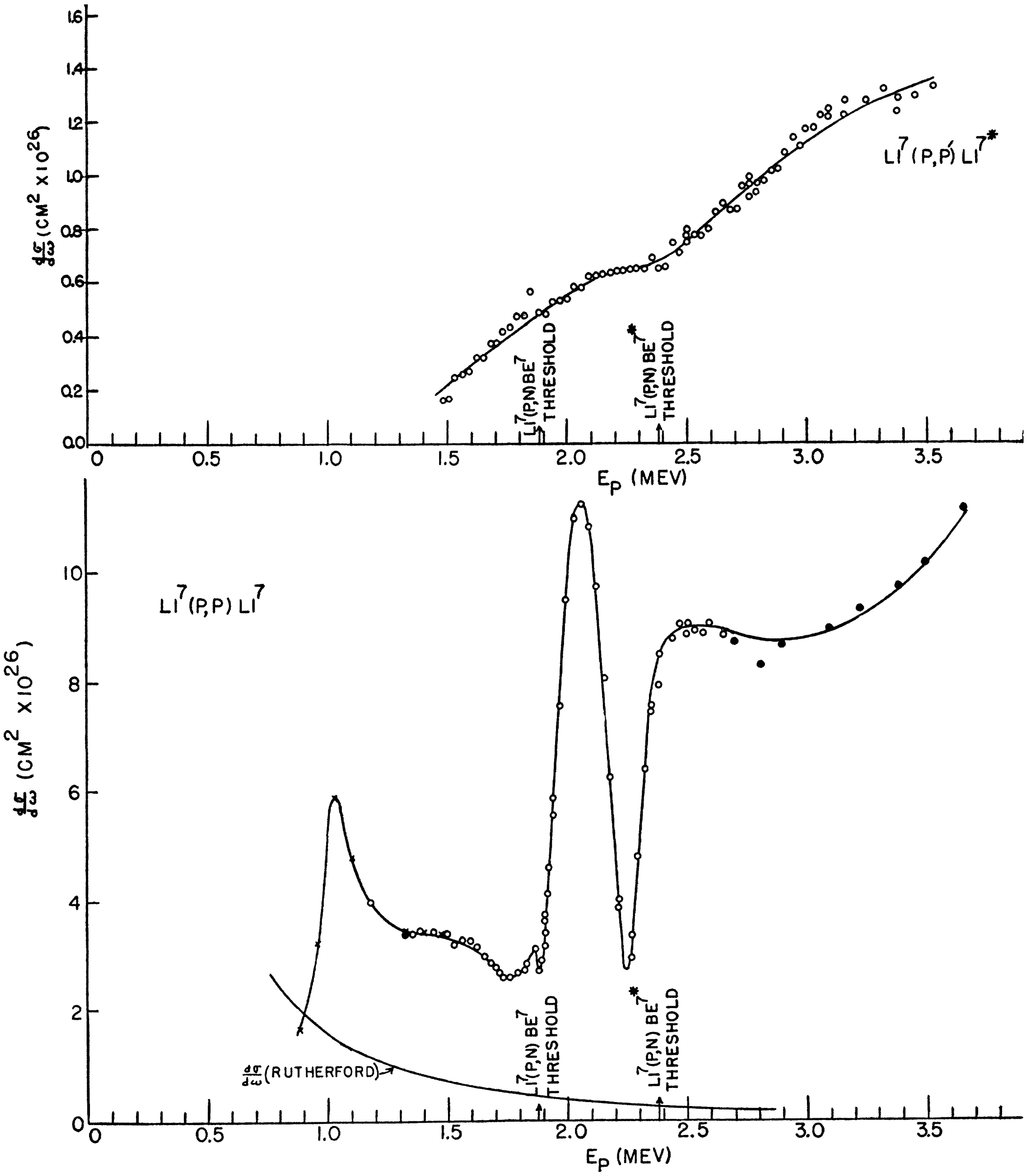


FIG. 7. Differential cross section at laboratory angle 164° for protons scattered elastically and inelastically from $Li^7$.

and Freeman[14] and in our data at 164 degrees. Apparently the $He^3$ are bunched forward and the $He^4$ backward. This asymmetry seems to increase markedly as the angle of observation approaches 0 or 180 degrees. Also for $E_p<0.9$ Mev it appears to increase with bombarding voltage. Such behavior is not in disagreement with our assumption of incident $s$ protons since in the differential cross section there may be interference effects between neighboring states of opposite parity. Since the next highest state of $Be^7$ has already been assigned odd parity (see above), this asymmetry is further evidence of a lower-lying even parity state in $Be^7$. Asymmetries have also been observed in the mirror reaction $Li^6(n, \alpha)H^3$ and given a similar interpretation.[11]

The effect on the differential cross section of the interference with the neighboring odd-parity level disappears in the total cross section which may be computed from $\sigma/4\pi=\frac{1}{2}(d\sigma_\alpha/d\Omega+d\sigma_{He^3}/d\Omega)$. Some attempts at fitting such computed total cross-section data with a one-level dispersion formula have been made. However, $\Gamma_p$ and $\Delta$ vary by such large factors over the resonance that such curve fitting is tedious and perhaps not too significant in view of the present experimental uncertainties in the very low energy data. A very rough fit was obtained for $(2J+1)\Gamma_\alpha=0.24$ Mev, $E_\lambda=(0.8+5.6)=6.4$ Mev (above the ground state of $Be^7$), and with a reduced proton width $\gamma^2 \sim 0.9\times 10^{-12}$ Mev-cm. The same interaction radius was used as for Table I. This value of the reduced width is of the order of $\hbar^2/mR$.

The existence of this low energy resonance accounts qualitatively for the observation of Gamow and Critchfield[16] that the difference in penetration factors for $s$ and $p$ wave collisions is a factor 10 too small to account for the cross-section ratio of $Li^6(p\alpha)$ to $Li^7(p\alpha)$ observed by RRH.[13]

If the same parameters are assumed for the level in $Li^7$ responsible for the high thermal neutrons cross section of $Li^6$, the observed thermal capture cross section of 910 barns may be used to fix the neutron resonance energy as $-0.88$ Mev (i.e., $\sim$6.4 Mev above the ground state of $Li^7$). There is perhaps some evidence for such a broad state in $Li^7$ from the inelastic alpha-scattering data of Gove and Harvey[3] (see in particular Figs. 2 and 3 of their article).

In Fig. 6 we have summarized the data on the energy levels of the mirror nuclei $Li^7$ and $Be^7$. Satisfactory correspondence of the energy levels is apparent wherever the corresponding regions of excitation have been carefully investigated.

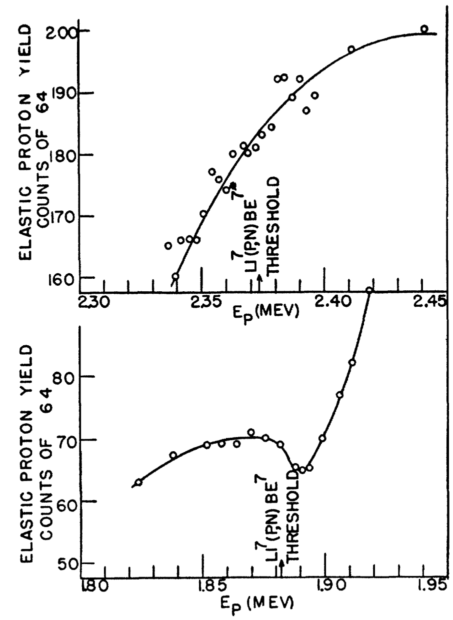


FIG. 8. Study of elastic proton scattering cross section from $Li^7$ in the vicinity of thresholds for neutron emission.

## $Li^7+p$ REACTIONS

Figure 7 shows the yield curves for the protons scattered elastically and inelastically from $Li^7$.

The counter window prevented following the elastic and inelastic scattering cross sections to lower proton energies than those shown. The maximum in the elastic scattering at 1.05 Mev corresponds to the $(p, p'\gamma)$ resonance first observed by Hudson, Herb, and Plain.[17] The Cal Tech group[18] has also measured the elastic scattering cross section at this resonance. In the gravicentric system, our peak differential cross section is $\sim$0.08 barn/steradian at 166°17′, while the Cal Tech group reports 0.12 barn/steradian at 143°25′ and 0.11 barn/steradian at 90°. It is not clear whether there is an appreciable departure from isotropy at this resonance.

A most interesting feature of the elastic scattering is the small wiggle, entirely reproducible, just at the threshold of the $Li^7(p, n)Be^7$ reaction. Figure 8 shows a more detailed examination of this anomaly. Wigner[19] has predicted that the yield from an extant reaction will exhibit a cusp at the threshold for the emission of $S$ neutrons. Perhaps the observed fluctuation provides verification of the prediction, but this is not certain. In an effort to obtain further information about the cusp suggestion, a careful study was made of the elastic scattering in the neighborhood of the threshold for the formation of $Be^7$ in its first excited state (see Fig. 8). However, the proton yield is changing so rapidly in that region that a small effect could not have been distinguished, and none was found.

Breit and Bloch[20] have studied the $Li^7(p, n)Be^7$ reaction and have concluded that the neutron yield is associated with two odd-parity resonances induced by $S$ protons. One of the resonances was presumed to be just below the neutron threshold, and it may be this which produced the wiggle in the yield of elastically scattered protons. The second resonance suggested by Breit and Bloch was at 2.2 Mev, the energy at which the neutron yield has a maximum and the elastic scattering shows a distinct minimum.

In contrast to the elastic scattering yield, with its large fluctuations in intensity, the only structure above $E_p=1.5$ Mev exhibited by the inelastic scattering is a slight change in slope between 2.2 Mev and 2.3 Mev.

It is a pleasure to thank the many people who assisted in taking the data in this work. Dr. Gerson Goldhaber was particularly helpful. F. Ajzenberg, Dr. C. P. Browne, D. Craig, D. J. Donahue, Dr. V. R. Johnson, M. J. W. Laubenstein, and D. H. Martin also contributed generous amounts of help.

[16] G. Gamow and C. Critchfield, *Atomic Nucleus and Nuclear Energy Sources* (Oxford Press, London, 1949), p. 255.
[17] Hudson, Herb, and Plain, Phys. Rev. **57**, 587 (1940).
[18] Brown, Snyder, Fowler, and Lauritsen, Phys. Rev. **82**, 159 (1951).
[19] E. P. Wigner, Phys. Rev. **73**, 1002 (1948).
[20] G. Breit and I. Bloch, Phys. Rev. **74**, 397 (1948).