

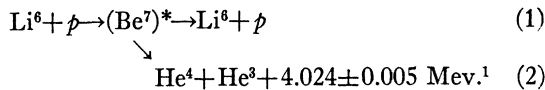
Proton Bombardment of the Lithium Isotopes*

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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 $\text{Li}^6(p, \alpha)\text{He}^3$ 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 $5.60 \text{ Mev} + 6E_p/7$, where E_p is the proton energy in laboratory coordinates. The two most probable modes of decay of these virtual states are



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 Blair² as a resonance in the $\text{Li}^6(n, \alpha)\text{H}^3$ reaction for 250-kev neutrons. Gove and Harvey³ have seen this level (7.50 ± 0.17 Mev) in the $\text{Be}^9(d, \alpha)\text{Li}^7$ 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 .

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 analyzer⁵ and struck by protons monoenergetic to 0.1 percent. Particles which emerged from the target at an angle of $164 \pm 5^\circ$ 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

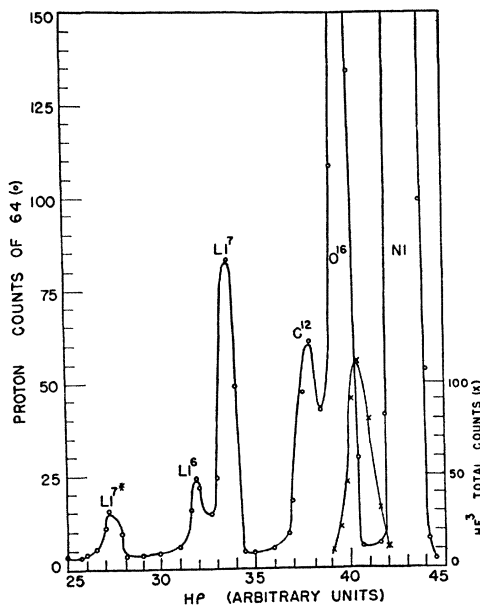


FIG. 1. Momentum spectrum at laboratory angle 164 ± 5 degrees of the protons scattered by the Li target, the 1000A nickel foil backing and by carbon and oxygen contaminants. The group at about 40 Hp units are He^3 reaction products and were separated from the scattered protons by pulse-height discrimination.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

* 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, Bourcius, Kaufmann, and Mooring, Phys. Rev. **83**, 1011 (1951).

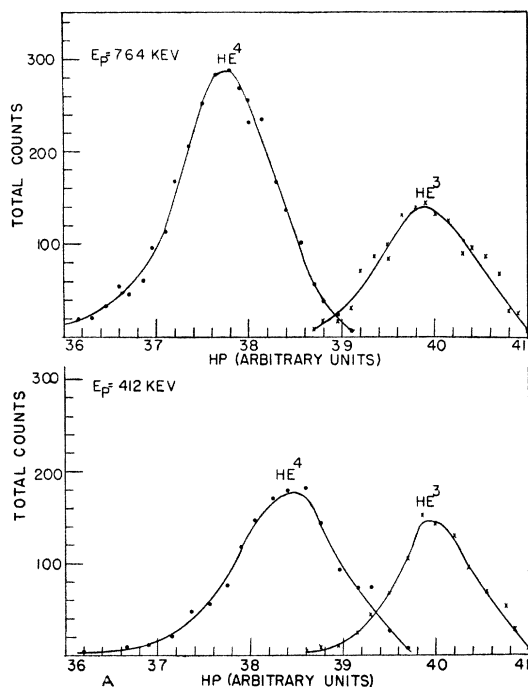


FIG. 2. Typical momentum spectrum of reaction products from $\text{Li}^6(p, \text{He}^4)\text{He}^3$ at low incident proton energies. The rapid variation of He^4/He^3 yield with proton energy is apparent.

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 $\text{Li}^7(p, n)\text{Be}^7$ reaction. A flat-response long counter,⁶ calibrated with a radium-beryllium source of known neutron strength, was used

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

as a detector. Taschek and Hemmendinger's data⁷ on the absolute differential cross section of the $\text{Li}^7(p, n)\text{Be}^7$ 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

$\text{Li}^6 + p$

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 $E_p = 1.82 \pm 0.08$ 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.)

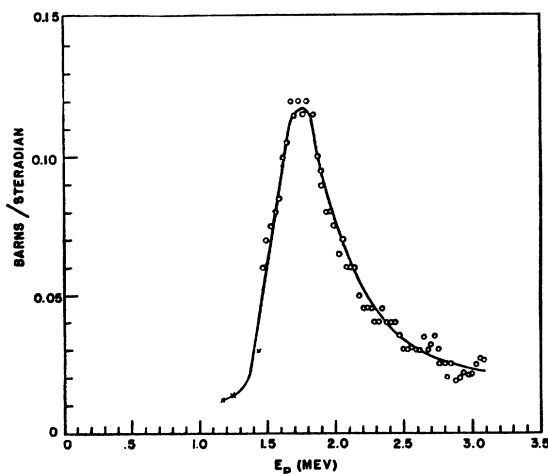


FIG. 3. Differential cross section (barns/steradian) at laboratory angle of 164° for protons scattered elastically from Li^6 .

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

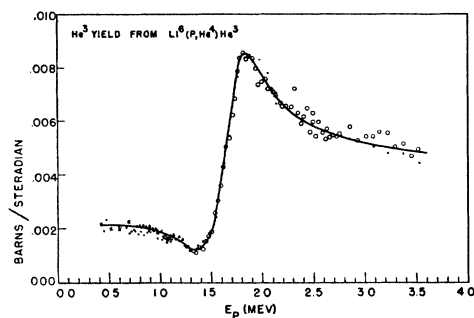


FIG. 4. Differential cross section (barns/steradian) at laboratory angle of 164° for the He^3 particles from $\text{Li}^6(p, \text{He}^3)\text{He}^4$.

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, Γ , 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, Γ_α , 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 ~ 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 Γ_α and hence our neglect of the unknown angular distribution is not serious. In the case of Li^6+n , it is the total (n, α) 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, α) cross section is ~ 3 barns. This experimental value points to $J=5/2$ since the experimental cross-section value is almost the maximum theoretical absorption for $J=5/2$: $\sigma_{\text{max}} = (2J+1)\pi\lambda^2/6$. If we therefore assume $J=5/2$ and $\Gamma_n > \Gamma_\alpha$ the experimental total cross section fixes Γ_α as ~ 0.036 Mev. This agreement with the Γ_α 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 $\gamma_0^2 = \Gamma_\alpha A_l^2/2k$ 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 Breit⁹) 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 Δ .

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 $R=0.4 \times 10^{-12}$ cm (i.e., $\sim \frac{1}{2}(\hbar^2/mc^2)(6^2+1^2)$) was assumed.

The experimental total widths are (in center-of-mass coordinates)

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

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

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 ($\times 10^{12}$ Mev-cm)		Level shift (Mev) $\Delta = -\gamma^2(g+l)/R$	Energy of level (Mev above ground state) $E_\lambda = E_R - \Delta$
		$\gamma_0^2 = \Gamma_\alpha A_l^2/2k$	$\gamma^2 = \gamma_0^2/(1 - \gamma_0^2/R \cdot dg/dE)$		
$L=0$	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			
	Be^{7*}	2.1			

(All values of γ^2 for $L \geq 2$ exceed $3\hbar^2/2mR \approx 1.8 \times 10^{-12}$.)

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).

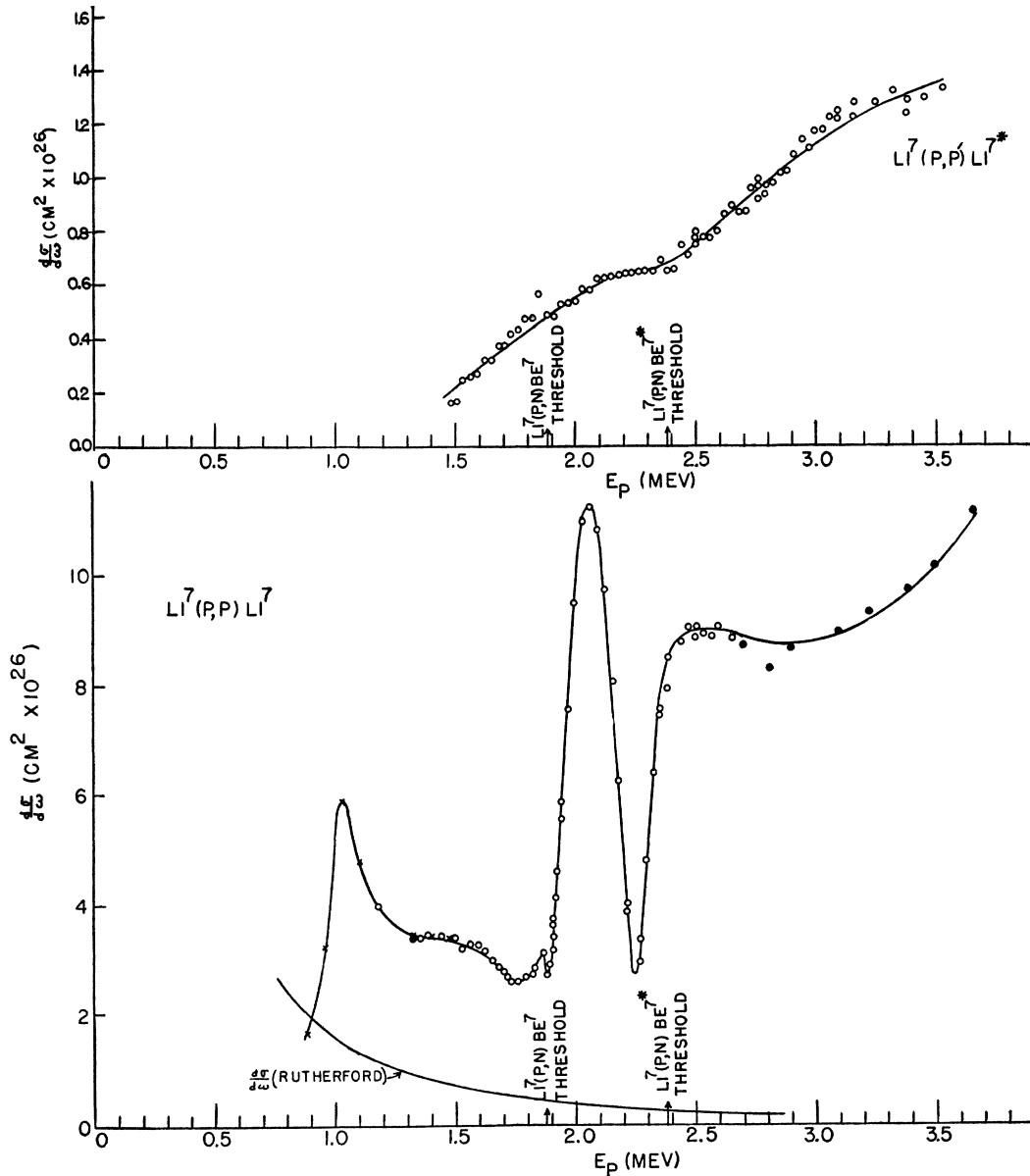


FIG. 7. Differential cross section at laboratory angle 164° for protons scattered elastically and inelastically from Li^7 .

and Freeman¹⁴ and in our data at 164° . 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° . 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 $\text{Li}^6(n, \alpha)\text{H}^3$ 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 $\sigma/4\pi = \frac{1}{2}(d\sigma_\alpha/d\Omega + d\sigma_{\text{He}^3}/d\Omega)$. Some attempts at fitting such computed total cross-section data with a one-level dispersion formula have been made. However, Γ_p and Δ 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 Critchfield¹⁶ 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 $\text{Li}^6(p\alpha)$ to $\text{Li}^7(p\alpha)$ 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., ~ 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 Harvey³ (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.

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 group¹⁸ has also measured the elastic scattering cross section at this resonance. In the gravicentric system, our peak differential cross section is ~ 0.08 barn/steradian at $166^\circ 17'$, while the Cal Tech group reports 0.12 barn/steradian at $143^\circ 25'$ 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 $\text{Li}^7(p, n)\text{Be}^7$ reaction. Figure 8 shows a more detailed examination of this anomaly. Wigner¹⁹ 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.

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).

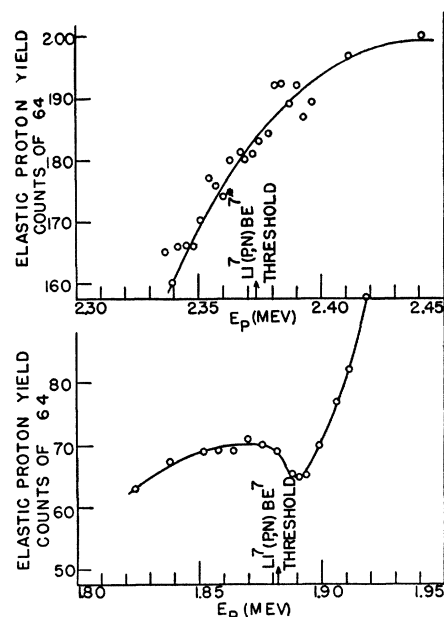


FIG. 8. Study of elastic proton scattering cross section from Li^7 in the vicinity of thresholds for neutron emission.

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 Bloch²⁰ have studied the $\text{Li}^7(p, n)\text{Be}^7$ 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.

²⁰ G. Breit and I. Bloch, *Phys. Rev.* **74**, 397 (1948).