with Doppler energy shift and finite solid angle of the detector[6] are presented in Table I for the bombarding energies investigated. These corrections in each case amounted to no more than 6 percent of the coefficient. On the basis of repeated runs, the probable error of the coefficients is less than ± 0.02. In order to correlate the thick target angular distribution data with thin target data, the thick target yield of 12-Mev gamma rays in the beam direction has also been obtained and is shown in Fig. 3.

The angular distribution at proton energy of 200 kev is in agreement with results obtained by others.[5,7]

[6] The authors express their appreciation to Dr. M. E. Rose for the opportunity to use his calculations on the analysis of angular distribution data before their publication.

[7] Kern, Moak, Good, and Robinson, Phys. Rev. **83**, 211 (1951).

The $\cos\theta$ term begins to appear at 300 kev and has become rather large at 350 kev. The 163-kev resonance has even parity.[5] The sudden appearance and behavior of the $\cos\theta$ term above this resonance means that at least one of the levels at 680 kev and 1388 kev has odd parity. The extremely large level widths of the 680-kev level and 1388-kev level would seem to imply that these levels are induced by s-wave protons and have odd parity. The small energy variation of the coefficients in the angular distribution may imply a three level interference between the 163-kev level and the two upper levels.

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The Elastic Scattering of Protons by Lithium*

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The cross section for the reaction $Li^7(p,p)$ has been measured over the proton energy range 360–1400 kev. Measurements were made at scattering angles of 50, 70, 89.2, 110, 130, 143.4, and 160 degrees in the center-of-mass system. Anomalous scattering was observed near 441.5 kev, the resonance energy for the reaction $Li^7(p,\gamma)$, and near 1030 kev, the resonance energy for the reaction $Li^7(p,p')$. Analysis of the results at 441.5 kev indicates a state in Be^8 with $J=1$, even parity, formed by p wave protons. The relative stopping cross section for protons in lithium was also measured from 200–1300 kev.

INTRODUCTION

THE transmutation of Li^7 by protons has been of interest for many years. In 1932 Cockroft and Walton[1] first observed alpha particles from the reaction $Li^7(p,\alpha)$. Gamma rays from the well-known 441-kev resonance in the reaction $Li^7(p,\gamma)$ were observed in 1934 by Lauritsen and Crane;[2] and the resonance was confirmed by Hafstad and Tuve[3] in 1935. The corresponding anomaly in the reaction $Li^7(p,p)$ was studied in 1939 by Creutz.[4] Accurate measurements of the resonance energies of the reactions $Li^7(p,\gamma)$ and $Li^7(p,p')$ have been made by Fowler and Lauritsen,[5] who give 441.4 ± 0.5 kev for the $Li^7(p,\gamma)$ resonance and 1030.0 ± 5 kev for the $Li^7(p,p')$ resonance. Hunt[6] has recently found 441.5 ± 0.5 kev for the resonance in $Li^7(p,\gamma)$ using an absolute electrostatic analyzer. The angular distribution of the gamma radiation near this resonance has been determined by Devons and Hine[7] who concluded that the excited state in Be^8 has $J=1$, odd parity and is formed by s wave protons.

A study of the elastic scattering of protons from Li^7 can be expected to provide additional information which will aid in the determination of the nature of the highly excited states of Be^8. One expects to find anomalies in the scattering corresponding to the resonances in $Li^7(p,\gamma)$ and $Li^7(p,p')$ with perhaps a small effect resulting from the broad resonance in the reaction $Li^7(p,\alpha)$ at 3 Mev. The cross section for the reaction $Li^7(p,p)$ has been measured by Brown *et al.*,[8] at 89 and 144 degrees in the center-of-mass system (see below). An analysis of their results near 441 kev by Cohen[9] indicated that the state in Be^8 has $J=1$, even parity, and is formed by p wave protons. This result is seen to be in disagreement with the results of Devons and Hine.

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† National Science Foundation Predoctoral Fellow.

[1] J. D. Cockroft and E. T. S. Walton, Proc. Roy. Soc. (London) **A137**, 229 (1932).

[2] C. C. Lauritsen and H. R. Crane, Phys. Rev. **45**, 63 (1934).

[3] L. R. Hafstad and M. A. Tuve, Phys. Rev. **47**, 506 (1935).

[4] E. Creutz, Phys. Rev. **55**, 819 (1939).

[5] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **76**, 314 (1949).

[6] S. E. Hunt, Proc. Phys. Soc. (London) **A65**, 982 (1952).

[7] S. Devons and M. G. N. Hine, Proc. Roy. Soc. (London) **199**, 56, 73 (1949).

[8] Brown, Snyder, Fowler, and Lauritsen, Phys. Rev. **82**, 159 (1951).

[9] E. R. Cohen, Ph.D. thesis, California Institute of Technology, 1949 (unpublished).

In the present experiment the cross section for $Li^7(p,p)$ has been measured at center-of-mass angles of 50, 70, 89.2, 110, 130, 143.4, and 160 degrees for incident protons of energies in the range 360–1400 kev. It is believed that sufficient data are provided to permit unique assignments for the 17.62-Mev and 18.14-Mev states in Be^8, which correspond to the observed anomalies in the scattering at proton energies near 441 kev and 1030 kev, respectively.

During these experiments it was found desirable to measure the stopping cross section of protons in lithium. A relative determination was performed over the energy range 200–1300 kev, and the results are included in this paper.

PROCEDURE

The incident proton beam used in these experiments was rendered mono-energetic to 0.05 percent by an 80° electrostatic analyzer of 1-meter radius and 1-millimeter entrance and exit slits. The scattered protons were analyzed by a $10\frac{1}{2}$-inch variable angle magnetic spectrometer[10] and detected by a scintillation counter. The 80° electrostatic analyzer was calibrated by observations on the resonances in the production of gamma radiation from the reactions $Li^7(p,\gamma)$ at 441.5 kev[6] and $Al^{27}(p,\gamma)$ at 993.3 kev.[11] The magnetic spectrometer was then calibrated by studying the protons elastically scattered from copper and gold, using the electrostatic analyzer calibration and the conservation laws of energy and momentum for the energy calibration and assuming pure Coulomb scattering from copper and gold for the solid angle and counter efficiency calibrations. The variable angle spectrometer is so constructed as to allow continuous variation of the scattering angle from 0 to 160 degrees. The angle is read from an attached protractor with vernier, which is set by sending the direct beam through the center of the spectrometer and adjusting the protractor to read zero degrees. Any required scattering angle can then be obtained to within 0.1 degree.

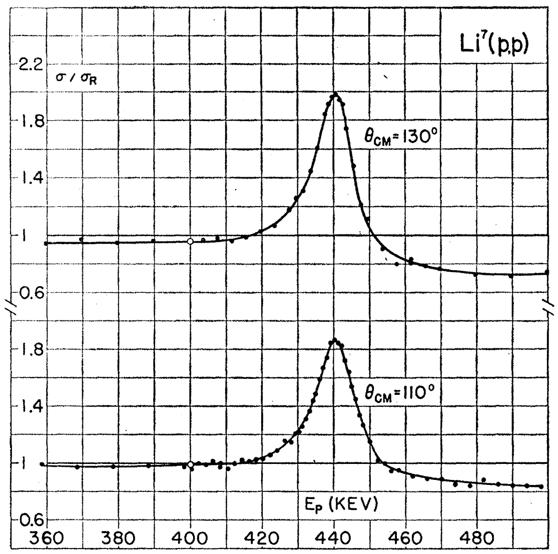

FIG. 2. Ratio of observed cross section to Rutherford cross section at $\theta_{CM}=110°$ and 130° for the elastic scattering of protons by lithium. The anomaly occurs near 441 kev, the resonance energy for $Li^7(p,\gamma)$.

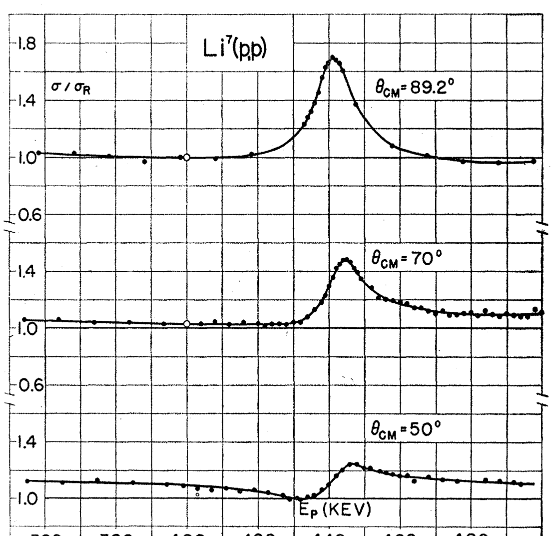

FIG. 1. Ratio of observed cross section to Rutherford cross section at $\theta_{CM}=50°$, 70°, and 89.2° for the elastic scattering of protons by lithium. The anomaly occurs near 441 kev, the resonance energy for $Li^7(p,\gamma)$.

It was thought that perhaps fringing fields, second-order focusing effects, or slight misalignments might change the spectrometer energy or solid angle calibration with angle, or might make the solid angle calibration depend upon the size of the spectrometer exit slit. The energy calibration was therefore checked at six different scattering angles and found to remain constant to within 0.5 percent. The solid angle calibration was repeated for each entrance aperture and exit slit combination at 90 and 160 degrees, and for one combination at ten different angles between 30 and 160 degrees. The maximum probable error found for any solid angle value was 2 percent.

Targets were prepared by evaporating, in vacuum, layers of natural lithium (92.5 percent Li^7) on a copper backing. The layers were made very thick as the high resolution of the spectrometer gives the instrument the ability to isolate a thin lamina at any desired depth in the target material. It was also possible to separate protons scattered by Li^7 from those scattered by Li^6 except at the two most forward angles, where a correction was made to the results assuming the scattering from Li^6 followed the Rutherford scattering law. The angle between the target normal and the incident beam was determined to within 0.3 degree by a target mounting equipped with a protractor. The methods

[10] W. D. Warters and E. A. Milne, Phys. Rev. 85, 716 (1952).
[11] Herb, Snowdon, and Sala, Phys. Rev. 75, 246 (1949).

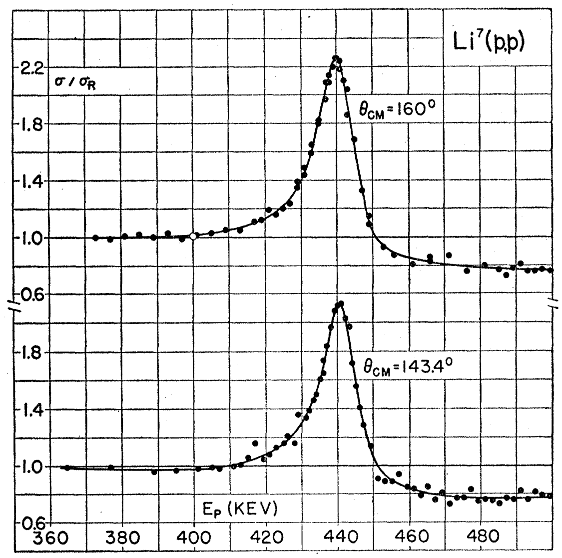

FIG. 3. Ratio of observed cross section to Rutherford cross section at $\theta_{CM}=143.4°$ and 160° for the elastic scattering of protons by lithium. The anomaly occurs near 441 kev, the resonance energy for $Li^7(p,\gamma)$.

used in calculating results were similar to those outlined by Brown *et al.*[8] It will be noted that the stopping cross section for protons in lithium must be known in order to calculate the scattering cross section.

Much time was spent during the course of the experiments in the attempt to obtain satisfactory targets. The requirements were a shiny mirror surface, no internal contaminations, and a minimum of surface layer contamination. Contaminations were determined with the spectrometer by running a momentum profile of protons scattered by the target. The target chamber was pumped directly by an auxiliary pump equipped with a liquid air trap; and another liquid air trap was installed which ran the length of the target chamber, passing about 2 cm from the target. With this arrangement vacua of about 5×10^{-6} mm Hg were maintained in the chamber during the experiments. By carefully outgassing the lithium furnace for several hours before making a target it was found possible to keep the pressure below 10^{-5} mm Hg even when evaporating lithium. Nevertheless it was found necessary to deposit the lithium as rapidly as possible in order that the target not be slightly contaminated throughout with oxygen as a result of continuous oxidation of the material as it was deposited. By trial and error a depositing rate was determined which gave a target with no detectable internal contamination and a true mirror surface. However, after such a target was made the surface slowly oxidized even though a high vacuum was maintained; so targets were not kept for longer than one day even if they were not used. Bombardment of a target with the proton beam deposited surface contamination layers of carbon and oxygen; so the condition of the target was checked frequently during runs and fresh targets were prepared whenever needed. Heating the target was found to practically eliminate the carbon contamination but also to make the lithium surface oxidize at a much greater rate; so the targets were used unheated.

In estimating the accuracy of these cross-section measurements, effects such as straggling in the target, contamination surface layers, uncertainties in the calibrations and angles of observation, and nonlinearity of the apparatus have been studied. Many of the measurements were repeated on several different days to check the reproducibility of the results. We believe that the relative uncertainty in the magnitudes of all the scattering cross sections quoted herein is within 5 percent. The uncertainty in the absolute magnitude of these measurements is less than 10 percent. This error comes chiefly from the uncertainty in the absolute magnitude of the stopping cross section of lithium, which is about 6 percent.

Note added in proof:—Since this paper was submitted for publication the absolute stopping cross section of lithium has been found to be $4.69\pm0.15\times10^{-15}$ *ev-cm*^{2} *for 440-kev protons by Bader, Wenzel, and Whaling of this laboratory. All of the circles in Fig. 7 should thus be lowered by 9 percent. In addition, results in this laboratory and by Cooper and Chilton at Ohio State University (private communication) indicate that the stopping cross section for Cu used in our calibrations is high by 4 percent. Hence all cross sections quoted in this paper should be*

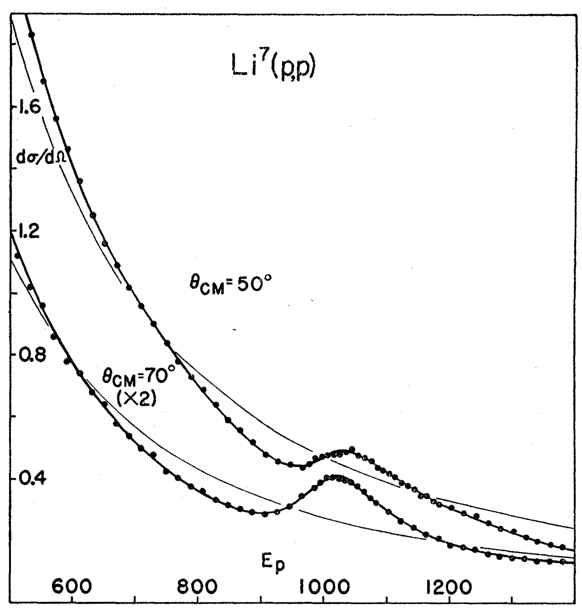

FIG. 4. Differential cross section in barns/steradian *versus* incident proton energy in kev at $\theta_{CM}=50°$ and 70° for the elastic scattering of protons by lithium. The plotted values at 70° are twice the actual values. Rutherford scattering is shown by the thin lines for reference. The anomaly occurs near 1030 kev, the resonance energy for $Li^7(p,p'\gamma)$.

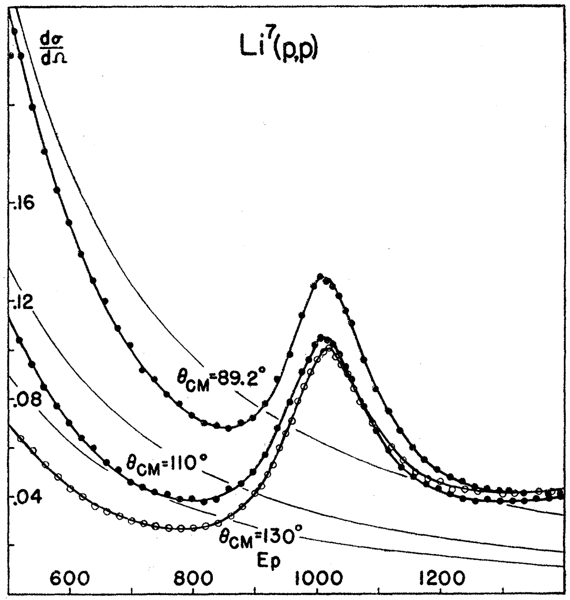

FIG. 5. Differential cross section in barns/steradian *versus* incident proton energy in kev at $\theta_{CM}=89.2°$, 110°, and 130° for the elastic scattering of protons by lithium. Rutherford scattering is shown by the thin lines for reference. The anomaly occurs near 1030 kev, the resonance energy for $Li^7(p,p'\gamma)$.

decreased by 5 percent. The absolute probable error of the resulting values can be taken as ±5 percent.

RESULTS

The ratio of observed cross section to the Rutherford scattering cross section over the incident proton energy range 360–500 kev at the angles studied is shown in Figs. 1, 2, and 3. The center-of-mass differential cross section over the energy range 500–1400 kev for these angles is shown in Figs. 4, 5, and 6. Table I gives the detailed experimental results at 160 degrees for the differential cross section and for the ratio to the Rutherford scattering at each energy measured. Such tables for the other angles studied are available on request. The maxima in the scattering near the 441-kev $Li^7(p,\gamma)$ and the 1030-kev $Li^7(p,p')$ resonances are shown in Table II. The values in Table II have been corrected for the resolution effects of the apparatus, while the others have not. It will be noted that the differential cross section near 1030 kev shows spherical symmetry at angles greater than 100 degrees.

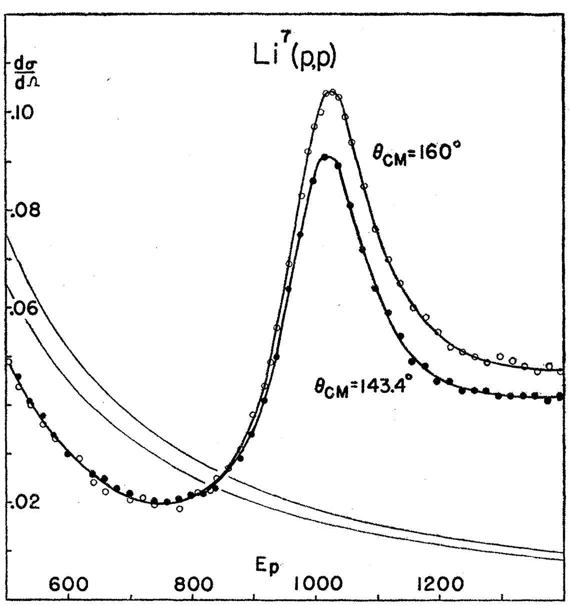

FIG. 6. Differential cross section in barns/steradian *versus* incident proton energy in kev at $\theta_{CM}=143.4°$ and 160° for the elastic scattering of protons by lithium. Rutherford scattering is shown by the thin lines for reference. The anomaly occurs near 1030 kev, the resonance energy for $Li^7(p,p'\gamma)$.

TABLE I. $Li^7(p,p)$, $\theta_{CM}=160°$. Observed differential cross section in barns/steradian and ratio to Rutherford cross section for incident proton energies in kev.

E_p	σ/σ_R	$d\sigma/d\Omega$	E_p	σ/σ_R	$d\sigma/d\Omega$	E_p	σ/σ_R	$d\sigma/d\Omega$
373	1.00	0.116	471	0.87	0.063	888	1.67	0.034
377	0.99	0.112	476	0.76	0.054	898	1.91	0.038
381	1.01	0.112	481	0.80	0.056	908	2.10	0.041
385	1.02	0.111	485	0.77	0.053	918	2.30	0.044
389	1.00	0.107	487	0.73	0.050	928	2.62	0.049
393	1.03	0.107	489	0.78	0.053	938	3.03	0.056
397	0.99	0.101	491	0.81	0.054	948	3.55	0.064
401	1.02	0.102	493	0.76	0.050	958	3.94	0.069
405	1.03	0.101	495	0.76	0.050	968	4.36	0.075
409	1.05	0.101	497	0.77	0.050	978	4.94	0.083
413	1.05	0.099	499	0.77	0.050	988	5.56	0.092
417	1.11	0.103	501	0.76	0.049	998	5.98	0.097
419	1.12	0.103	503	0.77	0.049	1008	6.30	0.100
421	1.19	0.108	519	0.74	0.044	1018	6.70	0.104
423	1.16	0.104	539	0.71	0.040	1028	6.79	0.104
425	1.20	0.107	559	0.70	0.036	1038	6.88	0.103
427	1.24	0.110	579	0.68	0.033	1048	6.74	0.099
429	1.37	0.120	599	0.66	0.030	1058	6.52	0.094
431	1.47	0.126	619	0.68	0.029	1078	6.15	0.085
433	1.62	0.139	639	0.60	0.024	1098	5.64	0.076
435	1.81	0.154	659	0.61	0.0223	1118	5.40	0.070
437	2.03	0.171	679	0.64	0.0224	1138	5.19	0.065
438	2.12	0.178	699	0.62	0.0205	1158	5.01	0.060
439	2.19	0.183	719	0.67	0.0210	1178	4.99	0.058
440	2.26	0.188	739	0.66	0.0195	1198	4.87	0.055
441	2.21	0.183	759	0.70	0.0197	1218	4.76	0.052
442	2.10	0.174	779	0.71	0.0189	1238	4.89	0.051
443	1.95	0.160	799	0.86	0.0218	1258	4.95	0.050
445	1.69	0.138	809	0.90	0.0222	1278	4.96	0.049
447	1.33	0.107	819	0.92	0.0221	1298	5.20	0.050
449	1.12	0.090	829	0.96	0.0226	1318	5.25	0.049
451	1.00	0.079	839	1.10	0.025	1338	5.38	0.048
453	0.93	0.073	849	1.12	0.025	1358	5.40	0.047
456	0.88	0.068	858	1.23	0.027	1378	5.60	0.048
461	0.81	0.061	868	1.39	0.030	1398	5.70	0.047
466	0.84	0.062	878	1.47	0.031			

Because of considerable improvement in experimental techniques, the present results are considered to be more accurate than the results of Brown *et al.*,[8] which were also obtained in this laboratory. Nevertheless, the present results at 89.2 and 143.4 degrees differ from those of Brown by at most 15 percent. The results at 143.4 degrees are brought within 6 percent agreement if Brown's data are recalculated using the curve for the stopping cross section of lithium which was measured and used in the present work. However, this correction leaves Brown's results at 89.2 degrees 20 percent lower than the results of the present experiment. The elastic scattering cross section near the 1030-kev anomaly has also been measured by Bashkin and Richards,[12] who give ~0.08 barn/steradian for the peak at 166.3 degrees in the center-of-mass system. As their uncertainty is 20 percent, the agreement with the present work is within experimental error.

The results of the present experiment near 441 kev are consistent with p wave protons forming a $J=1$, even parity, state in Be^8.[9] It has been found possible to reconcile the results of Devons and Hine with this assignment.[13] A more detailed theoretical analysis of the results at both anomalies will be presented in a forthcoming publication.

THE STOPPING CROSS SECTION OF LITHIUM

The relative stopping cross section for protons in lithium was measured over the proton energy range 200–1300 kev by measuring the energy lost by protons of various energies in passing through a thin film of lithium. This loss was determined by first measuring the energy of protons scattered from a clean copper target and then repeating the measurement after a thin film of lithium had been deposited on the copper. The energy loss of the protons in passing in and out of the film is proportional to the stopping cross section at a simply calculable intermediate energy. The results were normalized to the theoretical formula of Livingston and Bethe[14] at 952 kev, where this formula should be valid, using the value for the average ionization energy of lithium (32 ev) determined by Haworth and King.[15] When this was done, the remaining measurements fell in good agreement with the theory and with the results of Haworth and King, as shown in Fig. 7. However, the agreement remains reasonably good over a fairly wide variation in the assumed ionization energy; the errors in our measurements are such that we cannot exclude the value of 38 ev given originally by Mano[16] from early alpha-particle measurements nor the value of 34 ev determined at high proton energies by Bakker and Segrè.[17] The variation in ionization energy from 32 ev to 38 ev leads to an uncertainty of 6 percent in the absolute value of our stopping cross section, and we take this as the probable error in the values given in Fig. 7. This constitutes the main error in our scattering cross-section measurements as discussed previously.

TABLE II. Maxima of the observed differential cross section and of the ratio to Rutherford cross section near the 441- and 1030-kev anomalies at various center-of-mass angles. These values have been corrected for the effects of resolution in the apparatus. Note that the 1030-kev anomaly appears to be spherically symmetric at angles greater than 100 degrees.

θ_{CM}		50°	70°	89.2°	110°	130°	143.4°	160°
441	σ/σ_R	1.24	1.49	1.70	1.88	2.00	2.16	2.28
kev	$d\sigma/d\Omega$	2.97	1.04	0.549	0.328	0.233	0.207	0.190
1030	σ/σ_R	1.14	1.53	2.12	3.21	4.64	5.15	6.88
kev	$d\sigma/d\Omega$	0.49	0.204	0.129	0.105	0.101	0.091	0.104

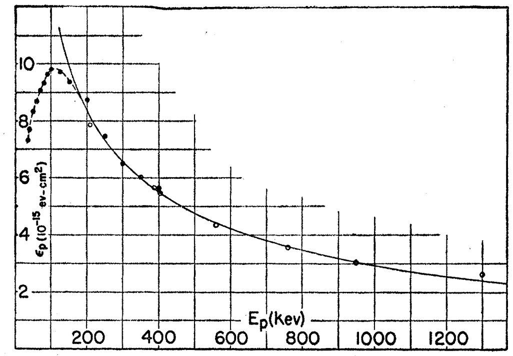

FIG. 7. The stopping cross section for protons in lithium. The solid line represents the theoretical formula of Livingston and Bethe, with $I=32$ ev. The solid points are the results of Haworth and King, and the open circles are the results of this experiment normalized to the solid curve at 952 kev.

We wish to thank Mr. E. A. Milne for many hours of help in taking the data. We also are grateful to Professor R. F. Christy and to Mr. David Liberman for discussions of the theoretical aspect of this problem.

[12] S. Bashkin and H. T. Richards, Phys. Rev. **84**, 1124 (1951).
[13] D. Liberman (private communication.)

[14] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 261 (1937).
[15] L. J. Haworth and L. D. P. King, Phys. Rev. **54**, 48 (1938).
[16] G. Mano, Ann. Physik **1**, 407 (1934).
[17] C. J. Bakker and E. Segrè, Phys. Rev. **81**, 489 (1951).