Inelastic Scattering of Alpha Particles by Lithium*

C. W. Li and R. Sherr†
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California
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The inelastic scattering of alpha particles by Li^7 leading to the formation of the 478-kev state of Li^7 has been studied by observation of the gamma ray emitted from that state. Singly charged helium ions accelerated by an electrostatic generator were used to determine the yield of the reaction up to an energy of 2.8 Mev. The excitation curve shows a resonance at 1.889±0.010 Mev, with a width of 200 kev and a peak cross section of 0.11±0.02 barn, and another broad resonance at 2.50±0.03 Mev with a peak cross section of 0.08±0.015 barn. These resonances correspond to levels of B^{11} at 9.86 Mev and 10.23 Mev. The thick target yield at $E_\alpha=2.3$ Mev is $1.5\times10^{-6}\gamma/\alpha$. The Doppler shift of the emitted gamma ray furnishes an upper limit of the lifetime for the 478-kev excited state of Li^7.

INTRODUCTION

THE excited state of Li^7 at 478 kev is the most extensively studied excited state in light nuclei.[1,2] The existence of this state was first indicated by the detection of gamma rays from lithium under bombardment of natural alpha particles by means of the process $Li^7(\alpha,\alpha')Li^{7*}$ used by Bothe and Becker and others.[3] Later, it was studied with different methods by means of the reactions (d,p), (p,p'), (d,d'), (n,α), and the K capture of Be^7. In the present work, the inelastic process $Li^7(\alpha,\alpha')Li^{7*}$ has been investigated by measurements on the 478-kev gamma ray emitted by the Li^{7*}. The results give information on the levels of the compound nucleus (B^{11}) in the region of excitation above 9.28 Mev. This region in B^{11} and the corresponding region in its mirror C^{11} have not been adequately investigated.

EXPERIMENTAL ARRANGEMENT

Singly-charged helium ions produced in a radiofrequency ion source[4] were accelerated by an electrostatic generator up to an energy of 2.8 Mev. The ion beam coming down the accelerating column was first separated into its different beam components with a magnetic field and then resolved and maintained homogeneous by an electrostatic analyzer of resolution 0.1 percent or better. The energy was calibrated by the 873.5-kev resonance in $F^{19}(p\alpha,\gamma)$. The beam current incident on the target was measured by a current integrator that has been in use for several years and is believed to be reliable to a few percent.

Targets were made by evaporating natural lithium metal onto a copper plate. The furnace consists of a strip of tantalum electrically heated and located inside the vacuum system. The copper plate could be moved over the furnace for evaporation and then retracted into the beam tube without breaking the vacuum. As lithium is notorious for its readiness to become contaminated, fresh, shiny targets were prepared from time to time during a day of measurements. The lithium furnace was first thoroughly outgassed and the deposit of lithium made as quickly as possible. A liquid nitrogen trap was located between the exit of the electrostatic analyzer and the target chamber. Both thick and thin targets have been used. The latter ranged in thickness from 5 to 30 kev for 2-Mev alpha particles. Thick targets of lithium hydroxide were used to check the yield.

The gamma rays were counted by means of a sodium iodide scintillation counter in conjunction with a ten-channel differential discriminator.[5] The counter consisted of a NaI(Tl) crystal $1\frac{1}{2}$ inches long and $1\frac{1}{2}$ inches in diameter mounted in a thin aluminum case with a quartz window, and placed on the flat top of a DuMont 6292 photomultiplier with silicone grease. Pulses from the photomultiplier were amplified and displayed in the ten channels. Usually, the bias was set so that the whole "photo" peak of the 478-kev gamma ray was displayed in the middle channels with the first and last channels indicating any background present.

The 478-Kev Gamma-Ray

Figure 1 shows the gamma-ray spectrum observed with a Li target 15 kev thick at $E_\alpha=2.5$ Mev with the counter at 90° to the beam. The annihilation radiation from Na^{22} was used as calibration of the gamma-ray energy. The resolution of the photopeak is seen to be 10 percent, and the peak-to-valley ratio for the 478-kev gamma ray is better than 20. The spectrum consists of the photopeak, the Compton plateau and two superposed peaks. Both the latter ones were produced by the lead shield which covers the top of the target and around the counter. The one at higher energy is due to

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† On sabbatical leave from Princeton University, Princeton, New Jersey.

[1] Brown, Snyder, Fowler, and Lauritsen, Phys. Rev. **82**, 159 (1951), and the references listed there.

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

[3] W. Bothe and H. Becker, Z. Physik **66**, 289 (1930); H. C. Webster, Proc. Roy. Soc. (London) **136**, 428 (1932).

[4] Thonemann, Moffatt, Roaf, and Sanders, Proc. Phys. Soc. (London) **61**, 483 (1948); Moak, Reese, and Good, Nucleonics **9**, No. 3, 18 (1951); C. W. Li (to be published).

[5] Hugh J. Woodbury, thesis, California Institute of Technology, 1953 (unpublished).

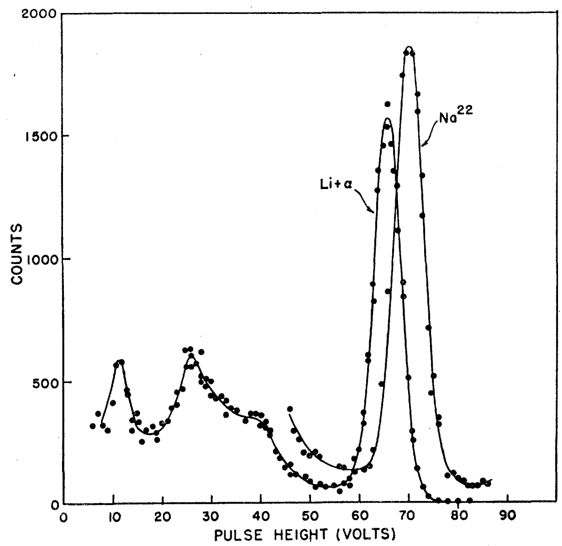

FIG. 1. Pulse-height spectrum of the gamma rays from lithium under bombardment of 2.5-Mev alpha particles. The photo-peak of the 511-kev annihilation radiation of Na^{22} is shown for comparison.

the gamma radiation emitted from the target and back-scattered by the lead shield into the crystal. The other one is the Pb K x-ray generated in the lead shield, following absorption of the gamma rays from the target. Using Cs^{137} and the annihilation radiation of Na^{22} as calibration points, we obtained the value 484±10 kev for the Li gamma ray, in adequate agreement with other measurements,[1,6,7] which average to 478.5 kev.

The angular distribution of the 478-kev gamma ray is known to be isotropic both from direct measurements and from the spin and parity assignment of the levels involved which are $\frac{3}{2}^-$ for the ground state of Li^7 and $\frac{1}{2}^-$ for the first excited state.[2] By measuring the relative intensity of gamma rays emitted from a thin target at angles from 0° to 160° relative to the alpha-particle beam at 1.9 Mev, we also obtained an isotropic distribution (within 10 percent).

Because of their relatively large mass, alpha particles are effective in producing Doppler shifts in the energy of the emitted gamma ray. By the comparison of the gamma-ray energy observed with the counter at 0° and at 160°, we obtained a rough measurement of the Doppler shift of the Li^7 gamma ray at a bombarding energy of 1.9 Mev. In this measurement, the NaI crystal subtended an angle of 15° at the target, which was a layer of lithium about 150 kev thick. As shown in Fig. 2, there was a shift of approximately 0.8 volt in the peak position, with the mean gamma-ray energy corresponding to a pulse height of 45 volts. The gain of the amplifier was monitored by the spectrum of Cs^{137} taken immediately before and after each measurement. The error of the shift can be set as ±0.3 volt. Therefore the Doppler shift is 1.8±0.7 percent, in rough agreement with the calculated Doppler shift (2.3 percent) corresponding to a spherical distribution of recoil. From estimates on the stopping power, the time for an average recoil Li^7 to slow down to half of its initial speed will be of the order of 3×10^{-13} sec. Thus, assuming that we observed the full Doppler shift, this measurement indicates an upper limit for the lifetime of the first excited state of Li^7 of approximately 3×10^{-13} sec. Better estimates might be obtained with a very thin target of lithium on backing material of high density and large stopping power, like gold, under bombardment by high-energy alpha particles. Elliott and Bell,[8] by a comparison of the Doppler broadening of the 478-kev gamma ray in different materials using the reaction $B^{10}(n,\alpha)Li^{7*}$, concluded a lifetime of $(0.75\pm0.25)\times10^{-13}$ sec for the first excited state of Li^7.

Excitation Function

The thick target yield (for natural lithium metal) was measured with the counter set at 90° to the direction of the bombarding beam. The result is shown in Fig. 3 where the yield is that integrated over a solid angle of 4π, assuming an isotropic distribution of the emitted gamma ray. Because of the large increase in yield toward higher bombarding energies, we had to move the detector away from the target correspondingly in order not to overload the counting equipment. Thus, the curve given in Fig. 3 is the result of normalizing and matching several sections of yield curves for different energy ranges. As a check on the purity of

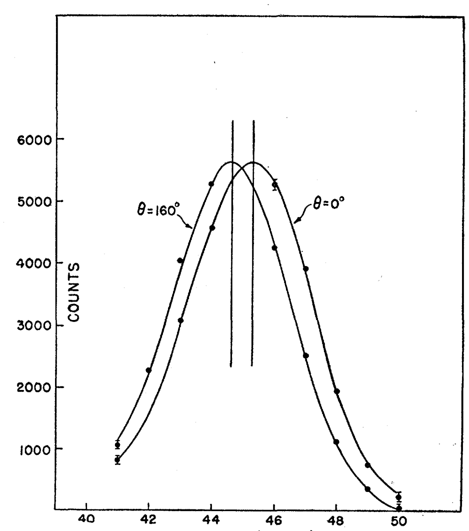

FIG. 2. The Doppler shift of the 478 gamma ray between the angles of observation, 0° and 160°, relative to the beam of incident alpha particles. $E_\alpha=1.9$ Mev. Target thickness=150 kev.

[6] Williamson, Browne, Craig, and Donahue, Phys. Rev. 84, 731 (1951).

[7] R. G. Thomas and T. Lauritsen, Phys. Rev. 88, 969 (1952).

[8] L. G. Elliott and R. E. Bell, Phys. Rev. 76, 168 (1949).

the target, we measured the yield from a target of fused LiOH known to be clean from measurements on scattering of protons. The yield obtained with this target had a similar energy dependence and was 3.5 times as small as the yield from lithium metal at same bombarding energies. This ratio of 3.5 is what we should expect from the stopping powers of lithium and LiOH. For the lithium metal target used, the possibility cannot be excluded that a surface layer a few kev thick for the alpha particles might have built up during the experiment. By leaving a thick target of lithium metal overnight in the untrapped vacuum system, we observed that the surface layer can grow to a thickness as large as 60 kev to alpha particles of 2 Mev. However, this possible source of error would introduce only a small correction to the resultant absolute yield. Also, the increment of the thick target yield with bombarding energy is, in general, quite reliable and is useful in estimating the thickness of thin targets from their yields.

Since the efficiency of the particular NaI crystal in use was known as a function of γ-ray energy[5] the counting rates were readily converted to give absolute disintegration rates. Correction for absorption (6 percent) in the target housing has been included in determining the yields of Fig. 3.

To obtain more accurate excitation data the yield from several thin targets of lithium was measured. Figure 4 shows the result obtained with two targets, matched at 2.3 Mev. The target for the portion of the curve below 2.3 Mev was 21 kev for 2.3-Mev alpha particles, as estimated from a comparison of the counting rate with the slope of the thick target yield curve. The other target was 35 kev thick for 2.3-Mev alpha particles. The excitation curve was corrected for target thickness. The dashed curve shown in Fig. 4 is obtained by differentiating the thick target yield with respect to energy and multiplying it with corresponding stopping cross sections. In view of the broadness of the resonance and the uncertainty in the stopping cross section of lithium for alpha particles of these energies, the agreement of this differential curve with the corrected thin target curve seems reasonable.

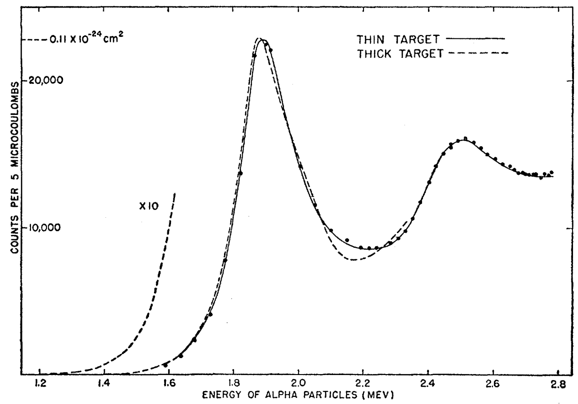

FIG. 4. Excitation function of $Li^7(\alpha,\alpha'\gamma)Li^7$. Solid curve: thin target results corrected for target thickness. Dashed curve: results of differentiating the thick target yield with respect to E_α and corrected for stopping power of the target for different E_α.

The stopping cross sections of different materials for alpha particles at the low-energy range are poorly known. In view of the uncertain capture and loss of electrons by the alpha particles and other difficulties, the energy loss at low energy is essentially not calculable.[9] In the present calculations we have used the range-energy relation of air for alpha particles given by Bethe[10] and a stopping power of 0.5 for a lithium atom relative to an air atom. The absolute cross sections given in Fig. 4 for the excitation curve has also been corrected for the concentration of Li^7 in natural lithium. These cross sections are believed to be accurate to 20 percent, the main uncertainty being the efficiency of the counter and the stopping cross section of lithium.

From Fig. 4 we see that there are two resonances for $Li^7(\alpha,\alpha')Li^{7*}$ in the energy range studied. The first peak is at 1.889 ± 0.010 Mev with width of 200 kev and cross section at peak 0.11 ± 0.02 barn, and the second broad peak at 2.50 ± 0.03 Mev, with a cross section of 0.08 ± 0.015 barn. Subtracting the tail of the first resonance we have the cross section of the second resonance $\sigma_R\approx0.03$ barn. The part of the excitation curve for bombarding energy below 1.6 Mev was obtained by differentiation of the thick target yield which was taken with steps of about 20 kev. The regions around both peaks, as well as the region $E_\alpha=2.3$ to 2.8 Mev, have been measured with targets as thin as 6 kev for 2.3-Mev alpha particles and with comparable steps. No structure other than background fluctuations was seen. The results are to be compared with the recent work of Heydenburg and Temmer[11] in which they reported strong resonances at

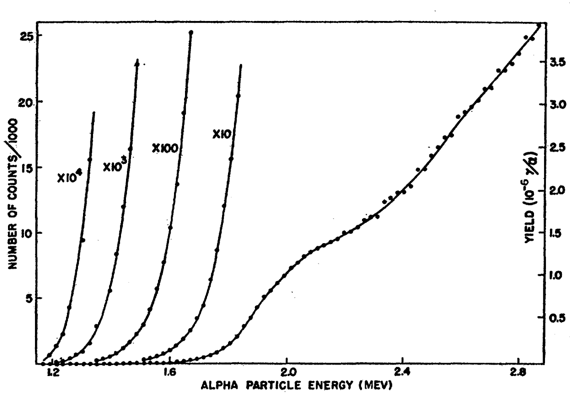

FIG. 3. Thick target yield of natural lithium metal for the 478-kev gamma ray.

[9] See, for example, E. Segrè, *Experimental Nuclear Physics* (John Wiley and Sons, Inc., New York, 1953), Vol. I, p. 166.

[10] H. A. Bethe, Revs. Modern Phys. **22**, 213 (1950); also reference 9.

[11] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **94**, 1252 (1954).

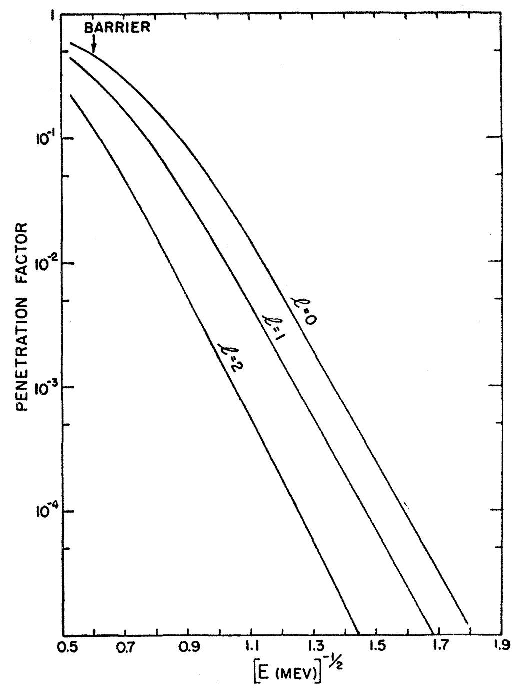

FIG. 5. Penetration factor of alpha particles for Li^7 for a channel radius of 4.9×10^{-13} cm. E_{Mev} is the energy of incident alpha particles in the laboratory system in Mev.

1.91, 2.46, and 3.06 Mev and some indication of weak resonances at 2.60 and 2.70 Mev.

DISCUSSION

In order to evaluate the level parameters it is convenient to remove the penetration factors from the excitation function. First, for purpose of reference, we give in Fig. 5 a plot of the barrier penetration factor of alpha particles in Li^7, following the style of Christy and Latter[12] for the case of protons. In Fig. 5, $P_l=1/[F_l^2(R)+G_l^2(R)]$ is the barrier penetration factor for alpha particles of orbital angular momentum l; $F_l(R)$ and $G_l(R)$, the usual Coulomb wave functions at the channel radius R. In making the computation, R was taken to be $1.4\times(7^{1/3}+4^{1/3})\times10^{-13}$ cm$=4.9\times10^{-13}$ cm, and tabulated Coulomb wave functions[13] were used.

Figure 6 shows the experimental excitation curve with the barrier penetration factors of the incoming and outgoing alpha particles removed. The combination $l=1$ for the incoming particle and $l'=1$ for the outgoing particle was used with the channel radius given above. The use of other orbital angular momenta and a different value of the channel radius would change the position and the width of the peaks only slightly. It can be seen that the width estimated directly from the experimental curve in the previous section is roughly right. We shall adopt the values 1.87 Mev and 2.45 Mev as the position of peaks without barrier. These correspond to levels of B^{11} at 9.86 Mev with $\Gamma=125\pm10$ kev, and 10.23 Mev with $\Gamma\approx155$ kev, after changing from laboratory system to center-of-mass system.

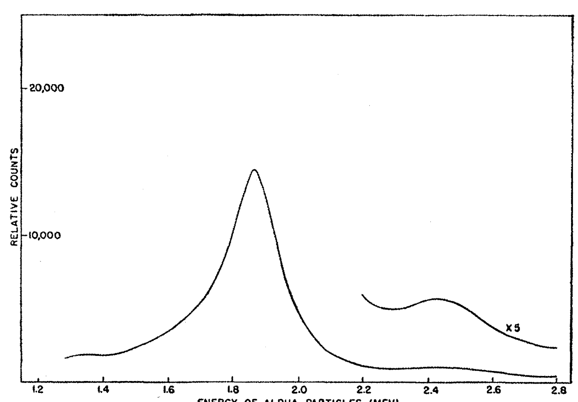

FIG. 6. Experimental excitation curve with the barrier penetration factors of the incoming and outgoing alpha particles removed. The combination of $l=1$ for the incoming particle and $l'=1$ for the outgoing particle is assumed.

TABLE I. Table of reduced widths for the incident and inelastically scattered α-particles at the 1.889-Mev resonance. The first column gives the spin and parity of the B^{11*} compound state; the second and third columns give the angular momenta of the incident and emerging α particles. The fourth and fifth columns give the reduced widths divided by $\frac{3}{2}\hbar^2/MR$.

1.889-Mev resonance J	l_1	l_2	$\frac{2MR\gamma_1^2}{3\hbar^2}$	$\frac{2MR\gamma_2^2}{3\hbar^2}$
1/2+	1	1	0.12	0.85
1/2−	2	0	0.48	0.31
3/2+	1	1	0.20	0.27
			0.037	1.44[a]
3/2−	0	2	0.108	1.76
	2	2	0.79	1.97
5/2+	1	3	0.22	6
5/2−	2	2	0.87	1.08
7/2+	3	3	5	6

[a] We have assumed that the incident α particle has the larger partial width; the second sets given for a particular compound state give the results for the reverse assumption.

Calculations of the reduced widths for the incoming and outgoing α particles at the two resonances were made taking the previously mentioned radius (4.9×10^{-13} cm) for the channel radius. Comparison of these results with the Wigner-Teichman limit[14] ($3\hbar^2/2MR$) are presented in Table I for the 1.889-Mev resonance and indicate that for the 1.889-Mev resonance $J\leq5/2$ if odd parity and $J\leq3/2$ if even parity. Similar computations for the 2.50-Mev resonance suggest J is probably $\leq7/2$. (We assumed because of uncertainty in the channel radius that a particular assignment was not in significant disagreement with

[12] R. F. Christy and R. Latter, Revs. Modern Phys. **20**, 185 (1948).

[13] Bloch, Hull, Broyles, Bouricius, Freemen, and Breit, Revs. Modern Phys. **23**, 147 (1951).

[14] T. Teichman and E. P. Wigner, Phys. Rev. **87**, 123 (1952).

theory if the reduced width was not more than a factor of two greater than the Wigner-Teichman limit.) Elkind[15] reports a new level of B^{11} at 10.32±0.02-Mev excitation with width 54±17 kev from the reaction $B^{10}(d,p)B^{11}$. This level is too narrow to be identified with our level at 10.23 Mev. From the limits of observation given by Elkind one can infer that if the intensities of groups corresponding to our broad levels at 9.86 and 10.23 Mev were less than half of the intensity of the 10.32-Mev group (at 90°), they would have escaped detection in Elkind's experiment. From our measurements we conclude that the cross section for excitation of the 10.32-Mev level is less than 0.006 barn for the $Li^7+\alpha$ reaction.

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[15] M. M. Elkind, Phys. Rev. 92, 127 (1953).

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Range of Nitrogen Ions in Emulsion

H. L. Reynolds and A. Zucker
Oak Ridge National Laboratory, Oak Ridge, Tennessee
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The range of nitrogen ions in Ilford C-2 emulsion was measured for energies from 4 to 28 Mev. The rate of energy loss over this entire energy region is approximately 1.5 Mev per micron.

INTRODUCTION

THE range-energy characteristics of particles heavier than helium are difficult to predict from theory because such particles pick up electrons as they near the end of their range. In general, charge pickup and loss is observed when the ion velocity is comparable to the velocities of orbital electrons. Experimentally determined ranges of lithium and boron in emulsion[1] have illustrated the process of charge pickup, although the range over which charge pickup occurs for these particles is rather short. Miller[2] has measured the range of carbon ions in emulsion but his results apply mainly to energies higher than 30 Mev, which is above the region of charge pickup.

The range-energy relation for nitrogen ions in nickel below 30 Mev has been discussed previously.[3] It was shown that as nitrogen ions slow down in nickel they pick up electrons in such a manner that dE/dx remains nearly constant. Such behavior in emulsion would be in contrast to a calculation by Freier *et al.*,[4] which indicates that the observable thinning of the tracks of heavy nuclei as they slow down in emulsion is due to a decrease in dE/dx as the charge of the particle decreases. The range in emulsion of nitrogen ions from 4 to 28 Mev was measured with the nitrogen beam of the ORNL 63-inch cyclotron by methods described below.

[1] W. H. Barkas, Phys. Rev. 89, 1019 (1953).
[2] J. F. Miller, University of California Radiation Laboratory Report UCRL-1902, 1952 (unpublished).
[3] Reynolds, Scott, and Zucker, Phys. Rev. 95, 671 (1954).
[4] Freier, Lofgren, Ney, and Oppenheimer, Phys. Rev. 74, 1818 (1948).

EXPERIMENTAL METHOD

Since the range of nitrogen ions in nickel is known for energies from 8 to 28 Mev, this portion of the range-energy curve was obtained by exposing 50-micron Ilford C-2 emulsions in the deflected cyclotron beam. To vary the energy, thin nickel foils were placed directly in front of the emulsions. The initial beam energy was determined as before[3] by observing the energy of recoil protons from a gas target. The emulsions were exposed in an evacuated chamber which was mounted on the exit port of the cyclotron. A $\frac{1}{4}$-in. brass plate with a $\frac{1}{32}$-in. slit was used as a shutter. The shutter was mounted on a Lucite rod which extended through a seal in the vacuum chamber. The shutter, thus insulated from ground, was used as a beam monitor. When a satisfactory current struck the plate the slit was rotated rapidly by means of the Lucite rod, thus exposing the emulsion to a short burst of ions. Results obtained in this manner are indicated by crosses in Fig. 1.

The low-energy portion of the curve was determined as follows: Plates exposed to the direct full-energy beam were scanned for nitrogen-proton elastic collisions. From conservation of momentum and energy it can be shown that

$$E_N = \frac{E_P[1-(M_P/M_N)]^2}{4(M_P/M_N)\cos^2\alpha},$$

where E_N and E_P are the nitrogen and proton energies after the collision, M_N and M_P are the nitrogen and proton masses, and α is the angle between the recoil proton and continuing nitrogen ion. E_P was determined