Excited States of Be^7 *

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(Received November 21, 1949)

Evidence for the existence of excited states of Be^7 below 1 Mev has been found from a study of the neutrons produced in the reaction $Li^7(p,n)Be^7$. Using a beam of homogeneous protons of 5 Mev energy from the Washington University cyclotron, the neutrons were detected by a standard photographic plate method. In addition to the ground state group of neutrons, three additional lower energy groups were observed indicating an excited level structure for Be^7. Three separate runs on three separate targets of varying thickness gave the same results. Observations were made at 20° and 90° to the proton beam for each target. In every case the shift in energy of the peaks as one goes from 90° to 20° is consistent with the assignment of definite levels to Be^7. Values obtained for the level excitation energies are: 0.205±0.070 Mev, 0.470±0.070 Mev, and 0.745±0.070 Mev above the ground state. The level at 470 kev is presumably analogous to the well-known level at 478 kev in the mirror nucleus Li^7. Levels in Li^7 corresponding to the other two levels found in Be^7 have as yet not been observed, and may, of course, not exist. The Q for the ground state reaction was found to be −1.65±0.04 Mev in good agreement with previously obtained values.

I. INTRODUCTION

THE assumption of equality between neutron-neutron and proton-proton forces suggests that the level structure of the so-called mirror nuclei is essentially identical. The lightest isotope known to have an excited level is Li^7. Hence it is of interest to inquire as to the level structure of the mirror nucleus, Be^7. In particular, one may expect that there should exist a level in Be^7 corresponding to the well-known 478-kev level in Li^7. A number of workers[1] have looked for such a level in Be^7 but with no success.

One method of attack is to investigate the energy spectrum of the neutrons from the reaction

$$Li^7+H^1\rightarrow Be^7+n^1-1.64 \text{ Mev}. \quad (1)$$

In this reaction, Freier, Lampi, and Williams[2] have shown that for incident protons of energy up to 3.66 Mev, only the ground state group of neutrons is present. Working on the assumption that a greater amount of energy supplied to the compound nucleus, Be^8, might result in the formation of Be^7 in excited states, reaction (1) has been investigated with the 5.11-Mev protons obtained from the Washington University cyclotron.

II. EXPERIMENTAL METHOD

The fringing field of the cyclotron magnet combined with a specially designed slit system is used to isolate a beam of monoenergetic protons for use in the experiment. The beam then passes down a long snout to a point well away from the cyclotron where investigation can be carried out with adequate shielding. The energy of the protons so obtained is determined by allowing them to strike a photographic emulsion at a glancing angle and recording their distribution in range. An energy of 5.11±0.06 Mev with a width at half-maximum of 30 kev is thus found for the proton beam.

A chamber originally designed by one of us (K.B.M.) for use in scattering experiments using photographic emulsions as detectors was modified to give the correct geometry for reaction studies. As seen in Fig. 1, the proton beam enters through a system of collimating slits and strikes a thin target at the center of the chamber. Nuclear track emulsions are arranged radially with respect to the target for detection of the disintegration particles. Since we are interested here in recording only the neutrons produced in the reaction, the emulsions were encased in light-tight steel holders of sufficient thickness to stop any charged particles produced in the target. This thickness is negligible, however, in contributing to a diminution in neutron energy. Neutrons produced in the reaction thus pass freely through the emulsion and an examination of the recoil proton tracks produced in the direction of the neutron flux will give an accurate measure of the neutron energy. Collimation of the neutrons at the various angles of detection results from the fact that the plates are almost tangential to the path of the incident neutrons.

Targets were prepared by evaporation of Li compounds in vacuum onto a 0.1-mil platinum foil supported at the edges by a thin steel frame. Two targets of LiF were prepared, 3.1 mg/cm^2 and 1.07 mg/cm^2, and one of LiCl. The thickness of the latter was not determined due to the rapid deliquescence of LiCl when removed from vacuum, but it is believed to have been of the same order of magnitude as the two LiF targets. The uniformity of the LiCl target is in serious doubt as a result of the deliquescence occuring during transfer of the foil from the evaporation chamber to the reaction chamber.

Exposures given the detecting plates were a function of the target thickness used. The thinner of the two LiF targets was given about twice that of the other two targets. The plates were examined by microscope following development and the track lengths recorded

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[1] Freier, Lampi, and Williams, Phys. Rev. 75, 901 (1949); W. E. Burcham, and J. M. Freeman, Nature 163, 167 (1949); Mandeville, Swann, and Snowden, Phys. Rev. 76, 980 (1949); A. O. Hanson and R. F. Taschek, National Research Council Preliminary Report No. 4, Nuclear Science Series.
[2] Freier, Lamp, and Williams, Phys. Rev. 75, 901 (1949).

using a procedure that has already been explained in detail.[3]

III. EXPERIMENTAL RESULTS

Figures 2 and 3 give the resulting neutron spectrum at 20° and 90° to the beam, respectively, for the various targets used. The plates exposed at 90° to the LiCl target did not contain sufficient tracks to give a reliable spectrum and it was not felt that an additional run using a longer exposure was justified at the time. A discussion of the data obtained from each target is given below.

160-kev LiF Target

LiF was chosen as a target material because of the ease in evaporation of the compound, plus the fact that neutrons from $F(p,n)Ne$ have quite low energies ($\sim$1.0 Mev at 20° to the beam) in comparison with those from Li^7.

Examination of the spectrum in Fig. 2 obtained at 20° to the incident beam shows what appears to be two unresolved groups at the high end of the energy axis, a well-defined peak at 2.75 Mev, and a point of inflection at $\sim$2.45 Mev. Below this the points do not fall into any definite arrangement. Turning now to the data taken at 90°, shown in Fig. 3, we see again the two unresolved high energy groups while the third group has now lost its definiteness. This "squeezing together" of the groups at 90° to the beam is due to the unfavorable increase of the slope of the range-energy curve for protons in the emulsion at lower energies. Finally a fourth group is now well defined at the 90° position. If one tentatively assigns to Be^7 energy levels correing to the groups observed at 20°, the position on the energy scale of the peaks at 90° is consistent with this assignment. Further, the well-defined fourth group at 90° corresponds in energy to the point of inflection at 2.45 Mev in the 20° data. Since subsequent runs have definitely indicated the existence of this peak at 20°, no explanation is readily forthcoming for its failure to appear in these data.

A run was made on a Pt foil to ascertain what neutrons, if any, were attributable to "background." We were able to show, as a result of this run, that a negligible number of neutrons were present above 2.2 Mev at the 20° position and none above 1.4 Mev at the 90° position. Hence, the four peaks observed are most certainly due to Li^7. ($Li^6(p,n)Be^6$ threshold is quite high. The basis for this statement is a lower limit calculation for the mass of Be^6 from which the Q for the reaction can be estimated. He^6, Li^6, and Be^6 belong to a triplet system and the triplet splitting energy can be found from the known masses of He^6 and Li^6. The Coulomb binding energy for Be^6 and the neutron-proton mass difference are also known; hence a lower limit for the value of the mass of Be^6 can be found.)

[3] J. C. Grosskreutz, Phys. Rev. **76**, 482 (1949).

Thin LiCl Target

As stated previously, the uniformity of this target is in doubt, but the main reason for running it was as a control over the LiF data. Neutrons from Cl^{37} will most certainly be present, as the Q for the reaction $Cl^{37}(p,n)A^{37}$ has been given as -1.596 Mev.[4] The other isotope of Cl will not be effective, the Q for $Cl^{35}(p,n)A^{35}$ being -6.6 Mev.

Figure 2 displays the 20° data from this target, and upon examination one finds again the two unresolved high energy peaks originally found in the LiF data. It must be mentioned that the ground state group of neutrons from $Cl^{37}(p,n)A^{37}$ falls at 3.31 Mev, which further confuses the resolution of the two high energy peaks. However, the intensity of the neutrons from Cl^{37} is probably quite low in comparison to those from Li^7 as a result of barrier penetration. Peaks again occur at 2.75 Mev and 2.45 Mev, corresponding to the ones observed in the case of LiF. Further, two low energy groups are manifest at 1.75 and 2.05 Mev. These two groups agree excellently with the first two excited levels found by Davison[5] in A^{37}. Our data yields values for the levels in A^{37} of 1.40 Mev and 1.65 Mev as compared to 1.38 and 1.63 Mev given by Davison.

50-kev LiF Target

The inability to resolve all groups in the runs just discussed prompted us to do the experiment again some months later using a much thinner LiF target. The uppermost curves in Figs. 2 and 3 display the neutron

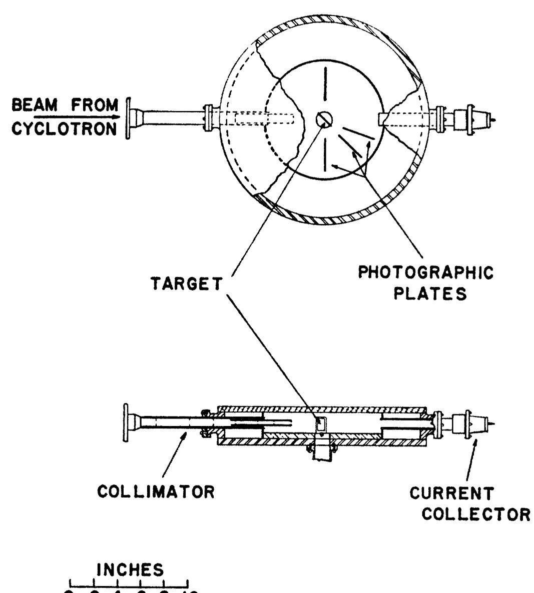

FIG. 1. Experimental arrangement for the study of the neutrons from $Li^7(p,n)Be^7$ by means of photographic plates.

[4] H. T. Richards and R. V. Smith, Phys. Rev. **74**, 1257 (1948).
[5] P. W. Davison, Yale University, Sloane Physics. Lab. Annual Report NR-024-002 (1948).

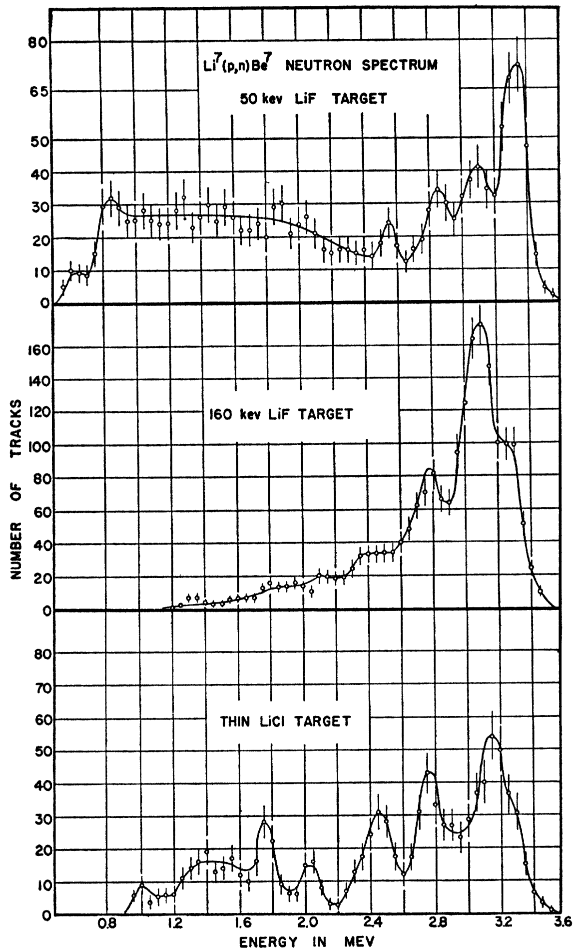

FIG. 2. Energy distribution of neutrons from $Li^7(p,n)Be^7$ observed at 20° to the bombarding beam of protons. The number of tracks in each 100-kev interval has been plotted every 50 kev. Corrections involving geometry and n–p scattering cross section have not been made in this plot. Reading from top to bottom, the spectra represent 772, 962, and 490 acceptable recoil proton tracks.

energy spectra obtained. As is evident from first glance, resolution of the two high energy peaks was indeed achieved. That the relative intensities are consistent with those found in the earlier runs is immediately evident from target thickness considerations; for the general shift of the groups toward lower energies as this thickness increases will cause the second peak to appear to have the greater intensity in the 160-kev LiF case. The position in energy of the ground state group is in excellent agreement with the predicted energy obtained from the known masses and Q-value. The next three groups are in agreement with those found in the earlier runs on thicker targets. The relative intensities of the groups at 20° and 90° are the same within experimental error. The energies of the groups at 20° and 90° correspond to the assignment of definite energy levels to Be^7.

It will be noticed that the background of low energy neutrons is considerably higher in this run than in the first two runs. This can be attributed to two factors. First, the exposure was approximately twice that given the former plates. Second, there is a strong observer bias in favor of the measurement of the long recoil proton tracks over that of the shorter ones. And it was not until scanning of the 50-kev LiF plates began that the microscopist was given strict instructions to measure *every* track that fulfilled the acceptance conditions in an attempt to locate the ground state neutrons from fluorine. These two factors when coupled together will certainly give rise to a higher background than that measured in the original two runs. Whether it accounts for the approximately threefold increase is a matter of conjecture. The significant thing is, however, that no definite grouping emerges from this increased background while the four energy groups found originally are confirmed.

IV. CALCULATIONS AND DISCUSSION

Since in no case are the neutron groups fully resolved into separate peaks, it was necessary to invoke the following procedure for obtaining mean energies for the groups. The ranges of the tracks in terms of the scale divisions of the eyepiece micrometer as recorded by the microscopist were plotted as a histogram. The histogram interval chosen was 1.5 scale divisions (~2 microns)

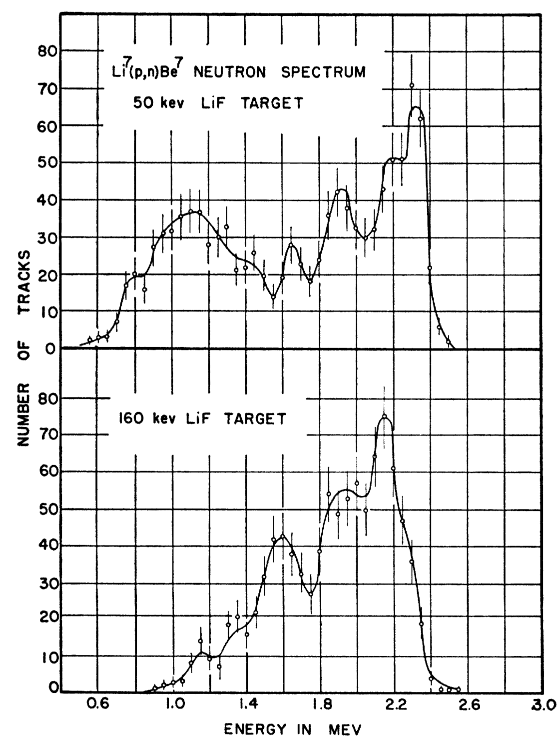

FIG. 3. Energy distribution of neutrons from $Li^7(p,n)Be^7$ observed at 90° to the bombarding proton beam. The number of tracks in each 100-kev interval has been plotted every 50 kev. Corrections involving geometry and n–p scattering cross section have not been made in this plot. Reading from top to bottom, the spectra represent 555 and 565 acceptable recoil proton tracks.

TABLE I. The neutron groups from $Li^7(p,n)Be^7$. Groups are numbered reading from right to left in Figs. 2 and 3. Relative intensities are the mean of the 20° and 90° positions, the differences in the two cases being within the experimental error. An assignment of energy levels is made to Be^7, the values given being the mean of those found at the 20° and 90° positions.

Group	Mean energy of neutrons (Mev) 20° to beam	90° to beam	Q (Mev) 20° to beam	90° to beam	Mean excitation energy of Be^7 (Mev)	Mean relative intensity
I	3.37±0.04	2.37±0.03	−1.64±0.04	−1.67±0.03	0.00	100.0
II	3.14±0.04	2.20±0.03	−1.86±0.04	−1.86±0.03	0.205±0.070	58.5
III	2.88±0.04	1.97±0.03	−2.12±0.04	−2.13±0.03	0.470±0.070	52.5
IV	2.61±0.04	1.72±0.03	−2.38±0.04	−2.42±0.03	0.745±0.070	32.0

which corresponds to approximately 50 kev in energy. The high energy side of the ground state peak was taken to be the true shape of the leading edge of all lower energy groups. This shape was then fitted to the next lowest group and the true shape of the trailing edge of the ground state group ascertained. This gave then a "standard shape" for the highest energy peak which was in turn fitted to all subsequent groups. Because of the fact that no background neutrons contribute to the first three peaks in any appreciable number, the fit was excellent. Only in the case of the fourth group, whose existence is least convincing anyway, did the standard shape fail to fit exactly the experimental points. Even here, however, the fit was satisfactory. Extrapolated ranges were found from the curves so obtained and reduced to mean ranges following the procedure of Bethe.[6] The mean ranges were converted to energy by recourse to the range-energy relation of Lattes, Fowler, and Cuer[7] for Ilford nuclear research emulsions.

The mean energies, Q-values, relative intensities, and a tentative assignment of excitation levels to Be^7 are given in Table I. In order to assign the correct relative intensities, the height of the peaks were corrected in magnitude for the variation with energy of the neutron-proton scattering cross section and for the decreasing probability of recoil protons being fully recorded in the emulsion as their energy increases.

The energy levels as here assigned to Be^7 neither affirm nor deny the expected similarity in structure of the Li^7-Be^7 isobaric pair. Although a level is established at 470 kev which might be analogous to the 478-kev level in Li^7, two additional levels are indicated by the experimental data which have no analog in Li^7. Of course it is possible that such levels do exist in Li^7 but have not yet been observed. To this end, experiments are underway at this laboratory to investigate the inelastic scattering of 5-Mev protons from Li^7, and the energy spectrum of the alpha-particles from the reaction $Be^9(d,\alpha)Li^7$ using 10-Mev deuterons. If additional levels in Li^7 are present, they may well be excited by incident bombarding particles of this energy.

The authors realize of course that the assignment of the proposed level scheme to Be^7 *per se* on the limited amount of evidence available would be somewhat presumptious. However, in order to make our data as convincing as possible, we have endeavored to make an exhaustive search for all possible sources of error. A summary of the conclusions drawn are given herewith.

All that is required of the cyclotron beam is that it be homogeneous in energy. The absolute value of the energy is unimportant since the level values depend only on differences in Q-values. The homogeneity of the proton beam is attested by the small half-width (30 kev) of the range distribution found in a photographic emulsion. That the lower energy groups are not due to inelastically scattered neutrons is borne out by the homogeneity of the groups and further by the fact that their positions in energy at 20° and 90° are entirely consistent with the picture of their having left an excited residual nucleus of Be^7.

One might also expect that (n,p) reactions take place in the AgBr present in the emulsion, thus producing extraneous protons. This is eliminated, however, on the grounds of the relative abundances of hydrogen and AgBr in the emulsion, and on the relative cross sections involved. There are 2.7 times as many atoms of hydrogen as molecules of AgBr present in the photographic plates. Hence, the probability of $n-p$ scattering is 2.7 times as great as an (n,p) reaction on Ag or Br, assuming the cross sections to be the same. A quantitative calculation of the cross sections for (n,p) reactions in Ag and Br at the energies under consideration can be made in the following manner. The actual cross section σ can be thought of as being made up of a geometrical cross section of the nucleus in question times a "penetration factor" P, which accounts for the potential barrier encountered by the emerging proton.

$$\sigma=\pi R^2 P, \tag{2}$$

where $R=1.45\times10^{-13}\times(A)^{\frac{1}{3}}$ is the nuclear radius. The factor P can be taken as simply the transmission coefficient of the potential barrier for a proton in the nucleus. Bethe[8] has worked out formulas for this quantity. Equation (600) of reference 8 has been used to calculate P for Ag and Br and the resulting values inserted in Eq. (2). The cross section σ is then found to be $\sim10^{-27}$ cm², which is considerably lower than the $n-p$ scattering cross sections at these energies ($\sim10^{-24}$ cm²). Thus extraneous protons from this source are completely ruled out.

[6] H. Bethe and M. S. Livingston, Rev. Mod. Phys. 9, 245 (1937).
[7] Lattes, Fowler, and Cuer, Proc. Phys. Soc. 59, 883 (1947).
[8] H. Bethe, Rev. Mod. Phys. 9, 69 (1937).

The LiF used for the targets was (C.P.) Baker's analyzed. The known impurities are either incapable of producing neutrons in the energy range considered, or produce them in quantities insufficient to account for the observed peaks.

We may summarize by saying that in the neutron spectra obtained from the reaction $Li^7(p,n)Be^7$, three groups in addition to the ground state groups are observed. The assignment of all these additional groups to the primary reaction seems to be consistent with the group energies at the two angles of observation. The assignment then leads to an energy level scheme for Be^7 in which excited levels are located at 205, 470, and 745 kev above the ground state. The evidence is weakest for the level at 745 kev. In addition, two levels in A^{37} are confirmed in the spectrum obtained from the bombardment of LiCl. These levels fall at 1.40 and 1.65 Mev above ground.

The authors wish to acknowledge the help of Dr. H. Primarkoff who originally suggested the investigation and with whom were held many invaluable discussions. One of us (K.B.M.) acknowledges his Studentship from the Science and Industry Endowment Fund, Commonwealth of Australia. The excellent work of Miss Eileen Dennison in scanning the plates is gratefully acknowledged.

PHYSICAL REVIEW VOLUME 77, NUMBER 5 MARCH 1, 1950

Study of the Multiple Scattering of Fast Charged Particles in a Gas and Its Role in the Interpretation of Cloud-Chamber Tracks*

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(Received September 19, 1949)

The curvature of the track of a fast charged particle in a magnetic cloud chamber varies along the track because of the multiple scattering of the particle by the gas in the chamber. By measurement of the mean and the fluctuations of the curvature, it is possible (1) to determine the multiple scattering in a gas of a particle of known mass, and (2) to estimate, on the basis of a verified multiple scattering law, the mass and energy of a particle. The statistical uncertainty inherent in such estimates is discussed. The multiple scattering of 132 beta-particles, ranging in energy from 50 to 1700 kev, with a total path length of 1800 cm in one atmosphere of argon, was measured and compared with the predictions of the theories of Bothe, Williams, Goudsmit and Saunderson, Molière, and Snyder and Scott. The theories of Molière, and Snyder and Scott, as well as that of Williams, if an available parameter is suitably adjusted, agree fairly well with our results.

I. INTRODUCTION

THERE is considerable experimental evidence concerning the multiple scattering of fast charged particles in foils, which in many instances does not conform very well to the various theories of multiple scattering developed by W. Bothe,[1] E. J. Williams,[2] S. Goudsmit and J. L. Saunderson,[3] G. Molière,[4] and H. S. Snyder and W. T. Scott.[5] Multiple scattering in gases, however, has been little investigated so far. During the course of a cloud-chamber investigation of electron-positron pair production, L. Simons and K. Zuber[6] have touched upon the multiple scattering of these particles in the mixture of argon and methyliodide with which their cloud chamber was filled, and found their results in agreement with the theory of Bothe. E. A. Luebke, G. S. Klaiber, and G. G. Baldwin[7] examined the cloud-chamber tracks of protons in air, and L. W. Smith and P. G. Kruger[8] those of electrons in air; their results are consistent with predictions by H. A. Bethe[9] based on the theory of Williams, concerning the errors introduced by multiple scattering in the evaluation of cloud-chamber tracks. On the other hand, Johanna Rüling and Herma Gheri[10] claim that the mean square scattering angle of electrons in air with energies from 4 to 10 Mev, as observed in a cloud chamber, is from five to fifty times greater than predicted by the theory of Williams.

The purpose of this paper is to study the multiple scattering of electrons in argon. Scattering data obtained from the cloud-chamber tracks of beta-particles will be compared with the predictions of various

* Assisted by the Joint Program of the ONR and AEC. Preliminary results of this paper have been presented at the 1948 Chicago meeting of the American Physical Society (Martin J. Berger and Gerhart Groetzinger, Phys. Rev. **75**, 342A (1949)). See also Ribe, Berger, and Groetzinger, Phys. Rev. **77**, 760 (1950).

[1] W. Bothe, *Handbuch der Physik* (Verlag Julius Springer, Berlin, 1933), Vol. 22, II, p. 1.

[2] E. J. Williams, Proc. Roy. Soc. **169**, 531 (1939); Phys. Rev. **58**, 292 (1940).

[3] S. Goudsmit and J. L. Saunderson, Phys. Rev. **57**, 24 (1940); Phys. Rev. **58**, 36 (1940).

[4] G. Molière, Zeits. f. Naturforsch. **3a**, 78 (1948). (This paper contains a summary of experimental results on scattering by foils.)

[5] H. S. Snyder and W. T. Scott, Phys. Rev. **76**, 220 (1949).

[6] L. Simons and K. Zuber, Proc. Roy. Soc. **159**, 383 (1937).

[7] E. A. Luebke, G. S. Klaiber and G. G. Baldwin, Phys. Rev. **71**, 657 (1947).

[8] L. W. Smith and P. G. Kruger, Phys. Rev. **72**, 357 (1948).

[9] H. A. Bethe, Phys. Rev. **70**, 821 (1946).

[10] Johanna Ruling and Herma Gheri, Acta Phys. Austriaca **2**, 335 (1948).