certain lines in hydrogen as the average electron energy passes through peaks in the excitation curves. These excitation or photon yields have their effect on γ modified by absorption in the gas and by photoelectric peculiarities of the cathode surface. Note for example the difference in the locations of the peaks for the platinum and the NaH surfaces. In agreement with this it should be noted that the peaks in the γ curve for the NaH cathode disappear at those values of X/p where α/p has its maximum point. Here hydrogen is being excited but the sodium compound removes some photons by ionization. At the higher values of X/p the platinum surface in hydrogen, as is known from the results of Curtis,[12] is a good secondary electron emitter under proton bombardment. NaH on the other hand is a sensitive photoelectric emitter but appears to be relatively insensitive to secondary electron emission on bombardment by ions of sodium and protons.

These results illustrate the different types of mechanisms producing the second Townsend coefficient. They clearly show the two types of secondary processes and the conditions under which they occur. They illustrate the fact that a good photoemitter may not be a good emitter under positive ion bombardment. This fact was also observed by the Farnsworth group in studies of the Cs-Ag-O surfaces under *electron* bombardment. These results also show why, with mercury contamination, the values of γ are low. The mercury vapor causes most of the peaks in the γ-curves to disappear. The radiation is destroyed by absorption by the mercury and its ionization while the mercury ions are known to be inefficient in producing secondary emission by ion bombardment of the cathodes.

In conclusion the writer wishes to express his thanks to Professor L. B. Loeb who suggested this problem and who has given generously of his time in discussions of the experimental results.

---

[12] L. F. Curtis, Phys. Rev. **31**, 1010, 1127 (1928).

MAY 1, 1939 PHYSICAL REVIEW VOLUME 55

The Resonance Scattering of Protons by Lithium

E. C. Creutz
University of Wisconsin, Madison, Wisconsin

(Received April 1, 1939)

The scattering of protons by a thick target of lithium has been studied in the energy region 272–586 kev at an angle of 156°, with a ball counter. The number of counts per microcoulomb at 458 kev is 2.08 times its value at 408 kev, and at 487 kev it has dropped to 1.48 times the value at 408 kev. The energy at which the maximum slope of the thick target curve occurs is within five kev of the energy for the lithium gamma-ray resonance maximum. The fact that the scattering from a beryllium crystal increased smoothly with proton energy throughout the region, showed that the resonance effect is not a peculiarity of the counter. This scattering anomaly indicates: (1) that the gamma-radiation obtained when Li^7 is bombarded with 440-kev protons arises from a virtual level of Be^8; (2) that the Be^8 state is odd; and (3) that there are no odd excited states of the alpha-particle below approximately 13 Mev.

Introduction

In 1934 Lauritsen and his collaborators[1] observed gamma-radiation produced when lithium was bombarded by protons. Hafstad and Tuve[2] showed later that the reaction occurs as a sharp resonance at 440-kev proton energy, and later work by them, with Heydenburg[3] showed the resonance half-width to be about 11 kev.

The process of this gamma-ray emission was not known.[4] Crane and Lauritsen assumed that

---

[1] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **46**, 531 (1934).

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

[3] Hafstad, Heydenburg and Tuve, Phys. Rev. **50**, 504 (1936).

[4] This problem is discussed by Breit in the paper by Hafstad, Heydenburg and Tuve, reference 3, pp. 510–514.

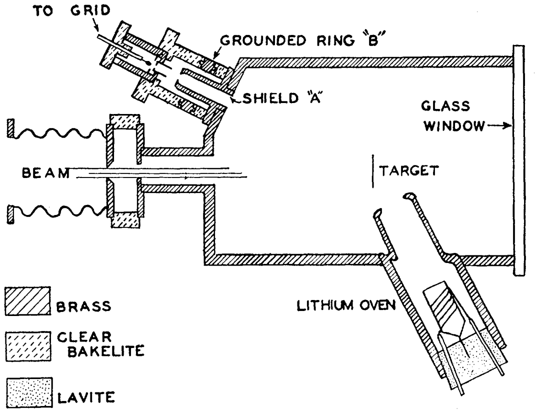

FIG. 1. Scattering chamber and proton counter.

semi-stable Be^8 was first formed, which disintegrated into two alpha-particles, one of which was excited and later emitted the gamma-radiation. Another possibility was that the emission was caused by Be^8 dropping from the excited to the normal state. In this case there should be a rather large probability for the Be^8 to disintegrate again into Li^7 and a proton, and thus give anomalous scattering of protons by lithium in the resonance region. Professor Breit suggested that experiments on the scattering of protons by lithium should help in differentiating between the two processes.

Apparatus and Procedure

The small Van de Graaff type electrostatic generator constructed by R. G. Herb and collaborators,[5] modified so as to give steady voltages up to 600 kev, was used to produce the high energy protons for these experiments. Essential modifications were: the construction of a new porcelain section accelerating tube, by Herb, of the type now used by him in the 2.4-Mv generator at this laboratory,[6] a new high voltage electrode with spun copper ends, by G. J. Plain; and remodeling of the proton source after the design now used by Herb,[6] which, because of its larger power consumption, necessitated the installation of a larger driving motor for the charging belt. With the generator at the higher voltages it was necessary to place tinfoil bands at three-inch intervals on the Pyrex capillary hydrogen lead (Fig. 2, reference 5) from ground to the high voltage electrode to prevent sparking down it and final explosion. Air at 45 lb./in.^{2} pressure in the generator was dried by KOH and kept saturated with CCl_4 as suggested by Herb.[7]

The scattering chamber and proton counter are shown in Fig. 1. Since preliminary experiments with a proportional counter carried out by G. J. Plain and the author indicated that the results of using it to count protons in this energy region would be difficult to interpret, several ball counters of the type shown in Fig. 1 were tried. Although not completely reliable these often gave consistent results from day to day. It was found necessary to shield all dielectrics in the counter in the region of the discharge and to keep the voltage on it constant to within one percent by means of a regulator, which was built with an Eimac 35T triode, manufactured by Eitel McCullough Incorporated, San Bruno, California.

Air at atmospheric pressure was used in the counter, the wall of which was kept at plus 1300 volts. The ball was connected to the grid of an amplifier whose output went to a scale-of-eight thyratron set, which activated a Cenco mechanical counter. The counter window was aluminum foil 0.00004 inch in thickness, fastened with clear Glyptal. The Glyptal was shielded from the ball by a platinum sheet. The ball was of platinum about one-tenth millimeter diameter made on platinum wire by holding it in a torch-flame.

Shields (not shown) were placed above and below the target so that protons scattered from other parts of the chamber, e.g., the glass

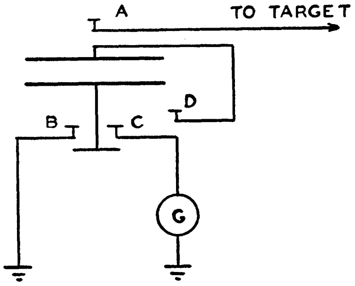

FIG. 2. Switching arrangement for measuring number of protons incident on target.

---

[5] Herb, Parkinson and Kerst, Rev. Sci. Inst. **6**, 261 (1935).

[6] Parkinson, Herb, Bernet and Mckibben, Phys. Rev. **53**, 642 (1938).

[7] M. T. Rodine and R. G. Herb, Phys. Rev. **51**, 508 (1937).

window, would be less likely to enter the counter. The number of protons entering the chamber was measured by leading them to the condenser, which was later discharged through a ballistic galvanometer. Protons striking the edge of the exit hole of the chamber knocked out secondary electrons which were pulled over to the counter wall by a rather strong field. This gave a false reading of the incident charge until the use of shield "*A*," eliminated this difficulty. Leakage across the insulating support of the counter was prevented by the grounded brass ring *B*.

Thick lithium films were evaporated by means of the oven onto a nickel sheet, freshly for each run, for about one hour at eight amp. oven current. The check runs on beryllium were made by scattering from a beryllium crystal, ground flat, polished and cleaned.

The switching arrangement used for charging and discharging the condenser, shown in Fig. 2 allows the same galvanometer to be used to measure the charging current and later the total collected charge. When charging, switches *A* and *C* are closed, and *B* and *D* are open. To interrupt charging, *A* is opened. To measure the charge, *A* is left open, *C* is opened, and *B* and *D* are closed. A Leeds & Northrup ballistic galvanometer was used, the current readings of which were of interest as to order of magnitude only. Proton currents of 0.01 to 0.2 microampere were used. After making a run on lithium, two or three check points were always made on beryllium, and several times complete runs were made on beryllium to certify that the efficiency of the counter was a smooth function of proton energy. Checks were also made by scattering first from lithium, then from beryllium, then from lithium again, finally changing the voltage and repeating the series lithium-beryllium-lithium. Good agreement was found in each case. This indicates that the observed resonance is not caused by a fluctuation in the counter sensitivity. The generating voltmeter was calibrated from the lithium gamma-ray resonance, which was observed with a Lauritsen electroscope.

RESULTS AND DISCUSSION

Curve *A* of Fig. 3 shows on an arbitrary scale the number of counts per incident proton obtained from a thick lithium film at a scattering angle of 156°. Curve *C* shows similarly the number of counts from the Be crystal at the same scattering angle. Each experimental point in these curves represents 1440 counts. Curve *A* has a peak at about 460 kev where the apparent yield is 2.1 times greater than at 408 kev. On the right of the peak (487 kev) the yield is 1.5 times greater than on the left (408 kev). Curve *C* can be used as a rough indicator of counter efficiency and a check on the reality of the scattering anomaly indicated by curve *A*. In comparing the two yield curves account must be taken of the variation of counter efficiency with proton energy and of the difference in recoil energy for the two targets. The fractions of the original energy retained on single scattering from Li^7 and Be^9 are, respectively, 0.577 and 0.65. Multiplying the abscissae of curve *C* by $0.65/0.577 = 1.125$ one obtains, therefore, a corrected Be scattering curve the abscissae of which correspond approximately to the same energy of protons at the counter as for the lithium curve *A*. Curve *D* of Fig. 3 has been obtained in this way. It is smooth in the energy region in which the Li curve shows a peak and indicates the reality of the scattering

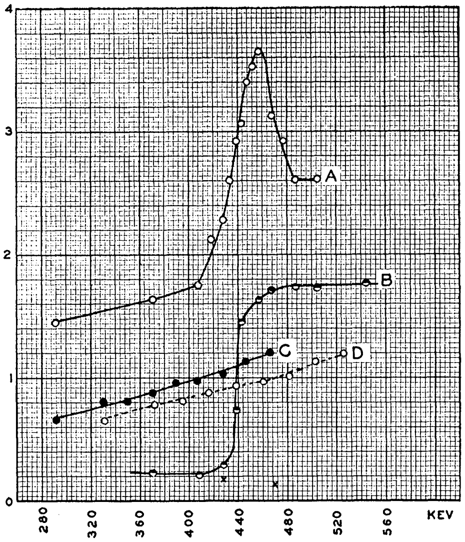

FIG. 3. Curve *A*: Yield of protons scattered from lithium thick target. Ordinate scale arbitrary. Curve *B*: Gamma-ray intensity from lithium thick target bombarded with protons. Ordinate scale: electroscope divisions per microampere per minute. Curve *C*: Yield of protons scattered from beryllium crystal. Ordinate scale arbitrary. Curve *D*: same as *C*, with abscissae multiplied by 1.125 (See Discussion). Crosses show background counts with brass shield covering counter window.

anomaly. In the same figure the position of the lithium gamma-ray resonance is shown by the gamma-ray yield curve *B* which was obtained with the same target shortly after the scattering observations. The points of maximum slope of curves *A* and *B* correspond to nearly the same energy. The possibility of attributing the observed scattering anomaly to a direct effect of gamma-rays on the counter has been eliminated by putting a brass shield over the counter window. This stopped the scattered protons but left the counter exposed to gamma-rays. The crosses in Fig. 3 show the smallness of the background count obtained in this way. It is too low to explain the anomaly of curve *A*. Curves *A* and *B* of Fig. 4 show the yields from lithium and beryllium as discussed above. Curve *C* of Fig. 4 is obtained from curve *B* by correcting for recoil as has been explained for curve *D* of Fig. 3. Since different currents were required to give about the same number of counts per minute from the two targets many more adjustments of the apparatus were required during this run which probably accounts for the scattering of the lithium points which is worse than in Fig. 3. All lithium runs taken since November 8, 1937 have been plotted for curve *D* of Fig. 4. Since the counter sensitivity varied from day to day, the ordinates have been adjusted to coincide at 508 kev. Such an adjustment does not take into account the variation of the "experimental width" with existing conditions, and tends to make the peak less pronounced, especially for those runs in which no points happened to be taken at the most effective energy, 460 kev.

Although a thick film of lithium was used, the yield of scattered protons drops down again after the resonance voltage is passed, because then protons which are to be resonantly scattered must have penetrated the film, and decrease in energy until they reach a value in the resonance region. If the incident energy is appreciably greater than 440 kev, the protons will have had to penetrate the film so deeply to reach the resonance region that they will be absorbed on their way out of the film, or at least slowed up so much that they cannot penetrate the counter window with enough energy to trip the counter. The countable yield expected for Coulomb scattering will now be estimated.

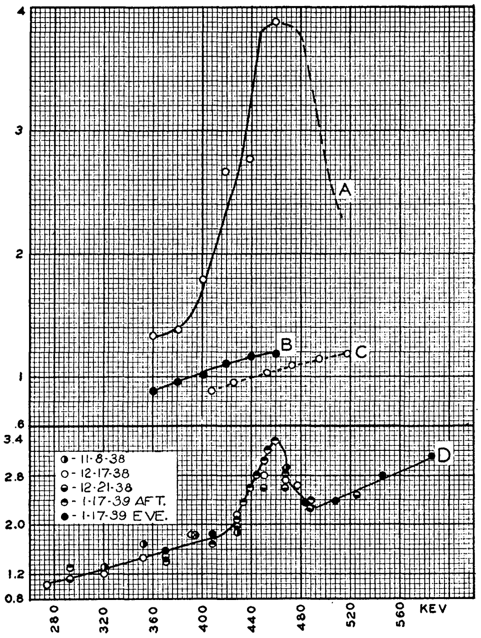

FIG. 4. Curve *A*: Yield of protons scattered from lithium thick film. Points taken alternately with those of curve *B*. Curve *B*: Yield of protons scattered from beryllium crystal. Curve *C*: same as *B* with abscissae multiplied by 1.125. Curve *D*: Yield of protons scattered from lithium thick film. Ordinate at 508 kev adjusted to coincide for all runs.

According to the Rutherford formula n, the number of protons scattered per incident proton, per unit thickness of film, per unit solid angle, at a given scattering angle, is inversely proportional to the square of their energy. Thus from film thickness dx, the number scattered is

$$ndx = KE^{-2}dx,$$

where K is a constant. The total number scattered from a film of thickness λ is then

$$N = \int_0^\lambda KE^{-2}dx.$$

For a small spread of energies, the range of the protons is approximately proportional to their energy, and that lost per centimeter of range (the "stopping power" of the film) is approximately independent of their energy, equal to a constant a. Thus if the energy when incident is E_0, that retained at a depth x in the film is

$$E = E_0 - ax.$$

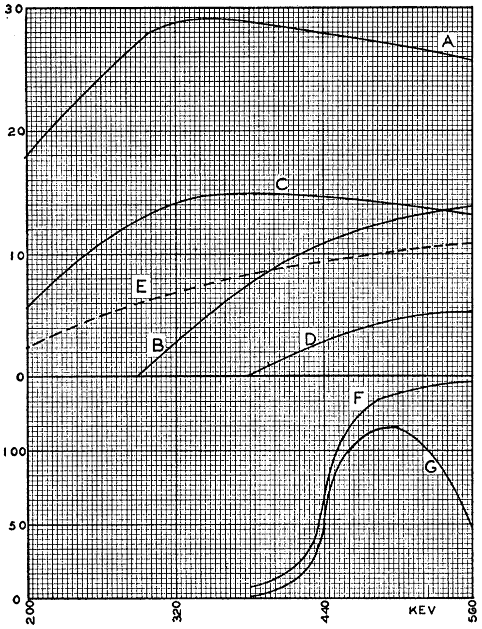

FIG. 5. Calculated curves, showing expected countable yield of scattered protons. Curve A: Yield from beryllium, counter cut-off 100 kev. Curve B: Yield from beryllium, counter cut-off 200 kev. Curve C: Yield from lithium, neglecting anomaly, counter cut-off 100 kev. Curve D: Yield from lithium, neglecting anomaly, counter cut-off 200 kev. Curve E: Yield from lithium, assuming all protons returned to counter with energy greater than 200 kev. are counted, as well as 50 percent of those with energy greater than 100 kev but less than 200 kev. Curve F: Yield of protons anomalously scattered from Li, cut-off 50 kev. Curve G: Same as F, counter cut-off 200 kev.

Thus the number scattered, of incident energy E_0, is

$$N=\int_0^\lambda K(E_0-ax)^{-2}dx.$$

Upon being scattered, the proton loses the fraction $(1-B)$ of its energy as recoil of the scattering particle, and retains the fraction B. Thus immediately after being scattered at a depth x the proton has a total energy $B(E_0-ax)$ of which it loses $ax/\cos\theta$ in getting back out, where θ is the supplement of the scattering angle. Thus upon reaching the counter, the total energy retained is

$$B(E_0-ax)-ax/\cos\theta$$

which must be greater than some value C, in order for it to trip the counter. Thus λ, the upper limit of the integral is evaluated, as the maximum depth in the film which will still yield countable scattered protons:

$$B(E_0-a\lambda)-a\lambda/\cos\theta=C.$$

The approximation $\cos\theta=1$ was used. The integral then gives for the countable yield of protons

$$N=K(BE_0-C)a^{-1}E_0^{-1}(E_0+C)^{-1}.$$

Curves of this function of E for various values of C, for $B=0.577$ corresponding to Li^7 and to Be^9 $(B=0.65)$ are shown in Fig. 5, curves A, B, C, D. The value of a was computed from Bragg's law (atomic stopping power proportional to the square root of atomic wt.) and Herb's data for the stopping power of aluminum.[8]

As a first approximation to the expected yield of anomalously scattered protons, the cross section for such scattering was assumed to follow the law

$$\sigma=\sigma_m\frac{\Gamma^2}{(E-E_m)^2+\Gamma^2},$$

where σ_m, the maximum value of σ, was taken to be roughly five times the Rutherford scattering cross section at 440 kev, E_m was taken as 440 kev, a half-width of 40 kev was used, and Γ was found accordingly. Curves of the countable anomalous yield for $C=50$ kev and $C=200$ kev are shown in Fig. 5, curves F and G, respectively. The half-width used (40 kev) is higher than the observed 12 kev. The conclusions will not be affected since this only tends to widen the peak of curve G and the step of curve F as well as to increase the expected relative importance of the anomaly.

A counter of the type used does not have a definite cut-off voltage (value of C), but if one assumes, for instance, that all protons incident on the counter window with energy greater than 200 kev are counted, as well as 50 percent of those with energy less than 200, but greater than 100 kev, the curve obtained is much the same as one for a value of C between 100 and 150, except for small values of E, as shown by the dotted curve of Fig. 5E, which was calculated in this way. Both curves F and G in Fig. 5, although calculated for widely different values of C, show a maximum positive slope very close to 440 kev, the value used for the resonance maximum in

---

[8] Parkinson, Herb, Bellamy and Hudson, Phys. Rev. **52**, 75 (1937).

these calculations, which indicates that the actual resonance maximum may be given closely by the energy corresponding to the greatest slope of the experimental curve, independently of the counter cut-off. Curves *A*, *B* of Fig. 3 show that the points of greatest slope for scattering and gamma-rays correspond to the same energy within five kev.

According to the Breit-Wigner formula, the cross section for a resonance process of this sort is given by

$$\sigma=\frac{\Lambda^2}{\pi}S\frac{\Gamma_s\Gamma_r}{(E-E_m)^2+(\Gamma_s+\Gamma_r)^2},$$

where Λ is the wave-length of the incident particle, E its energy, and E_m its energy at the resonance maximum; the statistical factor S is of the order of magnitude of unity and matters little in the estimates made below.

The contributions to the half-width of the resonance due to the probability of the compound nucleus scattering the incident particle, and emitting radiation are $2\Gamma_s$ and $2\Gamma_r$, respectively. The γ-yield at resonance as estimated by Gentner[9] is about eight percent of the number of disintegrations per proton in the reaction

$$Li^7+H^1\rightarrow He^4+He^4,$$

the cross section for which is about 2×10^{-27} cm^2 at 440 kev. Using these values and the wave-length of a 440-kev proton (4.3×10^{-12} cm) one obtains for one of the Γ's

$$\Gamma_1\cong2 \text{ ev},$$

while the rest of the width (about 5500 kev for Γ to give the total measured by Hafstad, Heydenburg and Tuve[3]) must be due to Γ_2. If the radiation takes place from an excited alpha-particle and Γ_1 be interpreted as Γ_r, the width is due to the disintegration

$$Be^{8*}\rightarrow He^4+He^{4*},$$

which would be expected to have a greater probability than indicated by such a small value of Γ, although the nuclear penetration factor for the alpha-particles depends on their energy which is not definitely known, because of the uncertainty in the gamma-ray energy. The fact that anomalous scattering is found is an argument for interpreting Γ_2 as Γ_s and attributing the gamma-radiation to direct emission from Be^{8*} as pointed out by Breit.[3]

CONCLUSION

There is a resonance in the 156° scattering of protons by lithium with a maximum at proton energy within five kev of that for the gamma-ray resonance maximum. The actual thick film yield at 458 kev is at least 1.7 times the yield at that voltage as it would be arrived at by interpolating between 408 and 487 kev (depending upon the way the interpolation is made) at which points the yield is probably almost entirely caused by scattering by a Coulomb field. This indicates that the gamma-radiation obtained by bombarding Li^7 with 440-kev protons arises from the reaction

$$Li^7+H^1\rightarrow Be^{8*};\quad Be^{8*}\rightarrow Be^8+\gamma \qquad (1)$$

and not from the reaction

$$Li^7+H^1\rightarrow He^4+He^{4*};\quad He^{4*}\rightarrow He^4+\gamma \qquad (2)$$

unless an explanation is found for the small nuclear penetration factor required to give process (2) a probability about 1/2700 of that for proton scattering. The experiment also shows, almost with certainty, that the excited state of Be^8 is odd, because if it were even there could be disintegration into two alpha-particles, which would exclude the anomalous scattering. Similarly the possibility of odd excited states of the alpha-particle below approximately 13 Mev is improbable because the disintegration into a normal and an excited alpha-particle would be then likely to suppress the chance of re-emission of the proton.

The author wishes to express his appreciation to Professor Breit, who suggested the problem and who furnished invaluable advice and assistance throughout the work; to Professor Herb for generous advice; to G. J. Plain who constructed some of the apparatus and with whom preliminary tests were made; and to Mrs. E. C. Creutz who read the electroscope during the gamma-ray runs. The author is also grateful for having received the Charles E. Mendenhall fellowship which helped support the work during the summer of 1938.

---

[9] W. Gentner, Zeits. f. Physik **107**, 354 (1937), see page 357.