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Experiments on the Elastic Single Scattering of Electrons by Nuclei*, **

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Experiments on the elastic single scattering of electrons by nuclei are described, the measurements extending over a range of voltages, angles, atomic numbers, and foil thicknesses. Observations were made at a number of voltages from 1.27 to 2.27 Mev and at angles from 20 degrees to 50 degrees on both sides of the incident electron beam. The scattering foils were aluminum, copper, silver, platinum, and gold, the atomic numbers thus varying from 13 to 79. When the foil thickness exceeded that for a "thin" target, a correction was made for multiple scattering. The use of an accurately focused homogeneous beam of electrons from an electrostatic generator made possible clear-cut control of the basic experimental variables. The experimental method was designed to minimize the effect of x-ray background, etc. The present results are in close agreement with the relativistic theory of electron scattering, as developed by Mott, over the entire range of the experimental variables except for the case of 2.27-Mev electrons on aluminum. Excepting only this case, the average of all the ratios of experimental result to theoretical prediction is 1.01 with a standard deviation of 0.06. This is in marked contrast with most of the previous work in this field where results have been widely divergent. The results of this paper, combined with spectroscopic data, extend the range of validity of the Coulomb law of attraction between electron and nucleus in close to the surface of the nucleus. The measurements of the scattering of 2.27-Mev electrons by aluminum will be repeated as soon as circumstances permit, as these results now indicate for the larger angles an interesting divergence from theory.

INTRODUCTION

SINCE the scattering of fast electrons offers the most direct method for determining experimentally the forces between electrons and nuclei at close distances of approach, a large number of researches have been performed in this field. As has been frequently pointed out,[1] the results have been widely divergent, various values having been reported for the ratio of the experimentally observed scattering to that predicted by the theory of Mott. In fact the values found for this ratio range from 0.15 to 100. Much of this spread may be accounted for by the experimental limitations associated with the inhomogeneity in energy and low intensity of the beta-ray sources usually employed. Recently, however, the availability of high speed electron beams of high intensity and accurately known and controllable energy has made possible an approach under clear-cut experimental conditions.

In the experiments described in detail below, a narrow parallel beam of electrons homogeneous in energy was made to fall on a thin target foil whose atomic number, thickness, and orientation with respect to the beam could be readily changed. The voltage of the electron beam could be read on a meter and easily varied. The detecting ionization chamber was arranged so that it could be calibrated to measure only the electrons elastically scattered by nuclei at a given angle, being at the same time shielded from those electrons which were either scattered by other electrons or inelastically scattered by nuclei. The effect of the x-ray background on the ionization chamber was substantially eliminated by means of a null arrangement.

EXPERIMENTAL METHOD

Scattering Chamber

Certain essential features of the scattering chamber are shown schematically in Fig. 1. The electron beam was produced by a high voltage electrostatic installation described elsewhere.[2] The beam as it descended from the accelerating tube was accurately parallel and somewhat larger than $\frac{1}{4}$ inch in diameter. The $\frac{1}{4}$-inch hole in the

* Because of circumstances associated with the national emergency, the preparation of this paper for publication has been considerably delayed. The scattering apparatus was dismantled at the termination of the experimental work in August, 1941.

** An abstract of this paper was presented on November 30, 1945 at the St. Louis meeting of the American Physical Society.

[1] For example, see the summaries in the following papers: F. C. Champion, *Reports on Progress in Physics* (1938), Vol. 5, p. 348; W. Bosshard and P. Scherrer, Helv. Phys. Acta **14**, 85 (1941); R. B. Randels, K. T. Chao, and H. R. Crane, Phys. Rev. **68**, 64 (1945).

[2] L. C. Van Atta, D. L. Northrup, R. J. Van de Graaff, and C. M. Van Atta, Rev. Sci. Inst. **12**, 534 (1941).

beryllium diaphragm[3] shown in Fig. 1 was used to define the beam more precisely. The effect of electrons scattered by the beryllium was minimized by placing an aluminum diaphragm with a $\frac{5}{16}$-inch hole at the entrance to the chamber as shown in Fig. 1. To check the definition and the accurate vertical alignment of the beam passing through the chamber, an insulated aluminum diaphragm having a $\frac{5}{16}$-inch hole was located at the exit of the chamber. The beam then continued downward into a Faraday cage. The vacuum maintained in the chamber was of the order of 10^{-5} mm of mercury so that gas scattering was negligible.

The scattering chamber was in the form of a hollow cylinder of welded steel 12 inches in diameter and 8 inches deep. One end was removable, being bolted on and sealed by means of a lead gasket. The target foils were mounted around the rim of an insulated aluminum disk. The disk in turn was mounted in such a way that any particular foil could be accurately placed in the center of the chamber and tipped at any angle about a horizontal axis passing through this center. This was accomplished by a simple arrangement consisting of a detent mechanism and two concentric shafts passing out through the lid of the chamber. The shafts pass through a region filled with a thick stopcock grease under pressure, thus affording a reliably vacuum-tight joint.

Collector Assembly

The collector assembly for measuring the electrons scattered at a given angle θ is shown in outline in Fig. 1 and in detail in Fig. 2. In order to conveniently and accurately control the angle θ, the collector assembly was mounted on a large disk fastened to the end of a hollow horizontal shaft passing out through the fixed end of the scattering chamber. The axis of this shaft was accurately in line with the horizontal axis of the chamber. The joint between shaft and chamber was made vacuum tight by a pressure grease seal. To the outer end of the shaft was fastened an accurate worm gear, 7.5 inches in diameter and having 360 teeth.[4] This was driven by a small worm mounted on the shaft of a Selsyn motor which could be remotely controlled. Thus, from the main control station, the angle θ could be quickly changed and reset to within the order of one minute of arc.

The design and essential arrangement of the collecting assembly can be seen in Fig. 2. The scattered electrons were measured by an ionization chamber which could be reached only by the electrons passing through the three diaphragms in front of the chamber. The diaphragm nearest the ionization chamber defined the small solid angle of the cone of electrons received from the foil. The other two diaphragms shield the ionization chamber from the stray electrons which may be initially scattered from the foil and subse-

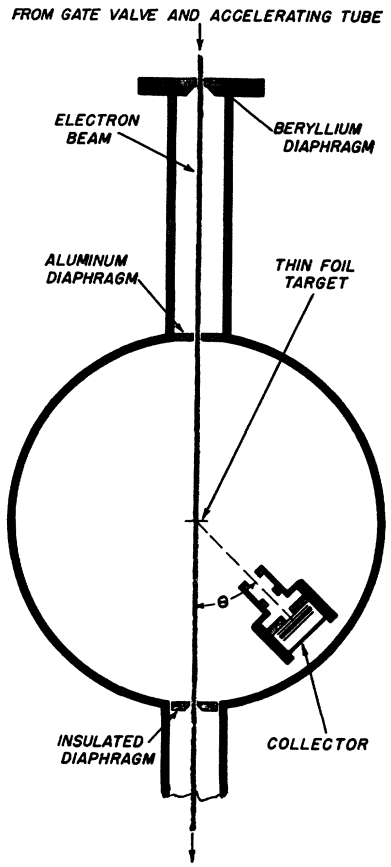

FIG. 1. Schematic diagram of scattering chamber.

[3] The beryllium disk was very kindly made for this purpose by Professor John Wulff of the Department of Metallurgy of Massachusetts Institute of Technology.

[4] It is a pleasure to acknowledge the valuable help of Mr. Walter H. Kallenbach in the construction of the worm gear drive and the steel scattering chamber.

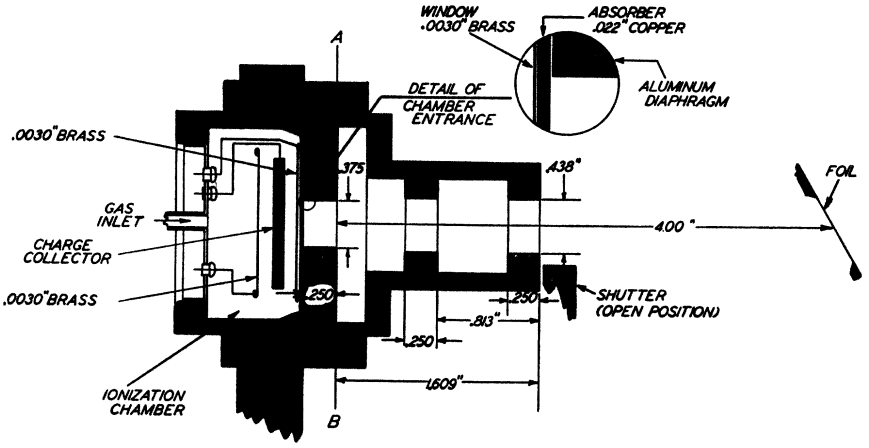

FIG. 2. Details of ionization chamber.

quently scattered back towards the ionization chamber by the walls of the scattering chamber.

Ionization Chamber

The ionization chamber was especially designed to minimize x-ray background. This background is produced principally by electrons scattered by the foil and subsequently striking the walls of the scattering chamber. The presence of such background is difficult to eliminate since it is so intimately associated with the scattering by the foil. The background due to the relatively weak x-radiation from the top beryllium diaphragm was substantially eliminated by lead packed around the neck of the scattering chamber. The ionization chamber was filled with air at atmospheric pressure which was maintained by a gas inlet tube connected to the outer atmosphere through the large hollow shaft supporting the collector assembly. The electrical leads for the ionization chamber were brought out through the shaft in a similar manner. The charge collector was a brass disk, 2 mm thick, sandwiched between the two thin brass disks as shown. The charge collector was at approximately zero potential while one disk was at approximately 1000 volts positive and the other at about 1000 volts negative. The background due to x-rays could be balanced out with this arrangement by suitably adjusting the potentials of the thin plates so that the collector current was zero when no electrons were entering the chamber. The scattered electrons entering the chamber produce a full net ionization current since they only pass through the half of the chamber nearest the foil. The scattered electrons could be prevented from entering the chamber by means of a remotely controlled shutter shown in Fig. 2, sufficiently thick to stop the electrons but small enough so its relatively slight shift in position did not appreciably change the x-ray background. The null ionization chamber with shutter proved very useful, since without means for measuring and minimizing the background considerable errors might have been made, particularly at the larger angles.

Another type of undesirable background might be owing to electrons which have been scattered from the primary beam and have suffered a loss in energy. This loss might be caused by inelastic nuclear scattering, to ionization losses, to electron-electron scattering, or to combinations of these three mechanisms. Such electrons can be screened from the ionization chamber by placing an absorber between it and the last diaphragm as is shown in Fig. 2. The absorber used in these measurements was of a thickness corresponding to slightly less than the range of 1.27-Mev electrons, the voltage used in the initial series of experiments.

Calibration of Ionization Chamber

In order to determine the ratio of the ionization currents observed to the current actually carried into the ionization chamber by the elastically scattered electrons, the following calibration

scheme was used. The collector assembly was rotated so that there was no foil or other obstruction in the path of the primary electron beam. The beam thus passed cleanly through the diaphragm system into the ionization chamber and produced an ionization current. The ratio between this current and the primary beam current which produced it gives the desired calibration factor for that particular voltage and absorber. The primary beam was then measured after swinging the collecting system clear of the beam, which then passed cleanly through the lower diaphragm shown in Fig. 1, and impinged on the beryllium bottom of the insulated Faraday cage mentioned previously. The potential across the ionization chamber was sufficient to insure saturation for all currents measured by the chamber.

Experimental Procedure

In making a series of measurements at a particular voltage and with a particular foil, the following procedure was used. First, the alignment of the chamber was checked. Secondly, after adjustment of the beam current to a suitably low value the ionization chamber was calibrated according to the method described above. The beam current was then increased to a value suitable for scattering experiments, the desired foil interposed and tipped to an angle appropriate to the scattering angle. At a given angle θ, the shutter was closed and the ionization chamber balanced. The shutter was then removed from the path of the scattered electrons and the ionization current observed. At the end of a run, both the beam current and the calibration of the ionization chamber were checked. During the course of a run, the total current to the scattering chamber was read continuously.

Runs were made at voltages 1.27, 1.81, 2.00, 2.27 Mev. At each voltage observations were in general made on foils of aluminum, copper, silver, platinum, and gold covering a range in atomic number from 13 to 79. The thickness of the foils ranged from approximately 0.0001 inch to 0.001 inch. The angular range covered in these experiments varied from 20° to 50° on each side of the beam. The beam currents ranged from about 2 microamperes to 100 microamperes, the ionization current due to scattered electrons from about 0.002 microampere to 0.3 microampere. The calibration currents used varied from about 0.5 microampere to 1 microampere. The calibration factor, ionization current/calibration current, varied from about 1 to 15.

The voltage was measured by a generating voltmeter which was calibrated both by the use of the threshold voltages of the photo-disintegration of deuterium and beryllium as well as by the more usual extrapolation methods. The voltage was known to within one percent and was kept steady to within that value. Calculations based on the analysis supplied by the manufacturers indicated that any errors due to impurities of the foils were inappreciable. Foil thicknesses were measured, in general, by weighing and by an optical lever method.[5] These determined the thickness to approximately one percent. The angle θ could be set by the remote control mechanism to within approximately one minute of arc. The beam current was measured by a microammeter to within an accuracy of 1 percent. The calibration and ionization current were measured by a sensitive galvanometer generally to within 1 percent, although for the lowest currents the error was somewhat greater.

Corrections and Possible Errors

In order to compare the experimental results with theoretical predictions it is necessary to consider the possibility of corrections for the finite beam diameter, finite solid angle subtended by the ionization chamber, the alignment of the scattering chamber, and the possible lack of symmetry of the beam. In addition, corrections must be considered for multiple and inelastic scattering.

The effect of a finite beam width of $\frac{1}{4}$ inch and finite size window of the ionization chamber was evaluated by use of the Mott formula. The effect was calculated to be less than 1 percent. Although the beam was approximately aligned with the scattering chamber as described above, there was no way of ensuring that the center of the beam as it passed through the aligning diaphragms corresponded exactly with the centers of these diaphragms. Assymmetry in this respect would result in unequal reading of the scattered current for angles of $+\theta$ and $-\theta$ particularly since the

[5] We are indebted to Mr. E. N. Strait for making these measurements.

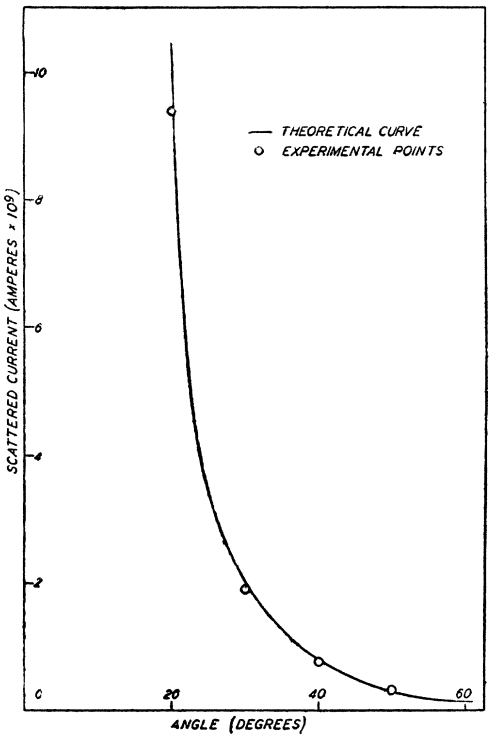

FIG. 3. Plot of scattered current *vs.* angle for aluminum at 2.00 Mev.

scattering in this angular range varies approximately with the inverse fourth power of the angle θ. A difference in the readings at plus and minus θ was actually observed. This was corrected for theoretically, using the Mott formula. It was found that a good measure of the scattering at angle θ could be found by taking the arithmetical mean of the arithmetical and geometrical means of the readings at $+\theta$ and $-\theta$. If these two means, the geometrical and the arithmetical, do not differ very much, this result is more than sufficiently precise. For the cases which occurred in the measurements reported in this paper, the error introduced by this assumption is about 1 percent.

The window to the ionization chamber was taken to be the 0.375″ hole in the plane AB, shown in Fig. 2. The solid angle corresponding to this window is 6.94×10^{-3} steradian. The effective size of the window may be somewhat reduced from this value because a few of the electrons passing through this window will strike the sides of the cylindrical hole of the diaphragm at a glancing angle. A fraction of these electrons will be lost by absorption in the aluminum, although the majority will probably be scattered into the ionization chamber. However, an effect counterbalancing this occurs because some of the electrons striking the aluminum just outside the circumference of the window may be scattered into the ionization chamber. It is estimated that these counterbalancing errors are of the same order and that their difference is small enough to be neglected.

A possible source of error in measurements of this kind is the inclusion of electron-electron scattering along with nuclear scattering. To check the order of magnitude of this scattering experimentally, the net current to a foil through which the primary beam was passing was measured. An aluminum foil was used. The ratio of electron-electron scattering to nuclear scattering will be less for other foils since they are of higher atomic number. With a suitable arrangement of bias potentials to eliminate low energy secondary electrons, it was found that the total number of extra electrons emitted in all directions from the foil due to electron-electron impacts was of the order of a few percent. This in accordance with the theoretical expectations.[6] Since electron-electron scattering involves an energy loss, only a small fraction of such scattered electrons could penetrate the absorber and enter the ionization chamber. Thus, there is both theoretical and experimental evidence that the error due to electron-electron scattering was considerably less than 1 percent.

Another possible source of error is the inclusion of inelastic nuclear scattering along with the elastic nuclear scatterings. Since the general theory of x-ray production in this energy range appears to be in general agreement with experiment,[7] the theory was used to calculate the amount of expected inelastic nuclear scattering.[8] The effect appears to be negligible under the conditions of these experiments. Moreover, the use of the absorber, as mentioned above, afforded an additional experimental precaution.

The thickness of the foils was chosen so as to

[6] Möller, Ann. d. Physik **14**, 568 (1932).
[7] A. A. Petrauskas, L. C. Van Atta, and F. E. Myers, Phys. Rev. **63**, 389 (1943).
[8] N. F. Mott, Proc. Camb. Phil. Soc. **27**, 255 (1931).

satisfy Wentzel's criterion and thus minimize the effect of multiple scattering. As is well known, Wentzel's criterion is rough and a correction of the data for possible multiple scattering still has to be applied. The procedure followed here was suggested by Saunderson and Duffendack.[9] This makes use of the results of Chase and Cox[10] giving the plural scattering error at angle θ as

$$\langle\theta^2\rangle_{Av}[\csc^2(\theta/2)-\tfrac{1}{2}],$$

where the average is taken with respect to the actual scattering distribution. This average has been computed by Goudsmit and Saunderson,[11] thus making it possible to evaluate the effect of multiple scattering. It should be mentioned here that this procedure, based on a statistical approach, is not completely accurate for the plural scattering of importance in these experiments.

Possibility of such corrections for multiple scattering was considered for all points reported here. Many of the points required no correction, although in one instance the correction ran as high as 20 percent. In certain cases where the foils were sufficiently thin, the observed scattering was accurately proportional to thickness, thus affording direct experimental evidence of true single scattering.

COMPARISON OF THEORY AND EXPERIMENT

Comparison of the results, after correction, was made to the predictions of Mott[12] based on the Dirac theory of the electron. If f is the ratio of the scattered current to incident current, the theory predicts for small atomic numbers, high incident velocities, and small solid angle that

$$f=nt\Omega\left(\frac{Ze^2}{2mc^2}\right)^2\frac{1-\beta^2}{\beta^4}\times\csc^4\frac{\theta}{2}\left[1-\beta^2\sin^2\frac{\theta}{2}+\frac{Z\pi\beta}{137}\cos^2\frac{\theta}{2}\sin\frac{\theta}{2}\right],$$

where n = number of atoms per unit volume; t = thickness of foil; Ω = solid angle subtended at foil by ionization chamber; Z = atomic number; β = velocity of electron divided by velocity of light; and θ = angle of scattering. This formula is not correct for high Z, even at these voltages, as has been shown by the calculations of Bartlett and Watson[13] for gold. However, their results indicate that the deviation of the exact calculation from the Mott formula is small within the angular range of these experiments except for gold and platinum. We have, therefore, used the above formula for aluminum, copper, and silver, whereas we used Bartlett and Watson's result for gold and platinum.

In Fig. 3 we have plotted f_{theo} and f_{exp} as a function of the angle θ for 2-Mev electrons incident on aluminum. This indicates the range and the rapidity of variation with angle in that range over which measurements were taken. This method of comparison is, however, not a very sensitive one for showing variations from theoretical predictions. We have, therefore, computed the ratio $f_{\text{exp}}/f_{\text{theo}}$. These results are given in Table I and plotted in Figs. 4 and 5. In the latter, the abscissa is the distance of closest distance of

TABLE I. Ratios of the experimental results to the theoretical predictions. Only those points have been included for which observations were made on both sides of the beam and for which the multiple scattering correction did not exceed 20 percent.

Energy (Mev)	20°	30°	40°	50°
		Nucleus: aluminum		
1.49		1.01	0.97	1.04
1.81		1.02	0.96	0.97
2.00		0.95	0.97	1.02
2.27	1.11	1.26	1.52	1.64
		Nucleus: copper		
1.49		0.97	0.88	1.12
1.81		0.96	1.09	1.07
2.00		1.05	0.96	0.96
2.27		1.15	1.06	
		Nucleus: silver		
1.27			0.93	
1.49		0.97	1.03	1.02
1.81		0.97	1.02	1.03
2.00		1.01	1.06	1.07
		Nucleus: gold and platinum		
1.49				1.08
1.81				1.09
2.00			1.10	1.00

[9] J. L. Saunderson and O. S. Duffendack, Phys. Rev. **60**, 190 (1941).
[10] C. T. Chase and R. T. Cox, Phys. Rev. **58**, 243 (1940).
[11] S. Goudsmit and J. L. Saunderson, Phys. Rev. **57**, 24 (1940).
[12] N. F. Mott, Proc. Roy. Soc. London **A124**, 425 (1929); **135**, 429 (1931). See also P. Urban, Zeits. f. Physik **119**, 67 (1942). The correction given by Urban to the Mott formula is negligible in the angular and voltage range occurring in these measurements.
[13] J. H. Bartlett and R. E. Watson, Proc. Am. Acad. Art Sci. **74**, 53 (1940).

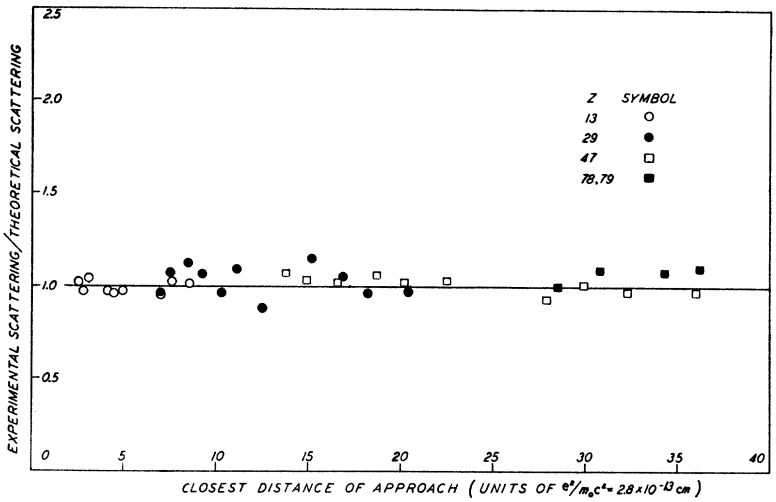

FIG. 4. Comparison of experimental results with theory (except for 2.27-Mev electrons on aluminum).

approach to the nucleus. The closest distance of approach is given by the formula

$$\frac{R}{(e^2/mc^2)}=Z\frac{\epsilon}{\epsilon^2-1}\left[\left\{\frac{1}{\epsilon^2}+A(\theta)\right\}^{\frac{1}{2}}-1\right],$$

$$A(\theta)=\cot^2\frac{\theta}{2}+2\beta^2\ln\sin\frac{\theta}{2}+\frac{2Z\pi\beta}{137}\left(\sin\frac{\theta}{2}+\csc\frac{\theta}{2}-2\right),$$

where ϵ is the total energy of the electron in units of its rest mass.

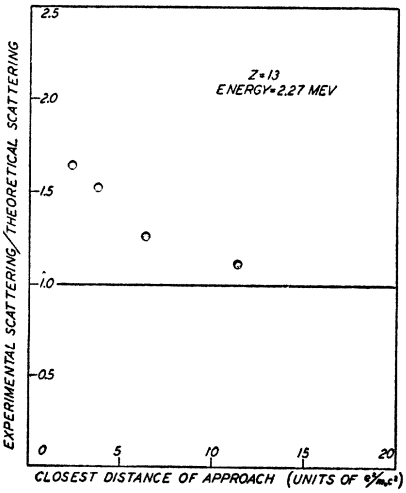

FIG. 5. Comparison of experimental results with theory for 2.27-Mev electrons on aluminum.

No undue importance should be attached to this choice of scattering parameter, especially since the distance of closest approach is much smaller than the wave-length and from the point of view of the uncertainty principle not very meaningful. However, it is a practical method in this angular and voltage range, for the comparison of different experiments involving different voltages, nuclei and scattering angles.

DISCUSSION

As can be seen in Figs. 4 and 5, the present results are in close agreement with the relativistic theory of electron scattering, as developed by Mott, over the entire range of the experimental variables except for the case of 2.27-Mev electrons on aluminum. Excepting only this case, the average of all the ratios of experimental result to theoretical prediction is 1.01 with a standard deviation of 0.06.

The points shown in Fig. 5, corresponding to 2.27-Mev electrons on aluminum, indicate a systematic departure from theory which increases with an increasing scattering angle. This group of points was taken under the same general experimental conditions as the points in Fig. 4. For example, copper points were taken at these angles and at the same voltage, and are in agreement with the Mott formula. Because the wave-length of the electrons is very much larger than the radius of the aluminum nucleus, these

points would require a radical departure of the force between electron and the aluminum nucleus from the Coulomb force. Moreover, it would have to be energy dependent and Z dependent in order to be consistent with the agreement of aluminum points at 2.00 Mev and copper points at 2.27 Mev with the Mott formula. Unfortunately, the data for aluminum at 2.27 Mev were among the last taken before research of this type was interrupted by the war. These measurements with aluminum will be repeated as soon as circumstances permit as they now indicate for the larger angles an interesting divergence from theory.

ACKNOWLEDGMENTS

It is a pleasure to thank Professor F. E. Myers, then on leave from New York University, for preliminary calculations of the Mott formula and Wentzel's criterion and also for his work on the design of the scattering chamber. We are particularly grateful to Mr. Anthony Sperduto for his many important contributions in carrying out the various experimental techniques involved in this work. Mr. Howard Rowland rendered valuable assistance particularly in making experimental observations. Mr. E. A. Burrill, Jr. helped in the computations and analysis of the experimental data. We wish to thank Professor C. F. Squire for his valuable help during the period in which the experimental observations were made. In connection with the construction of the apparatus used in these experiments, we acknowledge with pleasure the able help of Mr. E. W. Nickerson in charge of the shop of the High Voltage Laboratory.

We are glad to have this opportunity to express our great appreciation to the Research Corporation and to the Carnegie Corporation of New York for their generous grants made in support of this work.

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Isotope Separation by Thermal Diffusion: The Cylindrical Case

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All of the theoretical treatments of the thermal separation column published up to the present time have been restricted by the assumption that the column consists of two parallel plane walls, one hot and the other cold. Actually, nearly all of the separation columns used in practice consist of two concentric cylinders, the inner cylinder often being simply a hot wire. The theoretical treatment of the plane case which was given by Furry, Jones, and Onsager is here extended to include the cylindrical case. The extension is carried through in general, that is, for a gas whose physical properties are arbitrary functions of the temperature. It is found that the extended treatment is formally very similar to that already given for the plane case. The difficulty of the calculations is enormously increased, however, by the explicit appearance in the characteristic differential equation of the radius as a function of the temperature. The solution is here carried through in detail only for a perfect gas whose viscosity, thermal conductivity, and diffusivity have the same temperature dependences as those of a Maxwellian gas. Exact numerical solutions for a few cases have been obtained, but the computations were so tedious that it was found desirable to develop approximate methods of solution. Two different kinds of approximate solutions are given: a series solution useful when the ratio of radii is not larger than about four or five, and an asymptotic solution valid when the ratio of radii is large, as in the case of the hot-wire types of separation column.

THE theory of the functioning of the new apparatus[1] for isotope separation by thermal diffusion has been investigated by various writers.[2–7] The quantitative agreement between

* National Scholar, Harvard University, at the time this work was done. Now with Polaroid Corporation, Cambridge, Massachusetts.

† This paper was received for publication on the date indicated but was voluntarily withheld from publication until the end of the war.

[1] K. Clusius and G. Dickel, Naturwiss. **26**, 546 (L) (1938); Zeits. f. physik. Chemie **B44**, 397 (1939).

[2] L. Waldmann, Zeits. f. Physik **114**, 53 (1939).

[3] W. H. Furry, R. Clark Jones, and L. Onsager, Phys. Rev. **55**, 1083 (1939). This will be referred to as FJO.

[4] W. van der Grinten, Naturwiss. **27**, 317 (L) (1939).

[5] P. Debye, Ann. d. Physik **36**, 284 (1939).

[6] J. Bardeen, Phys. Rev. **57**, 35 (1940) (further considerations based on reference 3).

[7] For a general account of the subject, given mostly from

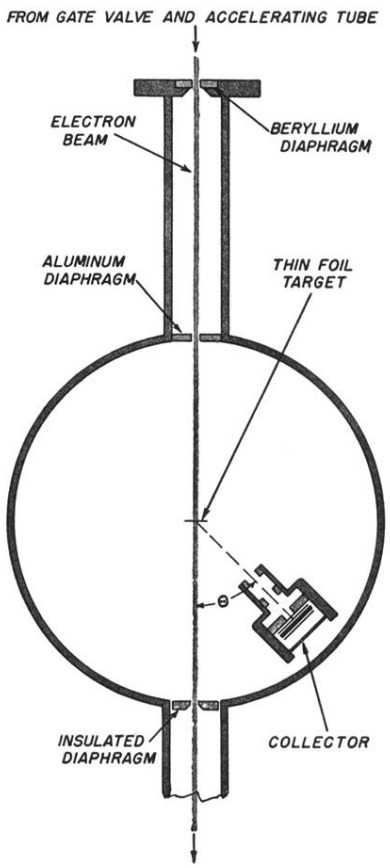

FIG. 1. Schematic diagram of scattering chamber.

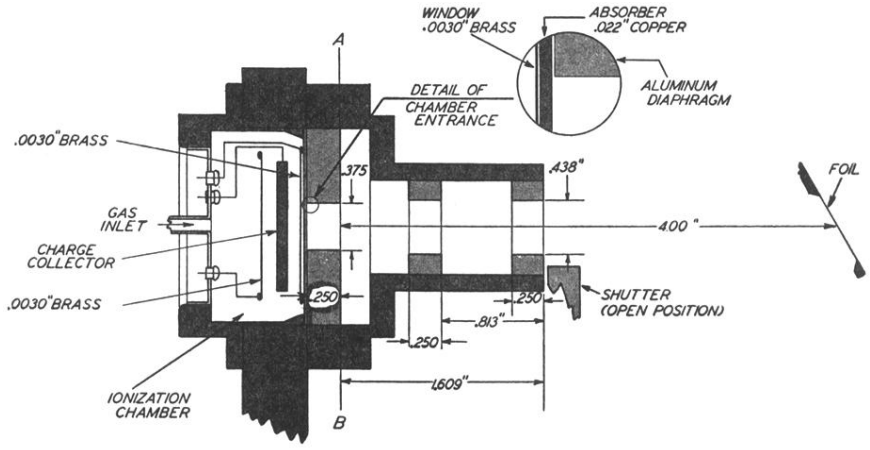

FIG. 2. Details of ionization chamber.