interpolation, the values of α for the e^{-x}/x and spherical well potentials were adjusted to give the same phase and therefore scattering cross section as the exponential interaction for 2.2 Mev neutrons. The phases for higher energies were then calculated for these values of α. Only the triplet phases were considered since the effect of the singlet state can be neglected[4] above $E_n=2$ Mev. According to the table the values of the phases for the spherical well and exponential potentials diverge slightly but run almost parallel for different values of E_n. However, the phases for the e^{-x}/x interaction first go below and then cross over to go above the phases of the other two potentials.

The observed[8] cross sections for the scattering of neutrons by protons are considerably smaller than those calculated with the usually accepted range of about 2×10^{-13} cm. Ranges as small as 0.5×10^{-13} cm would give agreement, but the experiments are at present too uncertain to draw conclusions.

[8] J. Chadwick, Proc. Roy. Soc. **A142**, 1 (1933). W. H. Zinn, S. Seely and V. W. Cohen, Bull. Am. Phys. Soc. **13**, 14 (1938). R. Ladenburg and M. H. Kanner, Phys. Rev. **51**, 1022 (1937). E. T. Booth and C. Hurst, Proc. Roy. Soc. **A161**, 248 (1937).

Conclusion

It appears that there is little possibility of distinguishing between this and other potentials even by means of scattering experiments over a large range of neutron energies. With the cross sections for the exponential and e^{-x}/x potentials adjusted to be approximately equal for 21.5 Mev neutrons, the total cross sections differ by only 6 percent for 2.2 Mev neutrons.

The ranges of force considered correspond to heavy electron masses ranging from about $700m_e(\alpha=0.5\times10^{-13}$ cm) to $150m_e(\alpha=2.4\times10^{-13}$ cm). Since it is generally accepted[4] that the range of the interaction in any case cannot be much larger than 2×10^{-13} cm, it appears that a lower limit to the mass of the heavy electron would be about 100 electron masses, on the assumption that this potential is the correct one.

The authors wish to thank Professor E. Teller for the suggestion of the problem and the interest taken in it.

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The Scattering of Fast Electrons in Gases *

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The angular distribution of elastically scattered electrons of energies between 49.5 and 87.7 Kev has been measured in argon, neon, and helium over the range 0.3° to 6°. Comparison of the results with the theoretical curves calculated from the Hartree functions with the "Born approximation" shows good agreement in the case of argon, and in neon except at the smallest angles, but there is no agreement at all in the case of helium. The discrepancies are very similar to those found at the smallest angles in studies of scattering of electrons of a few hundred volts energy, and it is felt that the explanation in terms of polarization of the atomic field by the passing electron may be accepted here also.

SINCE the pioneer work of Lenard[1] carried out more than forty years ago, various problems in connection with the passage of electrons through matter have attracted the attention of physicists down to the present time. The scattering of electrons (elastic and inelastic)

* The work here reported forms part of a dissertation presented to the faculty of Princeton University in candidacy for the degree of Doctor of Philosophy. The complete dissertation is on file in the Princeton University library. A preliminary report was given at the Washington meeting of the American Physical Society, 1937; Kuper, Phys. Rev. **51**, 1024A (1937).

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[1] Lenard, Wied. Ann. **51**, 225 (1894); **56**, 255 (1895).

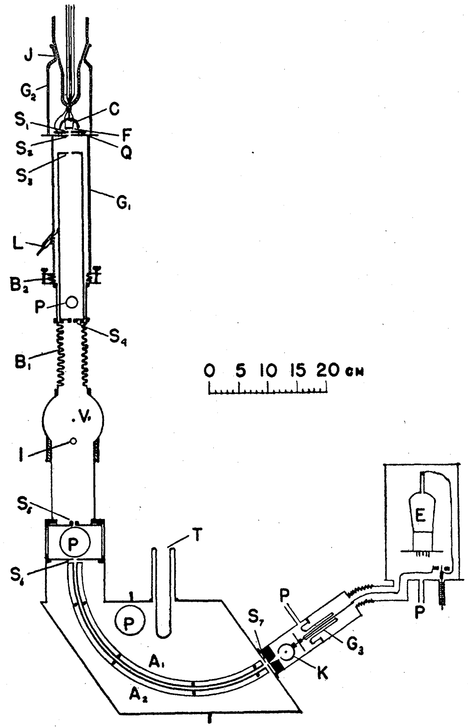

FIG. 1. Sketch of scattering apparatus.

in gases has been studied very thoroughly up to energies of the order of 2000 volts or so, but at higher energies (up to 100 Kev) interest has been concentrated instead on diffraction effects and on scattering in metal foils. While experimental difficulties (mostly attributable to the very small cross sections) prevented the completion of the full program originally planned it was found possible to study the elastic scattering in argon, neon, and helium over a small angular range. Comparison of the experimental results with the theoretical curves calculated with the aid of the "Born approximation" from the Hartree functions reveals agreements and discrepancies that are strikingly similar to those found at very small angles with electrons of a few hundred volts energy. Although various other possible explanations of the discrepancies must receive consideration, it seems likely that the effects are due to polarization of the atomic field by the passing electron[2] as in the low voltage experiments.

The apparatus was similar in general design to that used by S. N. Van Voorhis[3] but built on a larger scale and modified where necessary to permit the application of higher voltages. In this type of apparatus an electron "gun" furnishing a well-collimated beam of electrons of the desired energy is mounted so as to pivot about an axis in the center of a region in which the scattering is to take place. The gas under investigation is admitted to this region and differential pumping is employed. A pair of slits defines the scattered beam selected, which then passes through an electrostatic energy analyzer[4] before reaching the collector.

Electrons from the thin oxide-coated platinum ribbon filament F (see diagram, Fig. 1) are concentrated on the first slit, S_1, by the "reflector" electrode C, which is held about 25 volts negative with respect to the filament. The latter was about 160 volts negative with respect to S_1. The accelerating slit system, S_1 to S_3, was designed to act as an electron lens, producing an approximately parallel beam. All three slits were 0.5 mm wide, the first two being 7 mm long and the third 5 mm. A ring shaped insulator of quartz Q served to maintain a separation of about 3 mm for the first gap, and S_3 was 25 mm below S_2. S_3 and S_4 are mounted on the ends of a brass tube, 292 mm long, which is insulated from the rest of the apparatus. A compromise had to be made in the design of slits S_4 and S_5 in order to obtain sufficient pumping resistance and still have a reasonable beam with which to work. The dimensions finally chosen were: length, 5 mm; width, 0.1 mm; and depth, 5 mm, with the distance between them 343 mm. A pressure ratio of about 1000 could be maintained between the scattering volume and the analyzer. The entire electron gun could be rotated about an axis perpendicular to the plane of the drawing through the center of V. S_6, located 71 mm below S_5, was of the knife-edge type, 12.3 mm long and 0.2 mm wide. The deflecting plates for the energy analyzer A_1 and A_2 are arcs of circles of radii 20.4 and 20.9 cm, respectively, subtending an angle such that the electrons are

[2] Mott and Massey, *The Theory of Atomic Collisions*, (Oxford, 1933). Chap. IX; Chap. X, Sec. 10.

[3] S. N. Van Voorhis, Phys. Rev. **46**, 480 (1934).

[4] Hughes and Rojansky, Phys. Rev. **34**, 284 (1929).

swung through 127° as required for refocusing.[4] The exit slit S_7 was 0.5 mm wide and 12 mm long. Beyond it was another fixed slit 1 mm wide, covered by an aluminium foil 0.01 mm thick which shielded the collector from stray fields. The collector was mounted on a reentrant glass insulator G_3 which was carefully shielded to prevent building up of surface charges.

The electrical connections are indicated schematically in the diagram, Fig. 2. The high voltage was obtained from a Keleket transformer-rectifier outfit provided with an extra filter consisting of two, 50 kv, 0.25 mf Pyranol condensers charged through 0.1 megohm resistors. The divider made of one hundred 0.1 megohm, 50 watt, vitrified wire-wound radio resistors furnished the intermediate potential for the electron lens and potentials for the analyzer. Between 9 and 10 percent of the accelerating voltage was applied between S_1 and S_2. The system of condensers across the portion $n-p$ of the divider and from the midpoint of the high voltage apparatus to ground was necessary to bypass a small alternating current flowing from the main transformer through stray capacity to ground. Residual fluctuations in analyzer voltage limited the resolving power to 1 in 580, in contrast to a resolving power of 1 in 700 expected from the geometry.

The electrometer tube used was a Western Electric D-96475, operated in the modified Barth circuit as described by Penick.[5] Unusual care had to be taken with the shielding on account of the surges from the high voltage, and radiofrequency filters in the galvanometer and battery leads were indispensable. The sensitivity, which remained remarkably constant over a period of months, was 37,600 mm/volt.

Leads to the pumps were connected at the various points marked P, a separate pump being used for the analyzer. The gas under investigation was admitted to the apparatus at I after passing through an adjustable capillary leak and a liquid-air trap. The purity was checked spectroscopically, and on completion of the experiments the helium sample was analyzed with the mass spectrograph by Dr. L. G. Smith, who reported that no heavy impurity was present to as much as 1 part in 7000.

Under the conditions of focus and slit alignment finally chosen more than 90 percent of the electrons were concentrated into a beam less than 0.5° wide, but there was a rather large "wing" present on one side of the main beam.[6] Occasional check tests were made and as no difference in the net scattered currents on the two sides of the beam could be found all readings were taken on the clean side of the beam. Although the currents obtained at scattering angles as small as 0.6° were of the order of 10^{-4} times the direct beam or less the possibility of multiple scattering was carefully checked and excluded. Readings were taken with argon at various pressures, up to a limit considerably in excess of any ever used. Over a range greater than 5 to 1 the scattered current was very accurately proportional to the pressure.

Before taking any readings the apparatus was always thoroughly outgassed by operation at a voltage well above that to be used. The background current was measured over the range of angles to be studied then gas was admitted to the scattering chamber and readings were again taken at the same set of angles. In almost all cases the readings were taken by the rate of drift method (with 1 mm/sec. equal to 7.2 $\times 10^{-16}$ amp.). After the background had been subtracted and allowance made where needed for differences in pressure or filament emission

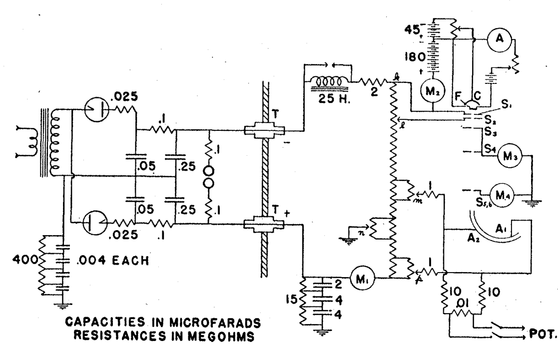

FIG. 2. Schematic diagram of electrical connections.

[5] Penick, Rev. Sci. Inst. 6, 115 (1935).

[6] It was possible to obtain a beam with the "wings" symmetrically arranged, but as the scattered currents to be measured were exceedingly small it was thought best to use the distorted beam and have a smaller background current to allow for.

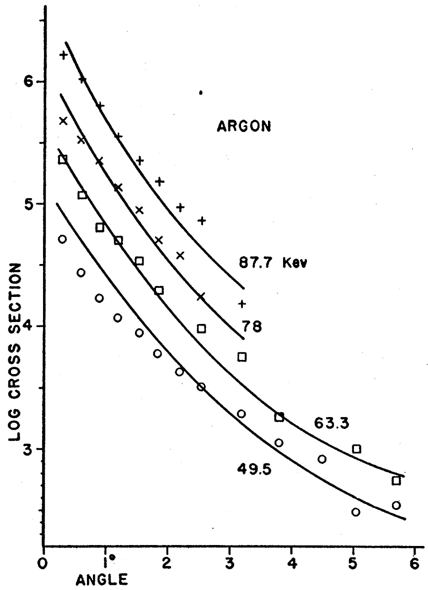

FIG. 3. Cross sections for scattering in argon for electron energies from 49.5 to 87.7 Kev. The ordinates are as shown for the 49.5 Kev curve. The curves for higher voltages are successively displaced upward through 0.5 units.

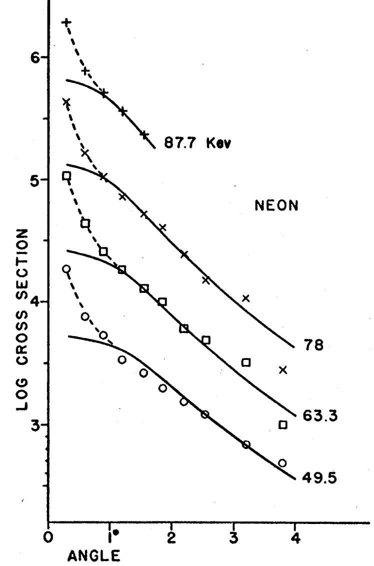

FIG. 4. Cross sections for scattering in neon, for electron energies from 49.5 to 87.7 Kev. The ordinates for the 49.5 Kev curve are as shown. The curves for higher voltages are successively displaced upward through 0.7 units.

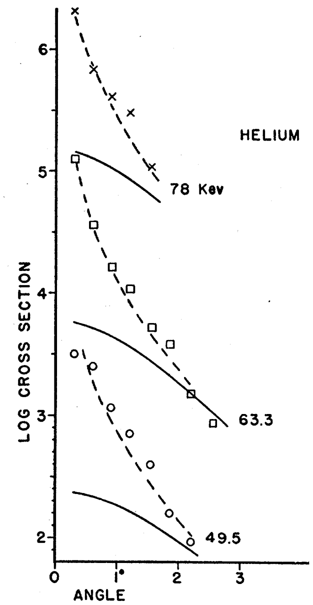

FIG. 5. Cross sections for scattering in helium, for electron energies from 49.5 to 78 Kev. The ordinates for the 49.5 Kev curve are as shown. The curves for higher voltages are successively displaced upward through 1.4 units.

the results of various runs were averaged. Different runs (made usually several days apart) always agreed with each other within the expected errors of the individual points, about 3 percent in the most favorable part of the angular range. A correction for the change in effective scattering volume with angle had to be applied. Although this type of apparatus is not suitable for determining absolute scattering cross sections, it is legitimate to assume that, provided the slits above and below the scattering chamber are parallel, the effective volume varies inversely as the sine of the angle of scattering. Accordingly the results were multiplied by a factor $1000 \sin\theta$, which gave numbers of a convenient size. Finally the points were fitted to the theoretical curves using an empirically determined multiplier. In the case of helium the experimental curves departed so widely from theory that it was necessary to use the average value of the multiplier found for argon and neon to locate the curves with respect to each other. Determination of this factor is practically equivalent to a measurement of the scattering volume, and confidence in the experimental results was increased by the fact that it remained nearly constant during the course of the work. Under standard conditions (pressure in scattering chamber 4×10^{-2} mm and current at 0° equivalent to a drift of 2×10^{6} mm/sec.) the average value of the multiplier was 21 to give numerical agreement with the cross sections given by Mott and Massey in units of 5.66×10^{-20} cm^2.

The results plotted on a logarithmic ordinate scale are shown in Figs. 3 to 5 where the solid lines are the theoretical curves. For clarity the curves have been separated from each other vertically and the order reversed. Actually, of course, the curves for the higher voltages should lie slightly below the low voltage ones. The curves for argon were successively displaced by 0.5 units on the logarithmic ordinate scale, for neon 0.7, and for helium 1.4 units. The scale is correct in each case for the 49.5 Kev curve. The theoretical curves were obtained by graphical interpolation from the tables of cross sections published by Mott and Massey.[7] It is interesting to note that the measurements in argon at lower voltages, although extending over less than 6 degrees, cover a range greater than that tabulated; the curves of Mott and Massey were extrapolated a small amount at each end.

It is difficult to make a reliable estimate of the probable errors in this work, especially as they varied so much along a single curve. The uncertainties in the pressure measurements could hardly exceed 4 or 5 percent, and in any case would only affect the constancy of the empirical multiplier mentioned above. At the smallest angles the possible error of about 0.05° in the angle could account for an error of 16 percent, but this would of course diminish on going to larger angles. Because of unsteadiness in the high voltage and other factors affecting the grid current of the electrometer tube an uncertainty in the natural rate of drift of 0.3 mm/sec. was not impossible, and as the curves were often followed down to currents that small the points at the largest angles cannot be trusted very much.

In general it may be said that as long as the theoretical curves are concave upward (as in argon or in neon except at the smallest angles) reasonably good agreement is found, but as soon as the theory predicts a bending over of the curve towards the axis (as it must in all cases if followed to small enough angles) the agreement disappears. The results for helium bear a strong resemblance to those for neon at small angles, but unfortunately it was impossible to follow them further to see if the curves would merge. Numerous attempts to obtain curves for hydrogen were all unsuccessful, but it was observed that the variation of cross section with angle was even more rapid than in helium, so the agreement with theory would have been poorer. The discrepancy found in this work seems to be exactly the same as that observed in helium at small angles with medium energy electrons.[8] It must be conceded that because of the limited resolving power of the energy analyzer some inelastically scattered electrons could have been recorded, and that they would tend to give rise to an excess of scattering at very small angles, but it is hard to understand why they would not be at least as abundant in argon as in the other gases, if not more so. It seems best to accept tentatively the qualitative explanation in terms of the polarization of the atomic field as applicable here also.[9]

In conclusion the author wishes to express his great appreciation to his colleagues and the staff of the Palmer Physical Laboratory for many helpful discussions and for technical assistance. In particular it is a pleasure to thank Professor G. P. Harnwell, who originally suggested the problem, for his continued interest and support.

[7] Reference 2, p. 124, for argon and neon, p. 120, for helium. I have corrected four obvious errors in the second column of this table, and also expressed the cross sections in the same units.

[8] Reference 2, p. 122.

[9] An attempt was made to apply the calculations of Massey and Mohr (Proc. Roy. Soc. **A146**, 880 (1934)) to the curves for helium although their results are not given in a convenient form for this purpose. They predict a departure from the Born approximation curves at angles smaller than about 2.2° as observed, but the experimental increase of scattering at smaller angles appears to be much more rapid than expected; in the neighborhood of 0.6° the scattering is about six times the Born approximation value instead of twice.