NUCLEAR SCATTERING

OF

HIGH VELOCITY ELECTRONS

Thesis

by

Henry Victor Neher

In Partial Fulfillment of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

California Institute of Technology

Pasadena, California

1931

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ABSTRACT OF RESULTS

The results reported in this thesis may be summarized as follows:

1. Nuclear scattering by thin foils has been extended from 80,000 to 145,000 volts.
2. A more critical criterion for single scattering by thin foils is obtained which depends on the shape of the curve connecting ρ, the amount of scattering, with the angle.
3. Secondary electrons are eliminated by applying high equivalent stopping potentials.
4. Dependence of scattering on energy of primary beam is found to agree well with either Mott's equation or with the relation k/V^2, but is at variance with the classical relativistic theory.
5. Comparison of values of scattering for Al, Ag and Au shows that ρ increases faster than Z^2.
6. Scattering is obtained as a function of angle from 95° to 173°. For Al the dependence found experimentally agrees well with either Mott's or Rutherford's equation. The latter also gives the correct dependence on angle for Ag and Au. Mott's equation is not applicable for those heavy elements.
7. Experimental absolute values for scattering for Al compared with theory give $\rho = 1.32$ of the value given by Mott's equation. This relation is valid within the ranges $\theta = 95^\circ - 173^\circ$, $V = 56-145$ Kv.
8. Secondary electrons coming from the foil are distributed according to the simple cosine law.
9. No evidence of loss of energy due to radiation is found.

STATEMENT OF PROBLEM

The scattering of swiftly moving charged particles by matter was first investigated quantitatively by Rutherford[1] and his associates, using α-particles from radioactive substances. These investigations led Rutherford to hypothesize an atomic model which consisted of a very small positively charged nucleus surrounded by negatively charged particles known as electrons, whose mass was small compared with that of the nucleus. An electron should be scattered in much the same manner by this nucleus. A point of difference arises, however, for while the mass of the electron in the atom is negligible compared with the mass of the α-particle, this is not true when electrons themselves are used as the bombarding particles. The phenomenon is thus complicated by another element which has been difficult to separate from true nuclear scattering. A second point of difference between the scattering of α-particles and of electrons is the much greater velocities obtainable with the latter. While the fastest α-particles may attain a velocity of .07 the velocity of light, electrons from radioactive substances may reach .99 the velocity of light. Even artifically, under controlled conditions, electrons with .65c (c is the velocity of light) can be produced easily. Such high velocities should make possible a means of obtaining information as to the effect of relativity change of mass on scattering of electrons. A third point of difference arises from the fact that α-particles are very inefficient in producing X-rays, while the production of the ordinary continuous X-ray spectrum has its origin in the scattering of electrons.

These three points of difference between the scattering of fast electrons and of α-particles are such as to complicate both experimentally and theoretically the study of pure nuclear scattering of high velocity electrons. The major purpose of this section of the thesis is to determine to what extent these three factors listed above affect the experimental values of scattering.

SECONDARY ELECTRONS

Effects Due to Secondary Electrons. This problem was the first encountered after the apparatus had been assembled and was working properly. It was found that if stopping potentials were applied to the electrons coming from a piece of metal foil which was being bombarded with primary electrons of high velocity, these electrons had a distribution of velocities. (See Figs. 12(a) and 12(b)). A large number of electrons so emitted have energies below 100 volts, but an appreciable number compared with the electrons collected which had been scattered elastically had higher energies. Stopping potentials up to -2000 volts could be applied directly to these electrons, and by a special means, equivalent stopping potentials up to -55,000 volts could be applied.

With primary energies up to 145 KV, appreciable electrons were still present of the highest stopping potential used.

<u>Origin of Secondary Electrons</u>. Secondary electrons have been defined by other investigators in various ways. Becher[2] and Stehberger[3], working at energies below 12,000 volts defined as secondary electrons all those with energies below 36 volts. Wagner[4] defined all electrons coming from the material bombarded as secondary. In this paper we shall adopt a different definition based upon the process of collision of two electrons. It is well known that as a purely mechanical process, when two electrons collide, one of them being initially at rest, they part at an angle of 90° to one another. When the path of each makes an angle of 45° with the direction of motion of the incident electron before collision, each will leave with one-half the energy of that electron. We shall distinguish them after collision by defining the one with the greater energy as the primary and the one with the lesser energy as the secondary.

In a foil which is being bombarded by electrons, if it were built up completely of free nuclei, we should have a certain angular distribution of electrons scattered by the nuclei. The whole foil from A to B, (See Fig. 1) acts as a new source of electrons. In an actual foil we have not only nuclei present but also Z electrons with

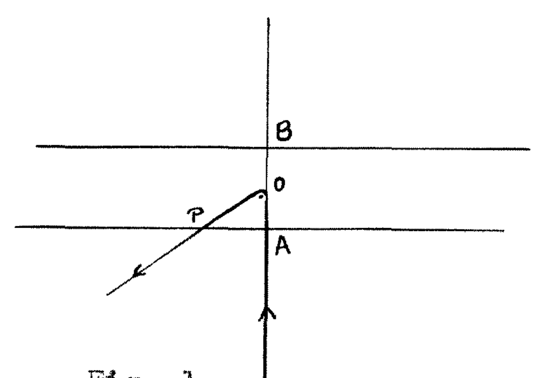


Fig. 1

every nucleus of atomic number Z. Consequently a scattered electron going along the path OP will scatter others as long as it remains within the foil. Since the binding energies of the electrons in the atoms in the foil are small compared with the energy of the scattered primary, the former may be considered free to a first approximation. Many secondaries so formed will be absorbed before emerging from the foil, but there will be many others, especially those formed near the surface, that will emerge. These will be collected with the electrons scattered by the nuclei alone.

It will also be apparent from the above considerations that for a sufficiently thin foil, many secondary electrons formed in the center of the foil will have sufficient energy to emerge. Consequently we may expect secondary electrons to be present all the way from zero volts energy up to one-half the energy of the primary beam. If then we apply stopping potentials up to one-half the energy of the initial beam, we may be assured that all secondaries are stopped and that the remaining electrons are those which have been scattered by nuclei alone. One remaining effect must be considered before the method given above is justified. This is the question as to whether or not the electron emerging has suffered more than one major collision. Assuming that it had made two major collisions, sharing one-third its energy each time with the other electron, all three electrons would then fail to go through the applied stopping potential and we would be stopping too many. The condition for single nuclear scattering will be given below. If this criterion is carried over in a slightly modified form for the case of electrons, it appears that if single scattering is the predominating factor for the nuclei in the foil, it will also be the major factor for the electrons in the foil.

RADIATION EFFECTS

When an electron is accelerated energy is lost due to radiation. The continuous X-ray spectrum is due to the hyperbolic orbits of the electron around the nuclei of the atoms composing the X-ray target. Some electrons will lose all their energy through radiation and these will give the short wave length limit or the maximum frequency of the radiation emitted according to the relation of Duane and Hunt,

$$Ve = h\nu_{max}.$$

The electrons that are accelerated most are the ones that will lose the greatest amount of energy and these are the electrons that are deflected through the largest angles. Hence it seems reasonable to assume that those electrons emerging from the foil at angles close to 180° are those which have lost the greatest amount of energy and some will have lost all their energy. It is known that the efficiency of X-ray production is very small, and decreases with the atomic number, but it is also true that very few electrons are deflected through these large angles. Kramers[5] has computed the amount of energy lost by an electron deflected through an angle θ upon the assumption that the orbit is not appreciably distrubed. He finds the expression,

$$R = \frac{4}{3}(\tfrac{1}{2}mv^2)\frac{\beta^3}{Z}\tan^5\frac{\theta}{2}\left[(\pi + \theta)(1 + \tfrac{1}{2}\csc^2\frac{\theta}{2}) + 3\cot\frac{\theta}{2}\right] .$$

For a 50,000 volt electron deflected through 90° by an aluminum nucleus, the relative amount of energy lost is 10% according to the above relation. The factor $\tan^5\theta/2$ in the coefficient increases very rapidly beyond 90° and the equation breaks down for the orbit no longer can be considered as Keplerian. It is interesting to note that R varies inversely as the atomic number which means that there is a greater percentage loss of energy due to radiation for the lighter elements. In the case of hydrogen we could not consider an electron of 50,000 volts energy when deflected through 90° as following anything like a hyperbolic orbit.

There are two theoretical problems which have not been solved up to the present time and which would hold great interest in the field of X-rays as well as in the field of scattering of electrons. The first is a general expression for the radiation from an electron deflected through large angles. The second is an expression for the scattering of electrons with the effect of radiation included. We may, however, draw some general conclusions as to the effect of radiation upon the angular distribution of electrons. If the loss of energy alone is considered as disturbing the path, a decrease in velocity will result in the electron being drawn closer to the nucleus. This will cause the electron to be bent through a larger angle than it otherwise would have been. Analytically the problem may be stated as follows. The rate of losing energy due to radiation is given classically by Lamor's equation,

$$\frac{dR}{dt} = \frac{2}{3}\frac{e^2}{c^3} j^2 ,$$

where j is the acceleration of the electron of charge e. If Ve is the original energy of the electron, then from the conservation of energy,

$$Ve = \tfrac{1}{2}m(\dot{r}^2 + r^2\dot{\theta}^2) - \frac{e^2 Z}{r} + \int \frac{2}{3}\frac{e^2}{c^3} j^2 \, dt$$

Before we can get the equation of motion, the momentum relations must be known. Since the direction of ejection of the momentum $h\nu/c$ is not known, and neither is it known whether or not the whole energy lost is given off as one quantum $h\nu_{max}$, in several steps or a combination of the two processes, the problem even classically seems quite hopeless at the present time. Further experimental work is needed to make possible certain assumptions necessary for its solution.

Experimental evidence for the effect of radiation will be considered later. Suffice it to say here that no conclusive evidence for an appreciable number of electrons having lost more than one-half their total energy for large angles has been found.

THEORIES OF NUCLEAR SCATTERING

The Rutherford equation for the probability of an α-particle being scattered within the solid angle $d\omega$,

$$d\rho = \frac{ntZ^2e^4}{4m^2v^4}\operatorname{cosec}^4\frac{\theta}{2}\cdot d\omega \qquad (1)$$

does not include a relativity correction and would not seem to be applicable in the case of high velocity electrons where β is large.

Darwin[6] has worked out the orbit of a high velocity electron in the field of a heavy positive nucleus, taking into account change of mass as the electron passes the nucleus. He arrives at the result that if the electron comes within a certain critical distance p_o, it will s piral in and be absorbed by the nucleus. This of course can have no physical meaning since no such transmutation of the elements is observed. Using Darwin's result, Crowther and Schonland[7] deduced the angular distribution of the electrons scattered by nuclei, neglecting those which spiraled into the nucleus. The value for the scattering between 90° and 160° for Al, Cu and Ag found experimentally by Schonland[8] agreed well with that deduced from Darwin's orbits. Later Schonland[9] showed that these spiraling electrons could not be neglected in his case and in order to get a solution to the problem he assumed that they emerged uniformly in all directions. This gave a result at variance with his experimental work.

The equation of Crowther and Schonland, both in the original and in the latter form given by Schonland, gives a dependence on β and θ as well as an absolute magnitude not found in work reported on in this thesis. There is also some confusion as to the form of the correction to be applied.[10,11,12] In addition, from considerations of wave mechanics, it appears quite clear that we can no longer consider the electron as a point when the distances of approach become of the order of $\frac{h}{mv}$, the wave length to be associated with the electron. This fact probably accounts for the spiraling orbits of Darwin. Comparison of Darwin's relativistic scattering equation with experiment is given in Table V1. It will be noticed that the relative as well as the absolute magnitudes do not agree over a wide range of energies. Consquently we shall not consider this theory further.

Perhaps the best treatment of the problem has been given by Mott[13] who uses Dirac's wave equation and includes corrections for both relativity and spin. The result arrived at may be expressed as,

$$d\rho = \frac{ntZ^2e^4}{4m^2\beta^4c^4}(1 - \beta^2)\Big[\mathrm{cosec}^4 \frac{\theta}{2} - \beta^2 \mathrm{cosec}^2 \frac{\theta}{2} + \frac{2\pi\beta Z}{137} \frac{\sin^3 \theta/2}{\cos^2 \theta/2} + \text{terms in } (\frac{Z}{137})^2\Big] d\omega$$

For the angles θ_1 and θ_2 this becomes,

$$\rho = \frac{\pi n t Z^2 e^4}{m^2 c^4} \frac{(1-\beta^2)}{\beta^4} \left[\cot^2 \frac{\theta_1}{2} - \cot^2 \frac{\theta_2}{2} - 2\beta^2 \log \frac{\sin\theta_1/2}{\sin\theta_2/2} + \frac{2\pi\beta Z}{137}\left(\sin\frac{\theta_1}{2} + \operatorname{cosec}\frac{\theta_1}{2} - \sin\frac{\theta_2}{2} - \operatorname{cosec}\frac{\theta_2}{2}\right) + \cdots \right]$$

Relativity correction contributes the term $(1-\beta^2)$ in the coefficient and spin correction is responsible for the last two expressions in the braces. The quantity ρ in all these equations gives the ratio of the number of electrons scattered between the angles θ_1 and θ_2 to the total number of electrons incident on the scatterer. The product nt is the number of electrons per square centimeter of the foil. All the quantities in the above equations can be determined experimentally and an absolute comparison with theory can be made, as well as relative comparisons with the other variables.

CRITERION FOR SINGLE SCATTERING

All scattering equations given above are based on the assumption that single scattering is the predominating factor present. It becomes of interest to note under what conditions we may expect this condition to exist. Suppose we have a foil of area A which is being bombarded with a beam of electrons. The probability of an electron going within a distance p of the nucleus is then,

$$\frac{\pi p^2 N t}{A}$$

where N is the total number of atoms present in the areaA and t is the thickness of the foil. Since the probabilities must be independent, none of the areas πp^2 must overlap or the following condition at least must be satisfied:

$$\pi p^2 nt \leqq 1$$

where n is the number of atoms per cm.[3] From the geometry of the hyperbola,

$$p = \frac{e^2 Z}{2Ve} \cot \frac{\theta}{2} ,$$

so that,

$$\frac{\pi nt Z^2 e^4}{4V^2 e^2} \cdot \cot^2 \frac{\theta}{2} \leqq 1$$

or,

$$\theta \geqq 2 \cot^{-1} \frac{2V}{Ze} \sqrt{\frac{1}{\pi nt}} \quad .$$

The above consideration shows why all scattering equations become infinite for $\theta = 0^\circ$, simply because the assumption of the independence of the probabilities is violated at small angles.

Wentzel[14] has shown that a much more stringent condition must be imposed for single scattering to be the predominating factor, namely that

$$\theta \geqq 32 \cot^{-1} \frac{2V}{Ze} \sqrt{\frac{2}{\pi nt}} \quad .$$

The form in which this criterion is usually stated is as follows.[8] If

$$4\omega_{min} = 8 \cot^{-1} \frac{2V}{Ze} \sqrt{\frac{2}{\pi nt}} \quad ,$$

then for single scattering,

$$\frac{\theta}{4\omega_{min}} \geqq 3 \text{ or } 4 \quad .$$

This criterion can be tested experimentally, for within the region in which it is satisfied, ρ should vary linearly with the product nt. It will be shown later that $\theta/4\omega_{min}$ increases with the energy of the primary electron and at 145,000 volts $\theta/4\omega_{min} \doteq 6$ or 7 for single scattering to be the predominating factor.

DESCRIPTION OF APPARATUS

General. The apparatus was originally built under the direction of Professor Watson in the shops of this Institute. Its design was similar to that used by Schonland[8,15] for studying the same problem as reported on in this thesis. The apparatus consisted of an electron "gun" mounted in a horizontal position and so arranged that the stream of electrons generated by the cold cathode discharge were sent into a magnetic field. Here they were bent through 90° and emerged through three circular openings three m.m. in diameter and separated by several centimeters. The homogeneous, collimated beam then entered two chambers insulated from each other and from the rest of the apparatus. The electrons scattered in the forward direction were collected by the upper chamber, and those scattered from 90° back to the opening through which the primary beam emerged, were collected in the lower chamber.

It was soon discovered that for obtaining steadier conditions a hot filament for the source of electrons was needed. It was also apparent that the small, adapted Shearer X-ray tube was not suitable for voltages above 80,000. Consquently, a new tube was designed which permitted steady operating conditions up to 145,000 volts. After a considerable amount of data had been taken it was found advisable to re-design the chambers in which the scattered electrons were collected. A general view of the apparatus in its finished form is shown in Fig. 2.

The Electron "Gun". The tube is shown in detail in Fig. 3. The metal parts were constructed in the shops of this Institute and were all turned from copper. This metal was chosen as more suitable for the purpose than other metals. Brass continuously gives off zinc vapor and a high vacuum was necessary. Iron and nickel are magnetic and special precuations had to be taken to avoid all magnetic substances in the vicinity of the solenoid. In designing the parts of the tube it was necessary to consider the effects of cold emission and gas discharge, and to protect the glass tube as much as possible. The shield fastened to the anode and extending back around the tube in which the filament is located was designed to protect the glass, while the shield at the other end of the tube was designed to distribute the electric field. This latter could perhaps be eliminated without impairing the working of the tube. To further eliminate the possibility of cold emission and to maintain a cleaner and harder surface, all the metal parts were polished, given two coatings of nickel, then plated with chromium, and finally given a very high polish. All joints were soldered with silver where practical. With all others soft solder was used. In the case of a metal glass joint, the glass was sealed to the metal. This eliminated all waxes or greases and made possible the attaining of a very high vacuum in a

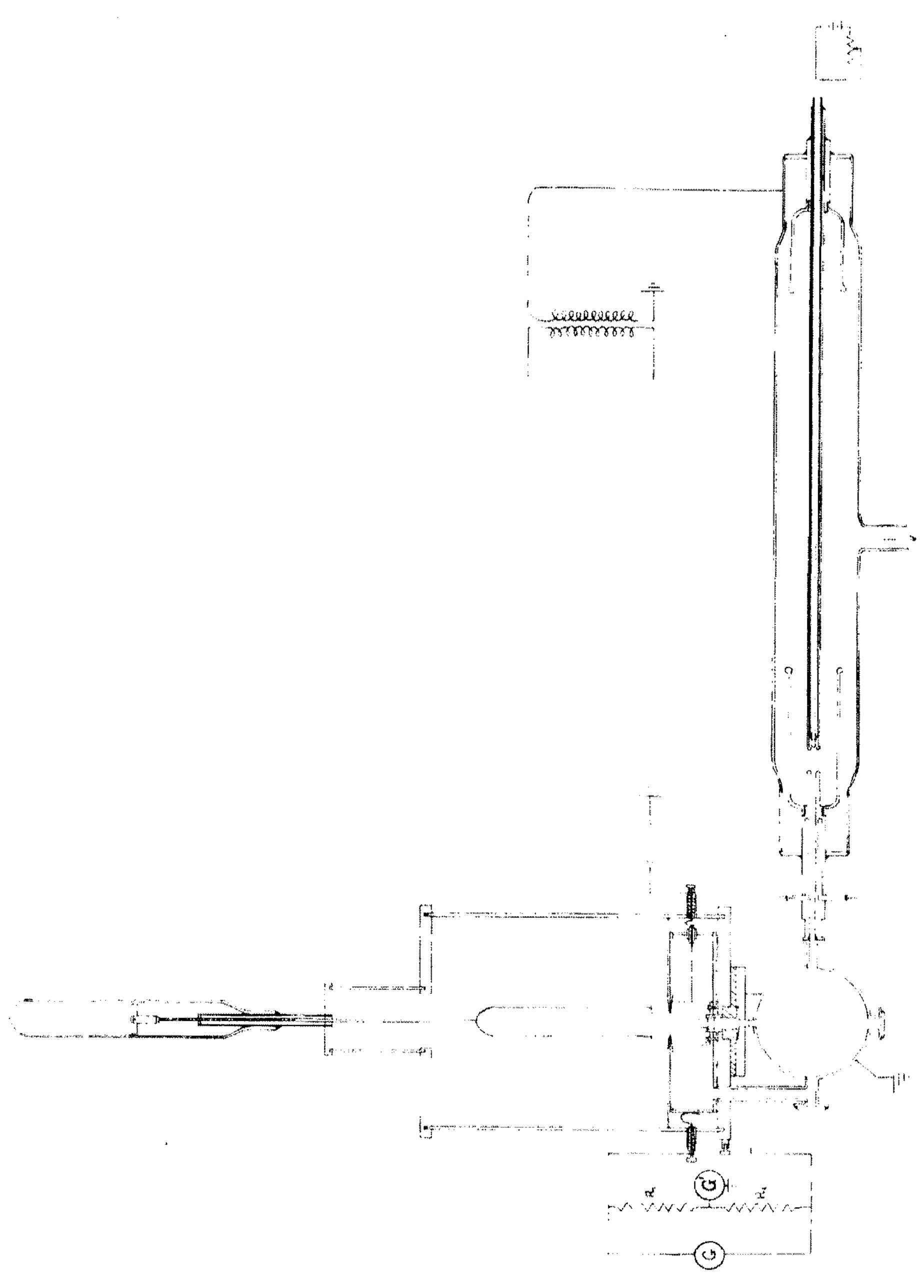


Fig. 2

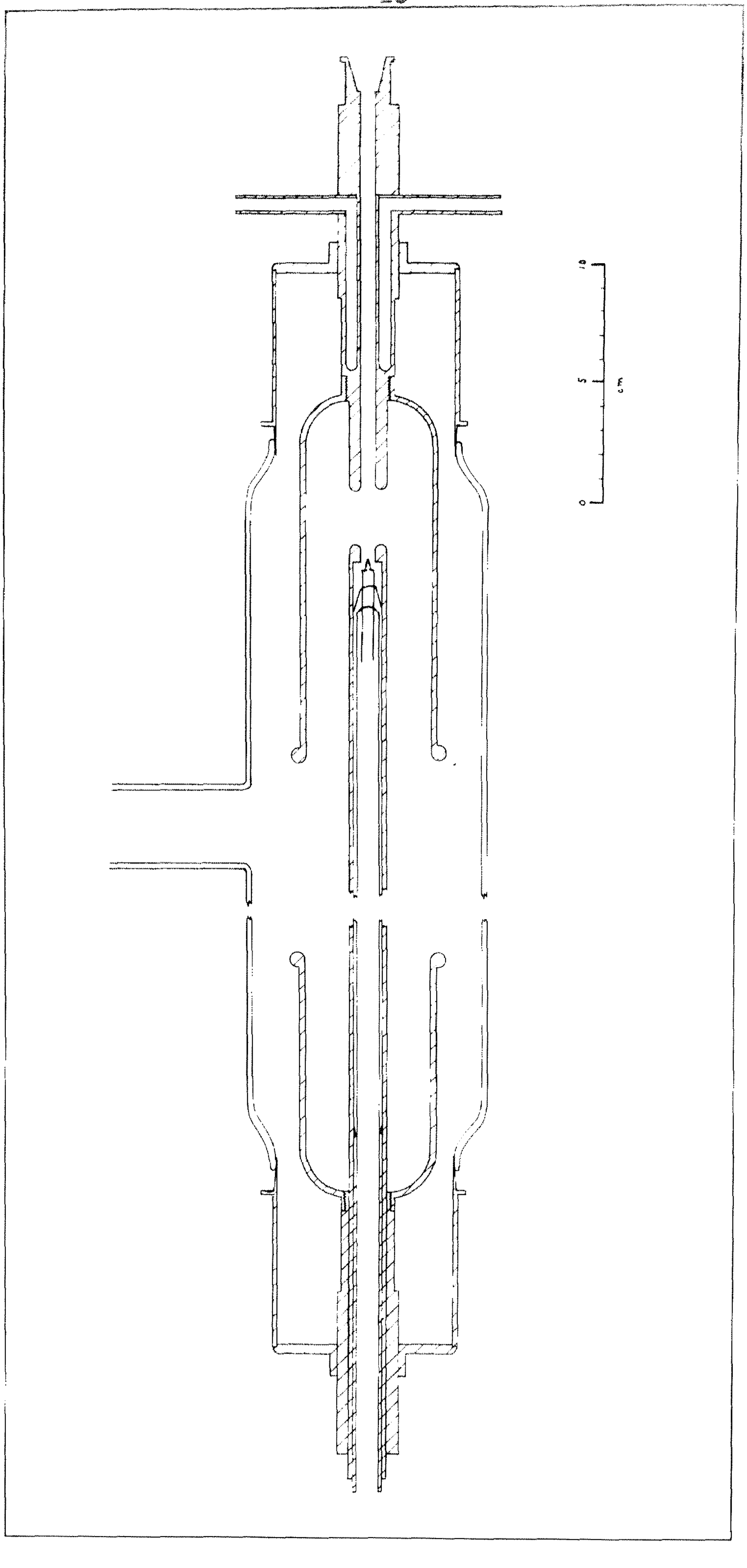


Fig. 3

short time. This was an important point. Although the volume of the apparatus was approximately 28 liters, one and one-half hours was sufficient time to take the pressure from one atmosphere to 10^{-5} m.m.

When the tube was first put into operation four or five days elapsed before the highest voltages could be applied. Although the pressure as measured with the Mc Leod guage was slightly less than 10^{-5} m.m. of Hg., as soon as high voltage was applied ionization would take place and the pressure would go up to $1\text{-}4 \times 10^{-4}$ m.m. As the tube was connected at all times to a two stage mercury pump, the pressure soon went down again when the voltage was removed. Each time this process was repeated ionization took place at a higher potential than before, until the desired 150,000 volts could be applied without noticeable gas discharge. Very little gas was collected by the walls of the tube if the apparatus was opened for fifteen minutes or less. If it stood at atmospheric pressure for several hours, some time was necessary to out-gas the tube again.

The filament used was that from a 32 c.p. automobile headlight lamp. The bulb was removed and the glass stem sealed to a tube made of similar glass, which in turn ended in a copper glass seal. This type of filament was found to give a more intense beam finally emerging into the scattering chambers, than that given by a number of other designs constructed. The position of the filament in relation to the end of the metal tube in which it was situated had to be adjusted very accurately to secure a maximum of current. It was also found, upon the suggestion of Professor Smythe, that a resistance of several hundred thousand ohms, placed between the filament and the metal tube surrounding it, increased the focusing action of the electric field between the cathode and anode and very materially strengthened the current received into the scattering chambers for a given total emission.

The Solenoid. This consisted of a brass cylinder 13 cm. in diameter and 50 cm. long wound with two layers of #14 B&S guage copper wire. A section 10 cm. long in the middle of the cylinder was partitioned from the remaining and could be evacuated with the rest of the apparatus. Each end of the solenoid was water cooled. Special precuations were taken to eliminate all magnetic substances in the neighborhood of the solenoid since the maximum field was only 250 gauss.

As the solenoid was used not only as a means of obtaining a homogeneous beam, but also for measuring the voltage of the electrons, it was necessary to know its constant. For an electron bent in a magnetic field,

$$(H\rho) = \frac{m_o v}{e\sqrt{1 - \beta^2}} \quad .$$

The energy of the electron is,

$$Ve = m_o c^2 \left(\frac{1}{\sqrt{1 - \beta^2}} - 1 \right)$$

Eliminating β between these two equations,

$$(H\rho) = \frac{1}{c}\sqrt{\frac{2m_o c^2}{e}\left(V + \frac{e}{2m_o c^2} V^2\right)}$$

At low voltages,

$$(H\rho)^2 = kI^2 = k'V \ .$$

The relation between high and low voltages can then be written in terms of the respective currents as,

$$I^2 = \frac{1}{K}(V + .982\text{x}10^{-6}\ V^2)$$

where $K = V/I^2$ for low voltages. V has been expressed in volts, I in amperes and the values of the constants inserted. The quantity K will be defined as the constant of the solenoid.

The solenoid was first calibrated by using known D.C. potentials from a motor generator set by applying the potential to the electron tube and adjusting for maximum current into the scattering chambers. Values of K obtained in this manner are given in the following table.

TABLE I

V	V(cor)	I	I(cor)	K
1375	1381	1.330	1.336	771
1059	1062	1.163	1.167	780
1626	1632	1.444	1.450	776
1060	1063	1.166	1.169	778
1698	1704	1.482	1.488	770
1482	1488	1.390	1.396	767
			av.	774

The axis of the solenoid was mounted in an east-west direction to reduce the effect of the earth's magnetic field to a minimum. A component of the earth's field amounting to .4% of the field of the solenoid when I = 1.5 amp. increases the above constant to 784 volt amp^{-2}.

It was suspected that this constant was not the same for high voltages as for lower. In consquence, the following tests were made. A 12.5 cm. sphere gap construct-according to A.I.E.E. specifications, kihdly loanod by tho Southern California Edison Co., was used. To insure that one-half of the alternating current wave was not distorted, only 1/10 milliampere of current was drawn from the secondary of the transformer. As the resistance of the secondary was 13,000 ohms at 25° C. this amount of current caused an inappreciable dissymmetry between the two halves of the wave. Data for the gap were taken from Peek's recent book, "Dielectric Phenomena in High Voltage Engineering" (1930) (General Electric Co.) Corrections were made for atmospheric pressure and temperature. Humidity has little effect on the calibration of the gap. The following values of K from Eq. (3) were obtained:

TABLE II

Radius of Spheres	6.25 cm.
Barometric Pressure	73.62 cm.
Temperature	24.0° C

I	d(cm)	V	K
8.92 amp.	2.00	56.1 K.V.	742
10.82	3.00	80.8	747
12.46	4.00	103.0	732
13.62	5.00	122.1	737
14.61	6.00	139.8	743
		av.	740

Individual readings of the gap can be trusted to 2% while the constant obtained above should be correct to within ½%.

It seemed best to obtain another check on the constant of the solenoid since the value obtained with the sphere gap was 5% lower than that obtained at lower voltages. The following method was used next. Two similar plates of aluminum 5 m.m. thick, 30 cm. long and 23 cm. wide were mounted as a condenser inside the scattering chamber. (See Fig. 4) The mean distance between the plates was adjusted to 3.00 ± .02 cm. and the plates were flat to .01 cm. The beam of electrons after emerging from the solenoid passed through four collimating openings 2.5 m.m. in diameter, the distance between the first and last being 4.5 cm. It then passed through two slits approximately .005 cm. wide, separated by 3.3 cm., and finally emerged at a point midway between and parallel to the condenser plates, and 3 cm. in front of the lower edge. (See Fig. 4) A photographic plate was mounted between the plates and down 2.5 cm. from the top to eliminate edge effect.

There existed a disturbance of the field caused by the stem holding the slits through which the electrons emerged. To correct for this effect, stems of different diameters of the same length were constructed. If all other factors are held constant , one can extrapolate to zero diameter and hence for zero disturbance of the field. It might be mentioned here that the applied D.C. potential was grounded in the middle so that the potential midway between the plates was zero. The stem was also grounded.

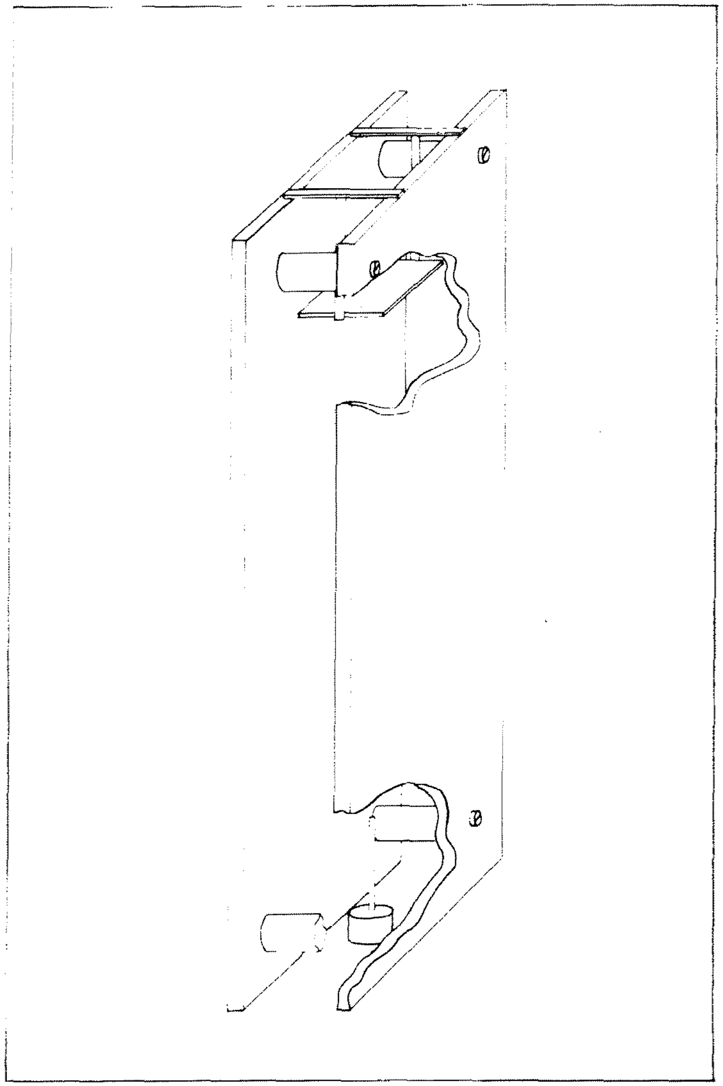


Fig. 4

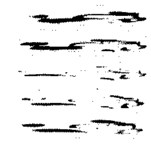


Fig. 6

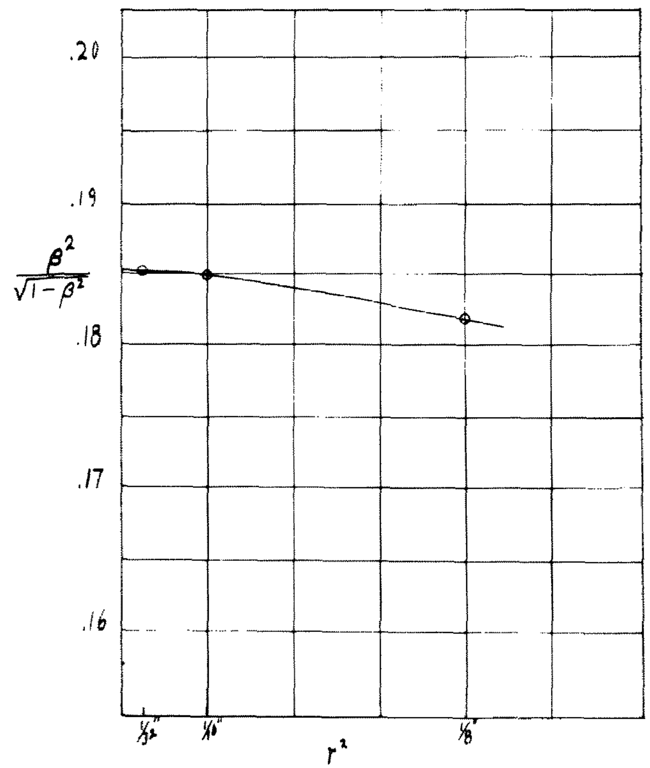


Fig. 5

The deflection of the beam can be computed easily. For a uniform field,

$$\frac{m_o}{\sqrt{1-\beta^2}} \frac{d^2x}{dt^2} = Ee$$

and,

$$\frac{dy}{dt} = \beta c .$$

Solving for x and y, putting in the boundary conditions and eliminating t,

$$x = \frac{\sqrt{1-\beta^2}}{\beta^2} \frac{e}{2mc^2} Ey^2 ,$$

or,

$$\frac{\beta^2}{\sqrt{1-\beta^2}} = 0.982 \times 10^{-6} \frac{y^2}{x} \frac{V}{d}$$

where V is the potential between the plates expressed in volts.

On each photograph taken, five equidistant lines were obtained as follows: The center line was obtained with both condenser plates grounded. One plate was then raised to a definite potential above ground and the other to the same potential below ground. After the exposure was taken the potentials were reversed. The outside lines were taken by doubling the potential applied to the plates. It is interesting to note that with the type of photographic plates used (Eastman Speedway) it was unnecessary to develop those where the energy of the electron beam was above 65,000 volts. Developing brought out more detail, but the lines were sufficiently sharp to be measured accurately without developing.

The curve showing the effect of radius on the factor $\beta^2/\sqrt{1-\beta^2}$ is shown in Fig. 5. Each point is the result of measurement on at least two plates. The distance between the lines on the photograph could be measured to 1 or 2% with a micrometer microscope and the distances between the five lines were averaged. A sample of the photographs taken is given in Fig. 6.

The constant for the solenoid obtained in this manner after correcting all meters is given below.

TABLE III

I	$\frac{\beta^2}{\sqrt{1-\beta^2}}$	V	K
9.01	.2320	56.1 K.V.	733
10.00	.2554	68.9	739
10.98	.3004	82.0	734
		av.	735

The values agree well with the constant obtained with the sphere gap. In all subsequent calculations where the value of β is desired in terms of I, the current in the solenoid, we shall use the average value

$$K = 737$$

obtained at high voltages.

Scattering Chambers. The arrangment of the scattering chambers can best be described by referring to Fig, 7. The purpose of using chambers of such large diameter was to eliminate as far as practical the effect of reflected electrons going from one into the other. When the inside was brass the reflection from the upper into the lower chamber amounted to .0003-.0009 of the main beam. When the whole inside was lined with aluminum this value was reduced to .0001-.0003. (For the reflect-

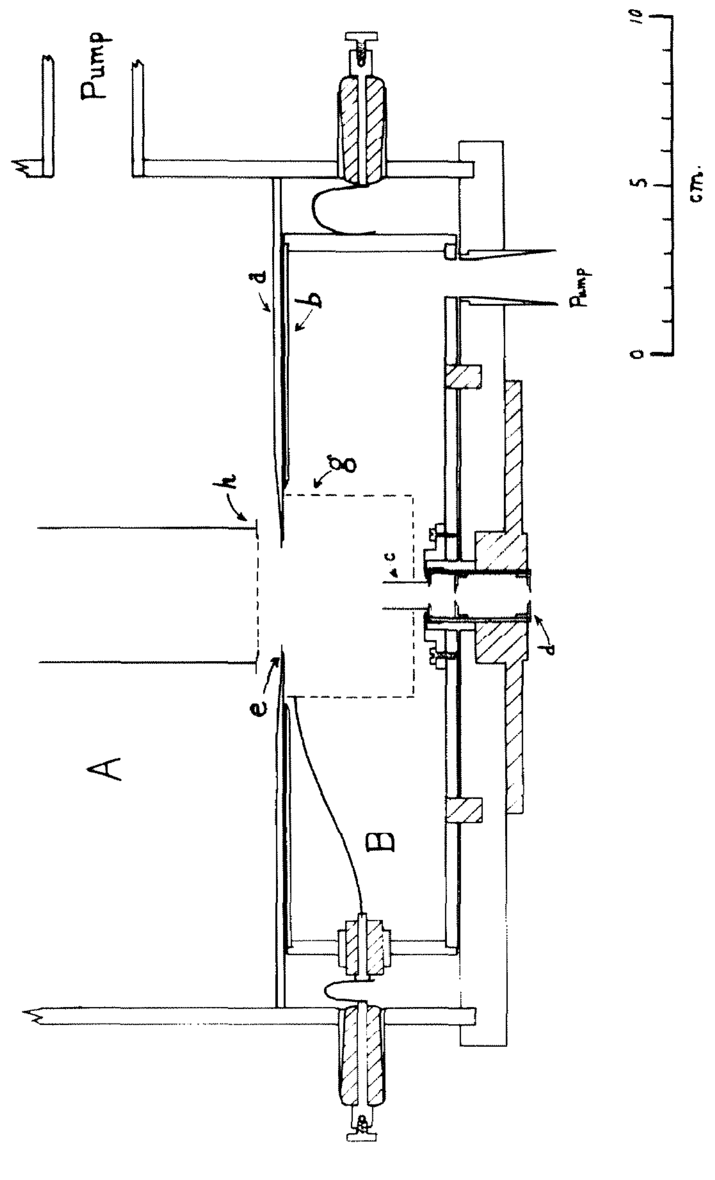


Fig. 7

ive powers of aluminum and brass see Fig. 2 in Part II of this thesis.)

The electrons are admitted from the solenoid into the scattering chamber through four collimating openings. (See Fig. 2) They are all made of aluminum and the last three are mounted in an aluminum tube. The first three openings are 2.8 m.m. in diameter and the last is 4 m.m. The purpose of the last opening is to stop scattered electrons from the openings below entering the lower chamber. All four collimating openings are grounded. The small, thin aluminum cylinder "c" is fastened to "d" and extends up into B a distance of 1.8 cm. It performs two functions: first, it further stops stray electrons from the openings below from reaching B, and, second, it definitely fixes the larger angle of scattering.

Chamber B is insulated from A by thin(.005 cm.) mica discs. The metal discs "a" and "b" are fastened to A and B respectively. The disc "a" is turned down to a thin edge. A thin aluminum ring .015 cm. thick, .8 cm. wide, with a 2.83 cm. opening in its center forms the final separation between A and B. The disc "b" has a hole cut from it slightly larger than the grid "g". This was found necessary since many slow electrons collect in the space within and part of them would be collected by B if "b" extended beyond the edge of "g".

Grids to Stop Secondary Electrons. For investigating secondary electrons up to 2000 volts energy, a wire grid was constructed. It consisted of a cylindrical framework made of 2 mil nickel wire. The ratio of wire to total space was 2.5% for the total framework. The reflection coefficient of nickel is .30, hence we shall apply a correction of 1.6% to the readings when this grid is used.

When secondary electrons of energies greater than 2000 volts are investigated other means must be resorted to than that of using actual potentials. It will be noticed from the curve for aluminum connecting ρ,(the ratio of transmitted electrons to the total number incident) with the voltage of the primary beam, (Fig. 8), that no electrons are transmitted up to a certain voltage after which there is a sudden increase. At voltages ordinarily used, from 90,000 to 145,000, even a piece of aluminum .001 cm. thick is very"transparent" and at the same time acts as an equivalent stopping potential of about 55,000 volts. A small correction for voltages below 120,000 can be applied to account for those electrons scattered elastically which are stopped by this foil. Secondary electrons will also be set free from the foil grid on the collector side by the electrons which go through. To investigate this point, a fine wire grid was placed around the foil grid and a stopping potential of 2000 volts applied. A decrease in ρ of 1 to 2% was found for primary voltages around 50,000, but for 100,000 volts the effect decreased to .3 to .4%. When necessary this correction will be applied.

A means is thus provided by which we can study secondary electron velocities up to one-half the energy of the initial beam. From arguments given previously, we are assured that when such a stopping potential is applied all the secondary electrons are stopped.

Method of Varying Angle. The foil is mounted on a thin metal ring "h" 3 cm. in diameter, supported by a fine nickel wire .06 cm. diameter. The whole is raised and lowered by means of a magnetic control as shown in Fig. 2. The height of the foil above the opening "e" can be measured to within .008 cm. by placing over the opening a disc with a pointed rod in its center, sighting through two windows in A and noting when the foil touches the point. The screw on the control mechanism wa s calibrated with a traveling microscope. The angles between which the electrons are collected are determined by the size of the openings "c" and "e" and by the height of the foil.

Homogeniety of Beam. The homogeniety of the beam for the case of alternating current applied to the tube was tested with D.C. stopping potentials and the result is shown in Fig. 9. The dotted line represents the voltage of the electrons computed from the constant of the solenoid. It will be noticed that the distribution of energies is almost symmetrical about the computed voltage. If $\pm \Delta V$ represents the heterogeniety of the beam, then,

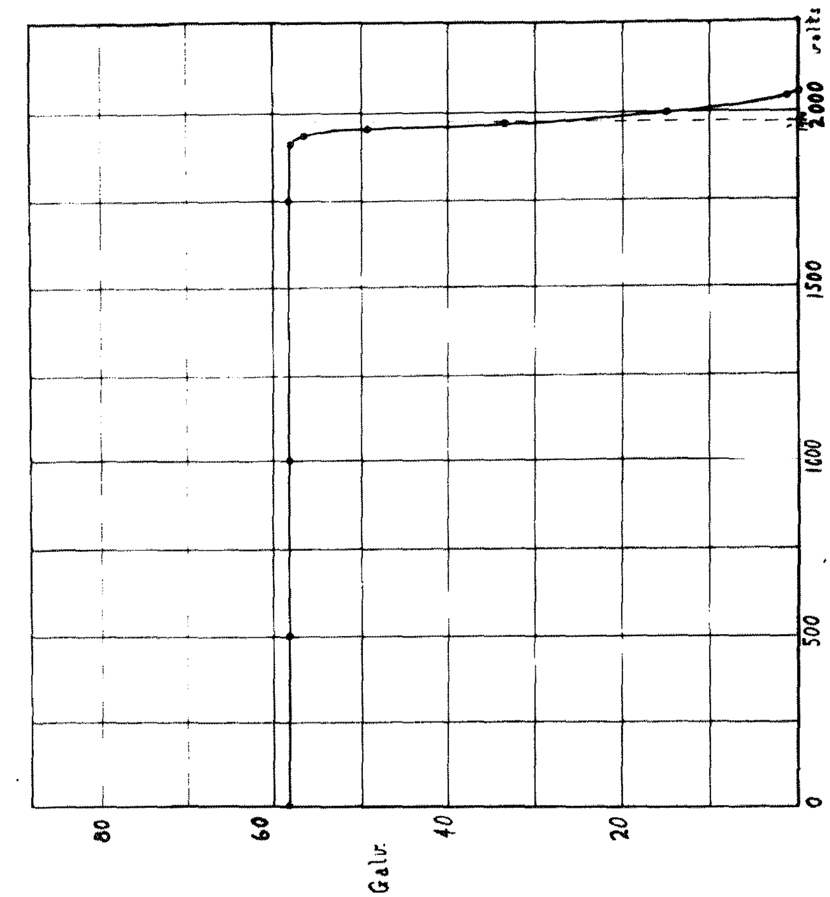

80
60
40
20
Galv.
0
500
1000
1500
2000
volts

Fig. 9

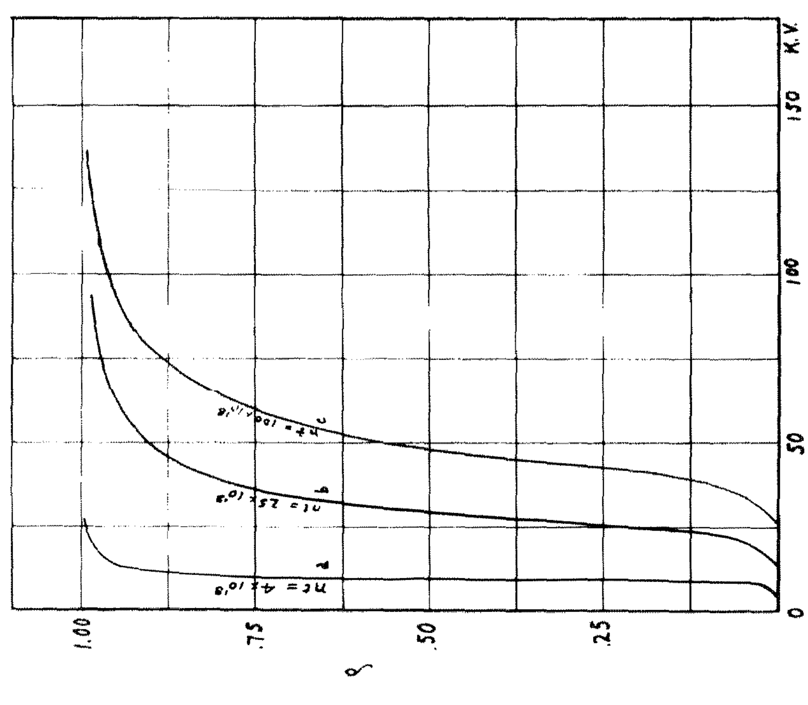

1.00
.75
.50
.25
ρ
0
50
100
150
K.V.
nt = 4x10^18 a
nt = 25x10^18 b
nt = 100x10^18 c

Fig. 8

$$\rho' = \frac{K}{(V+\Delta V)^2} = \frac{K}{V^2}(1 - \frac{2\Delta V}{V} + \cdots)$$

$$\rho'' = \frac{K}{(V-\Delta V)^2} = \frac{K}{V^2}(1 + \frac{2\Delta V}{V} + \cdots)$$

$$\frac{\rho' + \rho''}{2} \approx \frac{K}{V^2} = \rho$$

If the beam of electrons is symmetrical about a mean voltage given by the constant of the solenoid, this same reasoning will apply to all $\pm\Delta V$'s and if the spread of voltage is not more than 5% on either side, the error introduced into the value of ρ will be negligible.

Determination of nt. It was soon found that the variations in the thickness of the foils were too great to weigh a large sheet of the material and compute the average thickness. Consequently a quartz torsion balance was constructed which had a constant of $.1214 \times 10^{-6}$ g/div. The constant was determined by weighing small sections of very fine wire, a long piece of which was previously weighed on an analytical balance. Aluminum foils 5×10^{-5} cm. thick and 3 m.m. square could be weighed to 1%. The product nt can be determined as follows:

$$m = \sigma At$$

where m = mass of foil of area A and σ is its density.

Also, $$\sigma = nM$$

if M is the weight of each atom and n is the number of atoms per cm^3. So that,

$$nt = \frac{m}{A \cdot M} .$$

If M is express ed in molecular weight,

$$nt = \frac{6.06 \times 10^{23}}{M} \frac{m}{A}$$

The product nt which enters directly into the scattering equation, is independent of the density of the material. Since that portion of the foil where the beam passed through was cut out and weighed, local variations in uniformity should not introduce a large error if the beam is uniform. This point was tested with several foils by rotating the foil one turn and taking readings every 45°. Variations of not more than 2% were observed, while the average variation was 1%.

Meters. All meters were calibrated with a potentiometer and corrections applied to all the readings. Two galvanometers were used, one with a very high sensitivity (3.5×10^{-11} amp./div.) which was used for balancing, and the other of low sensitivity used to measure total electron current. An electrostatic voltmeter connected to the secondary of the transformer facilitated the adjustment of the high voltages.

METHODS USED IN TAKING READINGS

Adjustments. The current in the solenoid was set and kept at a constant value and the voltage of the electron beam increased until a maximum current came through into the scattering chambers as indicated by the galvanometer G' (See Fig. 2). R_2 was kept constant at 10^4 ohms and R_1 adjusted until G read zero deflection. To take into account thermal E.M.F. which was usually present to a more or less degree, the current in the solenoid was increased suddenly by a small amount. This made G' come back to zero and if G would seek a new zero, R_1 could be adjusted again. This process was continued until whether G' was reading full current or zero, G would remain stationary. A change of resistance in R_1 of 0.1 ohm would give a deflection of G of approximately 5 m.m. Since R_2 was 10^4 ohms, changes in ρ of 1 part in 10^6 of the main beam could be detected. When a balance of G was obtained, the drop in potential across R_1 was the same as that across R_2 and the apparent value of scattering within the given angles was then obtained from,

$$\rho = \frac{R_1}{R_1 + R_2}$$

To this value of ρ several corrections must be applied.

1. A correction for the value of ρ when no foil was present. This varied with the height of the ring "h", the kind of foil used as a stopping potential and the potential of the primary beam. This "zero correction" was checked at various times. A typical selection of values is given in the Table below for a foil with an equivalent stopping potential of -27,000 volts.

TABLE IV

V	θ_1	θ_2	ρ (correction)
68.9 K.V.	95°10'	172° 5'	.00022
96.9	"	"	.00026
129.0	"	"	.00028
145.0	"	"	.00030

This "zero correction" is to be subtracted from the apparent value of ρ.

2. A correction for the wire of which the grid was composed. It amounted to .8% for the foil covered grids and 1.6% for the fine mesh wire grid. This correction is to be added.
3. A correction for the stopping power of the foil grids for elastically scattered electrons. This was obtained from Fig. 8 and amounted to 0-4%, and is to be added.
4. A correction for the reflection out of chamber B and for the absorption by the foil grid of electrons reflected from the walls of B. This is directly related to the reflection coefficient for electrons of the metal of which B is made. We could either increase the dimensions of the scattering chamber and so extrapolate to an infinitely large one, or we could line the chamber with different metals which have different reflection coefficients and hence extrapolate to zero reflection. The latter method was chosen as the more practical. Consequently the reflection coefficients of aluminum and brass were determined (See Part II), as well as the angular distribution of these reflected electrons. The ratio of the coefficients for aluminum and brass is .13/.29 = .45. A typical example showing what effect lining the chamber B with brass and aluminum had is given below:

METAL	V_P	θ_1	θ_2	V_s	
Al	96.9 KV	108°	173°	-27 KV	.001260
Brass	"	"	"	"	.001253

The effect increased slightly for lower voltages and decreased for higher voltages. In most cases the correction was negligible.

When the foil grid was used, it was connected electrically to chamber A. This was necessary since B was to collect only those electrons scattered elastically while A was to collect all others. Secondaries emitted from the foil or other parts of A subtracted in one place but add in another so that the net result is nil.

RESULTS

Single Scattering. The first point tested was to determine under what conditions single scattering could be realized. Experimentally if ρ increases linearly with nt, single scattering is the predominating factor. The results of these tests are shown in Fig. 10. If we apply Wentzel's criterion to the point where the curves depart from linearity we obtain the following:

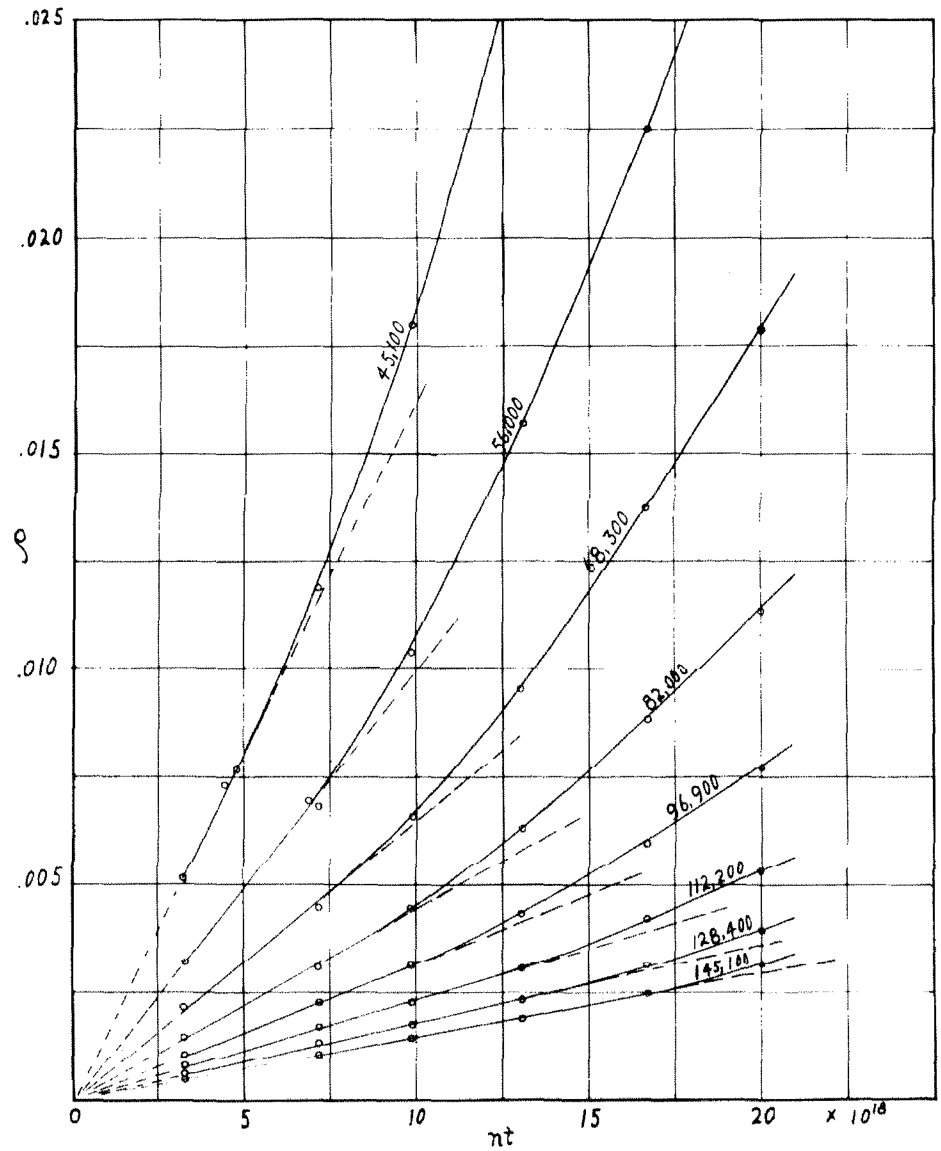

.025
.020
.015
.010
.005
ρ
0
5
10
15
20
× 10¹⁸
nt
45,100
56,000
68,300
82,000
96,900
112,200
128,400
145,100

Fig. 10

TABLE V

Aluminum

$\theta_1 = 95^{\circ}10'$ $\theta_2 = 172^{\circ}5'$

nt	V_p	$4\omega_{min}$	$\theta/4\omega_{min}$
6.0×10^{18}	45.0 KV	28°56'	3.3
7.4	56.0	25°52'	3.7
8.3	68.9	22°40'	4.2
9.4	82.0	20° 0'	4.7
11.3	96.9	18°40'	5.0
13.2	112.5	17°20'	5.5
15.5	129.0	16°24'	5.8
17.6	145.0	15°36'	6.1

The factor $\theta/4\omega_{min}$ is not a constant but increases with the voltage. The value reported by Schonland is $\theta/4\omega_{min} = 3.0$, which is for both 60,000 and 80,000 volts. Judging from the results given here, this value is much too low.

Perhaps a more accurate criterion for single scattering from a foil can be obtained experimentally from the shape of the curve showing the variation of ρ with angle. Near 90° a scattered electron emerging from the foil must go a farther distance through the metal than one coming out at larger angles. This will have the effect of decreasing the slope of the curve near 90°. These plurally scattered electrons will be partially thrown into larger angles and will give the hump shown in Fig. 11(a), which is for 45,000 volts with a stopping potential of 27,000. Fig. 11(b), for the same foil ($nt = 4.41\times10^{18}$) but a primary voltage of 128,000 volts and a stopping potential of 55,000, shows how the hump has completely disappeared.

Secondary Electrons. The energy distribution

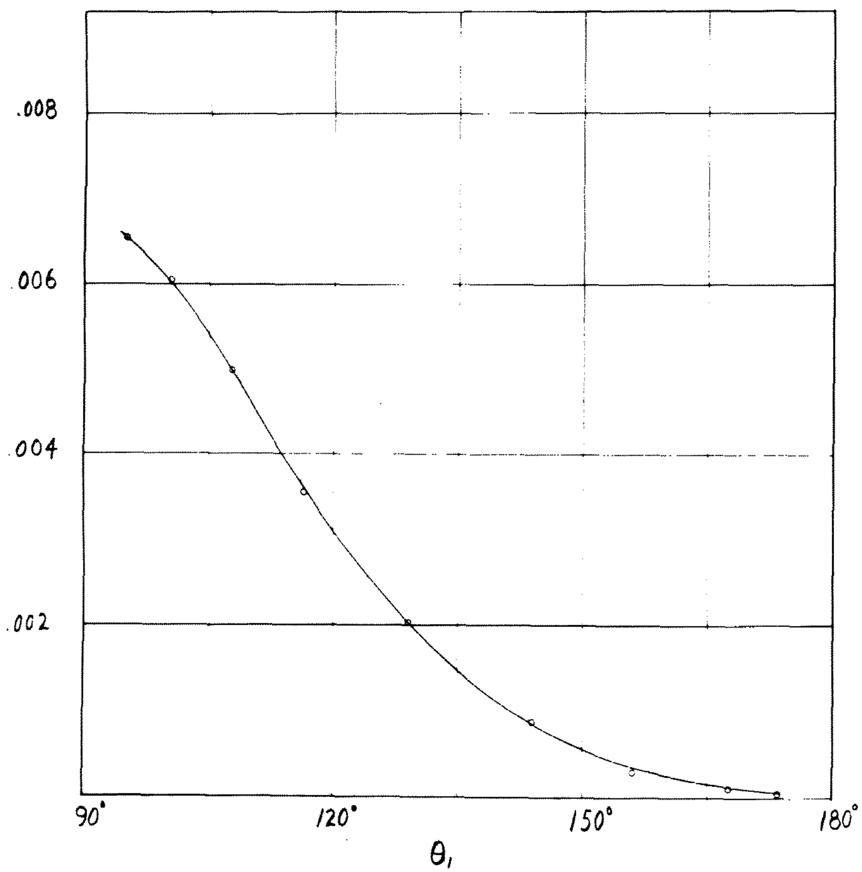


Fig. 11(a)

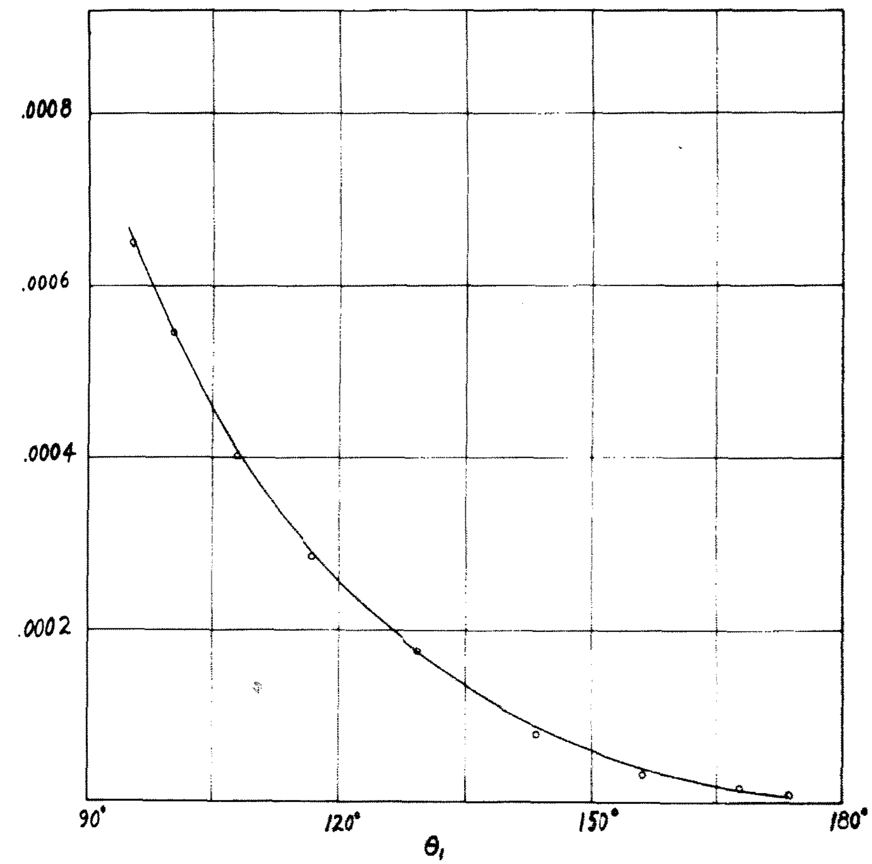


Fig. 11(b)

of secondary electrons is shown for two widely different atomic numbers, aluminum and gold, in Figs. 12(a) and 12(b). The relative number of secondary electrons present is less for larger values of nt than for smaller, which is shown in curve (b) for aluminum. (Note: (b) is fitted to (a) at 55,000 volts.) Similar curves were obtained for silver. It will be noticed that there are many slow secondaries but an appreciable number have energies above 10,000 volts. It is interesting to note that in Schonland's work he used 150 volts stopping potential and assumed that all secondaries were stopped. From what has been shown earlier in this thesis, all secondaries should be stopped at approximately one-half the primary voltage of the original beam. The fact that such high velocity secondary electrons are found is explained by the fact that some formed even on the opposite side of the metal have more than sufficient energy to penetrate the foil.

Dependence of Scattering on Energy of Primary Beam. The variation of the amount of scattering for aluminum between the angles of 95°10' and 172°5' as a function of the energy of the beam is shown in Fig. 13. Plotted in the same figure and fitted at $V_p = 56,000$ are also given Rutherford's equation and Mott's equation. There is very little difference between these two as far as dependence on energy is concerned. (Note: The form

$$\rho = \frac{ntZ^2e^4}{(Ve)^2}\left(\cot^2\frac{\theta_1}{2} - \cot^2\frac{\theta_2}{2}\right)$$

of Rutherford's equation is used)

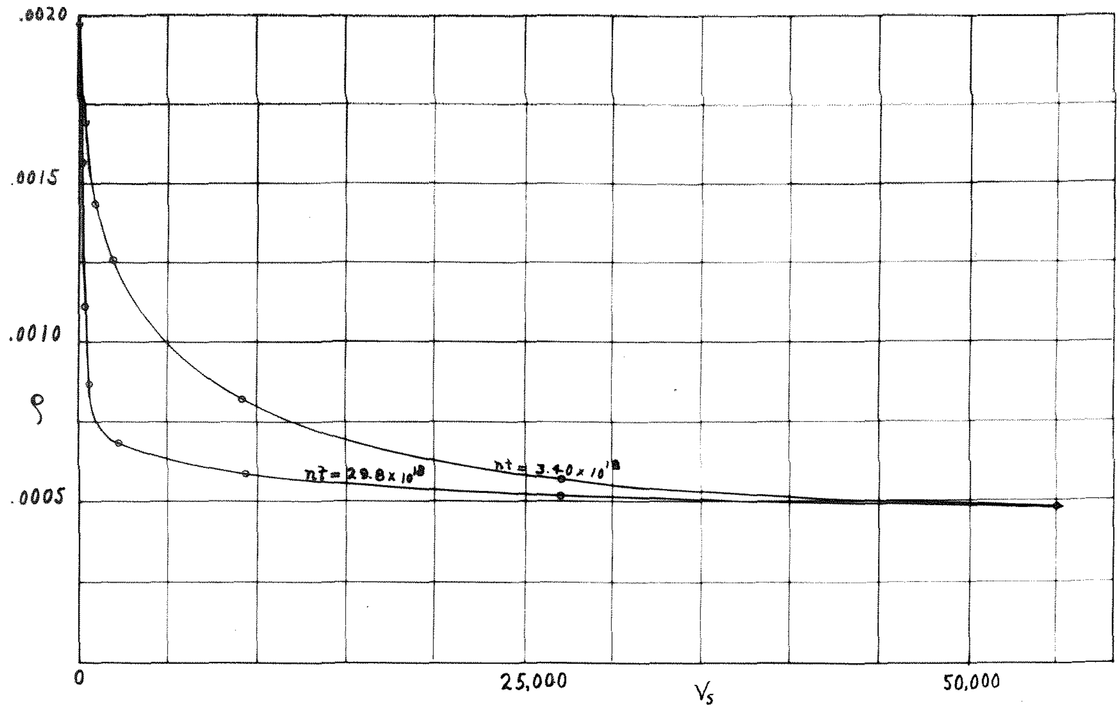


Fig. 12(a)

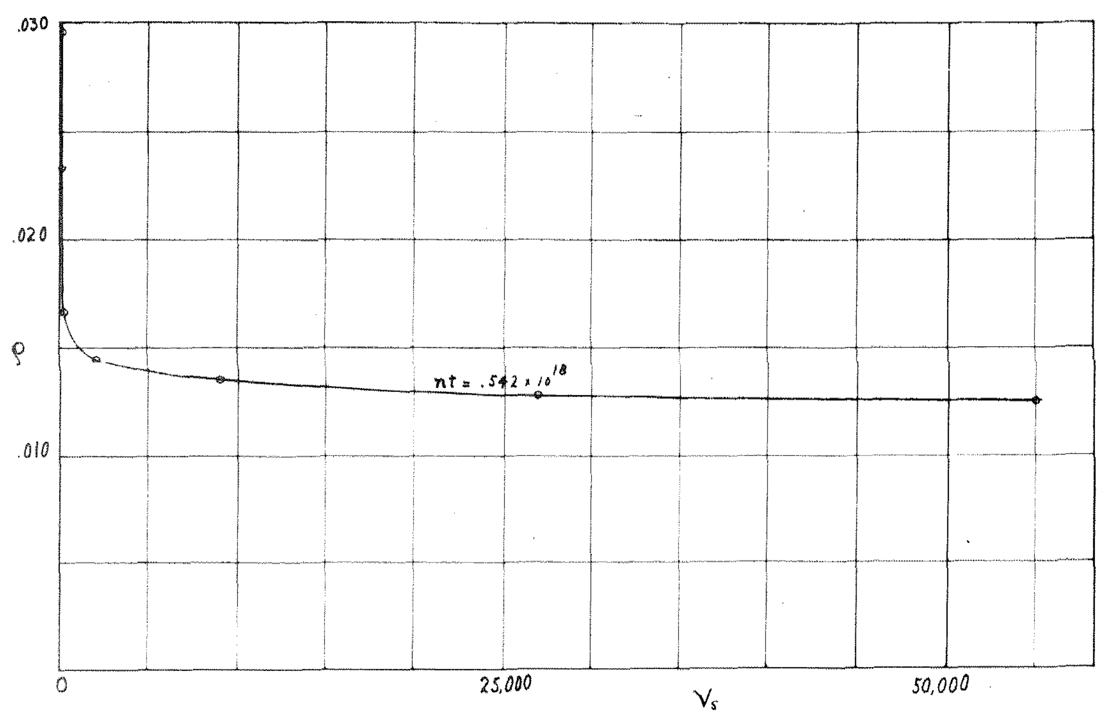


Fig. 12(b)

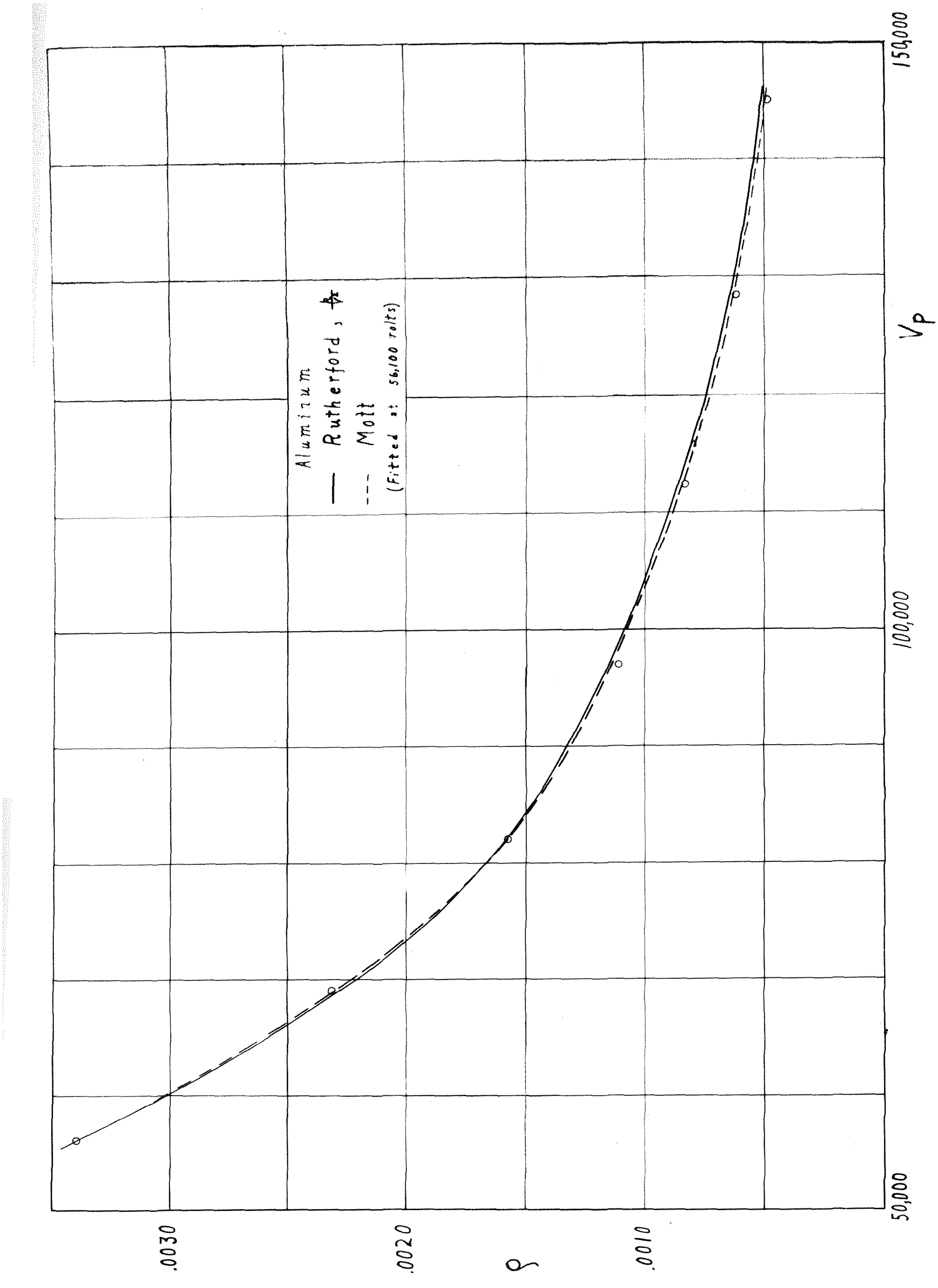

Aluminum
Rutherford ,
Mott
(Fitted at 56,100 volts)
.0030
.0020
.0010
ρ
50,000
100,000
150,000
V_p

Fig. 13

A comparison of the relative as well as the absolute values of ρ is given in the following Table:

TABLE VI

Aluminum

$nt = 3.68 \times 10^{18}$, $\theta_1 = 95^\circ 10'$, $\theta_2 = 172^\circ 5'$

β	V	Relative values of ρ Exp	Mott	Darwin	k/V^2
.436	56.1 KV	.00340	.00340	.00340	.00340
.474	68.9	.00231	.00229	.00241	.00226
.511	82.0	.00157	.00157	.00179	.00160
.543	96.9	.00110	.00114	.00134	.00115
.574	112.2	.00082	.00084	.00104	.00085
.603	128.4	.00061	.00064	.00088	.00065
.630	145.1	.000485	.000495	.00077	.000505

β	V	Absolute values of ρ Exp	Mott	Darwin	Rutherford
.436	56.1 KV	.00340	.00257	.00460	.00264
.474	68.9	.00231	.00174	.00326	.00176
.511	82.0	.00157	.00118	.00242	.00124
.543	96.9	.00110	.00086	.00182	.00089
.574	112.2	.00082	.00063	.00141	.00066
.603	128.4	.00061	.00049	.00119	.00051
.630	145.1	.000485	.000375	.00104	.00039

The following points should be noted in the above Table: (1) The dependence on energy of beam given by Mott's equation and by k/V^2 agrees well with experiment, while the equation based on relativity correction of the classical theory does not agree. (2) Absolute values of scattering within the angles given do not agree with any of the theories. There are reasons to be discussed later why Rutherford's equation cannot be written proportional to $1/V^2$. Mott's result is the one we shall consider most seriously. Comparing with the experimental values we obtain,

$$\text{Exp} = 1.32 \text{ Mott}, \qquad (4)$$

which represents the facts quite closely for aluminum. It will be shown in the next section that Mott's equa tion also gives the correct dependence on θ. Relation (4) then is valid in the case of Aluminum within the ranges, $V = 56,000$ to $145,000$ volts and $\theta = 95^\circ$ to 173°.

An example of the experimental value of ρ computed from average values of ρ/nt of several different foils is given in Table VII.

TABLE VII

Aluminum

$V_s = -27,000$ v, $\theta_1 = 95^\circ 10'$, $\theta_2 = 172^\circ 5'$

KV	56.1	68.9	82.0	96.9	112.2	128.4	145.1
	9.47	6.35	4.38	3.05	2.34	1.63	1.35×10^{-22}
	9.65	6.41	4.31	3.14	2.29		
$\frac{\rho}{nt}$	9.69	6.38	4.43	3.09	2.31	1.71	1.41
	8.70	6.31	4.17	2.97	2.31	1.72	
	8.92	6.12	4.38	3.10	2.28	1.73	1.35
av.	9.29	6.31	4.33	3.07	2.31	1.70	1.37×10^{-22}

The thinnest silver and gold foils used (2200 Å and 800 Å respectively) were not thin enough to expect single scattering to be the predominating factor below 128,000 volts, and the shape of the curves in Figs. 15 and 16 show that some plural scattering was present at 95° in both cases at this voltage.

<u>Dependence of Scattering on Z.</u> In Table VIII the factor $\rho/ntZ^2f(\theta/2)$ is compared for Al, Ag and Au at $\theta_1 = 95^\circ 10'$ and $\theta_2 = 172^\circ 5'$ for $\beta = .603$ and $\beta = .630$. This factor should be a constant for all elements. The ratios given in Table IX show that Mott's equation gives the ratio nearest to unity but there is much to be desired. Schonland also reports a value much too high for gold and attributes it to an abnormal emission of secondary electrons. This explanation is hardly tenable for the results reported here because of the stopping potentials used. It may be pointed out here that Mott's equation applies best to the lighter elements and neglecting further terms in the expansion is hardly justifiable in the cases of Silver and Gold.

TABLE XIII

	$\beta = .603$			$\beta = .630$		
	Al	Ag	Au	Al	Ag	Au
Mott	1.52	1.77	2.41×10^{-24}	1.24	1.38	1.95×10^{-24}
Ruth.	1.18	1.65	2.50	.94	1.19	1.77

TABLE IX

	$\beta = .603$			$\beta = .630$		
	Ag/Al	Au/Al	Au/Ag	Ag/Al	Au/Al	Au/Ag
Mott	1.16	1.59	1.36	1.11	1.57	1.41
Ruth.	1.39	2.10	1.51	1.27	1.95	1.48

In view of the fact that plural scattering contributed something to the value of ρ is the cases of Ag and Au, it would be expected that the value would be high. Wentzel's criterion for both Ag and Au gives $4\omega_{min} = 5.3$ at 128,000 volts and 6.0 at 145,000 volts. We should then expect mostly single scattering and the large values obtained for these elements must indicate that ρ increases faster than Z^2.

<u>Dependence of Scattering on Angle.</u> C.E. Eddy[16] has studied the angular distribution of β-rays scattered by thin foils from 0° to 50° but under conditions where plural scattering was very prominent. Klemperer[17] working with voltages between 10 KV and 40 KV using a Geiger counter found an angular dependence between 10° and 120° not given by any existing theory. This latter work, however, was probably too inaccurate to draw conclusions from. Certain definite angles have been used by other observers, but a consistent effort to obtain an accurate dependence on angle has not been made.

The experimental dependence of scattering on angle is well illustrated in Fig. 14(a) which is for Aluminum. θ_1 is plotted as abscissa so that any ordinate gives the value of the ratio of the number of electrons collected between θ_1 and θ_2 to the total number of electrons incident on the foil. θ_2 varies from 172° when $\theta_1 = 95^\circ$ to 178° when $\theta_1 = 173^\circ$. The primary voltage for each curve is 128,000 volts. The four curves plotted are for

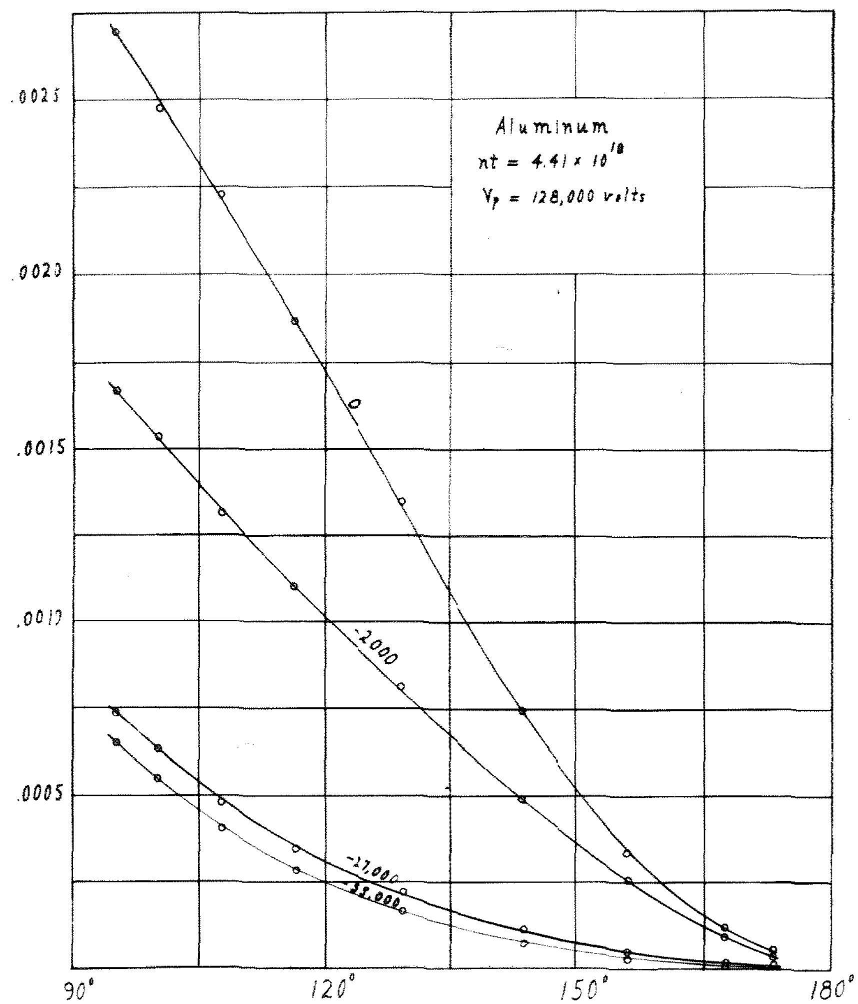


Fig. 14(a)

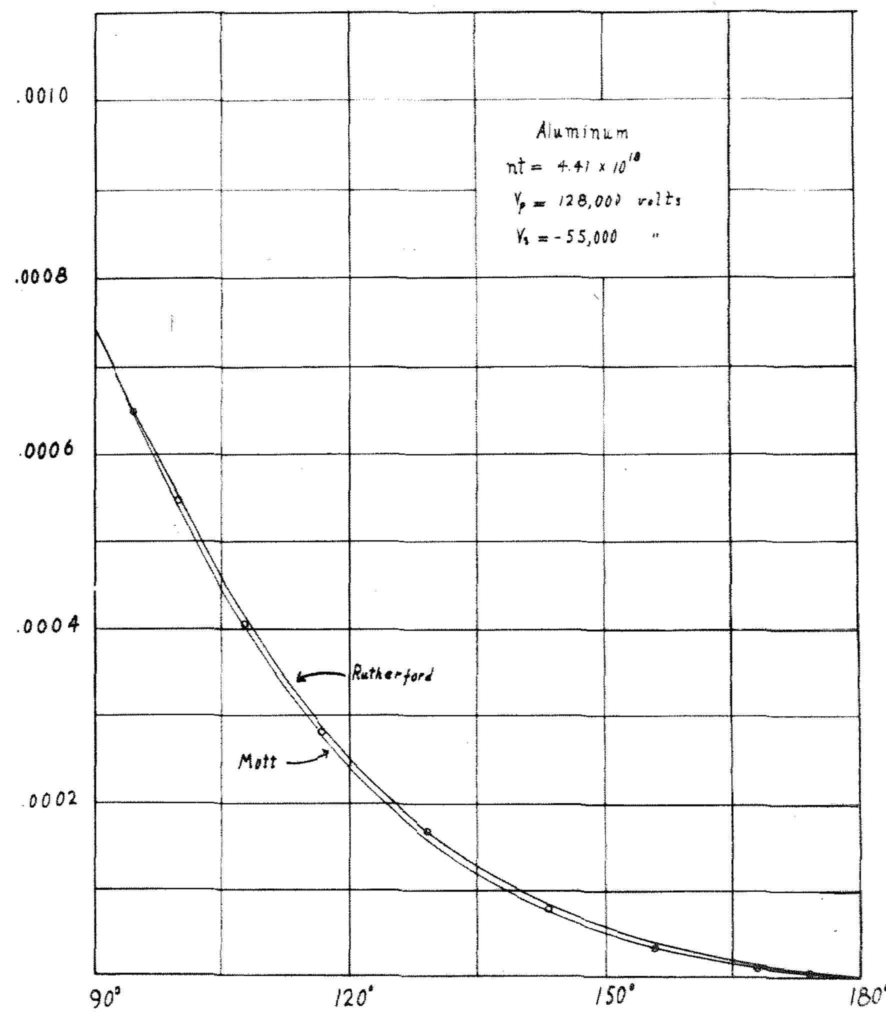


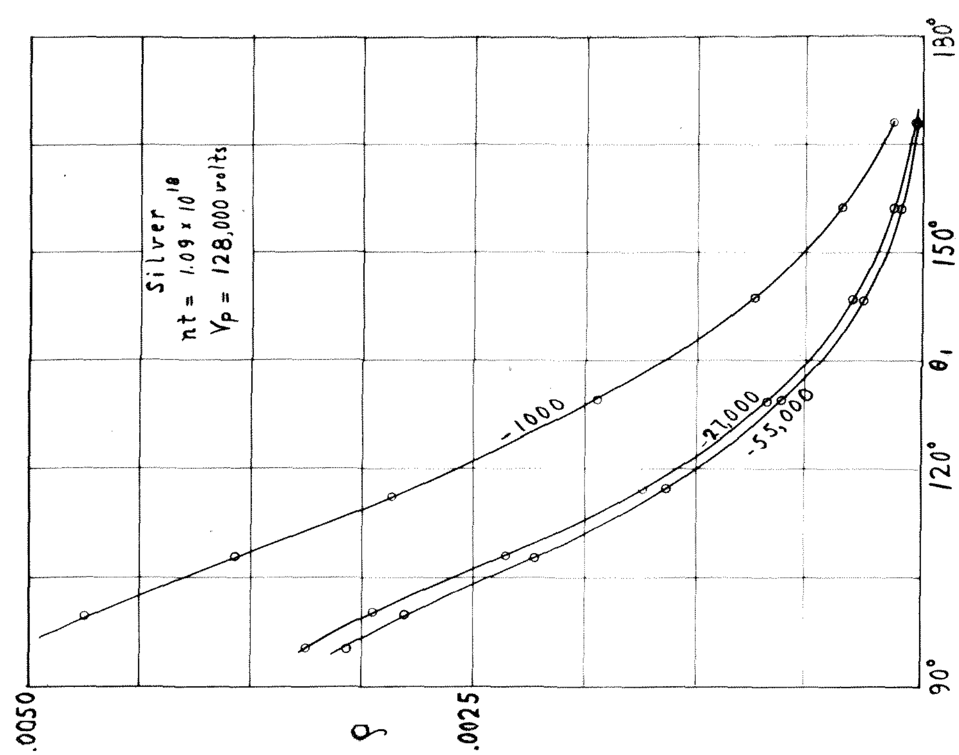
Fig. 14(b)

the stopping potentials given. In Fig. 14(b) plotted with values of ρ for $V_s = -55{,}000$ volts and fitted at 95°10' is given the variation with θ from both Mott's and Rutherford's equations. All curves which have been obtained from 97 to 145 KV are very similar to the one given in Fig. 14(b) if the proper stopping potential is applied. At voltages below 97 KV, the hump shown in Fig. 11(a) begins to appear and no comparison with theory based on the assumption of single scattering can be made. For sufficiently high voltages either the equation of Mott or of Rutherford gives a dependence on θ between 95° and 173° which agrees well with experiment.

Fig. 15 shows the results obtained for gold and Fig. 16 those for silver. The angular dependence for these two metals agrees well with Rutherford's $\cot^2\theta/2$ relation while the agreement is not so good with Mott's equa tion. This deviation is probably due to the fact that, as mentioned before, neglecting further terms in the expansion is not permissible for the heavy elements.

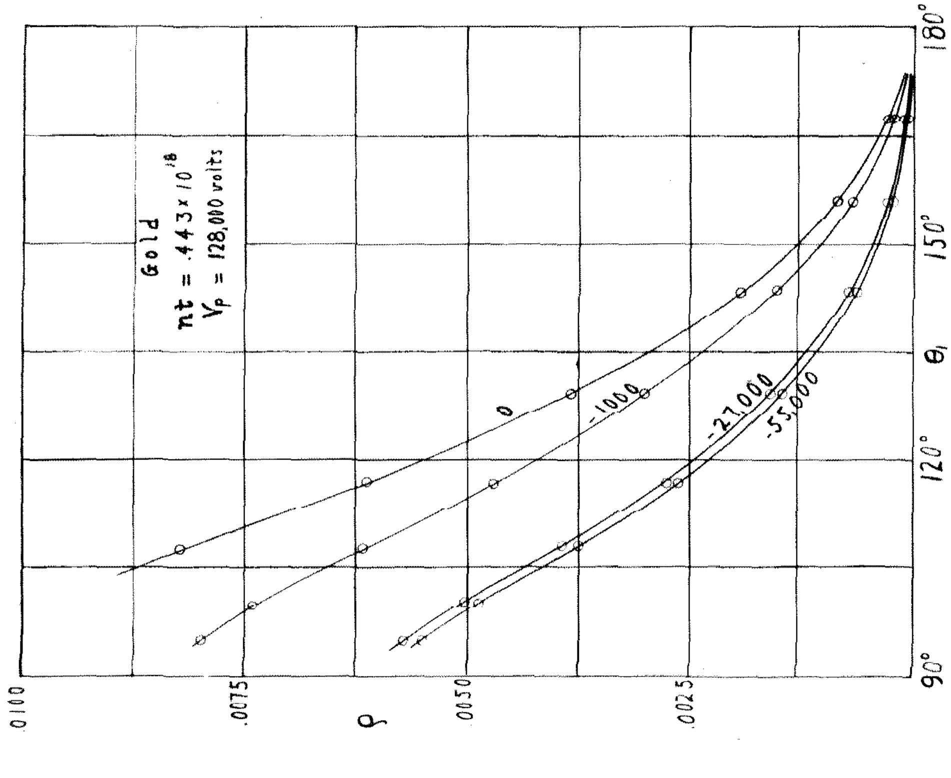
<u>Angular Distribution of Secondary Electrons.</u>

To find the dependence on angle of the secondary electrons emitted between two energies, we need only take the difference in ordinates of two curves for two different stopping potentials. Fig. 17 shows the result for aluminum taken from Fig. 14(a), and Fig. 18 that for gold taken from Fig. 15. It is found that the points agree very well with the curve $k'(\sin^2\theta_1 - \sin^2\theta_2)$. Since the



Silver
nt = 1.09 x 10^18
Vp = 128,000 volts
-1000
-27,000
-55,000
.0050
ρ
.0025
90°
120°
θ1
150°
180°

Fig. 16



Gold
nt = .443 x 10^18
Vp = 128,000 volts
0
-1000
-27,000
-55,000
.0100
.0075
ρ
.0050
.0025
90°
120°
θ1
150°
180°

Fig. 15

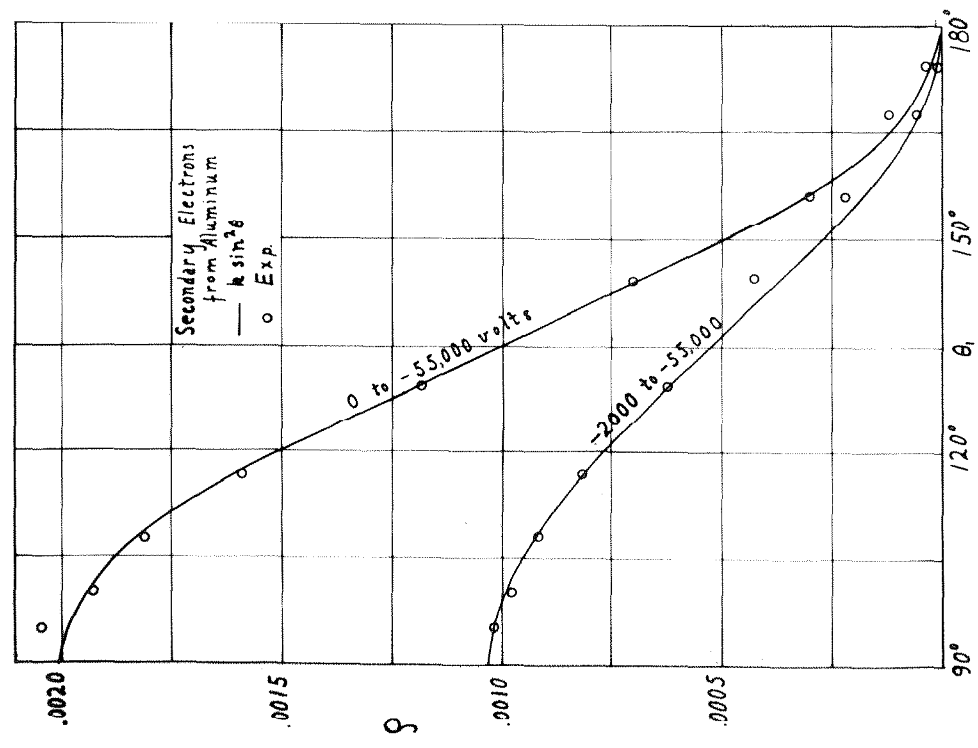

Secondary Electrons from Aluminum
— k sin²θ
○ Exp.
0 to -55,000 volts
-2000 to -55,000
.0020
.0015
.0010
.0005
ρ
90°
120°
θ₁
150°
180°

Fig. 17

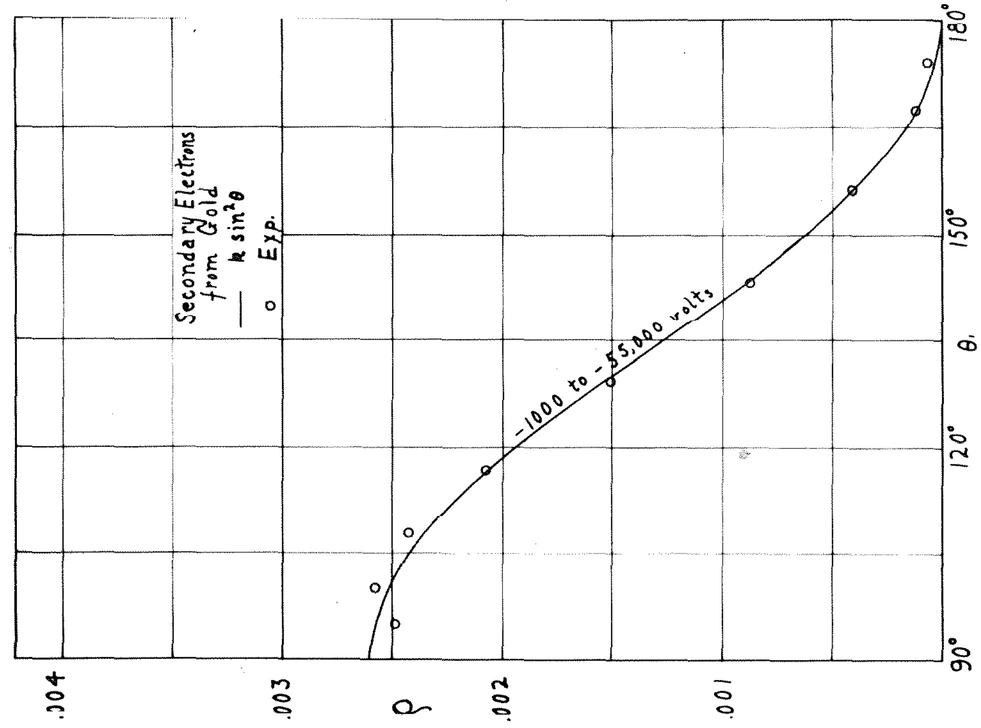

Secondary Electrons from Gold
— k sin²θ
○ Exp.
-1000 to -55,000 volts
.004
.003
.002
.001
ρ
90°
120°
θ₁
150°
180°

Fig. 18

second term in the parenthesis is small compared with the first we may write this as $k \sin^2\theta$. If we differentiate this with respect to θ and divide by $\sin\theta$ we get the intensity of the secondary electrons given at the angle θ. We may then draw the following conclusions: The electrons that come from a thin foil when bombarded with high velocity electrons may be divided into two definite and distinct groups,

1. Those that are scattered without appreciable loss of energy and follow the intensity distribution given by either Rutherford's $\mathrm{cosec}^4\theta/2$ law, or Mott's equation;
2. Those that come off with low velocities and follow the intensity distribution given by $\cos\theta$. It is interesting to note that the cosine distribution is also obtained for the reflection of electrons from solid surfaces. (See Part II of this thesis.)

<u>Experimental Test of Loss of Energy Due to Radiation.</u> Qualitative tests may be made as follows:

1. For large angles it might be expected that many electrons may have lost a large portion of their energy and that an appreciable number would be stopped by -55,000 volts if the original energy were 110,000. If this were true the curve showing the variation of ρ with θ would come close to the axis $\rho = \theta$ at large angles. No such effect is noticed.
2. Since light atoms according to Kramer's equation lose more energy than heavier atoms, we should expect a differently shaped curve connecting

ρ and θ for aluminum and gold. Both elements follow the same law experimentally.

3. The relative loss of energy according to Kramers is porportional to β^3. We should expect, then, that for two widely different potentials with one-half the primary voltage used as a stopping potential in each case, that we should get departures from scattering equations which are based on purely elastic scattering. No such departures are found.

What can be said then about the electrons that generate the continuous X-ray spectrum? There seem to be at least two possible explanations. Either,

1. The number losing one-half their energy or more is inappreciable compared with a given fraction of the main beam collected between 140° and 180°, or,
2. Momentum relations are such as to distribute over various angles those electrons losing energy.

Discussion of Errors. It is thought that the main error entering into the measurement of ρ experimentally came mostly from an inaccurate knowledge of the zero correction when the foil was in place. The foil distributed the electrons going through in a different way than was the case when the zero correction was taken with no foil present. It is estimated that this error will be small; first, because of the amount of zero correction when the foil was absent, (about .0002 of the main beam) and second, because with a very thin foil where the zero

zero correction is comparable with the true value of ρ the main beam is not scattered appreciably.

In measuring nt the area of a small portion of the foil where the beam went through could be measured to .5% or less with a traveling microscope. The weight might be in error 1% due to errors in the torsion balance. The balance was checked frequently with known weights.

Two different methods of determining the constant of the solenoid at high voltages gave a constant of 737 ± 3. It is assumed that the mean value of V is known to within .4%. This gives an error in V^2 or β^4 of .8%.

The error in θ can be estimated as follows. The height of the foil could be adjusted consistently to 1/8 turn, or since one turn was .0642 cm., to .008 cm. The radius of the opening was 1.41 cm. This gave an error at 90° of 20' in θ, or an error in $\cot^2\theta/2$ of 1%. The error due to the adjustment in height decreased as θ increased.

An analysis showed that the error due to the finite size of the beam and its slight divergence was negligible.[18]

To make certain that no appreciable impurities of large atomic number were present in the aluminum foil used, some very pure aluminum from Siegbahn's laboratory was tested. The values of ρ/nt agreed to within 1% of those obtained with the foil regularly used in this experiment.

Combining the above errors the value of ρ is found to be correct to 2%. Irregularities in the foil and an inaccurate knowledge of the exact stopping potential used may increase this error to 3% or possibly to 4%.

Comparison With Theory. The results as compared with the values predicted by theory may be summarized as follows:

1. Dependence on energy of primary beam: Either Mott's or Rutherford's equation gives very good agreement if we write the latter as porportional to $1/V^2$.
2. Dependence on Z: According to Mott's equation ρ increases faster than Z^2. This is found experimentally but the increase is not sufficient to give good agreement. All the other equations give ρ porportional to Z^2.
3. Dependence on angle: Here again the variation with angle is almost the same for Mott's or Rutherford's equations and agrees well with experiment.
4. Absolute values of ρ: The equations of Mott and Rutherford give values too low while that of Darwin gives values too high.

In general it is found that the simple result of Rutherford gives better agreement with experiment than any of the other more complicated equations. However, there are certain objections to Rutherford's equation.

We are surprised that agreement is as good as it is. In the first place, from the derivation of his equation if applied to electrons, it is not permissible to write $\rho \propto 1/V^2$ for energies above 30,000 or 40,000 volts.* No account is taken of relativity and we should expect important changes for velocities of .63 the velocity of light. In the second place, it seems certain that an effect will be introduced by the spin of the electron. Both these factors have been included in Mott's result. If we take the relativity correction alone, the variation of ρ with β does not agree with experiment. The spin terms for aluminum contribute a difference of 15% between the voltages of 56,000 and 145,000. Experimentally, a difference of 2% with Mott's equation was found between these voltages. Since a relativity correction seems necessary, it also seems necessary from this experimental work that a correction for the spin of the electron must be included.

A real difference, however, in absolute magnitude of ρ seems to exist between theory and experiment. The effect of a nuclear magnetic moment has been computed by Massey.[19] It is found to be negligible. The explanation must be looked for elsewhere. It might be expected that

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* The factors entering into the denominator of Rutherford's equation are mass x (Angular momentum)$^2 \propto 1/2\ mv^2$ = Ve only for low velocities.

since the discrepency becomes less for the lighter elements, some information might be obtained by using hydrogen, helium and beryllium. It is planned to extend this work to the case of gases in the near future.

Comparison With Other Observers. The absolute values of ρ for aluminum obtained in this report are from one-half to two-thirds those obtained by other observers both with cathode rays and β-particles . The results on silver and gold given here are from .7 to .8 of the values given by Schonland[8] and Chadwick and Mercier[20]. In Schonland's work it is quite apparent that the difference is mainly due to secondary electrons. In the other the cause may be due to the use of a heterogeneous beam of electrons from radioactive sources together with the inaccuracies due to their method of measurement.

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PART II

REFLECTION OF ELECTRONS FROM SOLID SURFACES

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ABSTRACT OF RESULTS

The main results obtained in Part II of this thesis may be summarized as follows:

1. Values of the reflection coefficient, ρ_o, for Be, C, Al, Cu, Brass, Sn and Pb are obtained from 45 to 128 KV.
2. A decrease of ρ_o with increase of voltage is found which is most pronounced for the light elements.
3. The angular distribution of emitted electrons is given very accurately by Lambert's cosine law of radiation.
4. Absorbed gases cause the surface to emit many slow electrons which is most noticable for the light elements. This fact probably accounts for the larger values reported by some observers.
5. With Be, C, and Al, a change with time of the number of slow electrons emitted was found upon going from high to low voltages.

INTRODUCTION

When a beam of electrons strikes a solid surface, there is an emission of electrons comparable with the number incident. These may arise because of several reasons. (1) There will be a small number of primary electrons which will be turned back by single encounters with the nuclei of the material. (2) Some will finally emerge after suffering several large nuclear deflections. (3) Electrons originally in the material will be set free by a collision process and may finally emerge. (4) X-rays formed by the primary or secondary electrons may set free secondary electrons. In any case the phenomenon of the emission of a cold surface bombarded with high velocity electrons is probably very complicated.

Becker[1] distinguished three kinds of electrons emitted in such a manner from a solid surface. (1) Those which have lost very little energy he called "reflected". (2) Those which have lost considerable energy, but have a more or less uniform velocity distribution, he called "rediffused". (3) The electrons coming off with energies in the range 0 to 36 volts he called "secondary". It is found that the relative importance of these groups changes with the energy of the original beam. Webster[2] defines all electrons emitted by the surface as "rediffused". He denotes the value of the total emission due to normal incidence of the primary beam as the "rediffusion constant". This quantity is not constant as will be shown later. In this report we shall define as the reflection coefficient the ratio of all electrons emitted from a surface being bombarded with a beam of electrons incident normally, to the total number. Its value will depend on the kind of material and the energy of the primary beam.

Work on the reflection coefficient of different metals has been carried on by a number of observers, both with cathode and β-rays.[3,4,5,6,7] Schonland's work was probably the most accurate of any for the case of cathode rays from 30 to 70 KV. It is difficult to say which can be considered most reliable for β-rays. There are large discrepancies existing among the available data. These will be discussed later. In view of this fact it was thought desirable to check some of the results. This work was undertaken primarily to determine to what extent reflection of electrons from the scattering chambers in Part I of this thesis was affecting the experimental values of scattering.

METHOD OF TAKING OBSERVATIONS

The same apparatus was used as in Part I. The sheet of metal to be studied was mounted in place of the foil. The variation with angle as well as the total reflection coefficient could be determined for each sample. In all cases the primary beam was normal to the surface. Simplification resulted from the fact that the effect being observed was of such an order of magnitude that practically all corrections could be neglected.

To obtain the total value ρ_0 for the angles 90° to 180° it is possible to correct the value obtained experimentally from 90° to 172° by adding the fraction to be expected from 172° to 180°. If the angular distribution is known this value can be predicted with certainty. It will be shown later that the distribution is given very accurately by the simple cosine law.

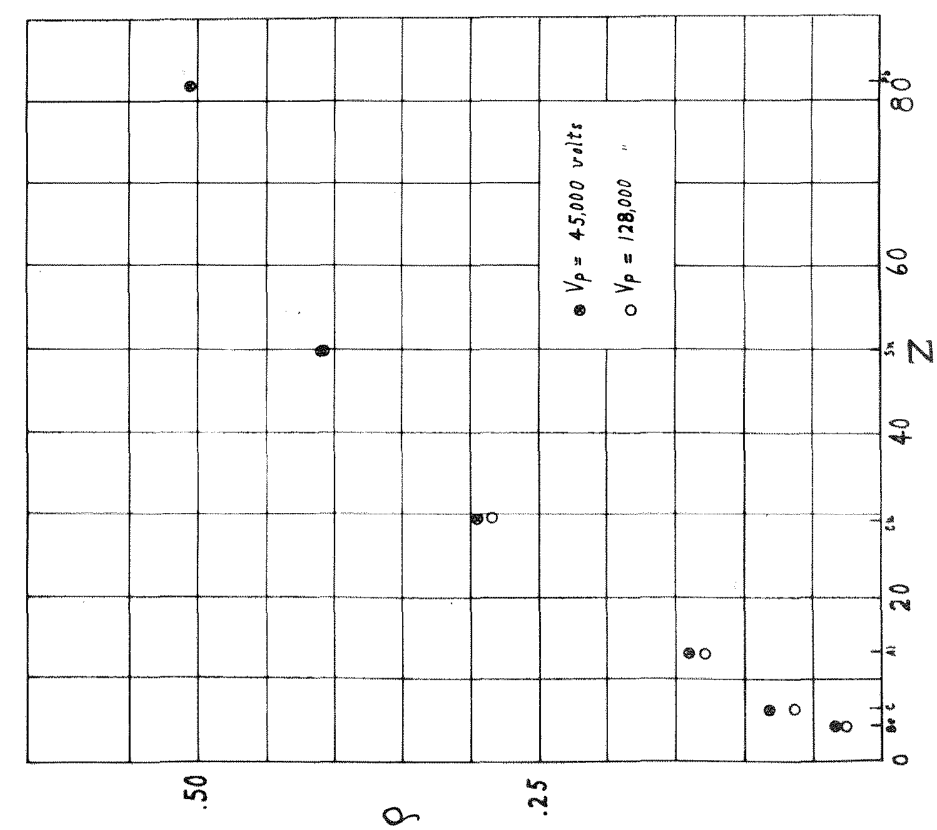
RESULTS

Dependence of Reflection on Atomic Number. Tests have been made with Be, C, Al, Cu, Brass, Sn and Pb. A comparison with other observers is given in Table I below. In all cases the values refer to total emission from 90° to 180°. The main points to be noted in this table are as follows: (1) At low voltages the values reported in this thesis are in good agreement with those of Schonland. (2) At high voltages and for heavy elements the results are in fair accord with the work of McClellan using radium, but for the lighter elements there is a wide discrepency. (3) A decrease in value of the reflection coefficient with increase in energy is found which is most pronounced for the lighter elements. In the case of lead, no change could be detected from 45 to 145 KV. With carbon as with several other materials, values of ρ_o have been obtained up to 145 KV. In the case of carbon, a decrease of 2% is found from the value at 128 KV. At this higher voltage agreement should be expected with McClelland's work since the mean value of the energy of the β-rays of radium is not far above this. He obtains a value for carbon 2.5 times as large. It is estimated that the values given here cannot be error more than 1%.

TABLE I

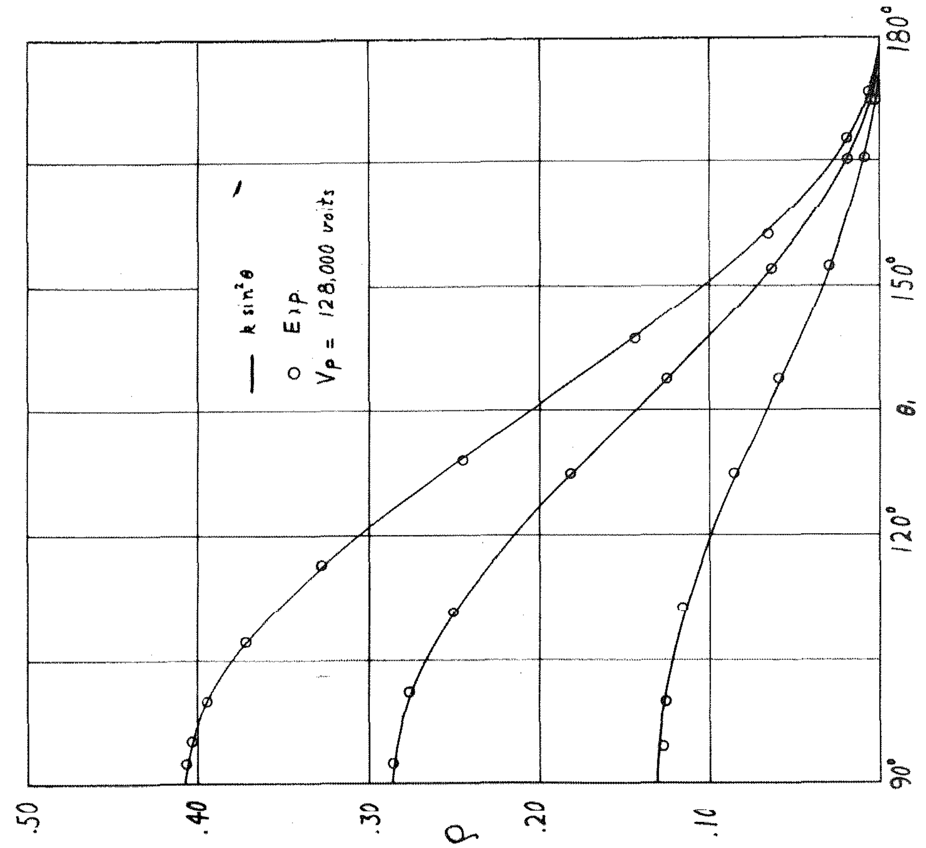
Element		Schonland	Neher		McClelland	Kovarick
		(50 KV ?)	45 KV	128 KV	Ra	Ac-C"
Be	4		.0291	.0248		
C	6		.081	.0658	.15	.274
Al	13	.13	.143	.129	.24	.383
Cu	29	.29	.295	.283	.36	.519
Ag	47	.37			.41	.635
Sn	50		.410	.407	.425	.697
Pb	82		.505	.505	.49	.800

The experimental results are also given in Fig. 1. All points are as designated except the low voltage value for beryllium which is for 70 KV. It is interesting to note that Schonland[8] reports a value of ρ_o independent of voltage for all metals studied. Kovarik[9] finds an increase of ρ with voltage up to about 500 KV after which there is a decrease.



.50
ρ
.25
0
20
40
60
80
Z
Be C
Al
Cu
Sn
Pb
● V_p = 45,000 volts
○ V_p = 128,000 "

Fig. 1



.50
.40
.30
ρ
.20
.10
90°
120°
150°
180°
θ_1
— $k \sin^2\theta$
○ Exp.
V_p = 128,000 volts

Fig. 2

Distribution of Reflected Electrons. Work upon the angular distribution of β-rays reflected from different metals was done in the years from 1905 to 1910. McMillan[10], Greinacher[11], and Schmidt[12] did the most important work. They found that the angular distribution of the emitted rays followed Lambert's cosine law of radiation. The same law was found independently while investigating the problem reported on in this thesis. In view of the fact, however, that nothing has been done on the angular distribution of electrons emitted from solid surfaces being bombarded with cathode rays, it may not be amiss to report the work that has been done using voltages from 12,500 to 145,000.

In Fig. 2 are shown the results for three different metals: (a) Tin, (b) Brass and (c) Aluminum. Plotted as the ordinate are the values of the ratios of the number of electrons emitted in the solid cone between θ_1 and θ_2, to the total number incident on the surface. It was found that the relation $k \sin^2 \theta$ fitted the experimental points very closely. More accurately, $k'(\sin^2 \theta_1 - \sin^2 \theta_2)$ should be used but in all cases $\sin^2 \theta_2$ is small compared with the first term. This law is the integrated form of the cosine law. This may be interpreted to mean that the probability of emission of the element of surface excited by the impinging electrons is the same for all directions. The cosine law of distribution applies equally well at voltages as low as 12,500. Fig. 3 illustrates the results for aluminum for the two voltages given.

Dependence of Reflection on Energy of Primary Beam and on the State of the Surface. As stated before, Schonland reported a constant value of total emission for his range of voltage (30-80 K.V.) The values given in Table I show that it is probably not a constant, but decreases with increase of voltage. However, the condition of the surface must be stated before agreement will be found between different observations.

Soller[13], using electron velocities up to 400 volts found that a thorough out-gassing of the metal at 1200° C. greatly reduced the number of slow secondary electrons emitted. Davisson and Germer[14,15] also found effects due to absorbed gases which were difficult to eliminate except by heating the metal to a high temperature for a considerable length of time. Also they found that even under the best vacuum, gas was absorbed by the surface when the metal was cold. Similar effects are found here for high velocity electrons.

Fig. 4 will tend to illustrate. A piece of brightly polished aluminum was placed in the apparatus, and the first point taken at 1740 volts. The pressure in the space where the aluminum was situated was 5×10^{-5} m.m. of Hg. Points were taken up to 112,000 volts. On returning to 12,500 volts, instead of obtaining the

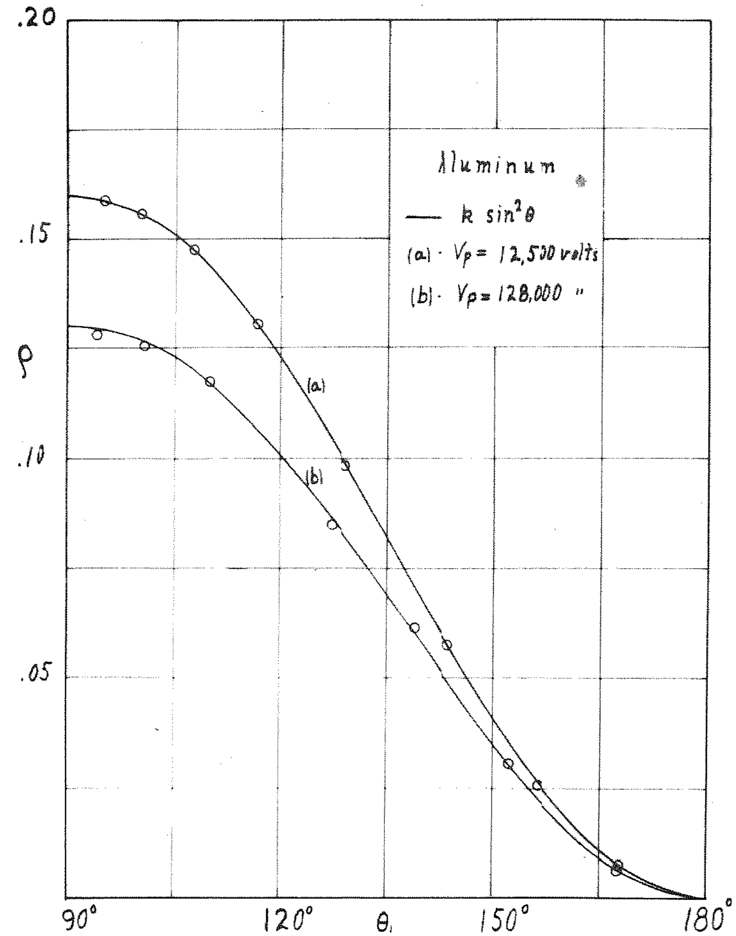

.20
.15
.10
.05
ρ
Aluminum
— k sin²θ
(a) · Vp = 12,500 volts
(b) · Vp = 128,000 "
(a)
(b)
90°
120°
θ
150°
180°

Fig. 3

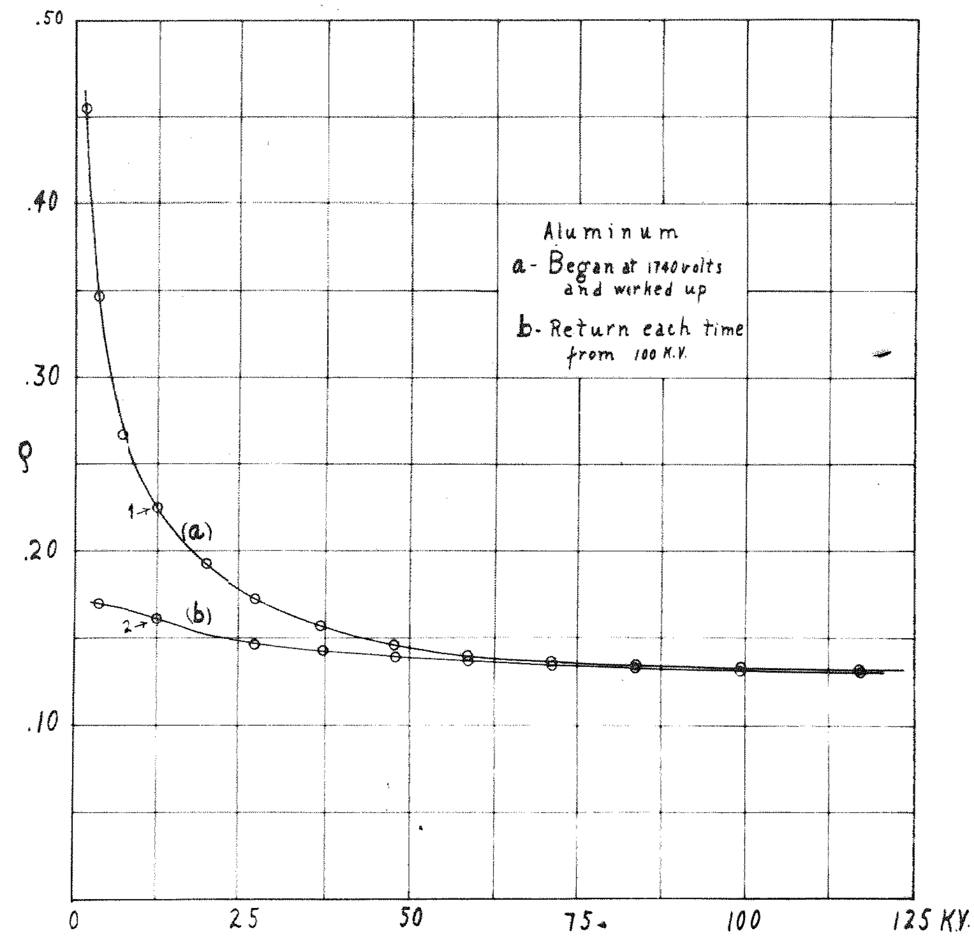

.50
.40
.30
.20
.10
ρ
Aluminum
a - Began at 1740 volts and worked up
b - Return each time from 100 K.V.
(a)
(b)
1→
2→
0
25
50
75
100
125 K.V.

Fig. 4

previous value of .225, the value .161 was obtained. After bombarding the metal for five minutes the value increased to .211. When the mercury pump was turned off the value went up to .223. (Pressure was $1.5x10^{-4}$) This furnished proof that at least some of the anomalous effect at low voltages was due to gas. The points on the curve (b) in Fig. 4 were obtained by returning each time from 100 K.V. and bombarding the surface as little as possible. It is interesting to note, also, that after the aluminum had been bombarded with 100 K.V. electrons for a few minutes and then allowed to stand for four hours, the point "2" and not the point "1" was obtained. From this it appears that bombarding the surface with relatively slow electrons causes it to absorb gas in a high vacuum, while bombarding it with high velocity electrons tends to out-gas the surface.

Stehberger gives the following values for aluminum for the total emission:

V	ρ_0
2000 volts	.60
9000	.42

Since he does not mention heating the metal or using stopping potentials, perhaps his high values can be partially attributed to absorbed gases.

With beryllium, if primary voltages below 70,000 were used, the increase of ρ with time was very noticeable. This was true even when 2500 volts stopping potential was applied. With carbon the lowest primary voltage which could be used without finding an increase of ρ with time was 60,000. With aluminum this phenomenon began at a still lower voltage. No such behavior was found for lead. It appears, then, that absorbed gases play a much more important rolê for the lighter elements at these primary voltages, than for the heavier elements.

The following peculiar behavior was also noticed. A stopping potential of 100 volts would bring the point "1" down to point "2". If the stopping potential were taken off, the point "1" was not obtained immediately. Several minutes bombarding at 12,500 was necessary before it returned to its original value. (See Fig. 4)

<u>Velocity of Electrons Emitted by Solid Surfaces</u>. Wagner[16] and others[17] have found that most of the electrons coming from a solid surface being bombarded with 20 to 40 K.V. electrons have energies .7 to .8 that of the primary beam. The following table will illustrate the relative amounts of slow electrons present for two widely different voltages. Several points should be noted. (1) Slow electrons emitted from the surface are very prominent for low primary voltages. (2) Very few slow electrons are emitted when the primary voltage is high.

TABLE II

Aluminum

V_p = 12,500 volts V_s = Stopping Potential

V_s	θ_1	θ_2	ρ
0	90°0'	172°	.225
100	"	"	.159
500	"	"	.155
1000	"	"	.152
1400	"	"	.149

V_p = 128,000

V_s	θ_1	θ_2	ρ
0	90°0'	172°	.1290
50	"	"	.1285
1000	"	"	.1280
2000	"	"	.1277
2500	"	"	.1275
27,000	"	"	.0945

When either a high or low stopping potential is applied to the electrons emitted by the surface, the cosine distribution of intensities is still found. This means that the slow electrons emitted also have a cosine distribution. The same distribution of secondary electrons was found in the case of thin foils. (See PartI)

More experimental work is needed to correlate more closely the somewhat disconnected facts reported here. It is planned to use a hot target which can be heated to a high temperature. Beryllium will be especially interesting to investigate; first, because it has a high melting point, and second, because absorbed gases seem to play an important role.

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