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Multiple Scattering of Fast Electrons

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The scattering of electrons and positrons of energy from 5 to 17 Mev has been measured in lead foils of thickness 0.015 and 0.038 cm, in carbon laminae of thickness 0.132 and 0.381 cm, and in an aluminum foil of thickness 0.118 cm. The scattering has been shown to be in agreement with the multiple scattering theory of Williams in that the distribution in the product of the scattering angle times the energy of the scattered particle is Gaussian in form, and in that the mean scattering angle times energy is independent of certain geometrical aspects of the experimental method of measurement, and of the energy and sign of charge of the scattered particles. For carbon the experimental magnitude of the mean scattering is in satisfactory agreement with theory, but in aluminum and lead the experimental results are only 85 percent and 60 percent, respectively, of the theoretical predictions.

EXPERIMENTAL results of measurements on the multiple scattering of 10-Mev electrons and positrons in a thin lead foil of 0.015 cm thickness have recently been published.[1] A comparison was made with the calculations of Williams[2] on multiple scattering. The result of this comparison revealed the experimental mean angle of scattering to be slightly less than one-half the theoretical mean angle. In the light of this discrepancy further measurements have been made upon foils of different thickness and atomic number. The results to be discussed in this paper supersede the preliminary values previously published.[3]

THE EXPERIMENTAL MATERIAL

Approximately 52,000 cloud-chamber pictures were examined, 17,000 of these being selected from those taken during the gamma-ray measurements on $B+H^1$ made in this laboratory,[4] and the remainder from the gamma-ray measurements on $Li+H^1$.[5] In these gamma-ray measurements thin scatterers were placed in the center of the chamber and the recoil electrons and pairs produced by the gamma-rays were measured. Large numbers of recoils and pairs originating in the chamber walls and surroundings were found which traversed the foil, and thus supplied material for the study of scattering.

Measurements were made on the scattering in four different foils. The thickness and superficial density of these and the original foil are included in Table I. The carbon employed was Acheson graphite. In the cloud-chamber photographs taken with the thicker lead foil there were two groups of pictures. In the first group the scatterer had been made somewhat smaller than the light beam which illuminated the chamber. For this reason an appreciable fraction of tracks missed the scatterer, were nevertheless photographed and produced deviations in the experimental results requiring correction. This group was used only in the study of single scattering where the results were not subject to any correction from this cause. In all the other sets of photographs, this difficulty did not arise.

THE THEORY OF MULTIPLE SCATTERING

The theory of multiple scattering has been given by Williams[2] and others. Williams considers the projection of the angle of scattering on a plane in order to facilitate comparison of the theoretical calculations with the results of cloud-chamber measurements. The distribution (Fig. 1) of this projected angle α is Gaussian in the multiple scattering region with an abrupt transition at a critical angle α_{ms} to a single scattering tail. The Gaussian portion is given by the expression

$$P_m(\alpha)d\alpha=(2/\pi\alpha_m)\exp\left[-(\alpha/\alpha_m)^2/\pi\right]d\alpha, \quad (1)$$

where α_m is the arithmetic mean angle of the Gaussian part of the curve. The distribution in (1) is obtained by superimposing the small angle

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[1] W. A. Fowler, Phys. Rev. **54**, 773 (1938).

[2] E. J. Williams, Proc. Roy. Soc. **A169**, 531 (1939).

[3] C. W. Sheppard and W. A. Fowler, Phys. Rev. **56**, 849 (1939).

[4] Fowler, Gaerttner and Lauritsen, Phys. Rev. **53**, 628 (1938).

[5] Delsasso, Fowler and Lauritsen, Phys. Rev. **51**, 391 (1937).

single scattering upon a Gaussian distribution which is purely multiple scattering. To a good approximation the total scattering curve remains Gaussian out to the tail. The Gaussian distribution due to multiple scattering alone has an arithmetic mean angle $\bar{\alpha}_1$, given by

$$\bar{\alpha}_1 = \delta(\log_e M)^{\frac{1}{2}}, \tag{2}$$

where δ is a natural scattering unit angle given by

$$\begin{aligned}\delta = 2(Nt)^{\frac{1}{2}}Zr_0/\beta^2\xi \simeq 2(Nt)^{\frac{1}{2}}Zr_0(m_0c^2/W) \\ = 12.7(\sigma/A)^{\frac{1}{2}}Z/W \text{ degrees}\end{aligned} \tag{3}$$

and M is a dimensionless quantity giving the mean number of collisions which occur in the multiple scattering process. It is expressible as

$$M = 2\pi Z^{4/3}Nt\hbar^2/1.75^2 m_0^2\beta^2c^2 \simeq 1850Z^{4/3}\sigma/A, \tag{4}$$

where N = number of atoms of scatterer per cc,
t = thickness of scatterer,
σ = superficial density in grams/cm^2,
Z = atomic number of scatterer,
A = atomic weight,
$r_0 = e^2/m_0c^2$ = classical electron radius,
βc = velocity of electrons,
$\xi = (1-\beta^2)^{-\frac{1}{2}}$,
W = kinetic plus mass energy of electrons (Mev).

The arithmetic mean $\bar{\alpha}$ of the entire distribution including the tail is

$$\bar{\alpha} = 0.80\bar{\alpha}_1 + 1.45\delta. \tag{5}$$

Williams also defines the quantity φ_2 as the angle of intersection of the multiple scattering curve whose mean angle is $\bar{\alpha}_1$ and the single scattering tail and finds it to be given by

$$\varphi_2 = 5.1\bar{\alpha}_1 - 4.0\delta. \tag{6}$$

The angle α_m described above is then found to be

$$\alpha_m = (\bar{\alpha} - \pi\delta^2/\varphi_2)(1 - \pi\delta^2/2\varphi_2^2)^{-1}. \tag{7}$$

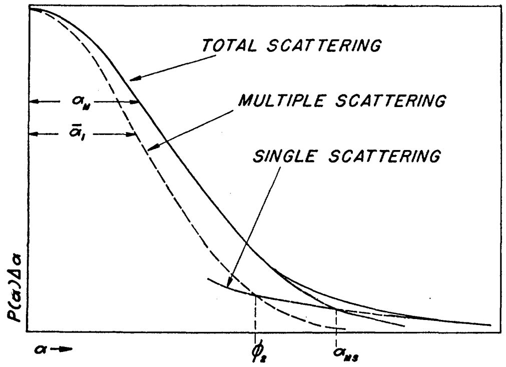

FIG. 1. Theoretical distribution of scattering according to Williams. The curve for purely multiple scattering is Gaussian with an arithmetic mean angle $\bar{\alpha}_1$. It intersects the single scattering curve at φ_2. The total scattering curve is nearly Gaussian merging at φ_2 into a single-scattering tail, taken as the sum of the two dashed curves beyond this point. α_m is the arithmetic mean angle of the Gaussian part of the solid curve. If continued beyond φ_2 it intersects the single scattering at α_{ms}. Single scattering is exaggerated for the sake of clarity.

Formulas (5), (6) and (7) have been taken from a paper by Williams to be published shortly, and are slightly more accurate for the scatterers used in these experiments than those in the previous paper. In Table I we have given the numerical values in units of δ of the above angles for the scatterers used in these experiments. The unit angle δ is given in degrees and is calculated using an effective value of Z corrected for the scattering due to extranuclear electrons, *viz.*, $Z_{\text{eff}} = (Z^2+Z)^{\frac{1}{2}}$. The value of W used in these calculations was arrived at by calculating the mean of $1/W$ for the energy spectrum of the electrons and positrons measured. This gave $\langle 1/W\rangle_{\text{Av}} = 1/21m_0c^2$ almost exactly for the data used for all scatterers. We have also included the values of M for each foil. Although the "experimental" values for M are somewhat less than those tabulated it is nevertheless clear that since $M \gg 1$ the great bulk of the scattering observed in these experiments is multiple.

TABLE I. *Numerical values of theoretical scattering angles for 10-Mev particles. Thickness t in cm, superficial density σ in g cm^{-2}, unit scattering angle δ in degrees, the last five quantities in units δ, M dimensionless.*

MATERIAL	t	σ	δ	M	$\bar{\alpha}_1$	$\bar{\alpha}$	φ_2	α_m	$\bar{\alpha}_{in}$
Pb	0.015	0.170	2.80	539	2.51	3.46	8.80	3.17	3.28
Pb	0.038	0.431	4.47	1365	2.68	3.60	9.68	3.33	3.42
Al	0.118	0.319	1.74	666	2.56	3.50	9.08	3.21	3.35
C	0.381	0.605	1.73	1017	2.63	3.56	9.41	3.28	3.42
C	0.132	0.210	1.01	352	2.42	3.39	8.35	3.08	3.28

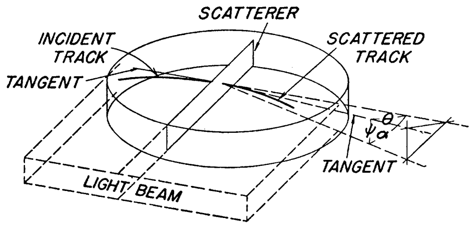

FIG. 2. Geometrical arrangement of the scattering experiment. α is the projection of the angle of scattering θ upon the plane of the cloud chamber. ψ is the vertical component of the scattering.

In Fig. 2 the geometry of the experiment is shown. The chamber is illuminated by a horizontal light beam. All tracks within the light beam are seen, disappearing when they go out of the illuminated portion of the chamber. Setting an arbitrary limit on the length of any track after leaving the scatterer imposes a limit on the vertical angle of scattering, ψ. In most of the work here reported this limit is 3 cm so that since the light beam was 1.6 cm deep we have $-15° \leq \psi \leq 15°$. This limitation does not affect the multiple scattering which is independent of the vertical angle, but changes the observed distribution of the single scattering tail. According to Williams[2] this altered distribution is

$$P_s(\alpha)d\alpha=(2\kappa/\pi\alpha^3)(\beta+\tfrac{1}{2}\sin 2\beta), \qquad (8)$$

where $\kappa=\pi\delta^2$ is the single scattering coefficient, $\tan\beta=\psi_l/\alpha=15°/\alpha$, and ψ_l is the upward or downward limit imposed on the vertical angle in the experiment.

It is necessary to make this correction in all calculations involving the single scattering including computations of $\bar{\alpha}$. This has been done for the theoretical calculations given in Table I. The corrected $\bar{\alpha}$ Williams denotes by $\bar{\alpha}_{in}$.

MEASUREMENT OF THE SCATTERING

The measurements were made in the same manner as described by Fowler and Oppenheimer.[6] From the data recorded we were able to compute the incident and emergent energy of the scattered electron or positron, the angle of scattering in the plane of the cloud chamber, and the straight line length of path in the scatterer.

In the measurements some of the tracks appearing on the photographs were rejected for the following reasons: (a) primary track too short for accurate energy measurement. (b) track not clear near the scatterer. (c) track visibly distorted in the gas of the chamber. (d) tracks offset at the scatterer more than two millimeters. (e) old tracks too diffuse to permit accurate measurement.

In the measurements on lead all the tracks not rejected were measured irrespective of the length of the emergent track. Since little use was later made of those with a scattered length less than 3 cm these tracks were not measured in the measurements on carbon and aluminum. The later measurements on lead and those on carbon and aluminum contained a record of the direction of scattering with respect to the tangent to the incident track. As should be expected the record gave approximately as many on one side as on the other.

It is difficult to estimate the experimental error but we have endeavored to do so by using a few tracks accidentally measured twice and some material measured by two different observers. We estimate our mean error in the

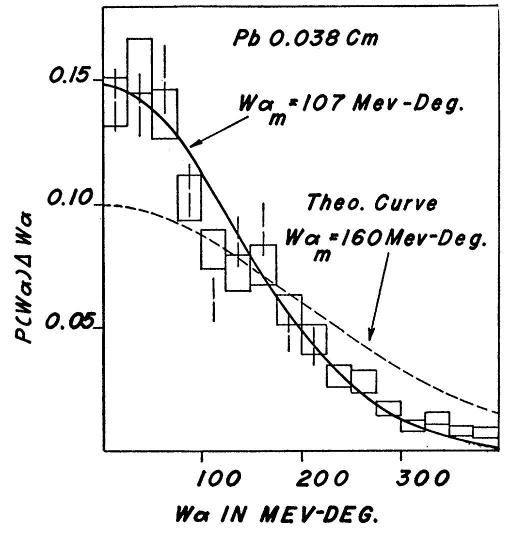

FIG. 3. Comparison of theory and experiment for Pb 0.038 cm thick. Squares represent all tracks with vertical angle of scattering between ±15 degrees. Vertical lines represent tracks of this group with vertical angle between ±7.5 degrees.

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[6] W. A. Fowler and J. Oppenheimer, Phys. Rev. **54**, 320 (1938).

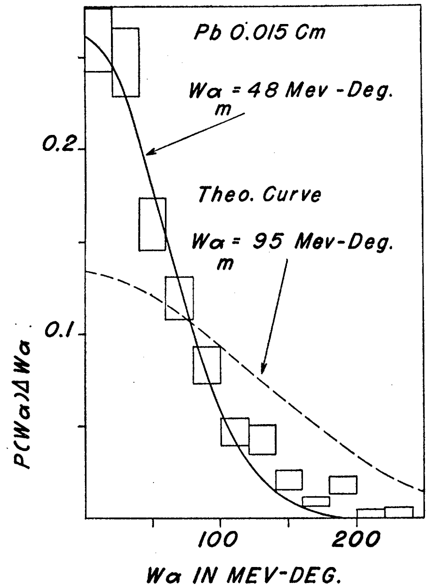

FIG. 4. Comparison of theory and experiment for Pb 0.015 cm thick. (Redrawn from the data of Fowler, reference 1.)

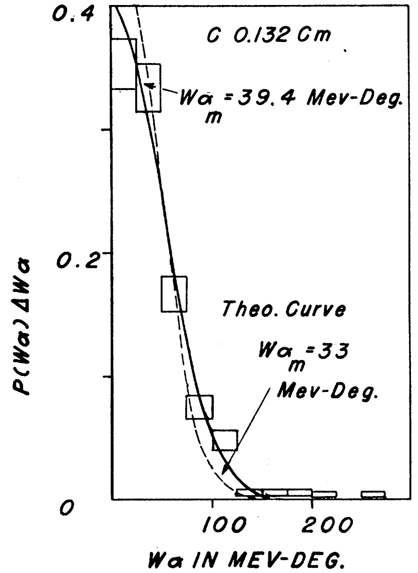

FIG. 5. Comparison of theory and experiment for C 0.132 cm thick.

measurement of the scattering angle not to exceed 1° and in the measurement of energy, 1 Mev.

COMPARISON OF THEORY AND EXPERIMENT

The electrons and positrons measured in these experiments had a rather broad distribution in energy with a maximum at a little over 10 Mev. In comparing the theoretical calculations with the scattering of particles having such a continuous distribution in energy it is profitable to rewrite (1) as follows:

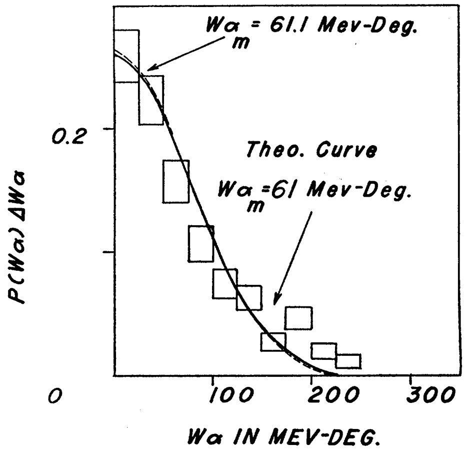

FIG. 6. Comparison of theory and experiment for C 0.381 cm thick.

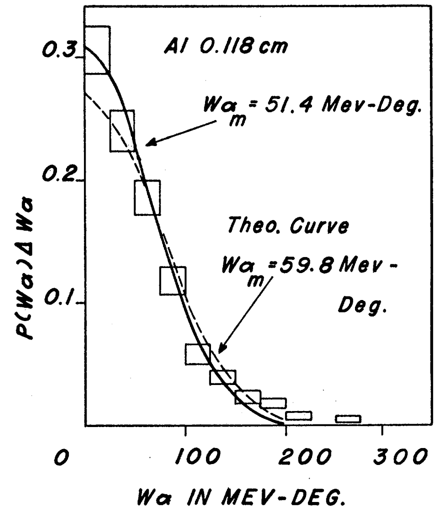

FIG. 7. Comparison of theory and experiment for Al 0.118 cm thick.

$$P_m(W\alpha)d(W\alpha) = (2/\pi W\alpha_m)\exp\left[-(W\alpha/W\alpha_m)^2/\pi\right]d(W\alpha). \quad (9)$$

In this form the distribution in $W\alpha$ is theoretically independent of the total energy W since to a good approximation α_m is inversely proportional to W.

The experimental distributions in $W\alpha$ for the various foils are shown in Figs. 3, 4, 5, 6 and 7.

In calculating $W\alpha$ for any given track we have used for W the mean of the incident and emergent energy of the track. We have chosen to compare the theoretical and experimental values both for $\langle W\alpha\rangle_{\text{Av}}$ and $(W\alpha)_m$ (see Table II) because $\langle W\alpha\rangle_{\text{Av}}$ is the easily computed mean of the entire distribution in $W\alpha$ and $(W\alpha)_m$ is directly proportional to the observed width of the Gaussian portion of the total scattering. Theoretically these quantities are equal, respectively, to $W\bar{\alpha}_{in}$ and $W\alpha_m$ since both $\bar{\alpha}_{in}$ and α_m are to a very good approximation inversely proportional to W. Within the statistical fluctuations this is also found to be true experimentally as will be more fully discussed later.

The "corrected" experimental values given in Table II have been found by computing the square root of the difference of the squares of the observed values and the estimated mean error of measurement of $W\alpha$. In this mean error the error in the measurement of W cancels out approximately since as Professor Williams points out, the error in W is less than the mean W. Thus $\Delta W\alpha \backsimeq \bar{W}\Delta\alpha$ which we estimate to be at most equal to 10 Mev-degrees.

For the thickness of the scatterer used in computing $W\bar{\alpha}_{in}$ and $W\alpha_m$ theoretically, a value was obtained by multiplying the measured thickness by the mean of the secants of the angle of incidence of the tracks, this being found by computation from a group of 100 tracks. It was found to be 1.155. It is this corrected and a similarly corrected superficial density which are used throughout this report. No correction was made for the additional scattering path due to the scattering as for average angles of scattering of approximately 5° to 10° this is quite small. In any case it will increase the theoretical values given.

TESTS OF THE MULTIPLE SCATTERING

(1) Stereoscopic measurements

Although practically all of the measurements were made on only one of the pair of stereoscopic cloud-chamber pictures available it was felt wise to make a stereoscopic check to insure that in no way could tracks get around the scatterer and thus decrease the mean $W\alpha$. For this reason 95 tracks taken from the 0.038-cm Pb group were remeasured in a stereoscopic projector. In this measurement only those tracks were taken which traversed the scatterer within $\frac{1}{4}''$ of its center. For these tracks $(W\alpha)_m$ was found to be 99 Mev-deg. as compared with 102 Mev-degrees for all tracks measured.

(2) The vertical angle of scattering

For the small angles of scattering found experimentally it is approximately true that $\theta^2=\alpha^2+\psi^2$ where θ is the angle of scattering, α is its projection on the horizontal plane and ψ on the vertical plane. Then since $e^{-\theta^2}=e^{-\alpha^2}e^{-\psi^2}$, it is a fundamental requirement of multiple scattering that the form of the distribution with projected scattering angle α be independent of the limits placed on the vertical angle of scattering ψ by the geometry of the scattering experiment. In the measurements on the scattering in the 0.038-cm Pb foil we have determined the distribution in $W\alpha$ for all tracks with emergent length over 6 cm ($\psi_l=\pm 7.5°$) and over 3 cm ($\psi_l=\pm 15°$). Both distributions properly normalized are shown in Fig. 3. Since the mean angle of scattering is 12° the distributions pertain, respectively, to 38 percent and 68 percent of the total number of scatterings and their agreement over the range in $W\alpha$ below 200 Mev-degrees is further evidence that the observed scattering is essentially multiple.

TABLE II. *Comparison of theory and experiment. All values in Mev-degrees. Corrected experimental values represent correction for the broadening of the Gaussian curve due to an error of measurement estimated to be 10 Mev-degrees.*

MATERIAL	t IN CM	NUMBER OF TRACKS	EXPERIMENTAL		CORRECTED EXP.		THEORETICAL		RATIO OF EXP. TO THEO.	
			$(W\alpha)_m$	$\langle W\alpha\rangle_{\text{Av}}$	$(W\alpha)_m$	$\langle W\alpha\rangle_{\text{Av}}$	$W\alpha_m$	$W\bar{\alpha}_{in}$	$(W\alpha)_m$	$\langle W\alpha\rangle_{\text{Av}}$
Pb	0.015	362	48.0	55.0	47	54	95	98	0.50	0.55
Pb	0.038	597	107.0	117.0	106	117	160	164	0.66	0.71
Al	0.118	441	51.4	56.6	50	56	60	62	0.83	0.90
C	0.381	252	61.1	71.6	60	71	61	63	0.98	1.13
C	0.132	400	39.4	41.4	38	40	33	35	1.15	1.14

(3) Energy and sign of charge of the scattered particles

It has been previously emphasized that $(W\alpha)_m$ should be independent of the energy W. In Table III $(W\alpha)_m$ is given for two energy ranges of the observed particles. For several scatterers $(W\alpha)_m$ appears to increase definitely with energy but in no case is the difference large compared to the expected statistical fluctuations.

Since the multiple scattering is due principally to small angle single scattering which obeys the relativistic modification of Rutherford's classical scattering formula, it should be independent of the sign of the charge of the scattered particle. We have also given in Table III $(W\alpha)_m$ for both positrons and electrons. Again, the differences do not exceed the expected fluctuations.

SINGLE SCATTERING

Unfortunately there are too few tracks in the single scattering region to make a satisfactory treatment of the subject possible. An approximate idea, however, could be had in the case of the scattering in the 0.038-cm lead foil. To do this we made use of the group of pictures in which the scatterer was smaller than the light beam. These were not used in the figures given for the multiple scattering. The first interval in $W\alpha$ which is increased by a large number of apparent zero angle scatterings was adjusted to fit a Gaussian curve, and when combined with the other material gave 1590 tracks. The distribution in the tail is shown in Fig. 8. For purposes of comparison the Rutherford single scattering curve has been shown as line B. The curve C represents a smooth joining of this scattering to the observed multiple scattering A. We can only conclude that in order of magnitude the single scattering is not far wrong.

TABLE III. *$(W\alpha)_m$ for two energy ranges and for positrons and electrons. Values are corrected for broadening due to estimated error in angle measurement of 1°. All values in Mev-degrees.*

MATERIAL	t IN CM	ENERGY RANGE 0-11 MEV	ENERGY RANGE 11-20 MEV	POSITRONS	ELECTRONS
Pb	0.015	43	44		
Pb	0.038	96	114	114	103
Al	0.118	37	38	36	40
C	0.132	46	56	47	52

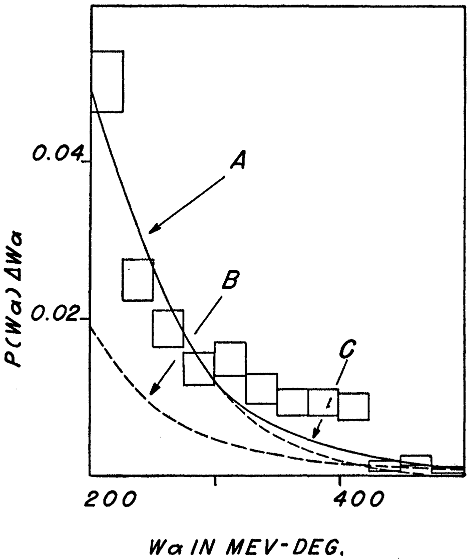

FIG. 8. Single-scattering tail for Pb 0.038 cm thick. A is the Gaussian portion of the total scattering curve. B is the theoretical single-scattering curve. An empirically selected cut-off at 375 Mev-degrees and addition to curve A gives tail C.

THE FORMATION OF HIGH ENERGY SECONDARIES AND PAIRS

Although the scattering measurements on 0.038 cm lead were nonstereoscopic, a special examination of this material was also made stereoscopically in a search for high energy secondaries and pairs. We observed 1887 traversals of the lead foil. In six cases secondaries were observed which close examination of the pictures proved to be authentic and to satisfy the conservation of energy. In none of these was momentum conserved. This is to be expected since the number of scatterings after the original secondary production is not small. The total cross section is of the order of 5×10^{-24} cm^2. This is not in serious disagreement with the theoretical cross section 10^{-23} cm^2 given by $\sigma\sim2\pi r_0^2Z/W_s$ where W_s is the minimum observable energy for secondaries.

Three cases were found which at first glance seemed to indicate the production of secondary pairs. In one the positron appeared alone. Careful examination of this showed that the track did not really intersect the primary track. In the other two cases energy was not conserved, and the energy of the pairs was close to 17 Mev which was the energy of the gamma-rays used to produce the recoil electrons. These cases were taken to be pairs produced by gamma-rays with their origin accidentally coincident with the point of traversal of an electron. The null results are in agreement with the low theoretical cross section for the process.

CONCLUSIONS

An inspection of Table II indicates that the marked discrepancy originally found between the experimental and theoretical scattering in lead has been confirmed but that a similar discrepancy has not been found in aluminum and carbon scatterers. The scattering in carbon shows a satisfactory agreement with theory. Although the scattering in the thinner carbon absorber is somewhat higher than theory permits, it is to be recalled that all of the experimental factors tend to increase the measured mean angle of scattering and for this reason we do not believe the discrepancy to be serious. For the same reason, however, it must be pointed out that the scattering in aluminum is definitely less than predicted by theory even though the deviation from theory is not nearly so great as in the case of lead.

Our new measurements on the scattering in lead, employing a thicker lead foil, indicate a definite deviation from the theoretical predictions. Although the deviation is somewhat smaller than for the original lead foil we hesitate to ascribe too much importance to this point as the measurements were made by two different observers.

Because of the discrepancy in the case of the scattering in lead we have endeavored to test the dependence of this scattering on various factors at our disposal. We have shown the mean angle of scattering to be independent to a good approximation of the vertical position of the incident track in the chamber, of the vertical angle of scattering and of the energy and sign of charge of the scattered particle. All of these findings as well as the Gaussian form of the scattering curves are readily accounted for by the multiple scattering theory and only in regard to the numerical value of the mean scattering does the theory break down.

Noted added in proof.—The recent work of Crane[7] and his collaborators at Ann Arbor can be compared with the results presented here. For electrons ranging in energy from 2 to 8 Mev they find the experimental scattering to be 0.86 of the theoretical in carbon and 0.65 in lead. For electrons of 0.9 Mev energy scattered in aluminum they find the most probable scattering angle to be only 0.75 of the theoretical value calculated by Bethe, Rose, and Smith.[8] For very thin aluminum, however, their observed mean scattering is 0.90 of the value given by Williams' theory. These results are to be compared with our average ratios for the experimental to the theoretical scattering of 1.13 for carbon, 0.90 for aluminum, and 0.63 for lead (see last column of Table II). Only in the case of the scattering in lead are the experimental results here and at Ann Arbor in sufficient agreement and in sufficient deviation from theory to warrant the assertion that Williams' theoretical calculations are in definite disagreement with the observed scattering.

Two attempts have been made recently to improve and extend Williams' calculations. Wheeler[9] has investigated the high order interference effects of the microcrystalline structure of the scattering material while Goudsmit and Saunderson[10] have proposed a new method of calculating the multiple scattering and have critically examined the effects of screening and of various approximations in Williams' theory. Both investigators report smaller theoretical values for the scattering in lead and it can be concluded that modifications of the existing theoretical calculations can still be made without necessitating a radical revision of our present

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[7] Oleson, Chao, Halpern and Crane, Phys. Rev. **56**, 482, 1171 (1939); M. M. Slawsky and H. R. Crane, Phys. Rev. **56**, 1203 (1939).

[8] Bethe, Rose, and Smith, Proc. Am. Phil. Soc. **78**, 573 (1938).

[9] J. A. Wheeler, Phys. Rev. **57**, 358 (1940).

[10] S. Goudsmit and J. L. Saunderson, Phys. Rev. **56**, 122 (1939); **57**, 24, 73 (1940). See also A. E. Ruark, Phys. Rev. **57**, 62 (1940).

concepts of the interaction between electrons and nuclei in the elementary scattering process. In addition, we wish to emphasize that the theoretical predictions for secondary production, a process intimately connected with scattering, have been found to be in satisfactory accord with experiment.

In conclusion we wish to express our appreciation to Professors E. J. Williams, J. R. Oppenheimer, and J. A. Wheeler for correspondence and discussions concerning the theoretical aspects of the scattering problem. Our indebtedness to Professor C. C. Lauritsen is also to be acknowledged.

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Scattering and Polarization of Electrons

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The possibility of accounting for the small polarization of electrons, as observed in the double scattering experiments and the anomalously small scattering of fast electrons ($E\gtrsim 500$ kev) in heavy scattering materials, by the assumption of non-Coulombian forces near the nucleus is investigated. It is assumed that the range of the anomalous forces is of the order of the nuclear (or electron) radius so that for all energies of interest ($E<2$ Mev), the range is much smaller than the wave-length of the electrons. Consequently, the scattering of only $s_{\frac{1}{2}}$ and $p_{\frac{1}{2}}$ electrons need be considered. Without any further assumptions as to the nature of the forces it is found that the phase shifts due to the deviation from the pure Coulomb field are too small to account for the observed scattering and asymmetry (relative difference between scattering at azimuth 0 and π in double scattering) unless the inside wave functions at the boundary are nearly equal to the irregular part of the outside wave functions. In general this can be the case for either the $s_{\frac{1}{2}}$ or the $p_{\frac{1}{2}}$ wave function so that either the $s_{\frac{1}{2}}$ or the $p_{\frac{1}{2}}$ waves are scattered anomalously with appreciable phase shifts, but not both. The results for the scattering and asymmetry, at 90° in Au, when only one wave is scattered are: For the scattering of $s_{\frac{1}{2}}$ waves the asymmetry has a minimum value which for low energies, 100 to 300 kev, is 5 to 6 times greater than the observations allow; at higher energies, 500 to 1500 kev the scattering intensity has a minimum value of 25 to 40 percent of the Coulomb scattering which is somewhat larger than the observed ratio but is perhaps not beyond the limits of experimental error. The asymmetry corresponding to this minimum scattering is about the same as the asymmetry for the Coulomb field, *viz.* about 5 percent at these energies. Without any measurements at high energies it is difficult to exclude the possibility that the asymmetry may be as large as this. When only $p_{\frac{1}{2}}$ waves are scattered anomalously the correct asymmetry and scattering may be obtained at low energies. At high energies the minimum scattering is 70 to 80 percent of the Coulomb scattering which seems much too large. Therefore in order to obtain an asymmetry and scattering which are not in obvious disagreement with the observations it is necessary to assume either a large range or a specialized form for the non-Coulombian forces. The specialized form must be such that either of the following may take place: (1) At low energies only the $p_{\frac{1}{2}}$ wave is scattered and at high energies only the $s_{\frac{1}{2}}$ wave is scattered. (2) Both waves are scattered at all energies despite the small range of the forces. In the first case it seems necessary to postulate an interaction which has a rather strong energy dependence in the energy region where the scattering begins to depart from the Coulombian value. In the second case it is seen that the interaction must be very large, several times $137mc^2$, and in addition a rather special energy dependence would seem necessary. Insofar as these possibilities do not seem plausible it would appear that the anomalous scattering and asymmetry must be explained on grounds other than the existence of non-Coulombian forces.

Introduction

It has been shown by Mott[1] on the basis of the relativistic wave equation of Dirac that an initially unpolarized beam of electrons becomes polarized after a large angle scattering by a heavy nucleus. Moreover, according to the theory the polarization should effect an asymmetry about the azimuth if the beam is scattered a second time from a similarly heavy scattering material through a similarly large scattering angle. It is supposed that the effect be observed under conditions insuring single scattering.

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* Sterling Fellow.

[1] N. F. Mott, Proc. Roy. Soc. **A135**, 429 (1932).