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Electron Polarization

C. G. Shull,* C. T. Chase, and F. E. Myers†
Department of Physics, New York University, University Heights, New York, New York

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The double scattering experiment has been repeated with a 400-kev beam of electrons obtained from a Van de Graaff electrostatic generator. The electrons are scattered by thin gold foils and are counted by Geiger-Müller counters. After eliminating spurious asymmetries, a polarization asymmetry of 8 percent for gold foils is found, which becomes 1 percent in the opposite direction when an aluminum foil is inserted in place of one of the gold foils. Reducing the atomic number of the scattering centers in this way should reduce the theoretical polarization asymmetry to a much smaller value. The reflection-transmission effect found by Chase and Cox has been confirmed and is shown to play an important part in polarization experiments. A reflection polarization experiment (in which only electrons which have been "reflected" from the inclined foils are studied) is shown to produce a much smaller asymmetry than does a transmission polarization experiment (in which only electrons which have been transmitted through the inclined foils are studied). A final polarization ratio of 1.12 ± 0.02 is obtained for comparison with the theory.

I. INTRODUCTION

In a number of experiments, starting with that of Cox, McIlwraith, and Kurrelmeyer[1] in 1928, the attempt has been made to find evidence of polarization in a beam of free electrons. The early experiments were made without the guidance of any clear theory, their methods being suggested by analogy with phenomena of light or x-rays or with the Stern-Gerlach experiment. The results were either negative or were rendered questionable by the results of later experiments or by theoretical developments.

The most recent experiments have been guided by Mott's theory. Using the Dirac equations in treating the scattering of electrons by atomic nuclei, Mott[2] has shown that under suitable conditions a beam of initially unpolarized electrons (no preferential spin direction) will become partially polarized (more spin axes pointing in one direction than in any other) upon scattering by atomic nuclei. By projecting a beam of electrons onto a thin foil (polarizer), and passing some of the scattered electrons onto a second thin foil (analyzer), one should observe a difference in the number of electrons scattered in the two directions F_2S and F_2N, cf. Fig. 1. The two positions S and N will be referred to in the later discussion as the anti-parallel (180°) and parallel (0°) positions, respectively.

In order that the polarization ratio η (the ratio of the number of electrons scattered in the direction F_2S to the number scattered in the direction F_2N) be not too close to unity, the following experimental conditions should be fulfilled:

(1) Energy of the incident electrons should not be too small,

$$E>30 \text{ kev}.$$

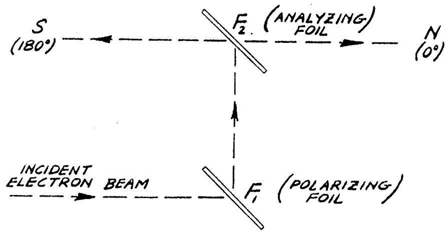

Fig. 1. Schematic diagram of experiment.

(2) Atomic number (Z) of the scattering nuclei should be such that

$$(Z/137)^2\sim 1.$$

(3) Scattering angles should be large, comparable with 90°.

(4) Scattering foils should be thin enough to insure single scattering.

The variation of η with electron energy as calculated by Mott for gold with scattering angles

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* Now with The Texas Company, Beacon, New York.

† Now at Frankford Arsenal, Philadelphia, Pennsylvania.

[1] R. T. Cox, C. G. McIlwraith, and B. Kurrelmeyer, Proc. Nat. Acad. Sci. **14**, 544 (1928). Some of the first experiments are described by G. P. Thomson, *Wave Mechanics of Free Electrons* (McGraw-Hill Book Company, New York, 1930). Most of the others are listed by F. E. Myers, J. F. Byrne, and R. T. Cox, Phys. Rev. **46**, 777 (1934).

[2] N. F. Mott, Proc. Roy. Soc. **124**, 425 (1929); **135**, 429 (1932).

of 90° can be seen in Fig. 2. Bartlett and Watson[3] have published recalculations of the equations used in Mott's treatment and their values are also shown in this graph. Recently, Massey and Mohr[4] have considered the effect of nuclear screening by the extra-nuclear electrons upon the expected polarization asymmetry values. Their results are also shown in Fig. 2. Unfortunately, the Massey-Mohr calculations did not consider electronic energies as high as those actually used in the present experiment. It might be mentioned, however, that the Massey-Mohr curve should merge into the Bartlett-Watson curve at the higher energies, where nuclear screening becomes less effective.

Of the several experiments on electron polarization which have been performed during the last decade, those of Dymond[5] and Richter[6] are perhaps the most noteworthy, in that they met the above experimental requirements most faithfully. Dymond scattered electrons of energy 160 kev from thin gold foils and obtained *no* polarization asymmetry within his experimental error of 1 percent. Using electrons of 120-kev energy and photographic technique in the determination of scattered intensity, Richter also has reported no observable effect. Kikuchi[7] has recently reported a positive effect but his use of thick scattering targets makes his results open to question. All of these experiments will be discussed in greater detail in a later section of this paper.

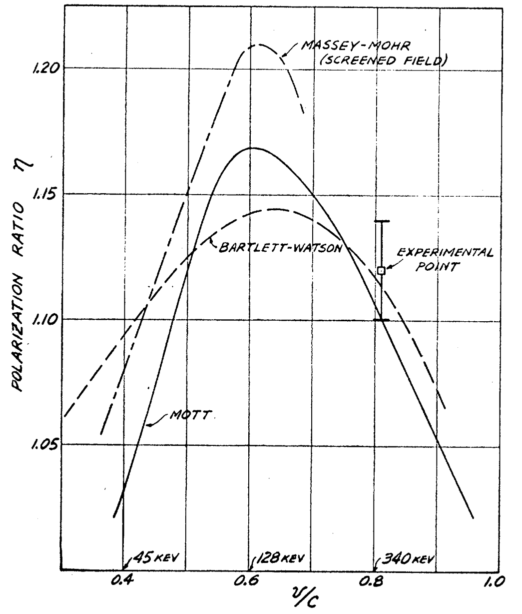

FIG. 2. Theoretical values for the polarization ratio as a function of the velocity v of the scattered electrons. ($c=3\times10^{10}$ cm/sec.).

II. EXPERIMENTAL APPARATUS

A. Electron Beam

The incident electron beam was obtained from a Van de Graaff electrostatic generator. The beam (normally 0.5–2μa) enters the scattering chamber through an insulated quadrant assembly (similar to that used on the electrostatic generator at M. I. T.). Four insulated steel quadrants surround the entrance diaphragm and each quadrant is connected electrically to ground through a small condenser shunted by a $\frac{1}{2}$ watt neon "blinker" tube. Frequency of blinking is thus a measure of beam position. Convenient control over the beam spot position is afforded by two large field coils used for neutralizing the earth's magnetic field along the beam trajectory.

A string of calibrated resistances was used in measuring the voltage of the generator. No great accuracy is claimed in the absolute voltage determination, but the voltage was maintained constant by a stabilizing circuit which controlled the spray current on the charging belts. Variations in voltage were thus kept less than $\frac{1}{2}$ of one percent. In a polarization experiment of this type, it is much more important to keep the energy of the electrons constant than to know that energy absolutely. For all of the data presented in this paper, the energy of the scattered electrons was 400 kev.

B. Scattering Chamber

Detail of the scattering chamber is shown in Fig. 3. The scattering chamber was designed so as to permit study of and correction for any spurious asymmetries which might mask the true

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[3] J. H. Bartlett and R. E. Watson, Phys. Rev. **56**, 612 (1939).

[4] H. S. W. Massey and C. B. O. Mohr, Proc. Roy. Soc. **A177**, 341 (1941).

[5] E. G. Dymond, Proc. Roy. Soc. **A145**, 657 (1934).

[6] H. Richter, Ann. d. Physik **28**, 533 (1937).

[7] K. Kikuchi, Proc. Phys. Math. Soc. Japan **22**, 805 (1940).

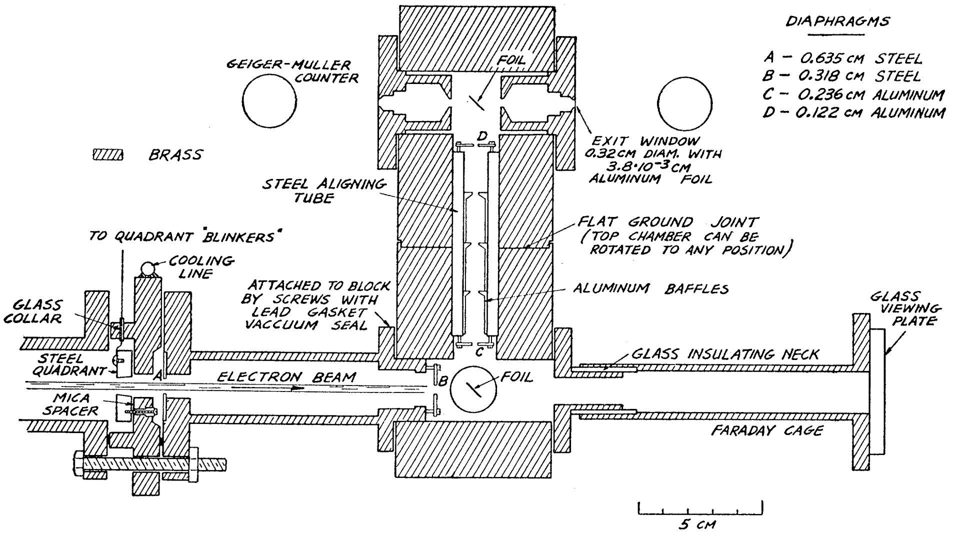

FIG. 3. Scattering chamber assembly.

polarization effect. These asymmetries will be considered at greater length in a later section.

Electrons which have been scattered at the first foil through angles of 90° pass up through two limiting diaphragms and three baffle diaphragms (all of aluminum) to the second foil. Those which are again scattered through angles of 90° pass through thin exit windows of aluminum ($t=3.8\times10^{-3}$ cm) and thence into Geiger-Müller counters. Simultaneous counting is done at the two positions, thereby eliminating the need for monitoring the incident beam.

The scattering chamber was constructed from two brass blocks which were joined together by a vacuum-tight flat ground joint. The analyzing chamber (containing the second scattering foil) could rotate about the vertical axis connecting the two foils without disturbing the vacuum system.

C. Scattering Foils

The foils were prepared by evaporating gold upon a thin collodion sheet and the collodion was dissolved away later in several rinses of acetone. The foil thickness was calculated according to the inverse-square law of deposition as 4.1×10^{-5} cm. Since the foils are inclined at an angle of 45° with the incident electron direction, the effective foil thickness was 5.8×10^{-5} cm—a value nearly four times thinner than the maximum thickness allowed by Wentzel's criterion for single scattering. It would appear that on the basis of Wentzel's criterion, single scattering is clearly insured.

The foils are mounted over quarter-inch holes cut in small tantalum strips. An uncovered, identical quarter-inch hole, adjacent to the one covered by the foil, can be inserted into the beam path by means of a sylphon bellows so as to permit investigation for electrons scattered from the chamber walls, foil holders, etc. Furthermore the whole foil assembly can be rotated 90° about an axis perpendicular to the plane of scattering.

D. Counters and Electrical Circuits

The Geiger-Müller counters were placed immediately outside the exit windows on the two sides of the second scattering foil. Because the counter area exposed toward the foil is considerably larger than the solid angle permitted the electrons by the exit window, counting rates should be independent of counter position. The counters, of thin-walled glass construction, were filled with argon (9-cm pressure) and alcohol vapor (1-cm pressure), and were operated at voltages of 1100 volts (about 100 volts above threshold) obtained from a stabilized power pack. Unfortunately in counting electrons of 400-kev energy, a rather large counter asymmetry developed. This asymmetry, due to a difference in wall thickness, was

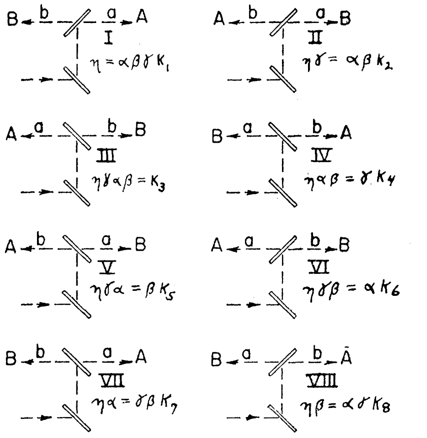

FIG. 4. Diagram which shows the eight different orientations that are possible with the analyzing foil set in the transmission orientation. *A* and *B* represent the two Geiger-Müller counters while *a* and *b* refer to the two exit faces of the analyzing chamber.

eliminated, however, in the calculation of the polarization asymmetry.

Each counter had its own electrical recording circuit consisting of a three-stage amplifier, a pulse skimmer (for elimination of small extraneous pulses), a scale-of-eight scaling circuit, and a mechanical recorder. The circuit pulses were continuously observed and checked with a cathode-ray oscilloscope. Inverse square tests were performed on the counters and their associated circuits and they seemed perfectly reliable with counting rates as high as 1500 per minute. In taking the actual data, counting rates were nearly always below 1000 per minute.

III. COLLECTION AND ANALYSIS OF DATA

Great care must be taken either to eliminate or correct for spurious asymmetries in an experiment of this kind. If no experimental asymmetries were present, then a direct comparison of the rates at the two positions, parallel and anti-parallel, would give the desired polarization result immediately. Three effects are recognized, however, which might contribute to the experimental result and these will be given detailed discussion in the following:

A. Geometrical Asymmetry

A geometrical asymmetry could be caused by factors originating in either the analyzing chamber or the polarizing chamber. Included in the former are differences in the solid angles or effective scattering angles of the two exit windows as seen from the analyzing foil. These can be eliminated by rotating the analyzing chamber 180° on its supporting flat ground joint (mentioned earlier), thereby interchanging the chamber sides with respect to the two counting positions and reversing the asymmetry. An asymmetry caused by a displacement of the incident electron beam from the axis of the polarizing chamber or by a wrinkle (unsymmetrically located with respect to the axis of the beam) in the polarizing foil, would not be eliminated by this chamber rotation procedure. It would be reversed by a 90° rotation of the polarizing foil about an axis perpendicular to the plane of scattering.

B. Reflection-Transmission Asymmetry

Chase and Cox[8] have observed a difference in the number of electrons scattered through angles of 90° on the two sides of an inclined foil. We shall refer to these electrons as "reflected" and "transmitted" electrons, implying those scattered to the side of incidence and to the side of transmission, respectively. Since in the present experiment, electron counting is done simultaneously on both sides of the foil, this reflection-transmission effect should be important. This asymmetry can be eliminated by rotating the analyzing foil through 90° about an axis per-

TABLE I. Sample set of data for scattering foils of gold ($t = 4.1\times10^{-5}$ cm) set in orientation VII of Fig. 4.

Counter *A*		Counter *B*		Electron counts		*B/A*
Total count (5 min.)	Back-ground (2 min.)	Total count (5 min.)	Back-ground (2 min.)	*A*	*B*	
3648		3656		3376	3416	1.012
	104		120			
3896		3840		3624	3600	0.993
	104		80			
4112		4112		3840	3872	1.008
	112		80			
3936		3744		3664	3504	0.956
	120		104			
3936		3808		3664	3568	0.974
	104		88			
Average background (corrected to 5 min.)	272		240		Mean *B/A*	0.988
		$\kappa_7 = 0.988 \pm 0.7\%$				

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[8] C. T. Chase and R. T. Cox, Phys. Rev. **58**, 243 (1940).

pendicular to the plane of scattering, thus reversing the "reflecting" and "transmitting" sides with respect to the two counting directions.

C. Counter Asymmetry

It might be expected that the two counters would respond differently to a beam of 400-kev electrons. This dissimilarity, caused by a difference in thickness of the glass walls, could be studied by simply interchanging the counters while keeping everything else unchanged. The two counters will be referred to as *A* and *B*.

For purposes of data analysis, let the following be defined:

η = true polarization ratio (i.e., number of electrons scattered to the 180° position divided by the number scattered to the 0° position, after correction for the other asymmetries which follow).

β = geometrical asymmetry ratio (i.e., ratio of the effect of face *a* upon the number of electrons scattered through it divided by that of face *b*).

α = reflection-transmission ratio (i.e., number of electrons scattered to the side of incidence of the foil divided by the number scattered at the same angle through the transmission side of the foil).

γ = counter asymmetry ratio (i.e., number of electrons counted by counter *A* and its associated circuit divided by the number counted by counter *B* with the same number incident on both).

Table II. Experimental counting ratios for gold scattering foils with the polarizing foil set in transmission orientation. Total electron count: 308,000.

$\kappa_1=0.399$	$\kappa_5=2.870$
$\kappa_2=1.249$	$\kappa_6=1.136$
$\kappa_3=2.923$	$\kappa_7=0.988$
$\kappa_4=0.972$	$\kappa_8=0.390$

κ_i = experimental counting ratio in the *i*th orientation (i.e., electron counts recorded at the 180° position divided by the number recorded at the 0° position).

With the polarizing foil in the orientation shown in Fig. 1, there exist eight possible orientations of the analyzing chamber and its assembly. These are shown diagrammatically in Fig. 4. The markings *a* and *b* refer to the two exit faces of the analyzing chamber block. As an illustration of the significance of the various orientations (I to VIII), consider orientations I and IV. In the transition from I to IV, the analyzing chamber (foil and exit windows) has been rotated 180° about an axis connecting the foils while the two counters, *A* and *B*, remain unchanged.

With the above definitions for the asymmetries, a series of symbolic equations can be written, one for each orientation, and these are included in Fig. 4. For example in orientation I, all of the ratios (except the polarization ratio) favor counting in the 0° position over that in the 180° position. By combining various equations suitably, the different asymmetries can be evaluated in terms of the experimentally-observed κ's. Thus for example:

$$\eta^2=\kappa_1\kappa_3, \quad \text{and} \quad \alpha^2=\kappa_3/\kappa_6.$$

Table III. Experimental counting ratios for the aluminum-gold combination experiment. Polarizing foil; gold ($t=4.1\times10^{-5}$ cm) set in transmission orientation. Analyzing foil; aluminum ($t=1.1\times10^{-3}$ cm). Total electron count: 309,000.

$\kappa_1=0.266$	$\kappa_5=4.110$
$\kappa_2=0.854$	$\kappa_6=0.932$
$\kappa_3=3.756$	$\kappa_7=1.113$
$\kappa_4=1.103$	$\kappa_8=0.2296$

IV. EXPERIMENTAL DATA

In taking data, five-minute electron counting periods were alternated with two-minute background periods. Two methods of taking the background rates were used: (*a*) the foils could be removed from the beam path and the uncovered holes inserted into position, and (*b*) an aluminum sheet of thickness 1.5 mm (sufficiently thick to stop all 400-kev electrons) could be placed between exit window and counter. Both methods were tried with no significant difference between the results. It appears from this then, that the electrons counted were necessarily those scattered by the foils and not by the foil holder or chamber walls. It might be mentioned that the background correction removes the possibility of the antiparallel counter giving consistently high results because of its location closer to the main beam-limiting diaphragms.

Table I shows a typical set of data obtained with gold foils in orientation VII. The percentage error as applied to the mean value of the ratio has been obtained from the internal consistency of the data. The results of a complete set of data for all of the various orientations listed in Fig. 4 are given in Table II. In obtaining the results in Table II, over 300,000 electron counts were recorded and tabulated.

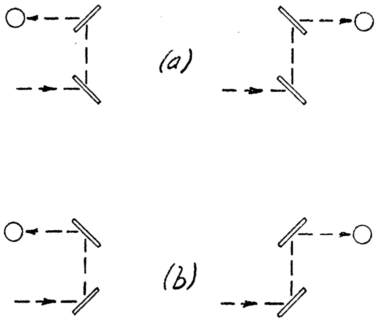

FIG. 5. Diagram showing (a) an ideal transmission experiment and (b) an ideal reflection experiment. Comparison of the two counting rates in either experiment would give directly the corresponding polarization asymmetry.

From the eight different ratios given in Table II, η may be evaluated in four completely independent ways:

$$\eta^2=\kappa_1\kappa_3=\kappa_5\kappa_8=\kappa_2\kappa_4=\kappa_6\kappa_7$$

from which

$$\eta_{\mathrm{Au}}=1.08,\ 1.06,\ 1.10,\ \text{and}\ 1.06,$$

with a geometric mean

$$\eta_{\mathrm{Au}}=1.08\pm0.01.$$

A residual asymmetry of 8 percent is thus obtained for gold foils. As a test on the reality of this asymmetry, the gold analyzing foil was replaced by one of aluminum (thickness 1.1×10^{-3} cm). Since the expected polarization asymmetry varies approximately as Z^2 for like foils, the combination of aluminum and gold foils should give a theoretical asymmetry of 1.7 percent.

The results obtained with the aluminum-gold combination are shown in Table III. If we calculate the residual asymmetry in the same manner as for the gold foils above, we find

$$\eta_{\mathrm{Al-Au}}=1.00,\ 0.97,\ 0.97,\ \text{and}\ 1.02,$$

with a geometric mean

$$\eta_{\mathrm{Al-Au}}=0.99\pm0.01.$$

This indicates a residual asymmetry of one percent in the direction opposite to the polarization effect. The 2.7 percent difference between the theoretical and experimental values for $\eta_{\mathrm{Al-Au}}$ is ascribed to some constant geometrical error which is not eliminated by the rotation of the analyzing chamber as outlined in Section III A. Such an error does not invalidate the main conclusion since it is present in all of the data preceding the evaluation of both η_{Au} and $\eta_{\mathrm{Al-Au}}$. Thus a positive effect has been found for gold foils which is considerably reduced upon the insertion of an aluminum foil, in qualitative agreement with the theory.

V. THE REFLECTION-TRANSMISSION EFFECT

It has been mentioned earlier that the reflection-transmission asymmetry plays a prominent role in double scattering experiments. The numerical value of this asymmetry can be easily obtained from the equations in Fig. 4 and the data given in Table II. Thus,

$$\alpha^2=\kappa_7/\kappa_1=\kappa_5/\kappa_2=\kappa_4/\kappa_8=\kappa_3/\kappa_6,$$

and substituting in values of the κ's for gold, we find $\alpha_{\mathrm{Au}}=1.59$, 1.54, 1.59, and 1.50 with a geometric mean, $\alpha_{\mathrm{Au}}=1.55\pm0.015$. In a similar manner, the reflection-transmission ratio for the aluminum foil ($t=1.1\times10^{-3}$ cm) can be obtained from the data in Table III. This results in $\alpha_{\mathrm{Al}}=2.12\pm0.035$.

This large asymmetry is interesting in that past theories of particle scattering by thin foils have overlooked the possibility of such an effect. Goertzel and Cox[9] show that an effect of this kind may be caused by a type of plural scattering which consists in the combination of two deflections of the same order of magnitude. Such plural scattering is unimportant at normal incidence on foils thin enough to satisfy Wentzel's criterion, but it may be serious at oblique incidence for the "reflected" electrons of our experiment. Their method allows the calculation of only a minimum value of the reflection-transmission asymmetry, which might be several times exceeded by the

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[9] G. Goertzel and R. T. Cox, Phys. Rev. **63**, 36 (1943).

actual value. The minimum value of the asymmetry calculated from their equation is 9 percent for the gold foil and 7 percent for the aluminum foil of our experiment. According to a calculation made for us by Goertzel, the minimum asymmetry for the gold foil is about doubled if Mott's theory of scattering is used.

If plural scattering is responsible for this effect, it is possible that a polarization experiment similar to the present one might be seriously affected by it because of the depolarization which accompanies plural scattering.[10,11] There is the possibility then that a reflection polarization experiment (in which only "reflected" electrons are studied) will yield an asymmetry different from a transmission experiment (in which only "transmitted" electrons are studied). These two types of ideal experiments are shown in Fig. 5. Since both "transmitted" and "reflected" electrons were utilized in calculating the polarization value given in IV, the result obtained is intermediate between that of a pure transmission experiment and that of a pure reflection experiment.

Values for the reflection polarization ratio η_r and the transmission polarization ratio η_t can be obtained by suitably combining the experimental data. All of the data presented in Tables II and III were taken with the first scattering foil set in the transmission position. In order to resolve the data into calculations of η_t and η_r, data must be available with the first foil set in the reflection position. Such data have been acquired and the values for κ are shown in Table IV. By combining all of the data taken with both foils gold, this distinction between the two polarization ratios can be quantitatively determined. The analysis and numerical calculations are included in the Appendix.

The results of these calculations can be written:

$$\eta_t = 1.11 \quad \text{and} \quad \eta_r = 1.02.$$

This indicates a transmission asymmetry of some five times that of a reflection asymmetry. The data preceding these calculations are subject to the same geometrical uncertainties as were present in the evaluation of $\eta_{\mathrm{Al-Au}}$ mentioned earlier. Thus these values are all uncertain to the same degree, about two percent.

VI. DISCUSSION OF RESULTS

The data presented above indicate a positive polarization effect which can be resolved into a transmission polarization asymmetry and a relatively small reflection polarization asymmetry. It is interesting to compare these results with those found in other experiments of this type.

As mentioned earlier, the work of Dymond showed no polarization effect greater than the experimental error of one percent. It would appear from the figure given in his publication, that his experiment was of the reflection type—all of the electrons studied were scattered through the "reflecting" sides of the foils. In view of the present findings in a reflection experiment, the results of Dymond are not in marked disagreement with those reported here. The calculations of Goertzel and Cox indicate that the plural scattering effect varies approximately as t/E^2 where t is the foil thickness and E is the electronic energy. This ratio is roughly the same for the two experiments and thus plural scattering, with its accompanying depolarization, would be as prominent in Dymond's work as in the present. Thus the difference between his result and ours is a matter of a very few, perhaps two, percent. It seems to us likely that, if he had happened to design his apparatus so that the electrons passed through the foils, the experiment would have shown an asymmetry in the twice scattered beam.

TABLE IV. Experimental counting ratios for gold scattering foils with the polarizing foil set in "reflection" orientation. Total electron count; 701,000.

$\kappa_1 = 0.392$	$\kappa_5 = 2.664$
$\kappa_2 = 1.130$	$\kappa_6 = 1.077$
$\kappa_3 = 2.551$	$\kappa_7 = 1.050$
$\kappa_4 = 0.921$	$\kappa_8 = 0.404$

These same arguments will apply to Richter's work, where the conditions of scattering (*viz.*, foil thickness, electron energy, "reflecting" orientation of foils, etc.) were much the same as in Dymond's experiment. It would be expected then that these two experiments should yield an

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[10] M. E. Rose and H. A. Bethe, Phys. Rev. **55**, 277 (1939).

[11] M. E. Rose, Phys. Rev. **57**, 280 (1940).

asymmetry considerably smaller than the original value predicted by Mott.

Kikuchi's experiment made use of thick scattering targets ($\sim 10^{-3}$ cm) also arranged as in a reflection experiment. His experiment has already been criticized by Rose[11] in that thick targets depolarize the scattered electrons. Kikuchi avoids counting inelastically scattered electrons by use of an energy analyzer, but even then the elastically scattered electrons could have suffered depolarizing collisions in the thick targets. In addition to the criticism against the use of thick scattering targets, the "reflecting" orientation of Kikuchi's targets makes his results all the more unexplainable.

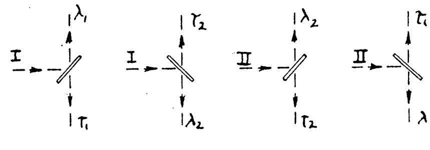

FIG. 6. Definitions of scattered currents when unit intensities of electrons with polarizations I and II strike inclined foils.

The polarization asymmetry for gold foils given in Section IV represents a value intermediate between η_t and η_r, the transmission and reflection asymmetry values. In comparing experimental results with the theoretical predictions those obtained in an ideal transmission experiment should be used, since here the theoretical requirement of single scattering is met most faithfully. The experimental evidence indicates a transmission asymmetry somewhat larger than the 10.4 percent polarization asymmetry calculated by Bartlett and Watson. The uncertainty in the evaluation of the geometrical asymmetry found by means of the aluminum data, prevents accurate determination of η_t. It is believed, however, that a value of $\eta_t = 1.12 \pm 0.02$ is representative of the experimental data. This has been included on the graph of Fig. 2, along with the theoretical curves.

ACKNOWLEDGMENTS

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APPENDIX

We can consider our initially unpolarized beam of electrons to consist of two components, those with polarization I and those with polarization II. We assume unit intensity of one polarization component as incident upon a scattering foil, then the four quantities λ_1, λ_2, τ_1, and τ_2 are defined as the scattered intensities shown in Fig. 6.

In a double scattering experiment, there are four orientations to be considered, and these are shown in Fig. 7. Here the electron intensities are written as sums, the first term in any sum referring to those electrons with polarization I and the second term to those with polarization II. The values of the anti-parallel, parallel ratio, numbered as in Fig. 7 are given by

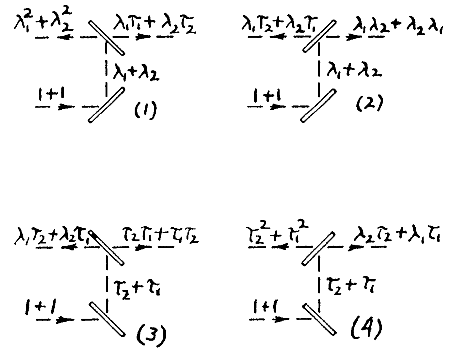

FIG. 7. Diagram showing the four orientations which furnish data for the evaluation of reflection and transmission polarization asymmetries. The first term in any sum represents those electrons with polarization I, cf. Fig. 6.

$$c_1 = (\lambda_1^2+\lambda_2^2)/(\lambda_1\tau_1+\lambda_2\tau_2), \tag{1}$$

$$c_2 = (\lambda_1\tau_2+\lambda_2\tau_1)/(2\lambda_1\lambda_2), \tag{2}$$

$$c_3 = (\lambda_1\tau_2+\lambda_2\tau_1)/(2\tau_1\tau_2), \tag{3}$$

and

$$c_4 = (\tau_1^2+\tau_2^2)/(\lambda_1\tau_1+\lambda_2\tau_2). \tag{4}$$

A true reflection experiment would determine a reflection polarization ratio η_r as

$$\eta_r = (\lambda_1^2+\lambda_2^2)/(2\lambda_1\lambda_2), \tag{5}$$

while a true transmission experiment would determine a transmission polarization ratio η_t as

$$\eta_t = (\tau_1^2+\tau_2^2)/(2\tau_1\tau_2). \tag{6}$$

The experimental data do not permit evaluation of the individual λ's and the τ's, but nevertheless, η_r and η_t can be calculated from the c's, which are obtainable directly from the experimental data. We have from (1), (2), (3), and (4) above,

$$c_3/c_2=(\lambda_1\lambda_2)/(\tau_1\tau_2), \tag{7}$$

$$c_1/c_4=(\lambda_1^2+\lambda_2^2)/(\tau_1^2+\tau_2^2), \tag{8}$$

$$2c_3=(\lambda_1/\tau_1)+(\lambda_2/\tau_2), \tag{9}$$

and

$$2c_2=(\tau_2/\lambda_2)+(\tau_1/\lambda_1). \tag{10}$$

Combining (9) and (10), one obtains

$$(\lambda_2/\tau_2)=c_3[1-(1-[1/c_2c_3])^{\frac{1}{2}}] \tag{11}$$

and

$$(\lambda_1/\tau_1)=c_3[1+(1-[1/c_2c_3])^{\frac{1}{2}}]. \tag{12}$$

Substituting (11) and (12) into (8), we can obtain the ratios τ_1/τ_2 and λ_1/λ_2 and these ratios suffice in determining η_r and η_t.

Using data given for gold foils in Tables II and IV, we can evaluate the c's and from these, then,

$$\eta_t=1.11 \quad \text{and} \quad \eta_r=1.02.$$

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The Effect of Oblique Incidence on the Conditions for Single Scattering of Electrons by Thin Foils

GERALD GOERTZEL AND R. T. COX
New York University, University Heights, New York

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In setting up and applying criteria for the single scattering of electrons by thin foils, it has been usual to assume that the principal deviations from single scattering are caused by the combination of small deflections with one large one. It is here shown that with electrons obliquely incident on the foil much more serious deviations may be caused by the combination of two deflections of the same order of magnitude. It is concluded that the difference observed by Chase and Cox between the scattering at 90° to the two sides of a foil on which electrons are incident at 45° may be ascribed to this cause. The bearing of this factor on the negative result of Dymond's experiment on the polarization of electrons is also considered.

In the theory of scattering of charged particles by thin foils it has been usual to assume normal incidence. In this case most of the deviations from single scattering are caused by the combination with one large deflection of one or several much smaller ones. Scattering through a large angle by two deflections of the same order of magnitude is an occurrence of lower probability.

The theory so derived has often been used in the discussion of experiments at oblique incidence. Thus when theoretical criteria of single scattering, such as Wentzel's, have been applied to experiments, it has been usual to assume that no more allowance for obliquity had to be made than to use the oblique thickness as the effective thickness of the foil. Bartlett[1] has called attention to the need for a more careful consideration of the effects of obliquity, but he published no calculations on the subject. Lately Chase and Cox,[2] studying the scattering of electrons incident at 45° on thin aluminum foils, observed that the scattering at 90° was greater toward the side from which the electrons were incident than toward the other side. This was in spite of the fact that their foil was much thinner than was necessary at this angle to satisfy Wentzel's criterion. Another, more empirical criterion, which they developed for the purpose, was also much more than satisfied. However, in developing this criterion they assumed that the probability of scattering at a large angle by the combination of two deflections of the same order of magnitude could be ignored.

This assumption is investigated in the present calculation. The calculation is made for incidence at 45° with the normal and scattering in the plane of incidence, also at 45° with the normal and thus at right angles to the direction of incidence. In Fig. 1, Oz is the normal. The electrons come from the direction of A, and hence the direction of their velocity at incidence is that of OA', the

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[1] J. H. Bartlett, Jr., Phys. Rev. **57**, 843 (1940).

[2] C. T. Chase and R. T. Cox, Phys. Rev. **58**, 243 (1940).