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DOUBLE MOTT SCATTERING OF ELECTRONS

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The asymmetry of the double scattering of electrons on gold is measured at energies 45—245 keV and angles 90—150°. The data are compared with other experimental and theoretical results.

1. INTRODUCTION

Mott[1] was the first to show that electrons scattered by the electric field of a nucleus are partially polarized perpendicular to the plane of scattering. Sherman[2,3] has calculated accurately the degree of polarization S for scattering by the Coulomb field of a point nucleus at practically all angles and energies. S increases with the nuclear charge; scattering by gold nuclei is of greatest experimental interest. In this case for not very high energies the screening effect of atomic electrons must be taken into account. Calculations in [4,5] have shown that the degree of polarization can be changed by 10—20% as a result of screening in the energy range 30—120 keV; however, the accuracy of these calculations is evidently not greater than 10%.

The results obtained in [2-5] indicate that the general behavior of polarization is as follows. In the energy range from a few tens to a few hundreds of keV the magnitude of S does not change by more than 30—40%. S as a function of the scattering angle θ exhibits a broad maximum in the region 120—135°, where polarization reaches ~40% in the case of scattering on gold. The polarization is extremely small at angles 70—160°.

Mott[1] proposed that the asymmetry of double scattering be observed in order to detect electron polarization. The intensity of doubly scattered electrons is proportional to $1 + S_1S_2 \cos\varphi$, where φ is the angle between the first and second scattering planes. In the appropriate experimental work one ordinarily observes the ratio x of intensities in the directions $\varphi = 0$ and π, obtaining $S_1S_2 = (x-1)/(x+1)$. Attempts to detect the asymmetry of double scattering did not yield positive results for a long time; this was caused by the lack of sufficiently perfected observational techniques and by the underestimation of the plural and multiple scattering effects, which mask polarization. Following a successful experiment by Shull et al[6] a number of double-scattering experiments were performed. However, the results of these investigations did not yield a sufficiently accurate and complete picture of the asymmetry over broad ranges of angles and energies. The results of this former work are included in the discussion of our present results.

Mott scattering constitutes the most sensitive method for determining the degree of polarization $\langle\sigma\rangle$ of an electron beam. The measured quantity is the product $\langle\sigma\rangle S$. Therefore after parity nonconservation in weak interactions was discovered in connection with the measurement of the longitudinal polarization of β electrons, the exact determination of S became urgent. Spivak et al[7] have reported measurements of S at 120° in the range 45—245 keV. The present work continues that of [7] by measuring the angular dependence of S for 90—150° at the energies 63, 133, 170, and 245 keV.

2. DESCRIPTION OF APPARATUS

A focused beam 1 of accelerated electrons was directed from a magnetic monochromator to a chamber containing the first scatterer (Fig. 1). The accelerating voltage was calibrated by means of the 187-keV conversion line of In^{114}, and was known to within at least 2% within the entire interval. The position and shape of the beam were checked by means of a fluorescent screen held in the transparent flanged holder 6. The intersection of the beam with the plane of the first scatterer was a circle of about 15-mm diameter. The electron current entering the chamber reached a few tens of microamperes. Following the first scattering at the angle $\theta_1 = 120°$, the electrons passed through a system of diaphragms before impinging

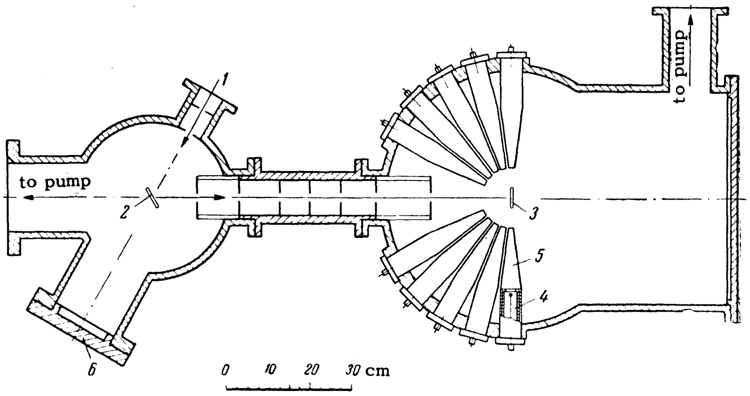


FIG. 1. Schematic drawing of apparatus. 1 – electron beam, 2 – first scatterer, 3 – second scatterer, 4 – counter, 5 – Plexiglas collimator, 6 – flanged holder of fluorescent screen.

on the second scatterer 3 located in a separate chamber at about the distance 70 cm from the first scatterer. Electrons scattered for the second time at angles $\theta_2 = 90°$, 105°, 120°, 135°, and 150° in the directions $\varphi = 0$ and π were registered by the Geiger end-window counters 4.

The scatterers positioned in the first chamber were deposited on aluminum foil 20—25 $\mu g/cm^2$ thick; several scatterers could be interchanged without disturbing the vacuum. The scatterers 3 were deposited on collodion film 10—50 $\mu g/cm^2$ thick stretched on rings 150 mm in diameter. These scatterers, which were interchanged through a vacuum lock, could be rotated around the vertical axis for measurements at $\theta_2 = 90—120°$.

3. BACKGROUND

One of the most serious difficulties in double-scattering experiments is encountered in eliminating the background of electrons scattered from the walls of the apparatus. The role of this effect was reduced by using large chambers; deep "traps" were installed at the places subjected to the most intense electron bombardment; all walls were lined with Plexiglas and the solid angle subtended by the walls at the counters was reduced as much as possible. Nevertheless, measurements performed with a magnetic spectrometer substituted for one counter revealed that the principal peak of doubly-scattered electrons was accompanied by low-energy electrons. It was shown experimentally that the latter electrons were mainly scattered by the walls of the first chamber and joined the beam entering the second chamber as a result of scattering in the first scatterer. Because of the strong energy dependence of scattering their relative intensity increased sharply following the second scattering. Thus, while they constituted only 2—3% of the beam entering the second scatterer for the accelerating voltage 245 keV, the intensity of "soft" electrons somewhat exceeded that of the main group in the spectrum at the counter window. With the reduction of the accelerating voltage the number of soft electrons decreases rapidly, becoming negligibly small at 60 keV. (The spectrometer threshold in these measurements was 15 keV.) The low-energy electrons form a quite broad peak; their energy is 4—6 times lower than that of the main electrons, and the two groups are separated by a large energy interval containing practically no electrons. The extraneous electrons could therefore be absorbed completely by filters placed in front of the counter windows. At 63 and 113 keV the filter was a polyethylene film (4.6 mg/cm^2) separating the working volume from the vacuum. At 170 and 245 keV additional aluminum filters 10 and 17 mg/cm^2 thick, were used.

From a careful investigation of scattering conditions in the second chamber we learned the following. For counters at 90—120° scattering from the walls could be neglected entirely. Counters at 135° and 150° were in a less favorable position because of the diminishing cross section as the scattering angle increased and because they could be reached with higher probability by electrons coming from the most intensely irradiated parts of the chamber. Under the actual operating conditions at these angles the extraneous electrons could be reduced to 1 and 2%, respectively. Further experimentation showed that there was no appreciable change in these percentages when the conditions of wall bombardment were changed as the scatterer was installed in its working position. The background could therefore be measured by removing the scatterer from the path of the beam. The background amounted to 1—7%, depending on the experimental conditions.

4. INSTRUMENTAL ASYMMETRY

The experimentally measured quantity was the intensity ratio of electrons scattered in the directions $\varphi = 0$ and π. Since this ratio includes the ratio of registration efficiencies, the effect of the latter was excluded by performing measurements with an aluminum scatterer replacing the first scatterer.

Time is gained by using aluminum films made as thick as permissible, but this leads to differences between the electron spectra from gold and aluminum. With the counter windows covered by filters the registration efficiencies were very strongly energy dependent, and their ratio, because of unavoidable constructional differences in the counters also depended somewhat on energy. We must remember that the asymmetry under the experimental conditions was such that an error of 1% in the intensity ratio produced an error of 3—10% in S. Therefore the accurate elimination of the instrumental factor was an extremely laborious task. Before starting the main measurements we measured the energy dependence of the counter-efficiency ratio; when necessary, correcting filters were used to achieve the result that a 10-keV change of electron energy was accompanied by a change of at most 0.5—1% in the ratio. This determined the maximum permissible smoothing of the spectrum and thickness of the scatterer. The spectrum of electrons scattered by aluminum was measured with a magnetic spectrometer. Under the operating conditions for eliminating the instrumental factor the scatterer thickness was 1.4 mg/cm^2 at 245 keV, 0.55 mg/cm^2 at 170 and 133 keV, and 0.27 mg/cm^2 at 63 keV. The counting rate with aluminum was 1.5—3 times lower than with gold.

5. DEPOLARIZATION IN THE SCATTERER

The great majority of the investigations to determine S did not take into account the depolarization of the beam in the scatterers, thus incurring more or less considerable errors. In the present work, in order to exclude plural and multiple scatterings we measured S for several (usually three or four) scatterers and extrapolated the results to zero thickness. In order to reduce extrapolation errors the thinnest scatterer was such that the corresponding value of S was within 10% of the extrapolated value. In most instances this difference did not exceed 4—6%. The measurements showed that for thicknesses differing by 20—30% linear extrapolation could be used with statistical errors of 2—3%. Extrapolation required exact values of the relative scatterer thicknesses, which were obtained by comparing the scattering intensities. The absolute values were known within about 10%.

The data accumulated in our present and earlier work[7,8] enabled us to obtain the coefficient α giving the dependence of relative depolarization on scatterer thickness, $\alpha = (1/S)\,dS/dl$, from 45 to 300 keV. The value of $|\alpha|$ decreases rapidly with increasing energy; in Fig. 2 we have for convenience plotted the product $-\alpha E$, where E is measured in keV and the thickness l included in α is measured in $\mu g/cm^2$. The data pertain to normal beam incidence on the scatterer at $\theta = 120°$. The figure indicates only the statistical errors comprising 10—20%, but not including the 10% error common to all points which is associated with uncertainty regarding the absolute thicknesses of the scatterers.

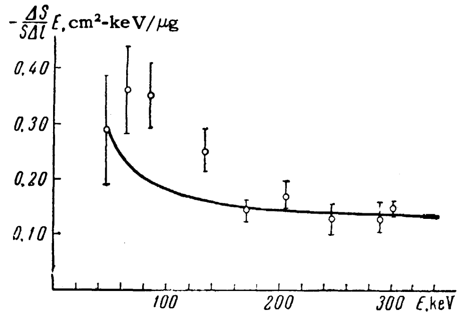


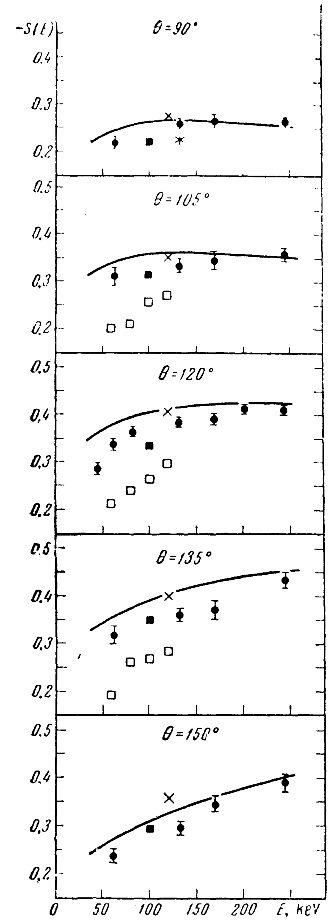
FIG. 2. Relative depolarization in gold scatterer as a function of electron energy.

Wegener[9] has calculated the depolarizing effect of plural and multiple scattering up to quadratic terms in the thickness l. Using tables and formulas given in [9], we calculated α numerically. It must be mentioned that, according to Wegener's work, this coefficient depends somewhat on the thickness. In the range of thicknesses for which $\Delta S/S$ varies from 0.05 to 0.3 the calculated value of α varies by not more than 10%. In Fig. 2 the continuous curve represents the calculated values of $-\alpha E$ for $\Delta S/S = 0.1$. Figure 2 shows that the calculations agree well with experiment at energies above 150 keV, while at lower energies the calculated values are ~1.5 times smaller than the experimental results.

6. MEASUREMENTS AND CORRECTIONS

The measurements were performed in short runs, wherein the first scatterer made of gold alternated with an aluminum scatterer. At each electron energy we used only one gold first scatterer and three or four second scatterers. As a result of the asymmetry measurements we introduced corrections of from 1 to 6% for scattering from the collodion film on which the second scatterers were deposited. The results were extrapolated to zero thickness of the second scatterer.

The angular dependence $S(\theta)$ was measured in two ways: for angles 150—120° with the scatterer



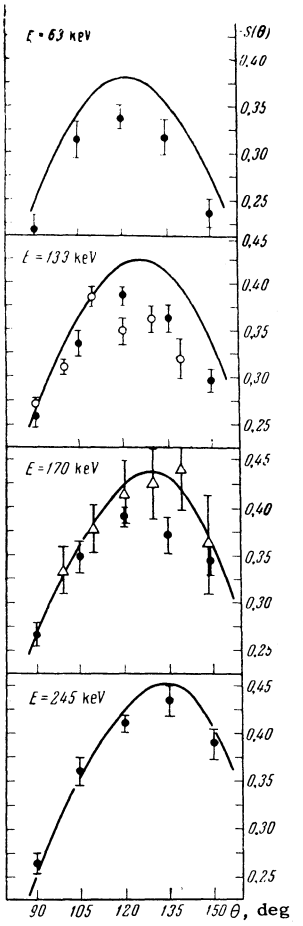


FIG. 3. Energy dependence of S. ● – present work, □ – [12], ∗ – [13]. The continuous curve was calculated[2] for an unscreened field (Z = 79). ■ and x denote calculations taking account of screening in [4] and [5], respectively.

FIG. 4. Angular dependence of S. ● – present work, ○ – [10], △ – [14]. The continuous curve represents calculations in [2] for an unscreened field.

normal to the beam, and for 120—90° with the beam striking the scatter at 60°. For 120° at each energy we obtained two straight extrapolation lines with somewhat different slopes; however the extrapolated values lay within the statistical errors. We used the averages of the extrapolations as our final results.

7. RESULTS AND DISCUSSION

The values of the asymmetry obtained by the foregoing procedure and extrapolated to zero thickness of the second scatterer equal $S(\theta_2)[P_{Au} - P_{Al}]$. Here P_{Au} and P_{Al} are the respective polarizations of the beam impinging on the second scatterer, independently of the angle θ_2. To obtain $S(\theta_2)$ we used previous results given in [7] for S(120°).

Our results are given in the table, which contains for each angle and energy the experimental values S_e, the theoretical values S_t obtained by interpolation of Sherman's data [2] and converted from Z = 80 to Z = 79, and the ratios S_e/S_t. For 120° the results and errors in [7] are given; errors for the other angles combine the errors at $\theta = 120°$ with those of the present work. In Fig. 3 the filled circles represent measurements of S at different energies and fixed angles, and in Fig. 4 at different angles and fixed energies. The continuous lines in these figures represent the theoretical values of S.[2]

Figures 3 and 4 and the table show that at 245 keV the experimental values do not differ from the theory by more than 5% and in most cases only 2—4%. With decreasing energy the differences are augmented for most angles, so that at 63 keV the experimental values are 8—13% below the theoretical values; this difference becomes 20% for 120° at 45 keV. The overall effect of screening is relatively small above 60 keV; this agrees qualitatively with the calculations of Bartlett and Welton [4] and of Mohr and Tassie.[5] A comparison with these calculations (Fig. 3) shows that the results of Bartlett and Welton agree satisfactorily with experiment at 150° and 135°, but are somewhat too low in the interval 120—90°. Mohr and Tassie give results 5—15% higher than the experimental values, and the discrepancy increases with the scattering angle.

The differences between the experimental and theoretical dependences are small but somewhat exceed the statistical errors. At 245 keV for 90° and 105° the experimental values are somewhat higher, and for the other angles are somewhat lower, than the theoretical results. In the range 245—133 keV, S_e at $\theta = 90°$ is everywhere very close to the theoretical values. At 63 keV the experimental curve duplicates the shape of the theoretical curve within experimental error and lies 11% below the latter. The angular dependence $S(\theta)$ confirms the theory as a whole with regard to the fact that with decreasing energy the maximum is shifted from 135° to 120°.

The comparison between our data and the results of other authors is sometimes hampered by the fact that the latter usually have given values of the product $S(\theta_1)S(\theta_2)$ instead of S. Since all publications on double scattering also give $S^2(\theta)$ for one of the angles, we were able to convert the results and represent $S(\theta)$ in Figs. 3 and 4; here the relative errors agree with those ascribed by other authors to the product $S(\theta_1)S(\theta_2)$. In two cases [10, 11] the electron energies differed by 10% from those in our measurements. Since S is slightly energy dependent, we considered that the

θ, deg		E, keV						
		245	204	170	133	83	63	45
90	S_t	0,255		0,265	0,267		0,247	
	S_e	0,265±4%		0,267±5%	0,258±4%		0,217±6%	
	S_e/S_t	1,04		1,01	0.97		0.88	
105	S_t	0.353		0.361	0.361		0.341	
	S_e	0.361±4%		0,348±5%	0,334±4%		0,313±6%	
	S_e/S_t	1,02		0,96	0,93		0.92	
120	S_t	0,426	0.427	0,424	0,418	0,397	0,382	0.364
	S_e	0,411±2%	0,413±2%	0,390±2,5%	0,385±2,5%	0,365±2,5%	0,337±4%	0,286±4%
	S_e/S_t	0,96	0,97	0,92	0,92	0,92	0,88	0,79
135	S_t	0.455		0,432	0,413		0.356	
	S_e	0,434±4%		0,371±5%	0.361±4%		0.317±6%	
	S_e/S_t	0,95		0,86	0,87		0,89	
150	S_t	0,401		0,359	0,335		0,273	
	S_e	0,389±4%		0,345±5%	0,295±4%		0,237±6%	
	S_e/S_t	0.97		0,96	0,88		0,87	

results in [10, 11] could be converted to our energies. The conversion factors obtained in accordance with Sherman's results did not differ from unity by more than 0.03.

The first attempt to investigate asymmetry systematically for angles greater than 90° was undertaken by Ryu et al.[12] The latest results of this work are shown in Fig. 3. These data support the theory qualitatively, although the quantitative discrepancies are seen to be extremely large.

In 1958 Pettus[13] published asymmetry measurements for $\theta_1 = 90°$ and $\theta_2 = 60°$, $90°$, and $120°$ at 130 keV. He also measured the energy dependence of S(90°) S(120°) in the range 80—190 keV. This author estimated the statistical errors at 15—40%, with the experimental results lying considerably below the theoretical values. From Pettus' results with the smallest errors we obtain a value of S(90°) at 130 keV lying 15% below our result.

One of the most accurate studies of double scattering is that of Nelson and Pidd,[10] who were the first to use sufficiently large apparatus, thus considerably reducing the effect of electron scattering from the walls. In addition, they placed before the counters an electrostatic analyzer for discriminating against lower-energy electrons. The angular dependence of the asymmetry S(90°) S(θ_2) was measured in the range $\theta_2 = 80$—140° at 121 keV;[10] the results converted to 133 keV are shown in Fig. 4. Good agreement with our results is observed for angles smaller than 120°. For larger angles the results of Nelson and Pidd lie somewhat below ours; these authors note the possible effect of depolarization in the scatterer at such angles.

We are not aware of any other measurements of S in experiments on double electron scattering within the given energy range. Some information regarding S can be obtained from asymmetry measurements of scattered polarized electrons emitted in β decay. Bienlein et al.[11] measured $\langle\sigma\rangle$ S(120°) in the scattering of Co^{60} β electrons on gold at 209, 155, and 120 keV. They estimated their measurements to possess the very high accuracy 2—3%.

Taking for $\langle\sigma\rangle$ the value $-v/c$ given by the two-component neutrino theory, the same authors determined S(120°). At 209 keV their results agree with ours within experimental error. However, at 120 keV S_e/S_T equals 0.84 ± 3%, which is 8% below our value. This appears to indicate that the degree of polarization of Co^{60} β electrons departs from $-v/c$. It should be noted that such discrepancies are encountered frequently;[8] therefore this procedure for determining S cannot be regarded as entirely correct.

Bienlein et al[14] also used Co^{60} β electrons to measure the angular dependence of S at 155 keV. The results for 100—150° converted to 170 keV are shown in Fig. 4. For large angles their results lie somewhat above ours and agree well with Sherman's calculations. At $\theta = 120°$ the two experimental curves agree within experimental error.

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