Rotation of the plane of polarization of γ quanta and left-right asymmetry of scattering by thick magnetized scatterers

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Rotation of the plane of polarization of linearly polarized γ quanta moving along the magnetization vector of a ferromagnet is observed experimentally. A mechanism is proposed for the large left-right asymmetry of scattering of γ quanta by relatively thick magnetized scatterers and is confirmed experimentally.

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Interest in this study arose on the one hand, out of the fact that the investigated effect is determined by radiative corrections of order α (α is the fine-structure constant) to the Born amplitude of Compton scattering of γ rays, and no effects of this order had previously been observed in γ-ray scattering. On the other hand, an investigation of the spin-dependent effects in Compton scattering is of methodological interest in connection with measurements of the small circular polarization in experiments aimed at observing P-nonconservation in nuclear forces[1]. This paper reports a more detailed investigation of the effects observed in[2-4].

ROTATION OF THE γ-RAY POLARIZATION PLANE

In the effect of magnetic rotation of the polarization plane, which is well known in optics (the Faraday effect), the angle of rotation of the polarization plane per unit path depends on the radiation energy like E^{-2}, and becomes negligibly small in the energy range 0.1–10 MeV. In this range, however, when radiation interacts with electrons that are actually free, another mechanism causing rotation of the polarization of the γ rays can come into play. This possibility was pointed out by Baryshevskiĭ and Lyuboshitz[5], who considered the contribution of radiative corrections of order α to the spin-dependent part of the Born amplitude of Compton scattering forward. Similar work was performed later on by Frolov[6].

According to[5], the rotation angle of the plane of linear polarization of the γ rays after traversing a path l through a medium with polarized electrons is given by

$$\varphi=-Nr_0^2\psi(k)(\mathbf{P}\mathbf{e})l, \qquad (1)$$

where N is the number of electrons per cm^3, r_0 is the classical radius of the electron, **P** is the electron polarization vector, **e** is the unit vector in the γ-ray propagation direction, and $\psi(k)$ is a function of the γ-quantum energy. The sign of the effect is such that the rotation is clockwise when viewed in the γ-ray propagation direction at $\mathbf{P}\uparrow\uparrow\mathbf{e}$ and counterclockwise at $\mathbf{P}\uparrow\downarrow\mathbf{e}$.

The rotation of the plane of polarization is connected with the real part of the radiative corrections. If the imaginary part of the radiative corrections differs from zero, elliptic polarization of the γ quanta takes place. In this case φ characterizes the rotation angle of the major axis of the ellipse relative to the initial direction of the beam polarization.

For iron magnetized to saturation (degree of electron polarization $|\mathbf{P}| = 7.69 \times 10^{-2}$), the angle of rotation of the polarization plane per centimeter of path amounts at the maximum to 5.3×10^{-3} rad at an γ-ray energy E E $\approx$ 0.6 MeV. Such a rotation of the plane of polarization can be observed experimentally.

EXPERIMENTAL OBSERVATION OF THE ROTATION OF THE γ-RAY POLARIZATION PLANE

The experimental setup and an overall view of the installation are shown in Figs. 1 and 2.

The γ-ray source was the isotope ^{198}Au (ground-state transition 412 keV). The activity of the employed sources was 100–500 Ci, which ensured a γ-ray counting rate at the detector $\approx 2 \times 10^3$ sec^{-1}. The γ rays were collimated into a beam that was scattered by aluminum. The linearly polarized beam was passed through iron or permalloy plates magnetized in the γ-ray propagation direction. The analyzer of the linear polarization of the beam was a Compton polarimeter consisting of a scatterer and a Ge(Li) detector of volume 30 cm^3.

The spectrum of the detected γ rays was accumulated in a multichannel DIDAC-4000 pulse-height analyzer in one memory subgroup corresponding to a definite magnetization direction. The magnetization direction changed every second. The memory subgroup in which the spectrum was accumulated was switched in accord-

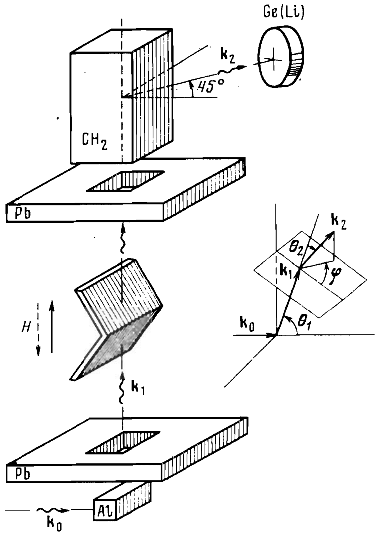

FIG. 1. Experimental setup for the observation of the rotation of the γ-ray polarization plane and the geometry of double scattering.

ance with the magnetization direction. The analyzer input was blocked during the magnetic-field switching time.

To eliminate possible asymmetries in the magnet and in the memory block, the correspondence between the magnetization direction and the number of the memory subgroup was changed every two—three hours. The time intervals were specified by a timer with stability 10^{-6}. The switching of the current in the magnetizing coil was effected with a thyristor switch.

The change of the γ-ray intensity with changing magnetization direction, $\delta = 2(I_1 - I_2)/(I_1 + I_2)$, is connected with the angle $\Delta\varphi$ of the polarization-plane rotation per centimeter of path in the ferromagnet by the formula

$$\delta = 4l \frac{\mathbf{Bk}}{|\mathbf{B}||\mathbf{k}|} \frac{B_{\mathrm{exp}}}{B_{\mathrm{satur}}} F \sin 2\Phi \cdot \Delta\varphi, \tag{2}$$

where l is the path traversed by the γ quantum in the ferromagnet, $\mathbf{B}$ is the magnetic-induction vector, $\mathbf{k}$ is the γ-quantum momentum, Φ is the angle between the planes of the first and second scatterings, and F is the polarization efficiency of the installation. Figure 3 shows the form of the spectrum and the value of the angle of polarization-plane rotation within the limits of the photoabsorption peak of doubly scattered quanta. We see that $\Delta\varphi$ remains unchanged within these limits. We chose for the analysis the part of the spectrum corresponding to the maximum ratio of the useful count to the background.

In the first experiments[4], the polarization efficiency was not determined with sufficient accuracy, and the theoretically calculated coefficient F was used in the computations. In subsequent experiments, the polarization efficiency was determined experimentally with accuracy 2—4 percent.

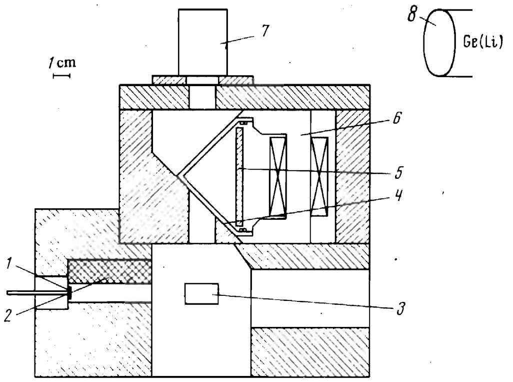

FIG. 2. Overall view of the setup: 1—γ-ray source, 2—tungsten screen, 3—first scatterer (Al), 4—ferromagnetic plate, 5—lead shield, 6—magnetic circuit, 7—second scattering (Plexiglas), 8—Ge(Li) detector.

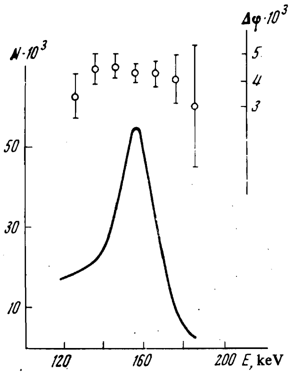

FIG. 3. Distribution of $\Delta\varphi$ over the sections of the photopeak of the spectrum of the doubly-scattered γ rays.

The quantity F was measured from the change of the intensity of the doubly scattered γ quanta when the angle Φ was changed by an amount $\Delta\Phi = \pm 10^\circ$. In this case

$$F = \frac{\delta}{\sin 2\Delta\Phi}, \quad \delta = \frac{I(\Phi+\Delta\Phi) - I(\Phi-\Delta\Phi)}{I(\Phi+\Delta\Phi) + I(\Phi-\Delta\Phi)}.$$

For the γ-ray energies E = 228 and 294 keV, the respective values of F were 0.52 ± 0.01 and 0.35 ± 0.01.

The rotation of the polarization plane was measured at various thicknesses of the magnetized plates. To carry out a null experiment, the ferromagnet plate was replaced with a copper plate. The results of the measurements are shown in Table I. The data are referred to the induction $B = B_{\mathrm{satur}} = 21.5$ kG. On the basis of the results of Table I we obtain $\Delta\varphi = (4.25 \pm 0.12) \times 10^{-3}$ rad/cm and $\Delta\varphi = (4.64 \pm 0.20) \times 10^{-3}$ rad/cm at γ-ray energies E = 228 and 294 keV, respectively.

The theoretical rotation angles per centimeter of γ-ray path in iron saturated to magnetization, according to Baryshevskiĭ et al.[7], are 4.12×10^{-3} and 4.61×10^{-3} rad for 230 and 290 keV, respectively. These figures are in good agreement with our data. Similar results were obtained by P. Bock[8].

ROTATION OF γ-RAY POLARIZATION PLANE AND LEFT-RIGHT SCATTERING ASYMMETRY

The left-right asymmetry that appears when γ-rays are scattered by magnetized ferromagnets is an important consequence of the rotation of the polarization plane. The mechanism whereby this effect is produced is illustrated in Fig. 4.

As a result of the first scattering, the γ rays acquire linear polarization and the γ rays propagating along the magnetization direction experience a rotation of the polarization plane. Since the rotation of the polarization plane, and consequently, of the second-scattering rosette around the magnetization vector, occur in the same direction for γ-quanta propagating parallel and antiparallel to the magnetization direction, this leads to a left-right asymmetry of the second scattering.

In quantum electrodynamics there is a known effect of left-right asymmetry following single scattering of γ rays by polarized electrons. This effect is described by the expression

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \left\{ 1 + A(k_0, k) \frac{\mathbf{s}[\mathbf{k}_0\mathbf{k}]}{|[\mathbf{k}_0\mathbf{k}]|} \right\}, \tag{3}$$

where $d\sigma_0/d\Omega$ is the γ-ray scattering cross section and does not depend on the particle polarization, $\mathbf{s}$ is the electron spin, and $\mathbf{k}_0$ and $\mathbf{k}$ are the momenta of the γ quanta before and after the scattering.

The left-right asymmetry coefficient A is equal to zero in first-order Compton scattering and appears as a result of interference of the first-order amplitude with the imaginary parts of the amplitudes of the next order in the expansion in the parameter α. This coefficient was calculated in[9,10]. In a later paper[11], the correlation coefficient was calculated with allowance for the linear polarization of the γ rays. The results of these calculations yield a value of the asymmetry coefficient in the range $(1-5) \times 10^{-4}$ (at 100% polarization of the electrons). On the other hand, the asymmetry resulting from the rotation of the polarization plane following double scattering of γ rays by scatterers of thickness

10—50% of the mean free path of the rays in the ferromagnet can reach a value 5×10^{-3} (at 100% polarization of the electrons), i.e., can exceed the asymmetry in single scattering by almost one order of magnitude. The first measurements of the left-right asymmetry, carried out by P. Bock[2], have shown that the asymmetry in scattering by relatively thick magnetized plates greatly exceeds the calculated value. Inasmuch as the mechanism whereby such a large asymmetry was produced was not clear at that time, we have investigated this effect[3].

In the experiment, we measured the change of the γ-ray intensity scattered by a magnetized plate following a change in the direction of the magnetic field. The experimental setup is shown in Fig. 5.

TABLE I. Results of measurements of the rotation of the polarization plane.

Φ, deg	$\sphericalangle(\mathbf{B},\mathbf{k})$, deg	Plate material	d *, cm	$\delta \cdot 10^3$ **	$\Delta\varphi \cdot 10^3$ ***, rad/cm
		$E=228$ кэв, $\theta_1=90°$			
45	45	Iron	0.1	1.87±0.20	4.50±0.50
45	45	»	0.2	3.62±0.11	4.35±0.13
45	45	»	0.25	4.30±0.14	4.13±0.13
45	45	Permalloy	0.2	3.51±0.56	4.22±0.67
45	45	Copper	0.15	0.24±0.24	—
45	45	»	0.04	0±0.3	—
		$E=294$ keV, $\theta_1=60°$			
45	45	Iron	0.1	1.31±0.20	4.68±0.71
45	45	»	0.2	2.71±0.12	4.84±0.21
45	45	»	0.25	3.18±0.21	4.54±0.30
45	45	»	0.3	3.80±0.16	4.52±0.19

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*d is the thickness of the magnetized plate.

**The result includes a correction for the background (5—10%) and for the analyzer dead time (5—10%).

***$\Delta\varphi$ was calculated from formula (2), $l = 2d/\sin \sphericalangle (\mathbf{B}, \mathbf{k})$.

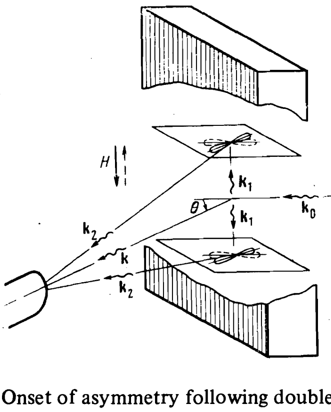

FIG. 4. Onset of asymmetry following double scattering, due to rotation of the polarization plane.

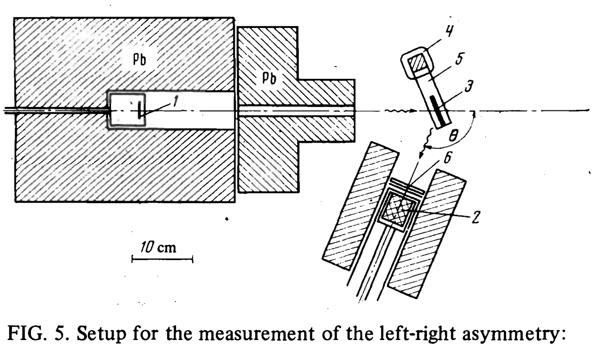

FIG. 5. Setup for the measurement of the left-right asymmetry: 1—source, 2—Ge(Li) detector, 3—scatterer, 4—magnetizing winding, 5—magnetic circuit, 6—absorbing filters. The scatterer is magnetized in a direction perpendicular to the plane of the figure.

Inasmuch as in most cases the observed effects were small, the measurements were performed by an integral method with resonant separation of the periodic signal, analogous to the method of [12]. The measured quantity was $\delta = 2(I_1 - I_2)/(I_1 + I_2)$, where $I_{1,2}$ are the intensities of the detected γ rays at opposite directions of the magnetization. The sources were the isotopes ^{198}Au (412-keV γ transition) and ^{177}Lu (fundamental γ lines 208 and 113 keV; the latter is effectively absorbed in the source). The source intensity was 200—1000 Ci.

An important confirmation of the multiple character of the scattering was measurement of the effective energy of the γ rays giving rise to the asymmetry. It can be determined from the dependence of δ on the thickness of filters placed on the detector. In this case the energy of the γ rays that make the main contribution to the detected intensity, i.e., the single-scattering energy, is determined by the geometry of the scattering. As seen from Tables II and III, in both cases, i.e., for both forward and backward scattering, the energy E_{as} with which the asymmetry is connected turns out to be the same and equal to 170—200 keV for E = 412 keV and 125—130 keV for E = 208 keV. These energies correspond approximately to the γ-ray double scattering shown in Fig. 2.

The dependence of δ on the thickness of the magnetized scatterer is shown in Fig. 6. The linearity of the

TABLE II. Dependence of the asymmetry on the filter thickness at E = 208 keV and at a scatterer thickness 2 mm.

Filter	$\theta=60°$		$\theta=135°$	
	$\delta \cdot 10^4$	energy, keV	$\delta \cdot 10^4$	energy, keV
0.35 mm Cd 1,35mm Cd	0.91±0,11 0.63±0,13	E Compt = 173 E_{as} = 130±25	—(1.48±0.15) —(1.44±0.15)	ECompt = 123 E_{as} = 123±5

TABLE III. Dependence of the asymmetry on the filter thickness for E = 412 keV and for a scatterer of thickness 4 mm.

Filter	$\theta=60°$		Filter	$\theta=135°$	
	$\delta \cdot 10^4$	energy, keV		$\delta \cdot 10^4$	energy, keV
Without filter 0.5 mm W 1 mm W 1 mm Pb	1,63±0.14 0.81±0.15 0.32±0.15 0.48±0.08	ECompt = 294 E_{as} = 170÷200	Without filter 3 mm Cd 1 mm Pb 1,5 mm Pb	—(3.6±0.2) —(3.1±0.2) —(3.30±0.25) —(3.6±0.4)	ECompt = 173 E as = 173±5

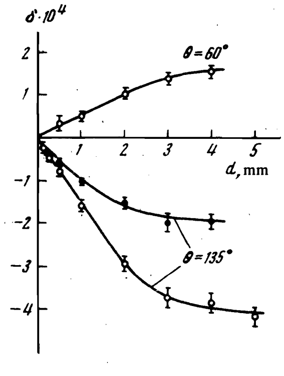

FIG. 6

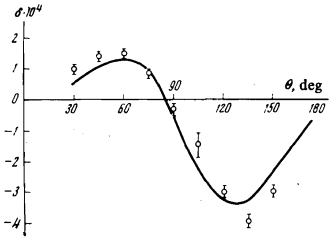

FIG. 7

FIG. 6. Dependence of the asymmetry on the scatterer thickness: ●—^{177}Lu (208 keV), ○—^{198}Au (412 keV). The data are referred to an induction of 18 kG.

FIG. 7. Calculated and experimental dependences of the asymmetry on the scattering angle.

initial sections of the curves also indicates that asymmetry takes place in the double scattering.

The experimental and calculated dependences of the asymmetry on the single-scattering angle of the γ quanta are shown in Fig. 7. In the calculation, which was performed by the Monte Carlo method, we used the theoretical dependence of $\Delta\varphi$ on the γ-ray energy.

Thus we see that the proposed mechanism, wherein a large left-right asymmetry is produced when γ rays are scattered by relatively thick magnetized scatterers, describes the phenomenon well both qualitatively and quantitatively.

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