

## LINEAR POLARIZATION OF ELASTICALLY SCATTERED GAMMA RAYS OF 279 AND 662 keV IN URANIUM

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Received 26 February 1976

*Abstract:* The degree of linear polarization of elastically scattered gamma rays in uranium was measured by means of a planar Ge(Li) detector. The measurements were performed with gamma rays of 279 keV at scattering angles of 45°, 60°, 75°, 90°, 105°, and 135° and with gamma rays of 662 keV at angles of 51°, 60°, 75°, 90°, 105°, 120°, and 135°. The results are compared with the values calculated from the theory of Brown et al., taking into account Rayleigh scattering by K- and L-shell electrons, and nuclear Thomson scattering. The data are in fair agreement with the theory.

*1. Introduction*

The elastic scattering of gamma rays is described by two complex amplitudes<sup>1 2)</sup>: the amplitude without change of polarization,  $A$ , and the amplitude with change of polarization,  $A'$ . Four independent measurements are required at each scattering angle to determine their real and imaginary parts<sup>3)</sup>. Accurate measurements of the differential cross sections<sup>9,10)</sup> are at present best tests of the theory of the elastic scattering of gamma rays. The differential cross section is proportional to the sum of absolute squares of the two amplitudes. Since the imaginary parts are small<sup>1)</sup>, the differential cross section is mainly given by the sum of squares of the real parts. The contributions of the imaginary parts to linear polarization are also small. Thus, measurements of the differential cross section and linear polarization allow essentially the determination of the real parts of the scattering amplitude. Several measurements<sup>4, 5)</sup> of linear polarization have been

performed. However, no attempt has been made to measure two additional independent magnitudes<sup>3)</sup> that would allow the determination of the imaginary parts of the scattering amplitudes. Such experiments seem to be prohibitively difficult at present.

Four processes contribute coherently to the elastic scattering of gamma rays. The two scattering amplitudes are sums

$$A = A_R + A_T + A_D + A_{NR} \quad \text{without change of polarization,} \quad (1a)$$

$$A' = A'_R + A'_T + A'_D + A'_{NR} \quad \text{with change of polarization,} \quad (1b)$$

where the terms represent the following contributions: Rayleigh scattering of photons by bound atomic electrons ( $A_R$  and  $A'_R$  are sums of amplitudes due to K-, L-, . . . shell electrons), nuclear Thomson scattering, Delbrück scattering, i. e., the virtual production and annihilation of electron-positron pairs in the nuclear Coulomb field, and nuclear resonance scattering.

Nuclear resonance scattering yields an observable contribution only under adequate conditions for resonance. Delbrück scattering has so far been observed only at high energies of incident photons<sup>6)</sup>; it represents an independent test of quantum electrodynamics. The amplitudes of Delbrück scattering were calculated by Ehlötzky and Sheppey<sup>7)</sup> for photons from 1.3 to 16 MeV and for scattering angles from 0° to 120°. They decrease with decreasing photon energy and below about 1 MeV the contribution of this process to elastic scattering becomes negligible. Nuclear Thomson scattering yields a small contribution, which is independent of photon energy; it is considered to be well understood. The amplitudes of Rayleigh scattering were calculated by Brown et al.<sup>1, 2)</sup> for K electrons in mercury at photon energies of 0.32, 0.64, 1.28, and 2.56 mc<sup>2</sup>. They applied second-order perturbation theory, relativistic electron theory and self-consistent field, treating electronic intermediate states correctly. Their calculations were extended by Cornille and Chapdelaine<sup>8)</sup> to a photon energy of 5.12 mc<sup>2</sup>. Although these exact calculations have, in principle, solved the problem, there still remain the questions concerning higher-shell electrons, other target nuclei, and (to a lesser degree) energy dependence. Brown and Mayers<sup>2)</sup> give approximate expressions for the extension of their results, but their application seems to lead to difficulties in the interpretation of experimental data.

Accurate measurements of the differential cross sections for lead at photon energies of 145, 279, 412, 662, 889, and 1120 keV<sup>9)</sup>, and at 1173 and 1332 keV<sup>10)</sup> have been made and analyzed, following the approximate expressions for the scattering amplitudes of Brown and Mayers<sup>2)</sup>. The extrapolation of the results for K-shell electrons of Brown et al.<sup>1, 2)</sup> to different energies and a lead target is considered adequate, but the results for higher-shell electrons seem to be erroneous. Measurements of the linear polarization of elastically scattered gamma rays offer

a test for the attempts to achieve agreement between experimental and theoretical values of the differential cross sections.

## 2. Experimental method

The method of Honzatko and Kajfosz<sup>1,1)</sup> and that of Ewan et al.<sup>1,2)</sup> was applied in the measurements. An Ortec planar Ge(Li) detector of a sensitive volume of 18 mm in diameter and 3 mm thick was used as a polarization analyzer. Fig. 1 shows the experimental arrangement. The disc of the detector was in the horizontal plane, and scattered photons entered sidewise. Since the detector could not be rotated about the horizontal axis, the scattering plane had to be made rotatable. This was accomplished by mounting the scatterer and the source in a lead shield on a horizontal shaft. In this way a very consistent geometry was achieved. To reduce systematic errors due to possible small misadjustment, which would result in a variation of the scattering angle at different positions, measurements were performed at four positions. The data for the vertical orientation of the scattering plane were taken by turning the source in the »up« or »down« position; the data for the horizontal orientation of the scattering plane were recorded by turning the source in the »left« or »right« position.

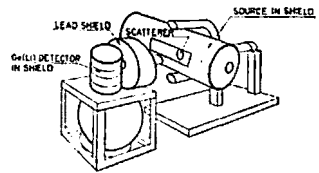


Fig. 1. The experimental arrangement.

The scatterer and the lead shield with the source were mounted inside a steel cylinder, which was pivoted on the shaft. By turning the cylinder, the scattering angle could be varied between  $45^\circ$  and  $135^\circ$ .

A 5 Ci source of  $^{137}\text{Cs}$  (supplied by the Radiochemical Centre, Amersham, England) was used in the measurements with gamma rays of 662 keV, and a  $^{203}\text{Hg}$  source of an initial activity of about 1 Ci (supplied by the Boris Kidrič Institute, Beograd) in the measurements with gamma rays of 279 keV. Gamma rays from either source emerged out of the shield through a profiled conical opening which was oriented in the direction of the axis of the steel cylinder. A scatterer of metallic uranium 40 mm in diameter and 10 mm thick was placed at the intersection of the axes of the cylinder and of the shaft. In order to minimize the absorption of elastically scattered photons, the uranium disc was oriented in the symmetry plane of the two axes. The distance between the source and the scatterer was about 220 mm. The planar Ge(Li) detector was placed in a separate shield at a distance of about 420 mm from the scatterer.

In positioning the detector, comparison of the counting rates and of positions of the peaks due to scattered Compton radiation was used as an indication of the deviation from the axis of the shaft. The detector was displaced up or down and left or right until equal response was achieved for the vertical and horizontal scat-

tering plane, respectively. The counting rates in the peaks of elastically scattered photons were compared for recheck.

A 256-channel analyzer was used to analyze pulses from the Ge(Li) detector.

### 3. Calibration of polarimetric efficiency

The application of a single planar Ge(Li) detector for measurements of the linear polarization of gamma rays<sup>11,12)</sup> is based on the dependence of Compton scattering on the azimuthal angle between the polarization plane and the Compton scattering plane.

Suppose first a beam of gamma rays totally polarized in the scattering plane of intensity  $n_{\parallel}$  (photons/cm<sup>2</sup>s) entered the detector. In the full-energy peak, the counting rates of  $N_v = \alpha n_{\parallel}$  and  $N_h = \beta n_{\parallel}$  would be measured with the source in the »up« or »down« position and with the source in the »left« or »right« position, respectively. Because of the azimuthal dependence of the Compton scattering cross section and because of the planar shape of the sensitive volume of the detector, the absorption in the peak of total energy is different for the two orientations, and  $\beta \approx \alpha$ . The asymmetry of the counting rates would be  $a = (N_v - N_h)/(N_v + N_h) = (\alpha - \beta)/(\alpha + \beta) = \varepsilon$ . If the beam were totally polarized perpendicularly to the scattering plane the result would be  $a = -(\alpha - \beta)/(\alpha + \beta) = -\varepsilon$ . The value of polarimetric efficiency  $\varepsilon$ , is equal to  $+a$  and  $-a$  for a beam totally polarized in and perpendicularly to the scattering plane, respectively. Some authors<sup>12)</sup> use the sensitivity  $Q = 2(\alpha - \beta)/(\alpha + \beta)$  instead of the polarimetric efficiency as defined above.

The scattered beam of gamma rays consists of photons of intensity  $n_{\parallel}$  and  $n_{\perp}$  polarized in and perpendicularly to the scattering plane, respectively. The counting rate with the source in the »up« or »down« position is  $N_v = \alpha n_{\parallel} + \beta n_{\perp}$ . When the scattering plane is rotated (the source in the »left« or »right« position), the counting rate is  $N_h = \beta n_{\parallel} + \alpha n_{\perp}$ . The asymmetry in this case is given by

$$a = \frac{N_v - N_h}{N_v + N_h} = \frac{\alpha - \beta}{\alpha + \beta} \frac{n_{\parallel} - n_{\perp}}{n_{\parallel} + n_{\perp}} = \varepsilon P. \quad (2)$$

Here  $P = (n_{\parallel} - n_{\perp})/(n_{\parallel} + n_{\perp})$  is the degree of linear polarization of the scattered beam.

The polarimetric efficiency of the Ge(Li) detector was determined in a separate experiment. Beams of known degree of linear polarization were produced by Compton scattering of 662-, 1173-, and 1332-keV gamma rays. A graphite scatterer was used. The following values of the polarimetric efficiency were obtained from the experimental values of  $a$  and the theoretical values of  $P$  for Compton scattering

$$\varepsilon (662\text{-keV}) = (6.54 \pm 0.96) \%, \quad (3a)$$

$$\varepsilon (279\text{-keV}) = (4.59 \pm 0.09) \%. \quad (3b)$$

#### 4. Results of measurements and discussion

The complete cycle of measurements of the spectra of scattered radiation at the four positions of the source was repeated several times at each scattering angle. The counting time at each position was between 6 and 14 hours. In the measurements with the  $^{137}\text{Cs}$  source it was not necessary to take into account corrections for the decay of the source, because of the long decay time. Therefore, at each scattering angle the total time of measurement at each position of the source was made equal at the end of the measurements. In the measurements with the  $^{203}\text{Hg}$  source, the four positions were regularly interchanged, in a pattern which caused cancellation to first order of the changes of the counting rates due to the decay of the source. Figure 2 shows the pulse-height spectrum of scattered radiation at a scattering angle of  $60^\circ$  with the  $^{137}\text{Cs}$  source and the uranium scatterer.

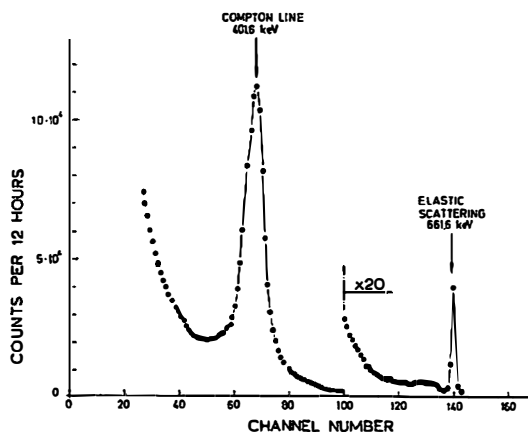


Fig. 2. Pulse-height spectrum due to scattered radiation. Gamma rays from a 5 Ci source  $^{137}\text{Cs}$  were scattered in uranium and the radiation at  $\Theta = 60^\circ$  was measured by means of a planar  $\text{Ge}(\text{Li})$  detector.

The pulse-height spectra were analyzed in a CAE-9040 computer. For each scattering angle, the numbers of counts and positions of the Compton peaks were compared for up-down and left-right asymmetry. The system was very stable in this respect. Also, the numbers of counts in the peaks due to elastic scattering were obtained by a background subtraction routine. This subtraction was relatively small. The counting rates in the region of full-energy peaks without the uranium scatterer were negligible.

Table 1.  
Linear polarization in the scattering of 662 keV gamma rays in uranium

$\Theta$	51°	60°	75°	90°
$a$ (%)	$-3.14 \pm 0.36$	$-4.75 \pm 0.42$	$-6.55 \pm 0.68$	$-3.74 \pm 0.50$
$P$ (%)	$-48.8 \pm 9.1$	$-72.5 \pm 12.4$	$-100.2 \pm 18.0$	$-57.1 \pm 11.3$
$P_{\text{calc}}$ (%)	-64.5	-86.9	-98.9	-71.5
$\Theta$	105°	120°	135°	—
$a$ (%)	$-1.85 \pm 0.66$	$-2.14 \pm 0.66$	$-0.67 \pm 0.83$	—
$P$ (%)	$-28.3 \pm 10.9$	$-32.7 \pm 11.2$	$-10.2 \pm 12.7$	—
$P_{\text{calc}}$ (%)	-44.0—	-22.9	-10.4	—

At each scattering angle the asymmetry was calculated from Equ. (2). The results for the scattering of gamma rays of 662 keV in uranium are shown in Table 1 and in Fig. 3, and the results for the scattering of gamma rays of 279 keV in uranium are shown in Table 2 and Fig. 4. The values of the degree of linear polarization were calculated from Equ. (2), taking into account the values of polarimetric efficiencies at 662 keV and 279 keV, Equs. (3a) and (3b), respectively.

The full curves were calculated by taking into account the Rayleigh scattering of gamma rays by K- and L-shell electrons in uranium, and nuclear Thomson

Table 2.  
Linear polarization in the scattering of 279 keV gamma rays in uranium

$\Theta$	45°	60°	75°
$a$ (%)	$-2.03 \pm 0.48$	$-2.61 \pm 0.25$	$-3.80 \pm 0.65$
$P$ (%)	$-44.2 \pm 10.5$	$-56.9 \pm 5.5$	$-82.8 \pm 14.2$
$P_{\text{calc}}$ (%)	-35.1	-63.0	-90.5
$\Theta$	90°	105°	135°
$a$ (%)	$-14.5 \pm 0.83$	$-3.12 \pm 0.44$	$-1.43 \pm 0.57$
$P$ (%)	$-90.4 \pm 18.1$	$-68.0 \pm 9.6$	$-31.2 \pm 12.5$
$P_{\text{calc}}$ (%)	-99.2	-86.3	-32.0

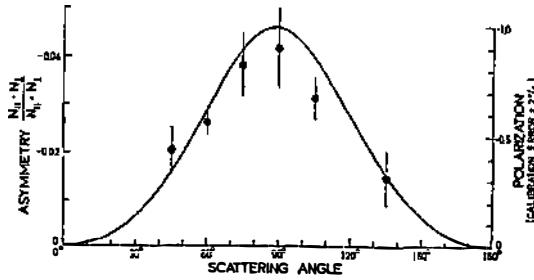


Fig. 3. The asymmetry and the degree of linear polarization of gamma rays of 662 keV elastically scattered in uranium. The full curve represents the results of calculations described in the text.

scattering. The amplitudes of Rayleigh scattering were calculated following the recommendation of Brown and Mayers<sup>2)</sup>

$$A_{K,L}(U, E_\gamma) = \text{Re} (A_K(Hg, E_\gamma^0)) \frac{g_{K,L}(U, E_\gamma)}{g_K(Hg, E_\gamma^0)}, \quad (4a)$$

$$A'_{K,L}(U, E_\gamma) = \text{Re} (A'_K(Hg, E_\gamma^0)) \frac{f_{K,L}(U, E_\gamma^0)}{f_K(Hg, E_\gamma^0)}. \quad (4b)$$

The real parts of the amplitudes without change of polarization,  $A_K(Hg E_\gamma^0)$ , and with change of polarization,  $A'_K(Hg E_\gamma^0)$  were taken from the tables of Brown et al.<sup>1,2)</sup> The value  $E_\gamma^0 = 1.28 \text{ mc}^2$  was taken in the calculations of the amplitudes at  $E_\gamma = 662 \text{ keV}$ , and the value  $E_\gamma^0 = 0.64 \text{ mc}^2$  was employed in the calculations

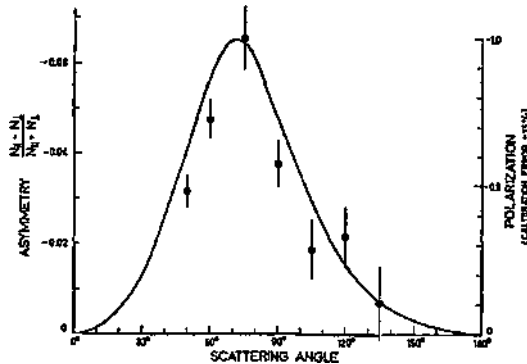


Fig. 4. The asymmetry and the degree of linear polarization of gamma rays of 279 keV elastically scattered in uranium. The full curve represents the results of calculations described in the text.

of the amplitudes at  $E_\gamma = 279$  keV. The scaling factors in Equ. (4a) of the amplitudes without change of polarization for K- and L-shell electrons are ratios of the »corrected form-factor amplitudes«<sup>2)</sup>

$$g = \int |\psi|^2 e^{i\vec{q}\cdot\vec{r}} \frac{mc^2}{E+V} d^3 r, \quad (5)$$

where  $\vec{q}$  is the momentum transfer,  $E$  the total energy of the K or L electron,  $V$  the negative of the electron potential energy, and  $\psi$  the electron wave function. Unperturbed Dirac wave functions were taken for K electrons, and functions with an effective charge  $Z-2$  for L electrons. Similarly, the scaling factors of the amplitudes with change of polarization for K- and L-shell electrons are ratios of the form factor amplitudes

$$f = \int |\psi|^2 e^{i\vec{q}\cdot\vec{r}} d^3 r. \quad (6)$$

The Bethe and Levinger<sup>1,3)</sup> expression was used for K electrons, and expression (6) was numerically integrated for L electrons.

Except at small angles, the calculated L-shell amplitudes were small compared with the K-shell amplitudes. Therefore, higher shells were not taken into account, and the Rayleigh scattering amplitudes were obtained by adding the K- and L-shell amplitudes,  $A_R = A_K + A_L$  and  $A'_R = A'_K + A'_L$ . The nuclear Thomson amplitudes were calculated from the expressions  $A_T = Z^2(m/M)(\cos \Theta + 1)/2$  and  $A'_T = Z^2(m/M)(\cos \Theta - 1)/2$ , where  $Z$  is the nuclear charge and  $m/M$  is the mass ratio of the electron and the nucleus, and  $\Theta$  is the scattering angle.

From the amplitudes  $A = A_R + A_T$  and  $A' = A + A'_T$ , the degree of linear polarization of scattered gamma rays was calculated by the formula

$$P = \frac{2\text{Re}(A' A^*)}{|A'|^2 + |A|^2}. \quad (7)$$

The imaginary parts of the amplitudes were neglected.

The calculated values of polarization are in fair agreement with experimental data. The positions of the maxima of linear polarizations are in agreement. However, the calculated curves appear broader than indicated by the experimental data.

#### Acknowledgement

The authors express their gratitude to the Institute of technology of nuclear and other minerals Beograd, Yugoslavia for the donation of the uranium disc. They acknowledge the skilful and precise work of the Institute machine workshop staff in making the mechanical parts of the polarimeter, and express their appreciation to the Electronics Department for the maintenance of the counting system.

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## LINEARNA POLARIZACIJA ELASTIČNO RASPRŠENIH GAMA ZRAKA

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## Sadržaj

Primjenom planarnog Ge(Li) brojača izvršena su mjerenja stupnja linearne polarizacije gama zraka, koje su bile elastično raspršene u uranovoj meti. Mjerenja su načinjena s gama zrakama energije 279-keV na kutovima raspršenja od 45°, 60°, 75°, 90°, 105° i 135°, i s gama zrakama energije 662-keV na kutovima rasprše- od 51°, 60°, 75°, 90°, 105°, 120° i 135°.

Rezultati mjerenja uspoređeni su s vrijednostima, koje su bile izračunate na osnovi teorije Browna i suradnika, uzimajući u račun doprinose Rayleighevog raspršenja na K- i L-elektronima i nuklearno Thomsonovo raspršenje. Slaganje eksperimentalnih i teorijskih rezultata je dobro.