The Polarization-Direction Correlation of Successive Gamma-Ray Quanta From Co^{60} and Na^{24}

I. V. ESTULIN, V. S. POPOV AND F. E. CHUKREEV
Moscow State University

(Submitted to JETP editor January 11, 1956)
J. Exptl. Theoret. Phys. (U.S.S.R.) 30, 1052-1057 (June, 1956)

Apparatus for observing the correlation of polarization and directions of propagation of successive gamma-ray quanta is described. The polarization sensitivity of this apparatus was determined experimentally and measurements were carried out for gamma-ray quanta of Co^{60} and Na^{24}. The first two excited states of Ni^{60} and Mg^{24} are shown to have even parity.

INTRODUCTION

BY measurements of the correlation of polarization and directions of propagation of gamma-ray quanta emitted by atomic nuclei in successive radiative transitions, it is possible to determine the multipolarity of the corresponding transitions and also to separate electric transitions from magnetic[1]. As a result, one succeeds in obtaining both the spins of the nuclei in the excited states and the parity of the wave function in those states. The dependence of the magnitude of polarization of the gamma-rays emitted in a cascade on the angle between their propagation directions was calculated by Falkoff[2] and Hamilton[3].

The first measurements of correlation of the polarization and the propagation direction of gamma-rays were made in 1950 by Metzger and Deutsch[4] and Williams and Wiedenbeck[5]. In recent years still several other experiments were reported[6-8] in which a similar method was used.

It should be noted that the multipolarity of radiative transitions can be determined from measurements of the angular correlation of gamma-rays emitted in cascade[1]. Furthermore, the theory of angular correlation of nuclear radiation is worked out satisfactorily[9], and the technique of measuring angular correlation of gamma-rays is considerably simpler than the technique for measuring polarization-direction correlation of gamma-rays. In those cases where the multipole order of radiative transitions has been determined from the measurements of angular correlation of gamma-rays, as for the transitions considered in the present work, it only remains to determine the parity of the corresponding excited states by a measurement of polarization-direction correlation. To this end it is not necessary, as in the initial experiments of Metzger and Deutsch[4], to measure the degree of polarization for various angles θ between the directions of propagation of the emitted gamma-rays. Sufficiently complete data on the parity of the excited states are obtained by measurements of the degree of polarization for a given angle θ. For this purpose the selected angle θ should be the one exhibiting the maximum degree of polarization of the gamma-rays.

DESCRIPTION OF APPARATUS

The apparatus used in the present work consisted of gamma-ray detectors insensitive to the direction of polarization and a detector (polarimeter) sensitive to the degree of polarization of gamma-rays. As gamma-ray detectors insensitive to the degree of polarization we used two scintillation counters with stilbene crystals. These counters (A and A' in Fig. 1) were 22 mm thick and placed

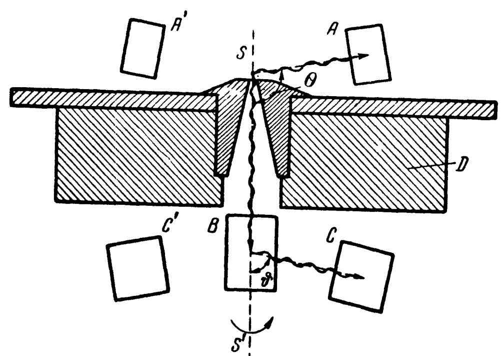

FIG. 1. Principal view of the apparatus: SS' -- symmetry axis of the instrument, S -- the source, A and A' -- scintillation crystals of detectors insensitive to the polarization of photons, B -- the central crystal of polarimeter, C and C' -- side crystals of polarimeter, D-- the shield.

symmetrically about the central axis of the apparatus SS' passing through the source S. The polarimeter consisted of three scintillation crystal counters: the central counter B was used as a scatterer and the side counters C and C' registered the radiation scattered from B. Tolane crystals

28 mm thick were used in the scintillation counters C and C', stilbene crystals were used in the counter B. The crystals C and C' were shielded by lead from the direct beam of gamma-rays emitted by the source.

The action of the polarimeter is based on the dependence of the differential cross section for Compton scattering on the angle δ between the direction of polarization of the incident photon and the plane of scattering. In that respect the described polarimeter is similar to others described previously[4,6]. The polarimeter can be rotated about the symmetry axis SS', which allows placing of crystals C and C' at any angle δ to the scattering plane of gamma-rays (see Fig. 1). Simultaneously, the counter B rotates about the axis of the apparatus. The ratio of the coincidence counting rates in crystals B and C at the position $\delta = 0$ to the coincidence counting rates for $\delta = \pi/2$ depends on the degree of polarization of gamma-rays incident on the counter B. The mean angle θ at which the photons were scattered from crystal B to crystals C or C' was equal to 80° (see Fig. 1).

Photomultiplier tubes FEU-19 were used in the scintillation counters. The selection of nonuniform distribution of potentials on the multiplier dynodes allowed an increase of the total potential supplied to the divider of the multiplier tube to 2200-2500 v. With this arrangement the positive pulses due to the gamma-rays emitted by Zn^{65} taken off the multiplier collector were of the order of 40-50 v and the noise level less than 1 v. The efficiency of detection of 1 mev gamma radiation was of the order of 25%, of 0.3 mev gamma-rays of the order of 50%.

The 0.5 μsec long pulses from FEU-19 were fed by means of a cascade cathode follower into the coincidence circuits (Fig. 2). In each channel of the coincidence circuits the noise was chopped off and the pulses were formed in a univibrator in a 6H15P tube with inductance $L \approx 100\,\mu$ henries, shunted by DGC-4 as a plate load. The pulses at the output of the univibrator had the form of a half of a sine wave with amplitude 12 v and duration of base 0.3 μsec. These pulses were fed into double coincidence channels through 6Zh2P mixing tubes with resolving time $\tau_{AC} = 2.8 \times 10^{-8}$ sec, $\tau_{BC} = 3.6 \times 10^{-8}$ sec and $\tau_{AB} = 5.6 \times 10^{-8}$ sec. The triple coincidence of pulses in channels A, B and C were selected by counting the coincidences AC and BC. The resolving time of the triple coincidence counters was determined by the resolution of the double coincidence stages AC and BC. The pulse rates of the photomultiplier tubes and the double coincidence rates must be known to take into account the accidental triple coincidences.

In our measurements of the correlation of polarization and directions of propagation of gamma-rays the accidental triple coincidences N^{acc}_{ABC} composed an important part of the total number of triple coincidences. N^{acc}_{ABC} was computed from the measured photomultiplier pulse rate, double coincidence rate and τ of the double coincidence circuits. Therefore, the stability of the resolving time of the double coincidence circuits was very important. Experiments showed that variations in τ of the circuits used in the present work did not exceed ±5% during a day of experiments.

POLARIZATION SENSITIVITY OF POLARIMETER

The polarization sensitivity R is determined by the ratio of the effective cross sections of the Compton scattering in the plane $\delta = 0$ and the plane $\delta = \pi/2$. Thus R depends on the photon energy according to the Klein-Nishina formula. Because of the finite dimensions of the gamma-ray detectors, the measurements are made in several angular intervals $\Delta\delta$ and $\Delta\theta$ and R then depends on the geometry of measurements and is determined experimentally.

For a known degree of polarization p of gamma-rays the ratio of the coincidence rates q' in channels B and C for $\delta = 0$ and $\delta = \pi/2$ is equal to

$$q' = (p + R)/(pR + 1). \tag{1}$$

In the measurements of R we used a lead target instead of a radiation source S. A Co^{60} gamma-ray source of an approximate intensity 500 millicuries was placed in the plane $\delta = 0$. A narrow beam of gamma-rays was directed on the target so that the gamma-rays scattered at an angle α (in the experiments α was chosen to be 90° or 60°) fell on the central crystal B of the polarimeter. Under these conditions the energy and polarization intensity of the gamma-rays incident on the polarimeter are well known (Table I).

In the described experiments we measured a ratio of the double coincidence rates n_{BC} for $\delta = 0$ and $\delta = \pi/2$; $q' = n(0) / n(\pi/2)$. The insertion of a target reduced the double coincidence counting rate to about 15% of the full rate at $\alpha = 90°$ and to 90% at $\alpha = 60°$. The counting rate in these experiments was 1 to 2 coincidences per second. In measurements of the soft gamma-rays in the scintillation counters C and C' the amplification of FEU-19 was changed somewhat because of the change in the magnetic fields (namely

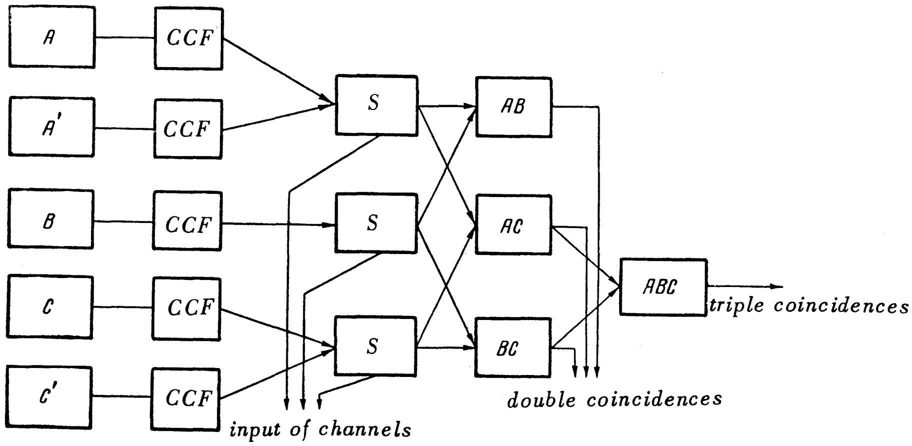

FIG. 2. Block diagram of the detection system: A, A', B, C and C' -- scintillation counters (same symbols as in Fig. 1); CCF -- cascade cathode follower; S -- pulse shaping circuit; AB, AC and BC -- double coincidence circuits, ABC -- triple coincidence circuit.

earth magnetic field) due to the rotation of the polarimeter. A check of the dependence of the double coincidence counting rate on the rotation of the polarimeter (asymmetry of double coincidences) was made with sources of unpolarized gamma-rays Sn^{113}, Cs^{137} and Co^{60} placed at the target location. The measured ratio of the double coincidence rates $n(0) / n(\pi/2)$ was different from unity only for the soft gamma-rays for Sn^{113} (1.08 ± 0.015). The value of q' obtained in the experiments with polarized gamma-rays, corrected for the asymmetry effect in the double coincidence counting rates, are given in Table I. The values of polarization sensitivity computed from Eq. (1) are also given in Table I. The most accurate measurements were made with scattering angle $\alpha = 60°$ because of a larger coincidence rate. It is evident from Table I that the polarization sensitivity of the above-described polarimeter is not in any way inferior to the polarimeters used in other experiments.

TABLE I. Measurements of the polarization sensitivity of polarimeter.

Scattering Angle α	Energy of the scattering photon, kev	Degree of polarization P	Ratio of coincidence rates q'	Sensitivity of polarimeter R
90°	360	0.46	1.44 ± 0.08	3.1 ± 0.6
60°	560	0.44	1.45 ± 0.02	2.8 ± 0.1

The experimental values of R allow for a calculation of the unknown geometrical factors $\Delta\delta$ and $\Delta\theta$ which are sufficient for calculation of the sensitivity of the polarimeter for gamma-rays of any energy. These calculations are used further in measurements of the polarization-direction correlation of Co^{60} and Na^{24} gamma radiation. Uncertainty in the choice $\Delta\delta$ and $\Delta\theta$ results in an error smaller than the error due to the experimental calibration of the polarization sensitivity of the polarimeter.

MEASUREMENTS ON Co^{60} AND Na^{24}

The gamma radiation accompanying disintegrations of Co^{60} and Na^{24} nuclei is well known. The sequence of emission of the cascade gamma-rays has been established. The measurements of angular correlation of gamma-rays emitted in the studied transitions[10-12], established with certainty the following sequence of spins of the ground state and the two excited states: 0; 2; 4, where both gamma-rays are quadrupoles. Consideration of the various combinations of parities of the excited levels leads to four possible transitions: $E2E2$, $E2M2$, $M2E2$, $M2M2$. The past measurements of the polarization direction correlation of Co^{60} gamma-rays selected one of these transitions as the actual one[4,6]. Therefore, the measurements on Co^{60} discussed below should be considered only as control measurements verifying the entire decay scheme. Using the detailed measurements of the pair conversion coefficients of Na^{24} gamma-rays of Bloom[13] we obtain data on the character of radiative transitions. Measurements of polarization-direction correlation were not made for Na^{24} gamma-rays. In the present work the data on parity of the excited levels of Mg^{24} are obtained by measuring polarization-direction correlation of gamma-rays.

To determine the correlation of polarization and propagation direction of gamma-rays we measured the ratio q of triple coincidence rates in channels A, B and C when crystals C and C' of the polarimeter (cf. Fig. 1) were placed in the plane of scattering of gamma-rays ($\delta = 0$) to the triple coincidence rate then the polarimeter was rotated into the plane $\delta = \pi/2$; $q = N(0) / N(\pi/2)$. In a general case both gamma-rays γ_1 and γ_2 entering the polarimeter can have various degrees of polarization and also different energy. We shall denote by $(I_{||})$ and $(I_{\perp})$ the intensity of radiation polarized in the plane of scattering of gamma-rays and in the plane perpendicular to the plane of scattering, respectively. Then we shall have for the ratio of the triple coincidence rates

$$q = \frac{(I_{\parallel})_{\gamma_1} a_{\gamma_1} b_{\gamma_2} + (I_{\parallel})_{\gamma_2} a_{\gamma_2} b_{\gamma_1} + R_1 (I_{\perp})_{\gamma_1} a_{\gamma_1} b_{\gamma_2} + R_2 (I_{\perp})_{\gamma_2} a_{\gamma_2} b_{\gamma_1}}{(I_{\perp})_{\gamma_1} a_{\gamma_1} b_{\gamma_2} + (I_{\perp})_{\gamma_2} a_{\gamma_2} b_{\gamma_1} + R_1 (I_{\parallel})_{\gamma_1} a_{\gamma_1} b_{\gamma_2} + R_2 (I_{\parallel})_{\gamma_2} a_{\gamma_2} b_{\gamma_1}}, \quad (2)$$

where a is the polarimeter efficiency, b is the detection efficiency of gamma-rays by channel A and R is the polarimeter sensitivity. The quantities $I_{||}$, $I_{\perp}$, a, b and R are different for the photons γ_1 and γ_2.

The quantities R_1 and R_2 can be calculated from the measurements of polarization sensitivity of the polarimeter as explained in the preceding section. The results of these calculations for gamma-rays of Co^{60} and Na^{24} are given in Table II. The distance of crystal A from the source was taken into account in the calculations of R_1 and R_2. It slightly changed $\Delta\delta$.

TABLE II. The relative efficiency of photon detection.

Isotope	Photon energy mev	Polarimeter sensitivity R	Polarimeter Detection a	Detection Efficiency b
Zn^{65}	1,12	—	1	1
Co^{60} γ_1 . . .	1.17	1.70	0.97	0.98
γ_2 . . .	1.33	1,64	0,87	0.90
Na^{24} γ_2 . . .	1,37	1.67	0.84	0.88
γ_1 . . .	2,75	1,33	0.52	0.54

For the quadrupole transitions that are of interest to us Eq. (2) simplifies into a form similar to Eq. (1),

$$q = (p + \bar{R})/(p\bar{R} + 1). \quad (3)$$

For $E2E2$ or $M2M2$ transitions the polarization intensity is the same for both cascade gamma-rays, $p = p_1 = p_2$ and the average value of the sensitivity $\bar{R}$ is equal to

$$\bar{R} = (R_1 + \eta R_2)/(1 + \eta), \quad (4)$$

where

$$\eta = (a_{\gamma_2}/a_{\gamma_1})\ b_{\gamma_1}/b_{\gamma_2}. \quad (5)$$

For $E2M2$ or $M2E2$ transitions $p = p_1 = 1/p_2$ and

$$\bar{R} = (R_1 + \eta)/(R_2\eta + 1). \quad (6)$$

The polarization intensity p of gamma-rays depends on the angle between the photons γ_1 and γ_2. For quadrupole transitions the maximum polarization intensity is at 90° angle between γ_1 and γ_2. In our measurements this angle was 100° and p was calculated for this angle.

If the multiplier $\eta = 1$, then Eq. (3) does not depend on the efficiency of the gamma detectors. For

TABLE III. Calculated and experimental ratios of triple coincidences $q = N(0)/N(\pi/2)$.

Type of transition	Degree of polarization p	Co^{60} $\bar{R}$	Co^{60} q calculated	Co^{60} q experimental	Na^{24} $\bar{R}$	Na^{24} q calculated	Na^{24} q experimental
$E2E2$	1,36	1,67	0,92		1,50	0,94	
$E2M2$	1,36	1,02	1,00	0,91±0,03	0,87	1,02	0,94±0,03
$M2E2$	0,73	1,02	1,00		0,87	0,98	
$M2M2$	0,73	1,67	1,08		1,50	1,06	

gamma-rays of different energies R may depend on the detection efficiency of gamma-rays. Therefore we also measured the relative detection efficiencies b and a of gamma-rays by the channel A and the polarimeter respectively. The efficiency of the polarimeter (of double coincidence counting rate n_{BC}) and the counter (pulse rate of channel A) was compared with a known efficiency of a Geiger counter previously calibrated using an ionization chamber[14]. The comparative data obtained with gamma radiation of isotopes Zn^{65}, Co^{60} and Na^{24} allow us to obtain by means of successive extrapolation the relative detection efficiency of monochromatic gamma-rays a and b (cf. Table II). The errors in these measurements are of the order ±0.02. From the data of Table II we obtain the experimental value η for Co^{60} gamma-rays: $\eta = 0.98 \pm 0.04$; for Na^{24} gamma-rays: $\eta = 0.99 \pm 0.04$. Thus $\eta = 1$ within the experimental error. This fact was evident for Co^{60} gamma-rays but not clear for Na^{24}.

The calculations of p, R and q for cascade gamma-rays Co^{60} and Na^{24} are given in Table III. In 1 min long measurements of the polarization-direction correlation of gamma-rays from Co^{60} and Na^{24} approximately 10 triple coincidences ABC were observed, of which 1/3 was accidental. The experimentally determined values of q (Table III) show that the transitions in Co^{60} and Na^{24} are $E2E2$ transitions. Parity and spin of the ground and the first two excited levels of Ni^{60} and Mg^{24} are then: 0^+, 2^+, 4^+. For Co^{60}, these results agree with the data obtained previously. Our conclusions about the parity of the excited states of Mg^{24} verify the results of Bloom[13].

In conclusion, the authors express gratitude to I. S. Shapiro for discussions of the results of this work.

1 L. V. Groshev and I. S. Shapiro, *Spectroscopy of Atomic Nuclei*, GITTL, Moscow, 1952.

2 D. L. Falkoff, Phys. Rev. **73**, 518 (1948).

3 D. R. Hamilton, Phys. Rev. **74**, 782 (1948).

4 F. Metzger and M. Deutsch, Phys. Rev. **78**, 551 (1950).

5 A. H. Williams and M. L. Wiedenbeck, Phys. Rev. **78**, 822 (1950).

6 Kloepper, Lenox and Wiedenbeck, Phys. Rev. **88**, 695 (1952).

7 J. J. Kraushaar and M. Goldhaber, Phys. Rev. **89**, 1081 (1953).

8 G. R. Bishop and J. P. Perez y Jorba, Phys. Rev. **98**, 89 (1955).

9 L. C. Biedenharn and M. E. Rose, Rev. Mod. Phys. **25**, 729 (1953).

10 R. M. Kloepper, Phys. Rev. **91**, 1026 (1953).

11 G. Charpalee and F. Suzor, J. Phys. Radium **11**, 633 (1950).

12 E. L. Brady and M. Deutsch, Phys. Rev. **78**, 558 (1950).

13 S. Bloom, Phys. Rev. **88**, 312 (1952).

14 I. V. Estulin, J. Exptl. Theoret. Phys. (U.S.S.R.) **24**, 221 (1953).

Translated by M. J. Stevenson
220