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《Original》

Measurements of the Direction and Polarization Correlation for Cascade Gamma-rays of Co-60 and Cs-134

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Co-60과 Cs-134의 連發감마線에 對한 方向 및 偏極相關 測定

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Abstract

Directional correlation measurements for the Co-60 and Cs-134 cascade gamma-rays have been performed in the angular range from 90° to 180° by use of the fast coincidence scintillation spectrometer incorporated with a gamma-ray polarimeter based on the Compton scattering effect to determine the polarization correlations. The experimental method together with the theoretical background is described, and the results are shown graphically to represent the consistency of the measurement with approximate theoretical estimates.

요 약

동시섬광분석기를 써서, 각도범위 90°에서 180°에 대하여, Co-60 및 Cs-134 감마선의 방향상관을 측정하였다. 그리고, 방향—편극상관의 측정에는 컴프턴산란효과를 응용한 감마선 편광분광기를 병용하였다. 이론적인 배경과 더불어 실험방법이 기술되었으며, 측정값이 이론적인 개산치와 일치함을 보이기위해 실험결과를 도식적으로 나타내었다.

I. Introduction

Angular correlations are to be expected between the directions of quanta emitted in cascade from an excited nucleus due to the coupling effect between the emitted quanta and the anisotropic radiation field of the preceding quantum. This effect has been very extensively utilized as a fundamental method for determining the spectroscopic properties of nuclear energy levels, and thereby the theory of angular correlation as well as the experimental techniques of nuclear spectroscopy became a well-established tool for interpreting the observed data.[1~8]

The information that can be obtained from the angular correlation measurement depends upon the types of the observed radiations, properties singled out by the experiment, and the extra-nuclear fields acting on the nucleus. As is well known, alpha-gamma and gamma-gamma directional correlations yield the spins of the nuclear levels, but not the parities. The relative parities can be, however, assigned, if one observes also the polarization of gamma-rays in addition to the direction, or if one measures the directional correlation between conversion electrons. The directional correlation of a beta-gamma cascade depends not only on the nuclear spins and parities, but also on the matrix elements involved in the beta transition.

The present experiment was undertaken to find the directional correlations of the successive gamma-rays emitted in cascade from Co-60 and Cs-134 socurces. The polarization correlations were also measured by means of a polarization sensitive device. The results will be graphically represented and compared with the theoretical estimates relevant to the polarization-direction correlation for the different parity assignments.

II. Experimental Method and Data Analysis

The experimental arrangements for the part of detector heads and electronic circuits are schematically represented in the following subsections. Two 3″×3″ NaI(TI) detectors are used for directional correlation measurements, and one 3″×3″ and two 2″×2″ NaI (Tl) detectors are used for polarization-direction correlation measurements. The lead shields, 10 cm thick at the front of each crystal, with beam hole of the diameter 5∼8 mm were used as the gamma-ray collimator.

1. Directional Correlation

Electronics setup of the fast coincidence spectrometer employing two 3″×3″ NaI (Tl) detectors A and B with lead collimator C is shown in Fig. 1. The bipolar output pulses of the spectroscopy amplifier with the 0.1 μsec rise time are fed into the timing single channel analyzer, and then the fast output signals generated through the crossover timing discrimination come into the fast coincidence circuit.

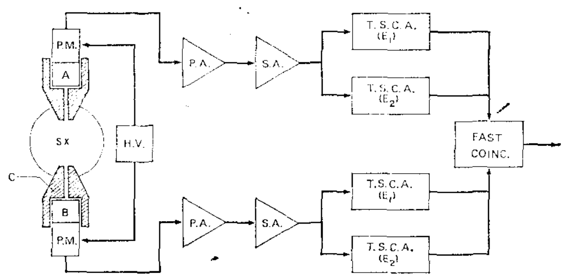

Fig. 1. Electronics setup for directional correlation measurement. P.M.=Photomultiplier tube, P.A.=Preamplifier, S.A.=Spectroscopy amplifier, T.S.C.A.=Timing single channel analyzer, C=Lead collimator.

The total coincidence count rate $C^{total}(\theta)$ for cascade gamma-rays emitted from the source of disintegration rate N_0 at the angle θ formed by their directions is given by the well-known expression

$$C^{total}(\theta)=N_0\varepsilon_f\varepsilon_m W(\theta)+2\tau N_0\varepsilon_f N_0\varepsilon_m, \qquad (1)$$

where ε_f and ε_m are the detection efficiencies for the fixed and movable counters, respectively, and τ gives the coincidence resolving time. $W(\theta)$ stands for the familiar directional correlation function. To guarantee the higher accuracy of coincidence measurements the ratio of accidental to true coincidence counts is prepared to be kept smaller than a ratio of 0.2.[9] Therefore the source intensity and the resolving time of the coincidence circuit have to be carefully optimized. Present measurements have been performed at a selected resolving time of about 30 nsec. The accidental coincidence rates were counted in practice by applying an arbitrary shifted delay (∼300 nsec) to disrupt true coincidences.

The true coincidence rate $C^{true}(\theta)$ is corrected for the detector position by introducing the coincidence ratio $R_c(\theta)$ defined by

$$R_c(\theta)=C^{true}(\theta)/N_m(\theta), \qquad (2)$$

where $N_m(\theta)$ is the counting rate of the rotating counter as a function of the angle θ. Then, the coincidence ratios $R_c(\theta)$ were fitted as usual by the following expansion in terms of Legendre polynomials,

$$R_c(\theta)=\text{constant}[1+A_2'P_2(\cos\theta)+\cdots + A_{\nu'max}'P_{\nu max}(\cos\theta)]. \qquad (3)$$

where A_ν''s are certain coefficients depending on the spins and parities of each nuclear state.

In order to correct the coefficients A_ν' for the effective divergence of the shielding collimator, the method developed by Walter[2] was applied.

The angular resolution of the present arrangement has been determined by observing the angle dependent coincidence rate due to the collinear emission of annihilation quanta from Na-22 position source. The result is shown in Fig. 2. The full width at half maximum of the angular resolution curve corresponds approximately to 1.7×10^{-2} steradian at the angle position $\theta=180°$ with the source to detector distance of 15cm.

2. Polarization Correlation

The block diagram of the triple coincidence electronic circuit with 3″×3″ NaI(Tl) crystal (A) and two 2″×2″ NaI(Tl) crystals(B and C) for the polarization arrangement is depicted in Fig. 3. The incident gamma-rays from the

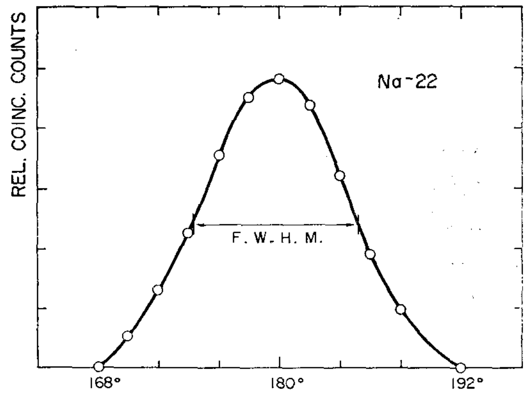

Fig. 2. Angular correlation of coincidences due to annihilation quanta from Na-22.

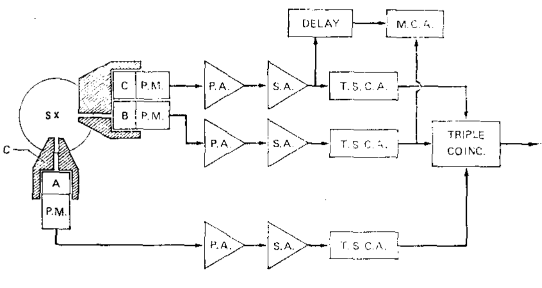

Fig. 3. Block diagram of the triple coincidence circuit used for the polarzation-direction correlation measurement.

source S suffer on energy loss due to the Compton scattering at the crystal B, and a certain intensity of the scattered quanta is then detected from the detection channel C by coincidece with the channel B. The observed pulse height spectrum of the channel C in coincidence with the channel B, but without any discrimination, is displayed in Fig. 4. In this figure the higher pulse height distribution around the 230 KeV peak corresponds to single-scattered gamma-rays from the scatterer B, and the lower hump at about 90 KeV is considered to be caused by double-scattered gamma-rays. This undesirable admixture of double-scattered component has been eliminated by discrimination in channel C for the triple coincidence spectrometry. Moreover, the source-detector geometry was carefully

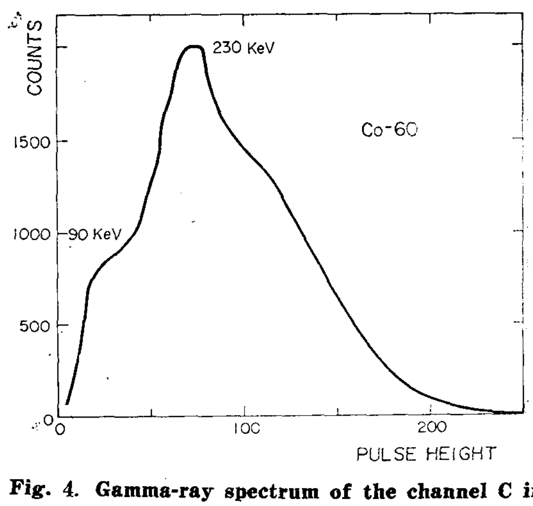

Fig. 4. Gamma-ray spectrum of the channel C in coincidence with all pulses in channel B.

tested, so that the B-C coincidence rate is equal to each other for both of the perpendicular and parallel detector orientations(B-C) with reference to the plane defined by two cascade gamma-rays.

The accidental coincidence rate in the triple coincidence measurement can be estimated by the formula[10)]

$$C_{ABC}^{acc}=2\tau(n_{AB}n_C+n_{AC}n_B+n_{BC}n_A-4\tau n_A n_B n_C), \tag{4}$$

where n_{AB}, n_{BC}, n_{AC} are the double-coincidence count rates between those corresponding detector channels, and n_A, n_C, n_B are the seperate counting rates for each channel. Each pulse width(τ) selected as appropriate was about 30 nsec. Obviously, $n_{BC}n_A$ in the parenthesis at the right side of the above equation is most dominant term, because the accidental coindences are expected to be caused mostly by pulses due to the B-C coincidence and those from the channel A, while the accidental B-C coincidence rate is quite negligible by comparing with its true coincidence rate. As mentioned in the foregoing subsection, the accidental coincidence count rates have been practically checked by means of the shifted delay.

For a fixed scattering angle δ, the differential Compton scattering cross-section $d\sigma$ assumes its extreme value at $\phi=0°$ and $\phi=90°$, where ϕ is the angle between the direction of polarization of the incident photon and the plane of scattering. For the present analysis the corresponding asymmetry factors have been calculated by use of the polarization dependent Klein-Nishina formula(ref. W. Heitler, Quantum Theory of Radiation, Oxford Univ. Press, London (1954)), under the simplified point-detector assumption for the crystal B with $\delta=80°$ chosen as a mean scattering angle, and the proper angular spans of $\Delta\delta=50°$ and $\Delta\phi=55°$.[10)]

III. Results and Discussion

1. Co-60

The Co-60 source with about 0.15 mGi has been prepared, and the true coincidence count rates for the directional correlation were around 45 cpm. Corrections for the effect of finite divergence of the collimator were applied and the data were fitted by a least squares method to give the experimental angular correlation function. The correlation function with the fitted values of coefficients is then given by

$$W(\theta)=1+(0.110\pm0.003)P_2(\cos\theta)$$
$$+(0.015\pm0.001)P_4(\cos\theta). \tag{5}$$

The result is also represented graphically in Fig. 5 to demonstrate the agreement with the theoretical estimation.

The result of directional correlation measurement can be simply expressed by anisotropy A, which is defined by

$$A=[W(180°)-W(90°)]/W(90°). \tag{6}$$

The experimental value deviates from the theoretical estimation about several percent and are in fairly good agreement within the range of counting error. The deviation is considered to be much reduced by the improvement of the measuring system such as multi-detector system[4)] and proper correction of the experimental data for angular resolution, but it is considered that

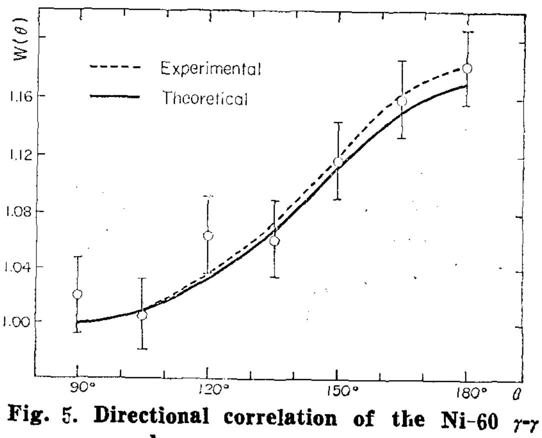

Fig. 5. Directional correlation of the Ni-60 γ-γ cascade.

the present data of the directional correlation measurement is sufficient for the analysis of the polarization correlation measurement.

All the polarization sensitive information can be interpreted in terms of the intensities $J_{\parallel}$ and $J_{\perp}$ of the linear polarizations parallel and perpendicular to the plane defined by two cascade gamma-rays. The intensities $J_{\parallel}$ and $J_{\perp}$ are correlated in general with the coefficients a_2, a_4, …of the angular correlation function rewritten by the form of

$$W(\theta)=1+a^2\cos^2\theta+a_4\cos^4\theta+\cdots. \quad (7)$$

However, in exact half of the 16 significant combinations of dipole and quadrupole trasitions, such as $E1$-$E1$, $E1$-$M1$, $E1$-$M2$, $E2$-$E2$,…, $J_{\parallel}$ is equal to $J_{\perp}$; i.e., there exists no polarization correlation. In the other half, the ratio $J_{\parallel}/J_{\perp}$ has the form

$$P=J_{\parallel}/J_{\perp}=[1+a_2+a_4-\tfrac{1}{2}a_4\sin^2 2\theta]/[1+(a_2+a_4)\cos 2\theta] \quad (8)$$

or its reciprocal, depending upon the type of the two transitions. From the values of coefficients $a_2=0.126$ and $a_4=0.042$ deduced by theory,[11] the ratio P to predict polarization-direction correlation for each of the four different types of quadrupole cascades can be calculated by the formulas

$$E2\text{-}E2:\quad P=J_{\parallel}/J_{\perp}=\frac{(1.17-0.02\sin^2 2\theta)}{(1+0.17\cos 2\theta)},$$

$$E2\text{-}M2,\ M2-E2:\ P=J_{\parallel}/J_{\perp}=1, \quad (9)$$

$$M2-M2:\quad P=J_{\parallel}/J_{\perp}=\frac{(1+0.17\cos 2\theta)}{(1.17-0.02\sin^2 2\theta)}.$$

The ratio of the counting rates in the two extreme angular positions $\phi=0°$ sand $\phi=90°$ is to be a measure of the sensitivity of the polarization analyzer, and then called an asymmetry ratio(R) defined by

$$R=(d\sigma)_{\phi=90°}/(d\sigma)_{\phi=0°}. \quad (10)$$

The numbers of scattered quanta in the two extreme positions corresponding to each prefered direction of polarization, are given by the following relations:

$$N_{\parallel}=J_{\parallel}(d\sigma)_{\phi=0°}+J_{\perp}(d\sigma)_{\phi=90°},$$

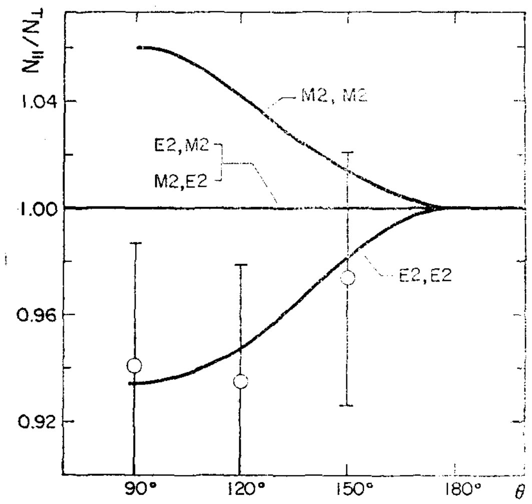

Fig. 6. Polarization-direction correlation for Co-60. The three curves correspond to different parity assignments.

$$N_{\perp}=J_{\parallel}(d\sigma)_{\phi=90°}+J_{\perp}(d\sigma)_{\phi=0°}. \quad (11)$$

Then, the ratio $N_{\parallel}/N_{\perp}$ can be expressed in terms of P and R by

$$N_{\parallel}/N_{\perp}=(P+R)/(PR+1d), \quad (12)$$

of which the experimental values are plotted against the angle θ. The experimental ratio ($N_{\parallel}/N_{\perp}$) was found to be 0.943 ± 0.044 at $\theta=90°$. Results are graphically shown in Fig. 6 and compared with the theoretical curve calculated with an asymmetry ratio $R=1.5$ as a rough estimation for $\Delta\delta=50°$ and $\Delta\phi=55°$ as already mentioned, and the mean gamma-ray energy of 1.25 MeV for the 1.17 MeV and 1.33 MeV cascade gamma-rays of Ni-60.

If one does not consider multipoles of orders higher than quadrupole, as seen in the result, the spins of each states can be assigned as 1= 4, 2 and 0. In addition, EQ-EQ is the only one consistent with the correlation measurement and such a process may not be accompanied with any parity change due to the selection rule for gamma-ray transitions.

2. Cs-134

The measurement for Cs-134 has been performed according to the similar method to evaluate the experimental data, as described above

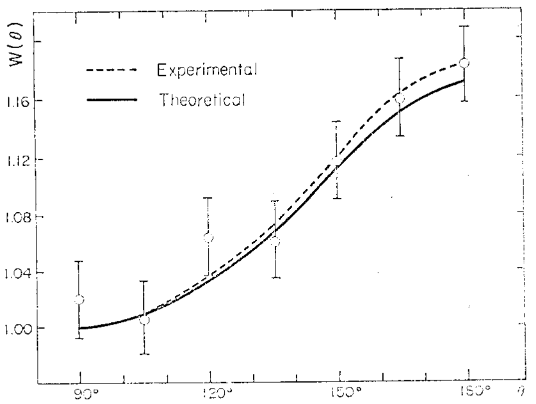

Fig. 7. Directional correlation of the 797 keV-604 keV cascade in Cs-134.

for the case of Co-60. The decay scheme of Cs-134 is somewhat complex, but the main mode with its large branching ratio looks very similar to that of Co-60. The successive gamma-rays have energies of 0.797 and 0.604 MeV, respectively.

The Cs-134 powder source of about 60 μCi has been prepared and imbeded in a small lucite sample holder, which can be accounted as a point source with the size of 2 mm. The true coincidence rate in the direction correlation measurement was found to be about 200 cpm on an average. The normalized angular correlation function with numerical values deduced from the measurement of the cascade gamma-rys becomes

$$W(\theta)=1+(0.091\pm0.002)P_2(\cos\theta)+(0.003\pm0.001)P_4(\cos\theta).$$

The result is represented graphically in Fig. 7 and compared with theoretical estimation. The agreement is good within the error range.

The discrepancy between the theoretical and experimental values of anisotropy A is somewhat greater than that in the case of Co^{60}. This relatively large discrepancy is believed to be caused by interfering radiations in the pulse height discriminations.

In polarization correlation measurement, the true coincidence rate has been found to be about 2 cpm at the angle of 90°. But the extended counting time has resulted in an improved accuracy with the standard deviation of about 4~5%. The ratio between the coincidence rates for the two extreme polarimetric positions of $\phi=0°$ and $\phi=90°$, was deduced to be

$$N_{\parallel}/N_{\perp}=0.880\pm0.067 \text{ at } \theta=90°.$$

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References

1. L.C. Biedenharn and M.E. Rose. Rev. Mod. Phys., 25, 729 (1953).
2. P.H. Stelson and F.K. Mcgowan, Phys. Rev., 105, 1346 (1957); 109, 901 (1958).
3. J.B.A. England, "Techniques in Nuclear Structure Physics," Macmillan Press, p. 504 (1974).
4. J.T. Larsen and D.I. Haddad, Nucl. Instr. and Methods, 69, 229 (1969).
5. R. Bass and H. Hanle, Nucl. Instr. and Methods, 104, 33 (1972).
6. J. Hattula and A. Sarmanto, Nucl. Instr. and Methods, 65, 77 (1968).
7. S.P. Sud and P.N. Trehan, Nucl. Instr. and Methods, 30, 919 (1971).
8. P.L. Gardulski and M.L. Wiedenbeck, Physical Review, C7, 2080 (1973).
9. H. Frauenfelder, "Angular Correlation," "Alpha, Beta and Gamma-ray Spectroscopy," K. Siegbahn, ed., North Holland, Amsterdam, p. 997(1968).
10. M. Deutsch and F. Metzger, Phys. Rev., 78, 551 (1950).
11. K. Way, "Nuclear Data Tables," Academic Press, New York and London, Vol. 9, No. 1 (1971).