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Angular and Direction-Polarization Correlation for Co^{60}, Cs^{134}, and Sb^{124}†

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Using the experimental techniques of Metzger and Deutsch the gamma-gamma angular and direction-polarization correlations have been measured for Co^{60}, Cs^{134} and Sb^{124}. The reliable results of previous investigations were confirmed for Co^{60} and served to check the instrument. The direction-polarization of Cs^{134} is consistent with a 4–2–0; *EQ,EQ* spin assignment. The absence of gamma-gamma angular and direction-polarization correlation in Sb^{124} requires a multipole mixture for the upper transition and a 3–2–0 spin assignment to the levels involved in the gamma-gamma transitions with no parity changes. The beta-gamma angular and direction-polarization correlation in Sb^{124} agrees with the 3–2–0 spin assignments for the levels of the beta-gamma transitions and with an *EQ* gamma.

WE have measured the angular correlation (between the directions of emission of one gamma-ray and of a successive gamma-ray) as well as the direction-polarization correlation (between the direction of emission of a gamma-ray and the polarization of another accompanying quantum) of successive nuclear transitions in Co^{60}, Cs^{134}, and Sb^{124}. In addition, we have measured the beta-gamma correlation functions for Sb^{124}.

The direction-polarization correlation functions, when interpreted in light of angular correlation data, allow one to assign both the multipole order of the gamma-transitions and the parity changes involved. Parity change is directly related to the electric or magnetic nature of the gamma-ray (if its multipole order is known). One may determine not only the over-all parity change from initial-to-final states but also the individual parity changes from initial-to-intermediate and intermediate-to-final states. The Compton scattering process is utilized as the polarization-sensitive process in the polarimeter.

I. GAMMA-GAMMA CORRELATION MEASUREMENTS

Apparatus

The experimental arrangement (Fig. 1) is essentially that of Metzger and Deutsch[1] in which plastic scintillation phosphors on 5819 photomultipliers have been used throughout. The source, mounted at the center of the white azimuth circle, is (behind the lead shield) at the intersection of the axes of rotation of the polarization-sensitive counters (2 and 3) and of the polarization-insensitive direction counter (1). The source is attached to and rotates (at its axis) with the direction counter.

Stability of mechanical alignment is extremely important and is maintained by suitable, stable mounting brackets and bearings. The scintillation counters are shielded from the effects of external magnetic fields with $\frac{1}{4}$-in. wall soft-iron tubing. Tests show that with all orientations the variation of the counting rate in each counter is $<\pm 0.5$ percent; the effect of such variation is eliminated to first order by dividing the triple coincidence rate by the single channel counting rates at the various positions. The scattering phosphor is a truncated cone, 4.0 cm long with a base diameter of 4.3 cm, attached to photomultiplier 3 which in turn is clamped at its base and not rotated. The magnetic shield for this counter and the polarimeter arms ($2'$ and $2''$) rotate about the center-line as axis. The plastic phosphors and extensive lead shielding provide collimation for counters 1 and 3 and limit each to a solid angle of about 0.04π steradian.

Triode-connected 6AK5 cathode-followers are used at the base of all photomultipliers. The outputs of the polarimeter photomultipliers ($2'$ and $2''$) are combined in a summing circuit and connected to a modified Atomic Instrument Company model 204-B linear amplifier. Each of the outputs from 1 and 3 is likewise amplified. The three discriminator outputs of the 204-B's are applied to a threefold crystal coincidence circuit whose output is, in turn, passed through a 204-B. Four scalers simultaneously monitor the three single channel counting rates and the triple total coincidence rate. Double coincidence rates and resolving

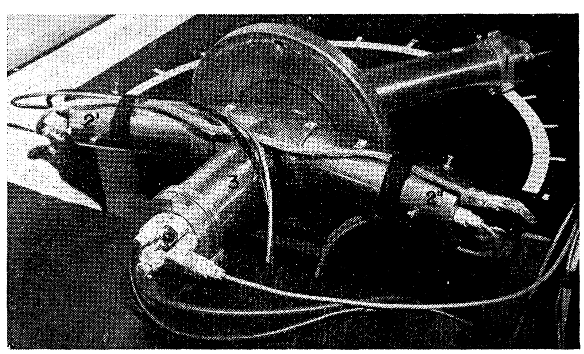


FIG. 1. Photograph showing direction-polarization correlation detector head. Counters 1 and 3 comprise the angular correlation (direction-sensing) counters and define the θ-plane. Counters 2 ($2'$ and $2''$) and 3 are the polarimeter elements and define the ϕ plane.

† This paper is part of a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the University of Michigan by R.M.K. under the faculty supervision of M.L.W.
* Now at Los Alamos Scientific Laboratory.
[1] F. Metzger and M. Deutsch, Phys. Rev. 78, 551 (1950).

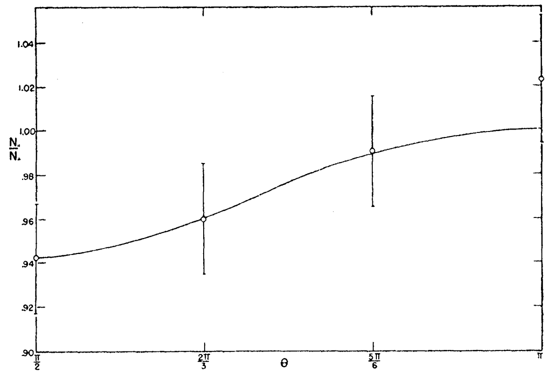


FIG. 2. Direction-polarization correlation of Co^{60}. Solid line is theoretical correlation function, assuming 4–2–0; EQ,EQ transitions and R equal 1.44.

time measurements are made very frequently to provide reliable corrections for accidentals. The resolving time is maintained at 0.200 ± 0.004 μsec by slight, occasional pulse-shape adjustments, being constant to ±1 percent for periods of a few days to four weeks and to $<\pm0.5$ percent during a day's operation.

The probable errors have been computed from statistical considerations, with each run weighted in accord with observed instrument stability. These probable errors agree well with the probable deviations from the mean, giving a measure of the statistical consistency. For one run approximately 2400 total triple coincidences were recorded at each setting of ϕ at 0, $\pi/2$, π, and $3\pi/2$. Counting rates differed, depending upon, for example, gain settings, source strength, particle energy of the source being measured, and counter efficiency. Typical single channel rates in counts/second are 5000 to 11,000 for counters 1 and 3 and 800 to 1700 for the sum of counters $2'$ and $2''$. The total triple coincidence rate varied from 0.45 to 1.20 counts-second, again depending upon the equipment adjustment, which was never changed during a run. Approximately seven runs comprised the data for one point. The source strength was adjusted to give a total accidental rate about equal to the triple real rate. All sources were obtained from Oak Ridge.

The θ-plane is defined by the lines from the source to the scatterer (3) and from the source to the direction counter (1). The detector plane contains the lines from source to scatterer and from scatterer to polarimeter phosphors $2'$ and $2''$. $N_{\parallel}$ is the real triple coincidence rate with $\phi=0$, π; i.e., with the detector plane *in* the θ-plane. $N_{\perp}$ is the real triple coincidence rate with $\phi=\pi/2$, $3\pi/2$. No direction-polarization correlation should be observed at $\theta=\pi$; i.e., $N_{\parallel}/N_{\perp}$ should equal 1.0. Data taken at $\theta=\pi$ serve as an additional check on the instrument. For measuring angular correlation the polarimeter counters ($2'$ and $2''$) are inactivated and double coincidences between counters 1 and 3 are recorded as a function of θ. All beta-components are shielded from the detectors by aluminum absorbers.

Cobalt 60

Our gamma-gamma angular correlation measurement for Co^{60} agrees very well with other measurements[2,3] after correction for finite solid angle and fits theoretical values calculated on the 4–2–0; $L=2$, $L=2$, assumption. A direction-polarization correlation measurement of this nuclide is in agreement with previous work[1,4] and is an indication of the reliability of the instrument. The experimental results are presented in Fig. 2. The solid line is calculated on the 4–2–0, EQ,EQ, scheme assuming an asymmetry ratio[1] R of 1.44.

Cesium 134

The gamma-gamma angular correlation data for Cs^{134} are fit reasonably well by the 4–2–0; $L=2$, $L=2$, function in which one assumes a symmetrical component of 35 percent; i.e., $1+0.65[W(\theta)-1]$. Our $W(\pi)$ value of 1.108 ± 0.010 agrees well with that of Robinson and Madansky.[5] At $\theta=2\pi/3$ the experimental value is about 1.8 percent lower than the calculated value; the experimental error at this point is ±0.6 percent. This low value at $\theta=2\pi/3$ agrees with the results of Beyster[4] and may indicate that a symmetrical (no correlation) component does not adequately explain the angular correlation of Cs^{134}.

Previous determinations[1,4] of the direction-polarization correlation function of Cs^{134} differ. The gamma-gamma direction-polarization correlation results for Cs^{134} are presented in Fig. 3 and agree with those of Metzger and Deutsch.[1] For the experimental arrangement used, a value of R equal to 2.0 was calculated at 0.7 Mev, assuming that R is 1.44 at 1.24 Mev (Co^{60}). The solid line is obtained by using the value $R=2.0$, the angular correlation coefficients as calculated above (with the symmetrical component), and an EQ,EQ cascade.

Antimony 124

We have reinvestigated the gamma-gamma angular correlation and, in addition, have searched for a gamma-gamma direction-polarization correlation in Sb^{124}. Antimony 124 has previously been reported[6,7] to give no gamma-gamma angular correlation. Table I shows the results of our measurements, where the angular correlation function $W(\theta)$, the ratio of counting rates $N(\theta)/N(\pi/2)$, has been corrected for finite solid angle. The probable errors are calculated from statistics and the probable error of $N(\pi/2)$ is included in all $W(\theta)$. The higher value $W(\pi)$ could be due to a trace of positron contamination in our source; this possibility

[2] E. L. Brady and M. Deutsch, Phys. Rev. **78**, 558 (1950).
[3] J. R. Beyster and M. L. Wiedenbeck, Phys. Rev. **79**, 411 (1950).
[4] A. H. Williams and M. L. Wiedenbeck, Phys. Rev. **78**, 822 (1950).
[5] B. L. Robinson and L. Madansky, Phys. Rev. **84**, 604 (1951).
[6] J. R. Beyster and M. L. Wiedenbeck, Phys. Rev. **79**, 169 (1950).
[7] D. T. Stevenson and M. Deutsch, Phys. Rev. **83**, 1202 (1951).

of correlation due to annihilation radiation cannot be ruled out. All betas were shielded from the detectors with aluminum.

The complexity of the decay scheme of Sb^{124} as now proposed[8] gives rise to some uncertainty as to the gamma-rays involved in a gamma-gamma correlation measurement which does not discriminate between the various gamma-ray energies. On the basis of the proposed scheme, considering the abundances, one can best assume that most of the gamma-gamma coincidences and correlation arise from the 1.7-Mev and the 0.60-Mev (lowest) gamma-rays.

The absence of gamma-gamma angular correlation and direction-polarization correlation requires that one of the transitions be mixed and further places restrictions on the angular momenta of the levels that are involved. For the ground state we take $J=0$ (even-even) and for the first excited state $J=2$ on the basis of internal conversion data.[9,10] For the transitions $[MD,EQ;EQ]$ we then have the choice for the upper level $J=3$, 2, 1. Using the calculations of Ling and Falkoff[11] and of Zinnes,[12] we find that only $J=3$ with $\beta=0.09$ (i.e., ~ 10 percent mixture of EQ with MD) fits the experimental results. The arbitrariness of the relative phase is only to a sign of the interference term. For this case $R/Q=0$; $S/Q=0.3$ percent for the angular correlation and $J_{\parallel}/J_{\perp}\approx 87$ percent (for $\theta=\pi/2$) for the direction-polarization correlation. This much polarization correlation could have been missed because of the inefficiency of the scattering crystal as a polarimeter. For $J_{\parallel}/J_{\perp}=0.87$ and R calculated as 1.56, we compute an expected $N_{\parallel}/N_{\perp}=1.03$ at $\theta=\pi/2$, which is almost within the quoted statistical uncertainty. If the upper transition were of higher multipole order than MD or EQ,

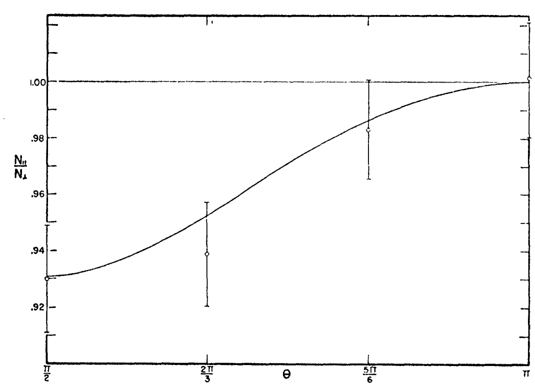


FIG. 3. Direction-polarization correlation of Cs^{134}. Solid line is theoretical correlation function, assuming J-values of 4–2–0 with EQ,EQ transitions, R equal 2.0, and a 35 percent symmetrical component.

TABLE I. Gamma-gamma angular correlation $W(\theta)$ and direction-polarization correlation $N_{\parallel}/N_{\perp}$ for Sb^{124}.

θ	$W(\theta)$	Probable error	$N_{\parallel}/N_{\perp}$	Probable error
$\pi/2$	1.000	...	0.985	0.024
$2\pi/3$	0.983	0.006	...	...
$3\pi/4$	...	...	1.017	0.028
$5\pi/6$	0.996	0.006	...	...
π	1.021	0.007	0.994	0.019

this probably would have been detected as internal conversion in the work of Hutchinson.[9]

II. BETA-GAMMA CORRELATION MEASUREMENTS OF ANTIMONY 124

Accepting an integral portion of the higher energy components of the beta-spectrum of Sb^{124}, we have remeasured the beta-gamma angular correlation and have investigated the beta-gamma direction-polarization correlation as a function of θ.

Apparatus

The equipment of the gamma-gamma correlation work was adapted for beta-gamma correlation experiments by substituting for the plastic phosphor of the direction counter 1 an anthracene crystal 1 mm thick and 29 mm in diameter, making a beta-detector of the direction counter. The source (about 0.008 cm thick) is mounted on a cellophane backing, 0.003 cm thick, by evaporating a $SbCl_3$ solution to dryness. The backing and the source are adequately thin because the correlation is associated with the higher energy betas, which are not seriously scattered by these thicknesses of backing and source. The beta-rays were collimated by a circular aluminum slit and by the size of the beta-detector crystal. To eliminate the lower energy components from the beta-spectrum, a total absorber thickness of 217 mg/cm^2 was inserted between the source and the beta detector, of which 208 mg/cm^2 was an aluminum shield on the front of the anthracene crystal. All betas were shielded from the scatterer by 1300-mg/cm^2 aluminum.

Beta-Gamma Angular Correlation

The integral beta-gamma angular correlation function, obtained with this experimental arrangement, is plotted in Fig. 4. The solid line (A) is the observed angular correlation function while the dotted line (B) is this correlation function corrected for the effect of gamma-gamma coincidences. The mean energy of emission of those betas which pass through the absorber has been calculated graphically from spectral data[9] as 1.31 ± 0.2 Mev. This calculation assumes that, within the range of energies admitted, each beta carries the same angular correlation. From the differential correlation value calculated at this energy for spins 3–2–0

[8] Kern, Zaffarano, and Mitchell, Phys. Rev. **73**, 1142 (1948).
[9] D. R. Hutchinson and M. L. Wiedenbeck, Phys. Rev. **88**, 699 (1952).
[10] F. R. Metzger, Phys. Rev. **86**, 435 (1952).
[11] D. S. Ling, Jr., and D. L. Falkoff, Phys. Rev. **76**, 1639 (1949).
[12] I. Zinnes, Phys. Rev. **80**, 386 (1950).

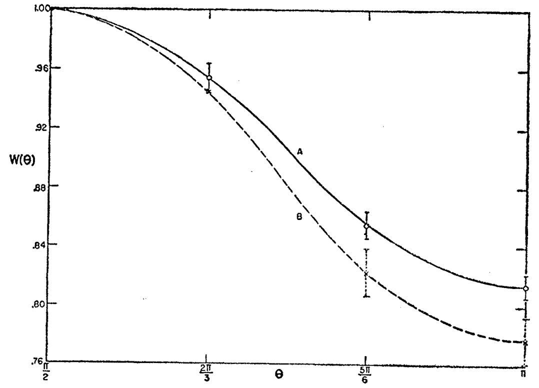


FIG. 4. (*A*) Observed beta-gamma integral angular correlation function; the average energy accepted is approximately 1.3 Mev. (*B*) Correlation function (*A*) corrected for gamma-gamma coincidences.

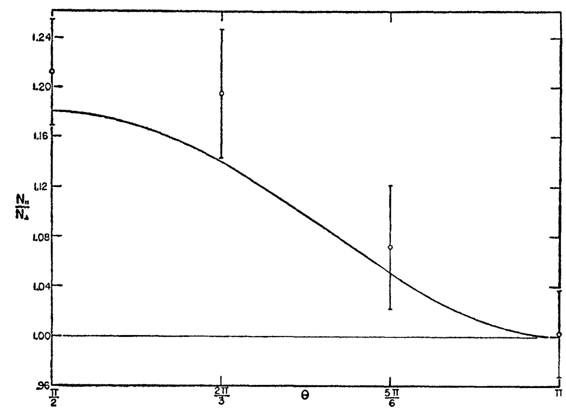


FIG. 5. Experimental beta-gamma direction-polarization correlation function for Sb^{124}. Solid line is calculated assuming no parity change in the gamma-transition.

with the B_{ij} matrix element effective in the beta transition, one obtains $W(\pi)=0.80\pm0.03$, after accounting for finite solid angle and the symmetries of the gamma-gamma angular correlation, in good agreement with the observed 0.814 ± 0.008. For a 1–1–0 spin assignment we calculate a $W(\pi)=0.76\pm0.03$. However, it is to be pointed out that this integral angular correlation work is not as sensitive for differentiating between the 3–2–0 and the 1–1–0 assignments as are the data of differential angular correlation.[7]

Beta-Gamma Direction-Polarization Correlation

The observed beta-gamma direction-polarization correlation values for Sb^{124} are presented in Fig. 5. Lloyd[13] has given a theoretical direction-polarization correlation function which reduces in second order in the coefficients of the Legendre polynomials to

$$N_{\beta\gamma}(\theta;\phi)=1+A\{P_2(\mu)+(\rho/2\epsilon)P_2^2(\mu)\cos 2\phi\},$$

where $N_{\beta\gamma}(\theta;\phi)$ is the counting rate with angle θ between counter 1, the source, and counter 3 and with the angle ϕ between the detector plane and the θ-plane, $P_2(\mu)$ and $P_2^2(\mu)$ are the Legendre and associated Legendre polynomials, respectively, with $\mu=\cos\theta$, and $\rho/\epsilon=-(R-1)/(R+1)$. ($R$ is the asymmetry ratio of the polarimeter.) This reduction also includes an assumption that the gamma-ray is a pure multipole with no parity change (*EQ* or *MD*).

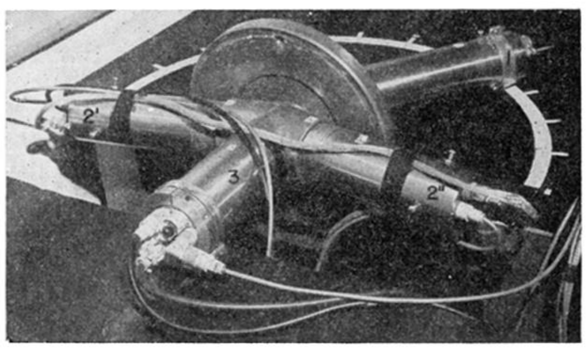
The coefficient A is determined experimentally from the beta-gamma angular correlation data. For angular correlation $\rho_\delta=0$ in the above function and $W(\pi)$ becomes $(1+A)/(1-A/2)$, from which one can calculate A. Correcting A for finite solid angle and using a calculated value of $R=2.2$ for 0.60 Mev, we have determined the function shown by the solid line in Fig. 5. For a yes parity change (*ED* or *MQ*) the reciprocal of this function results. Our experimental value of $N_{\parallel}/N_{\perp}$ at $\theta=\pi/2$ is 1.211 ± 0.042; Stump[14] finds 1.075 ± 0.043 for approximately the same absorber thickness.

The angular correlation data suggest 3–2–0 for the spins of the states involved in the beta-gamma transitions, requiring the gamma-ray to be quadrupole. The direction-polarization correlation (no parity change) is that of an *EQ* gamma-ray. These assignments are further substantiated by internal conversion coefficient data.[9,10]

We are grateful to S. P. Lloyd for making the results of his work on polarization correlations available to us.

[13] Stuart P. Lloyd (private communication).

[14] R. Stump, Phys. Rev. 86, 249 (1952).



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