A Study of the Polarization-Direction Correlation of Successive Gamma-Ray Quanta*

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A gamma-ray polarimeter utilizing Compton scattering as the analyzing process is described. Measurements of the polarization-direction correlations of the gamma-rays emitted in the disintegration of Sc^{46}, Co^{60}, Rh^{106}, and Cs^{134} are reported.

1. INTRODUCTION

THE angular correlation of two gamma-rays, successively emitted by a nucleus, is intimately connected with the multipolarity of the two transitions and with the total angular momenta of the nuclear levels involved,[1,2] but does not depend on the parity changes occurring. Information concerning the electric or magnetic nature of the radiating multipoles may be obtained, as was shown by Falkoff[3] and Hamilton,[4] through an investigation of the polarization properties of the emitted radiation. Such a study, involving the simultaneous measurement of several gamma-rays, became possible through the development of the scintillation counters. These detectors with their high efficiency for gamma-rays and excellent properties regarding high speed counting are especially suited for coincidence measurements with gamma-rays. Their use increases the coincidence rates by several orders of magnitude as compared with Geiger-Müller counters in a similar arrangement.

As any process analyzing the polarization of gamma-rays is apt to reduce the intensity by a large factor, the simultaneous measurement of the polarization of both quanta[3] is most unfavorable in view of the small counting rates expected even if one uses the scintillation counters available today.

We therefore restricted ourselves to a combination of a polarization-insensitive detector, used to define the direction of one of the quanta, with a polarization-sensitive device for the analysis of the polarization of the other quantum. This combination had been suggested by Hamilton,[4] who gave the explicit form of the correlations expected in this case for dipole and quadrupole radiation.

As a polarization-sensitive process we chose the Compton scattering of the gamma-rays, a method that had previously proven adequate in the investigation of the polarization of the annihilation radiation.[5]

The arrangement used is shown schematically in Fig. 1. A, B, and C are the crystals of three scintillation counters. A is the polarization-insensitive detector, B and C together form the polarization-sensitive detector, which we shall call the analyzer. S is the source which is surrounded by enough material to stop all beta-rays. Crustal C is heavily shielded against direct radiation from the source and scattered radiation from A; therefore it detects preferentially the radiation scattered from B. However, as the counting rate in C due to direct radiation is still large (see Table I), it is necessary to use a counter B instead of a simple scatterer, selecting in this way the significant events. For a polarized beam of gamma-rays coming from B, the coincidence counting rate BC depends, as we shall discuss later, on the angle ϕ, the amount of asymmetry being directly related to the degree of polarization.

All the information about the polarization of the quantum going to B (the other quantum going to A) can be expressed in terms of the intensities $J_{\parallel}$ and $J_{\perp}$ of the linear polarizations parallel and perpendicular to the plane defined by the two gamma-rays.[3] The direction of polarization is identified with the direction of the electric vector; $J_{\parallel}$ corresponds to J_θ, $J_{\perp}$ to J_ϕ in the notation of Hamilton.[4] For a given degree of polarization we expect the largest ratio of coincidence rates (triple coincidences ABC) between the two positions $\phi=0$ and $\phi=\pi/2$, ϕ being the angle between the planes BSA and BSC (Fig. 1).

The intensities $J_{\parallel}$ and $J_{\perp}$ in general depend on the coefficients $a_2, a_4\cdots$ of the angular correlation which are

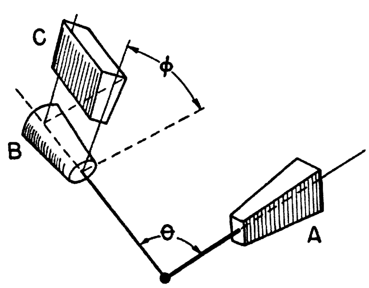

FIG. 1. Schematic diagram of experimental arrangement of polarimeter.

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[1] D. R. Hamilton, Phys. Rev. 58, 122 (1940).

[2] E. L. Brady and M. Deutsch, Phys. Rev. 74, 1541 (1948).

[3] D. L. Falkoff, Phys. Rev. 73, 518 (1948).

[4] D. R. Hamilton, Phys. Rev. 74, 782 (1948).

[5] Snyder, Pasternack, and Hornbostel, Phys. Rev. 73, 440 (1948), E. Bleuler and H. L. Bradt, Phys. Rev. 73, 1398 (1948) and R. C. Hanna, Nature 162, 332 (1948).

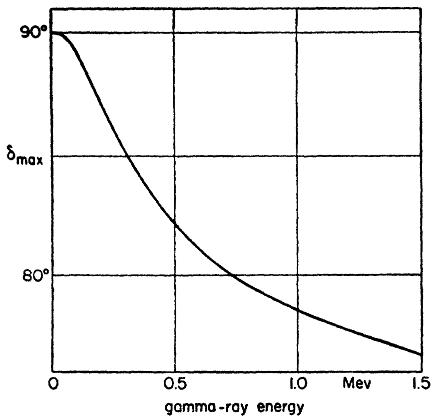

FIG. 2. Angle of maximum asymmetry, δ_{max}, for ideal geometry, as a function of the gamma-ray energy of the primary photons.

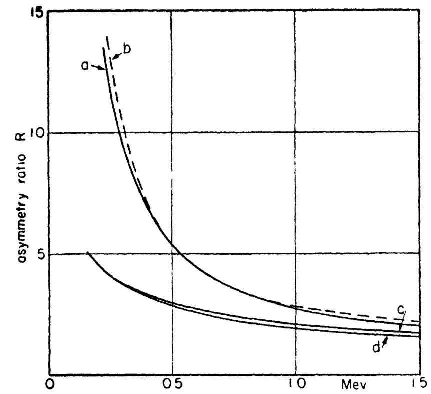

FIG. 3. Compton scattering of polarized gamma-rays. Asymmetry ratio R as a function of gamma-energy for different geometries: (a) $\delta=80°$, ideal geometry; (b) $\delta=\delta_{max}$, ideal geometry; (c) $\delta=80°$, $\Delta\delta=55°$, $\Delta\phi=60°$; (d) like (c) but corrected for scattering from C to B.

defined by the equation

$$W(\theta)=1+a_2\cos^2\theta+a_4\cos^4\theta\cdots,$$

where $W(\theta)$ is the relative probability of the second quantum being emitted at an angle θ with respect to the first one.

If both detectors (A, $B+C$) have the same dependence of gamma-ray efficiency on energy, then in exactly half of the 16 possible combinations of dipole and quadrupole transitions $J_{\parallel}$ is equal to $J_{\perp}$, independently of a_2 and a_4, i.e., there exists no polarization correlation. In the other half, $J_{\parallel}/J_{\perp}$ has the form

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

or its reciprocal, depending on the type of the two transitions.

A closer inspection shows that for all the cascades for which $J_{\parallel}$ is equal to $J_{\perp}$ an over-all parity change is brought about by the two transitions, while the cascades with $J_{\parallel}\neq J_{\perp}$ are characterized by no over-all change in parity. The mere statement of the existence or nonexistence of a polarization correlation therefore unambiguously describes the cascade with respect to the over-all parity change provided that not all the coefficients a_n of the angular correlation vanish.

As soon as the existence of a polarization correlation is established for a given cascade, the sign of the difference $J_{\parallel}-J_{\perp}$ is also determined. If we then know the multipole order from the coefficients of the angular correlation, the sign of $J_{\parallel}-J_{\perp}$ enables us to characterize the two transitions in more detail. In the case of two quadrupole transitions, for instance, the sign of $J_{\parallel}-J_{\perp}$ tells us whether the two transitions are both magnetic or both electric quadrupoles.

The sign of $J_{\parallel}-J_{\perp}$ and the coefficients $a_2, a_4\cdots$ of the angular correlation rigorously determine the detailed shape of the polarization correlation. A careful investigation of the angular dependence of the polarization and the absolute value of $J_{\parallel}/J_{\perp}$ may therefore be used to confirm the results of the angular correlation experiments, but does not yield any information which could not be derived from the sign of $J_{\parallel}-J_{\perp}$, if a_2, a_4 are precisely known.

2. THE POLARIMETER

A. Compton Scattering as Analyzing Process

The differential cross section $d\sigma$ for the scattering of a photon of energy k_0 through an angle δ is given by the Klein-Nishina formula[6] which, averaged over all polarizations of the scattered quantum, can be expressed as

$$d\sigma=\frac{r_0^2}{2}d\Omega\frac{k^2}{k_0}\left[\frac{k}{k_0}+\frac{k_0}{k}-2\sin^2\delta\cos^2\phi\right],$$

where $k=k_0[1+k_0/mc^2(1-\cos\delta)]$ is the energy of the photon after scattering. ϕ is the angle between the direction of polarization of the incident photon and the plane of scattering, $r_0=e^2/mc^2$ is the classical radius of the electron and $d\Omega$ the element of solid angle.

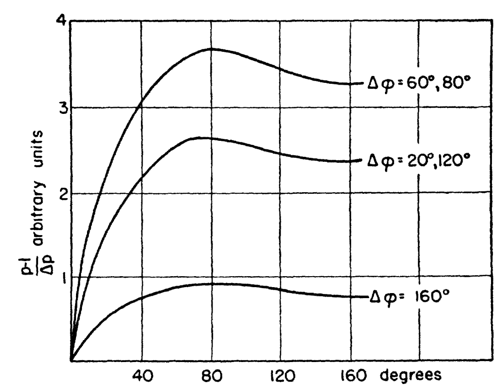

FIG. 4. Figure of merit of the polarimeter, for finite geometry, as a function of the spread in the angle δ for various spreads of ϕ.

[6] O. Klein and Y. Nishina, Zeits. f. Physik 52, 853 (1929).

For a fixed value of δ the differential cross section assumes its extreme values for $\phi=0$ and $\phi=90°$. The ratio of the counting rates which we obtain in the two extreme angular positions for a linearly polarized gamma-ray beam is a measure of the sensitivity of the analyzer. This ratio we shall call asymmetry ratio R and define it such that it is always larger than unity. For the ideal geometry dealt with in this section, R is simply the ratio of two differential cross sections, i.e., $R=(d\sigma)_{\phi=\pi/2}/(d\sigma)_{\phi=0}$.

Owing to the δ-dependence of k, the asymmetry ratio R, which is unity for $\delta=0$ and $\delta=\pi$, reaches its maximum value at an angle δ somewhat smaller than $\pi/2$. In Fig. 2 the dependence of this angle $\delta_{\max}$ for maximum asymmetry is given as a function of the energy of the primary photons.

For our analyzer we chose a mean angle δ of 80°. The energy dependence of the asymmetry ratio R for this angle is illustrated in Fig. 3. In this figure the dotted line, which almost coincides with the curve for $\delta=80°$, represents the upper limit for the sensitivity of any analyzer which uses Compton scattering as the analyzing process; it was calculated taking for each energy the corresponding value of $\delta_{\max}$ (Fig. 2).

In the actual design of an analyzer one has to allow rather large spreads of both δ and ϕ in order to obtain practical counting rates. If p denotes the ratio $J_{\parallel}/J_{\perp}$ of the components polarized perpendicular to each other and Δp the standard deviation of p, then $p-1/\Delta p$ may be used as a criterion for the usefulness of a polarization sensitive arrangement.

Using the Klein-Nishina formula we calculated the value of this ratio $p-1/\Delta p$ for a point scatterer and a variety of values $\Delta\delta$ and $\Delta\phi$. The results of these calculations are represented in Figs. 4 and 5. The characteristic quantity $(p-1)/\Delta p$ is plotted as a function of the spreads of δ and ϕ. Both figures refer to a gamma-ray energy of 1 Mev and a value $p=1.2$. Within the energy range which is of main interest in the present study (0.3–1.5 Mev), the shapes of the curves do not change appreciably. The optimum spreads in both δ and ϕ lie between 50 and 80°.

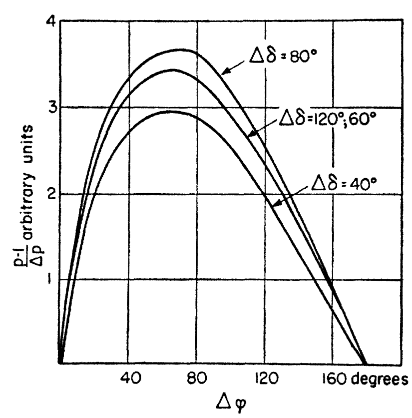

FIG. 5. Figure of merit of the polarimeter, for finite geometry, as a function of the spread in the angle ϕ for various spreads in δ.

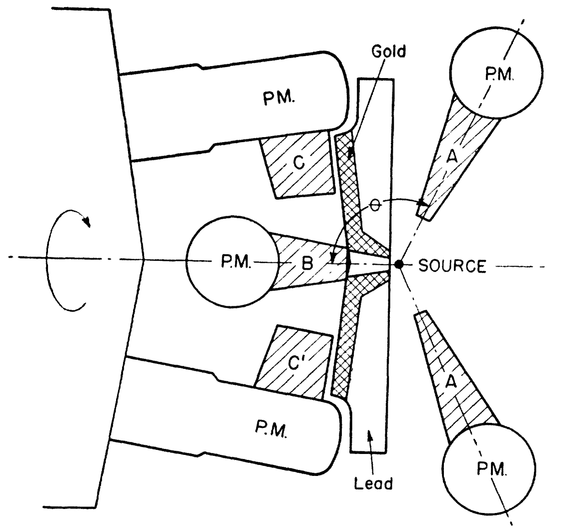

FIG. 6. Cross section through the polarimeter in the position $\phi=0$. P.M.: Photo-multiplier tube 931-A.

The spans of δ and ϕ realized in the actual analyzer are $\Delta\delta=55°$ and $\Delta\phi=60°$. Experimental evidence for these values will be presented later. The asymmetry ratio R for this finite geometry may be compared in Fig. 3 with the ratio for the ideal arrangement.

The ratio $N_{\parallel}/N_{\perp}$ of the triple coincidence rates in the two extreme positions ($\phi=0$, $\phi=\pi/2$) of the analyzer, the asymmetry ratio R, and the ratio of the polarization intensities $p=J_{\parallel}/J_{\perp}$ are connected through the relation

$$N_{\parallel}/N_{\perp}=(p+R)/(pR+1). \tag{2}$$

For $p=0$ and $p=\infty$, i.e., for linearly polarized gamma-rays, $N_{\parallel}/N_{\perp}$ takes on the values R and $1/R$ as is to be expected from the definitions of p and R. We might point out that owing to the preference of scattering at right angles with respect to the plane of polarization the ratio $N_{\parallel}/N_{\perp}$ is smaller than unity when $p=J_{\parallel}/J_{\perp}$ is larger than unity, and vice versa.

B. Design of the Polarimeter

The arrangement of the counters and shields in our polarimeter is illustrated in Fig. 6, which represents a cross section through the polarimeter, the plane of the two gamma-rays coinciding with the plane of the paper. The rotating element (with counters C and C') is shown in the position corresponding to $\phi=0$ (see Fig. 1).

TABLE I. Data on scandium[46] taken at $\theta=120°$; numbers represent counts per second. Total number of counts: 10^6 in each single channel, 2.10^4 in each double coincidence channel.

Pos.	n_A	n_B	n_C	n_{AB}	n_{AC}	n_{BC}	$n_{ABC}\cdot 10^2$ Total	Chance	True
∥	6420	3552	735	13.4	4.08	19.0	8.95±0.11	2.79	6.16±0.11
⊥	6490	3550	732	13.3	4.05	19.2	9.39±0.11	2.82	2.82±0.11

This measurement: $(N_{\parallel}/N_{\perp})_{120}=0.938\pm0.024$
Final value: $(N_{\parallel}/N_{\perp})_{120}=0.934\pm0.014$

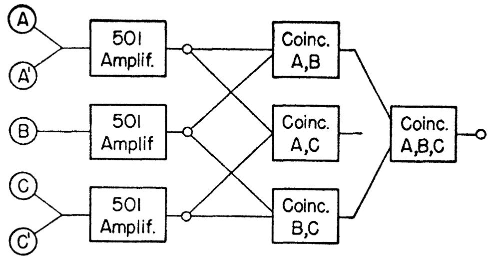

FIG. 7. Schematic circuit diagram.

The counters A' and C', displaced with respect to A and C by 180° in azimuth, add to the original polarimeter ABC the equivalent combinations ABC', $A'BC$, and $A'BC'$, thus increasing the coincidence counting rates by a factor of four.

The addition of C' not only increases the counting rate, but at the same time improves the symmetry of the apparatus, since any small asymmetry due to misalignment of the axis of the rotating part is canceled to a first approximation.

Naphthalene was used as fluorescent substance for all five gamma-ray detectors. At the time of the construction of the polarimeter this substance had the advantages of being readily available and of having good mechanical properties. Today it might be preferable to replace naphthalene by anthracene or one of the other substances which in the meantime have been found to have good counting properties. Most of the inorganic phosphors, however, are excluded in view of their rather long "decay-times."

The photo-multiplier tubes are selected 931-A, 1P21, and 1P28 RCA tubes. The whole polarimeter is cooled to dry ice temperature. Owing to the fact that the quanta scattered into C and C' have rather low energies, the improvement obtained by the cooling is quite remarkable, especially with naphthalene as the counter substance.

The shield is rotationally symmetrical with respect to the main axis of the apparatus, which coincides with the axis of the conical crystal B. The shield mainly serves the following two purposes: (a) It attenuates the direct radiation which would go to the counters C and C', and (b) it prevents scattering from A to C.

Poor shielding of the counters C and C' against the direct radiation from the source would give rise to a large number of triple coincidences due to quanta scattered from C to B through almost 180°. As scattering of polarized photons through zero or 180° shows no azimuthal asymmetry, the additional coincidences would reduce the sensitivity of the analyzer appreciably. Moreover, due to the angular correlation of the gamma-rays, the number of these undesirable coincidences would depend on the position ($\phi=0$, $\phi=\pi/2$) of the counters C, C' and would therefore change the ratio $N_{\parallel}/N_{\perp}$ and consequently suggest a different polarization correlation.

A similar falsification of the data arises from insufficient shielding of C against the radiation scattered from A. The consequences of this effect can be much more detrimental than those of the effect mentioned. In this case, not only the solid angle subtended by C at A changes, when C goes from $\phi=0$ to $\phi=\pi/2$, but also the energy of the radiation and the amount of absorber change radically. One expects in this case more additional coincidences in the position $\phi=0$ than in the position $\phi=\pi/2$; i.e., a trend of $N_{\parallel}/N_{\perp}$ toward larger values than those corresponding to the polarization correlation of the substance being investigated. The effect is largest for $\theta=90°$, in which case A is nearest to C and the energy of the quanta scattered into C is highest. The rises at $\theta=\pi/2$ in the measured correlations of Sc^{46} and Co^{60} (Figs. 9 and 10) are probably due to residual effects of the two types just described.

The existence of strong asymmetries due to these effects made it necessary to replace part of the lead in the shield by gold. (See Fig. 6.) The reduction in sensitivity (i.e. in R) due to the additional coincidences C, B is still about 12 percent for the hardest gamma-rays (Co^{60}), the asymmetry in the triple coincidences is of the order of one percent.

C. Counting Devices

A schematic diagram of the arrangement of the circuits is shown in Fig. 7. The tubes of A and A' and of C and C' are connected in parallel; their pulses are fed into Los Almos Model 501 amplifiers (0.1-μsec. rise time). The outputs of these amplifiers are taken by pairs into separate coincidence circuits. The pulses of two of these coincidence channels are then mixed again in a fourth coincidence arrangement. In this way one is able to count all the double coincidences separately, a possibility which is essential for monitoring the performance of the polarimeter. The difference in the number of double coincidences A, C for the two positions $\phi=0$ and $\phi=90°$ gives, for instance, information concerning the amount of undesired scattering from A to C.

The resolving time of the final coincidence channel is not important as the question of the existence or non-existence of a triple coincidence is decided in the previous coincidence stages. One can therefore use rather broad and large output pulses of the three double coincidence channels, a fact that contributes to the reliability of the whole device.

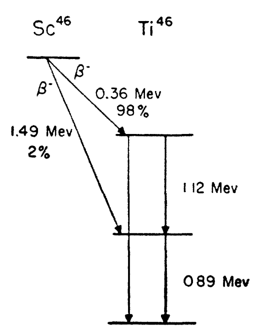

FIG. 8. Disintegration scheme of Sc^{46}.

All the double coincidence channels have the same resolving time of 0.1 μsec. as well as can be measured. Denoting this common resolving time by τ, the triple coincidence chance rate for a simple cascade is given by

$$n_{ABC}^{\text{chance}}=2\tau(n_{AB}n_C+n_{AC}n_B+n_{BC}n_A-4\tau n_An_Bn_C),$$

where n_{AB}, n_{AC}, n_{BC} are the numbers of double coincidences between the corresponding counters and where n_A, n_B, n_C are the single counting rates.

In the case of positron emitters the existence of two annihilation quanta per cascade adds five possible combinations of two gamma-rays to the pair representing the cascade. Consequently the cascade gamma-rays will contribute only a small fraction of the total coincidence rate and any asymmetry in this contribution will be very hard to detect. As the shielding of counter C is not perfect we might expect true triple coincidences not due to scattering in B which cause an additional reduction of the actual sensitivity. With the present apparatus we therefore can hope to detect a polarization correlation in a positron emitter only if this correlation is very large.

Table I contains typical counting rates and demonstrates the degree of symmetry obtained as well as the large contribution of the direct radiation to the counting rate in C.

In order to obtain a sufficient number of coincidences, the apparatus was arranged to take the data automatically, the position of the analyzer changing every half hour. Sources giving about 8.10^5 disintegrations per second were used.

3. THE SENSITIVITY OF THE ANALYZER

Owing to the rather complicated geometry of the polarimeter it is difficult to make a reliable estimate of the effective spreads $\Delta\delta$ and $\Delta\phi$, which determine the sensitivity of the analyzer. The values $\Delta\delta=55°$ and $\Delta\phi=60°$, on which we based our calibration, were derived from the following experiment.

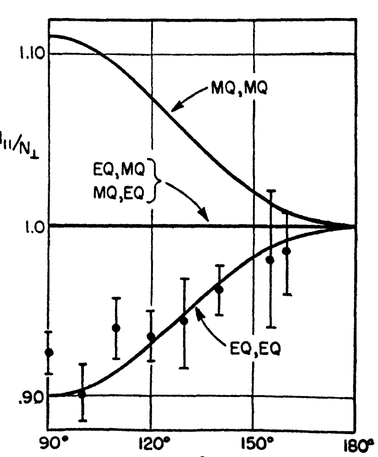

FIG. 9. Polarization-direction correlation for Sc^{46}. The three curves correspond to the different parity assignments.

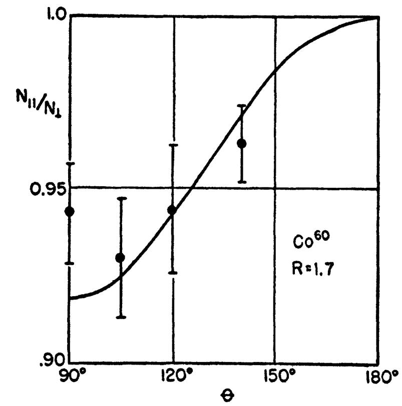

FIG. 10. Polarization-direction correlation of Co^{60}.

A collimated beam of gamma-rays from a strong ($\frac{3}{4}$ curie) Co^{60} source is scattered through an angle of 90°, becoming partially polarized in a manner predictable from the Klein-Nishina formula. For this beam of known polarization the ratio $N_{\parallel}/N_{\perp}$ is measured in our analyzer. In this way the asymmetry ratio R is determined for the energy of the scattered quanta (360 kev for Co^{60}).

If the two gamma-rays of Co^{60} (1.117 and 1.332 Mev)[7] are detected with equal over-all efficiency, the average polarization $p=J_{\parallel}/J_{\perp}$ is 2.2 for scattering through 90°. The measured ratio $N_{\perp}/N_{\parallel}=1.61\pm0.06$ of the counting rates in the two extreme positions then leads to an asymmetry ratio R_{exp} of 4.3 ± 0.7 for a gamma-ray energy of 360 kev. The spreads in δ and ϕ for our apparatus are approximately equal and their value R_{exp} is compatible with $\Delta\delta=\Delta\phi=45\pm15°$.

When the analyzer is used in the polarimeter, the finite size of crystal A increases the spreads of both δ and ϕ, the change in δ being 10°, with the one in ϕ being 15°. Thus we arrive at effective spreads $\Delta\delta=55\pm15$ and $\Delta\phi=60\pm15°$. The asymmetry ratio $R(60/55)$ for these spreads is plotted in Fig. 3 as a function of the gamma-ray energy. This asymmetry ratio is, however, still not the actual one. In order to arrive at the true value of the asymmetry ratio for our polarimeter, we have to correct $R(60/55)$ for the reduction in sensitivity due to the scattering from C to B which we mentioned earlier in connection with the shielding problem.

For the "regular" scattering from B to C the asymmetry ratio R_{BC} is equal to $R(60/55)$. For the undesirable scattering from C to B, however, R_{CB} is practically unity. The actual value of R is then the weighted average of these two asymmetry ratios R_{BC} and R_{CB}. The geometry of the analyzer suggests as appropriate weights the single counting rates n_B and n_C in the counters B and C. The actual asymmetry ratio is therefore given by

$$R_{\text{actual}}=(n_B\cdot R_{BC}+n_C\cdot R_{CB})/(n_B+n_C)$$

[7] Lind, Brown, and DuMond, Phys. Rev. 76, 591 (1949).

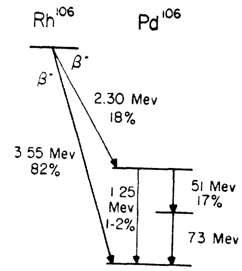

FIG. 11. Disintegration scheme of Rh^{106}.

or, if we use the values 1 and $R(60/55)$ for R_{CB} and R_{BC}

$$R_{\text{actual}}=[n_B\cdot R(60/55)+n_C]/(n_B+n_C).$$

This actual asymmetry ratio is also plotted in Fig. 3; it was used for the calculation of the expected polarization correlations in all the cases presented in this paper.

4. RESULTS

A. Scandium 46

The disintegration scheme of Sc^{46} is shown in Fig. 8. The angular correlation of the two gamma-rays has been studied by Brady and Deutsch.[2] Their data are consistent with the correlation function

$$W(\theta)=1+(1/8)\cos^2\theta+(1/24)\cos^4\theta,$$

which is expected[1] for two quadrupole transitions between states with spins 4, 2, and 0.

The knowledge of the coefficients $a_2=1/8$ and $a_4=1/24$ enables us to predict the polarization direction correlation for each of the four different types of quadrupole cascades:

$$EQ, EQ\quad p=J_{\parallel}/J_{\perp}=(1.17-0.02\sin^2 2\theta)/(1+0.17\cos 2\theta),$$

$$EQ, MQ;\ MQ, EQ\quad p=J_{\parallel}/J_{\perp}=1,$$

$$MQ, MQ\quad p=J_{\parallel}/J_{\perp}=(1+0.17\cos 2\theta)/(1.17-0.02\sin^2 2\theta).$$

The ratios $N_{\parallel}/N_{\perp}$ expected for these four cases are plotted against the angle θ in Fig. 9. An asymmetry ratio $R=1.9$ (see Fig. 3) was used for the conversion of the ratios $J_{\parallel}/J_{\perp}$ into coincidence counting ratios. The experimental points with their standard deviations are indicated on the same graph. The agreement with the correlation expected for two electric quadrupole transitions is as good as can be expected for this kind of experiment. If one does not consider multipoles of orders higher than quadrupole, the assignment 4, 2, 0; *EQ*, *EQ* is the only one consistent with the correlation experiments.

The lack of calculations for higher multipoles and the possibility of interference for mixed radiation[8] cause ambiguities in the interpretation of the correlation experiments for all the substances studied. As magnetic octupole transitions and electric or magnetic radiation of higher multipole order are extremely improbable from lifetime considerations, the most important transitions of higher multipolarity which have to be considered are electric octupoles.

Many of the cascades involving electric octupoles can be excluded: The existence of a polarization-direction correlation rules out[8a] the combinations with an over-all parity change; i.e., *EO*, *EQ*; *EQ*, *EO*; *EO*, *MD*; *MD*, *EO*; the sign of the polarization is inconsistent with the sequence *EO*, *EO*.

The conversion coefficients reported by Peacock and Wilkinson[9] would call for higher multipole orders, in disagreement with the fact that coincidences are observed with resolving times as small as 10^{-7} sec. In view of the difficulty of the measurement of very small conversion coefficients it seems advisable to repeat these experiments.

There is good reason to believe that calculations for the combinations with octupoles will soon be available and that the assignment of spins and parities will then be unambiguous.

Fluharty and Deutsch[10] have searched for the 2.01-Mev cross-over transition in Sc^{46}. They were able to establish the existence of gamma-rays with energies larger than 1.63 Mev and smaller than 2.2 Mev in 1.2×10^{-5} percent of the disintegrations. This abundance is of the order of magnitude which one expects, based on the approximate formulas for the transition probabilities, for the (4, 2, 0; *EQ*, *EQ*) assignment.

B. Cobalt 60

Both Co^{60} and Sc^{46} disintegrate to even-even nuclei by the emission of a soft beta-ray spectrum followed by

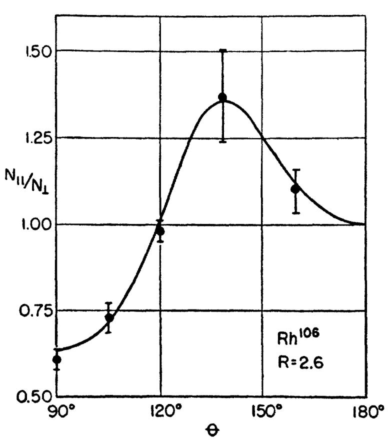

FIG. 12. Polarization-direction correlation of Rh^{106}.

[8] D. S. Ling and D. L. Falkoff, Phys. Rev. 74, 1224 (1948).

[8a] We assume here, that the general relations between the character of the transitions and the polarization-direction correlation (existence, sign), which are correct for dipole and quadrupole radiation, are also valid for combinations with higher multipoles.

[9] C. L. Peacock and R. G. Wilkinson, Phys. Rev. 74, 297 (1948).

[10] R. G. Fluharty and M. Deutsch, Phys. Rev. 76, 182 (1949).

a cascade of two gamma-rays with energies of about 1 Mev.

Within the experimental uncertainty the angular correlations[2] of the gamma-rays from Sc^{46} and Co^{60} are identical. The same is true for the polarization-direction correlations of these two substances (Figs. 9 and 10). It is therefore very likely that the levels of Ni^{60}, involved in the disintegration of Co^{60}, have the same properties as those of Ti^{46} connected with the decay of Sc^{46}, i.e., that the three levels have the same parity and spins 4, 2, and 0.

The discussion of the cascades including electric octupoles follows the one of Sc^{46}. Deutsch and Siegbahn[11] measured the coefficients of internal conversion. Their results indicate that there is no over-all change in parity in the cascade and that both gamma-rays are probably quadrupoles.

Fluharty and Deutsch[10] limited the intensity of the cross-over gamma-ray of 2.45 Mev, if present, to less than 2.5×10^{-5} percent of the Co^{60} disintegrations. The cross-over transition in Sc^{46}, though present, has an abundance smaller than the limit of detection quoted for Co^{60}. It is still possible, therefore, that the two cross-over transitions have about the same abundance as one would expect from the similarity of the disintegration schemes.

C. Rhodium 106

The disintegration scheme[12] of the 30-sec. daughter of Ru^{106} (Fig. 11) has not been definitely established, the identification of the 1.25-Mev gamma-ray as the cross-over transition being justified only by an agreement of energy values which might be fortuitous.

Due to the low abundance of the 1.25-Mev gamma-ray the main contribution to both angular and polarization-direction correlation has to be attributed to the two gamma-rays of 0.51 and 0.73 Mev even if the decay scheme should be modified with respect to the high energy gamma-ray.

Rh^{106} exhibits a very strong angular correlation[2] which can be represented quite well by a probability function of the form

$$W(\theta)=1-1.5\cos^2\theta+2.0\cos^4\theta.$$

The occurrence of a $\cos^4\theta$ term excludes dipole transitions. None of the correlations expected for two quadrupole transitions fits the experimental distribution. The theoretical coefficients for a spin assignment $0-2-0$ are just twice as large as the experimental ones. As long as we have no explanation[12a] for this fact we may as well assume that the inclusion of higher multipoles will provide a solution.

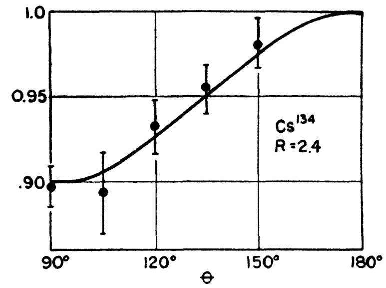

FIG. 13. Polarization-direction correlation of Cs^{134}.

Having found large coefficients $a_2=-1.5$ and $a_4=2$ for the angular correlation, one expects either a very large polarization for Rh^{106} or none. The experimental results as illustrated in Fig. 12 reveal a large polarization with an angular dependence which is represented quite well by

$$p=J_{\parallel}/J_{\perp}=(1.5-\sin^2 2\theta)/(1+0.5\cos 2\theta),$$

i.e., the distribution obtained from the general relation (1) using the experimentally determined angular correlation coefficients.

D. Cesium 134

As the disintegration scheme[13] of Cs^{134} comprises several gamma-rays coinciding with each other, one cannot hope to arrive at a clear decision concerning the properties of the nuclear levels from correlation experiments alone. However, any future analysis must be able to account for the experimentally established correlations and it is for this reason that we present our data on Cs^{134} in Fig. 13. The asymmetry ratio R for the average gamma-ray energy of Cs^{134} is 2.4. The experimental value of $N_{\parallel}/N_{\perp}$ at $\theta=90°$ therefore corresponds to a polarization $p=1.3$, which in turn leads to[14] a ratio $W(\pi)/W(\pi/2)=1.13$ for the angular correlation. This value is in good agreement with that measured by Brady and Deutsch.[2] The solid line in Fig. 13 was calculated under the somewhat arbitrary assumption of a distribution of the form $1+0.13\cos^2\theta$ for the angular correlation. More precise measurements of the angular correlation are needed for this isotope. A decision concerning the position of the cross-over transition would reduce considerably the number of possible interpretations.

5. CONCLUSIONS

In combination with reliable measurements of the angular correlation of successive gamma-rays, the investigation of the polarization-direction correlation

[11] M. Deutsch and K. Siegbahn, Phys. Rev. **77**, 680 (1950).
[12] W. C. Peacock, Phys. Rev. **72**, 1049 (1947).
[12a] If one of the transitions proceeds with a mixture of different radiations, the correlations may be changed radically as was shown by D. S. Ling and D. L. Falkoff (reference 8). Still another change in the correlation coefficients might be caused by atomic-nuclear interactions. See G. Goertzel, Phys. Rev. **70**, 897 (1946).

[13] K. Siegbahn and M. Deutsch, Phys. Rev. **71**, 483 (1947); **73**, 410 (1948). L. G. Elliott and R. E. Bell, Phys. Rev. **72**, 979 (1947).
[14] At $\theta=90°$, $p=(1+\Sigma a_i)/(1-\Sigma a_i)$ or its reciprocal, and $W(\pi)/W(\pi/2)=1+\Sigma a_i$.

yields very definite information concerning the parities of the nuclear levels involved. The ambiguities left in the examples discussed in this paper arise from a paucity of theoretical predictions for higher multipole transitions, to the possibility of interference for mixed radiation, and to the preliminary character of the angular correlation data. If these obstacles are eliminated the experiments with the polarimeter have only to decide the existence or non-existence of a polarization in the position (θ) at which we expect the largest effect.[15] For this purpose the polarimeter described in this paper has sufficient sensitivity. For gamma-ray energies above a few hundred kev the correlation method compares favorably with other methods which lead to the assignment of spins to nuclear levels and of parity changes to the transitions between these levels.

[15] p is largest at $\theta=90°$ in most of the cases, but not in all of them.

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Angular Correlation of Successive Gamma-Rays*

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The angular correlation of successive gamma-rays emitted by six even-even nuclei has been investigated and found to be anisotropic in every case, and of the magnitude expected theoretically. Effects of external magnetic fields and of chemical binding on the correlations are found to be smaller than the experimental uncertainty for some exploratory experiments. Interpretation of the results in terms of the nuclear states involved is in general possible by use of additional evidence such as relative transition probabilities.

1. INTRODUCTION

CONSIDERABLE progress has been made during the last few years in studies of nuclear radiation spectra from radioactive processes. The experiments have mainly yielded results concerning the energies of excited states. Only little unambiguous systematic evidence on the spins of these states has appeared. Coefficients of internal conversion have revealed the multipole character of nuclear gamma-rays in some cases. Although this method is in principle universally applicable, limitations on the precision of both theoretical and experimental results have so far restricted it to the more favorable cases. No values of nuclear angular momenta are obtained directly by this method, but probable values can frequently be assigned from the multipole orders.

If the life time of a gamma-ray transition is long enough to be measured a probable multipole order can be obtained. This is usually done by means of Bethe's life-time formulas as modified by Segrè. With a few notable exceptions only transitions of rather low energy or high multipole order have been studied so far by this method because of the difficulty in measuring extremely short life-times. There is considerable uncertainty about the exact validity of the life-time formula because it neglects necessarily all details of the nuclear configuration.

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It would be most desirable to have a method of the general validity and applicability available to atomic spectroscopy in the Zeeman effect. Unfortunately, it seems at present entirely unfeasible to separate the nuclear magnetic substates by application of external fields sufficiently to observe the transitions between the individual m-values separately. It has been proposed to change the relative populations of the several magnetic substates of an excited state by applying a magnetic field at very low temperatures where the magnetic energy μH is comparable to the thermal agitation energy kT.[1] Information about the multipole nature of the radiation and about the angular momenta of the initial and final states could then be obtained from the space distribution and the polarization of the emitted radiation. This method has not yet been tried. It presents formidable experimental difficulties and is probably limited to long-lived excited states.

Although it is difficult to change the relative populations of the several substates it is frequently possible to make measurements on a sample of nuclei for which these relative populations are different from their equilibrium values. This is in general the case when two successive rays are emitted by one nucleus. If we observe the first ray to be emitted in the z-direction the probability of the intermediate state being in any one of the possible m_z states is no longer the same as in the absence of this information. Thus, by observing the space distribution and polarization of those gamma-rays which

[1] J. A. Spiers, Nature **161**, 807 (1948).