aluminum and tantalum. In the case of aluminum the angular distribution supports Levinger's quasi-deuteron model, and the energy distribution is not definitely in disagreement with it. This happens in an energy region where the model was not intended to be applied. If this theory is interpreted in a literal fashion, the magnitude of the asymmetric peaking at 60° indicates that electric quadrupole absorption is about nine percent as strong as electric dipole absorption of photons. This is of the order of magnitude to be expected from sum-rule considerations.[20]

It is then rather strange to find that this theory seems not to apply to tantalum. In this substance the directly ejected protons appear to obey a pure $\sin^2\theta$ law. This is characteristic of electric dipole absorption but it tells little about the nature of the absorption mechanism. The independent-particle model calculations of Courant appear to be excluded by the result, and similar calculations based on an alpha-particle model may well be similarly excluded. The quasi-deuteron model can explain the results only if $p\approx 0$, which, if the literal interpretation of the theory is correct, implies that the electric quadrupole absorption in tantalum is much less than one would expect.

It therefore appears that none of the postulated photon interaction mechanisms gives suitable predictions applicable to any element in the "intermediate" energy range.

[20] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950).

ACKNOWLEDGMENT

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Beta-Gamma Polarization Correlations*

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The polarization of the gamma ray emitted at an angle of 90 degrees to the preceding beta particle has been measured for certain beta-gamma cascades in potassium-42, arsenic-76, rubidium-86, antimony-124, and cesium-134, as selected by beta absorbers when necessary. The polarimeter was checked by observing the polarization of the gamma rays of cesium-137 and cobalt-60 when Compton-scattered through 90 degrees. Of the gammas investigated, those of potassium-42 and cesium-134 have no observable polarization. For the other three elements, the sign of the polarization correlation, taken in combination with the sign of the angular correlation reported by other observers, uniquely determines that no parity change occurs in the gamma emission, corresponding to electric quadrupole radiation in decay of the excited state.

INTRODUCTION

THE gamma-gamma and beta-gamma angular correlations[1,2] have become recognized tools of nuclear spectroscopy and of the search for the fundamental beta interaction; concerning the gamma rays involved, these angular correlations usually tell the angular momenta of the levels involved and the multipole order of the gammas. If the gamma detector is in addition polarization-sensitive, then one may expect to learn whether the given multipole is electric or magnetic (that is, the parity change in the transition), for the fields of the electric and magnetic type of given order multipole differ by interchange of E and H and hence by a 90 degree rotation of polarization, and differ in parity.

Information concerning multipole order and parity change may also be obtained from internal conversion data. This procedure involves elaborate calculations using relativistic electron wave functions and is, in principle, perhaps not quite so direct as a measurement of gamma angular distribution and polarization; but with the exact calculations now available, the interpretation of experiments seems just as satisfactory. The principal difference between the two methods lies, therefore, in convenience of use; and one relevant factor here is the energy dependence of the two effects. Internal conversion coefficients become small for high energies and low Z; for example, for an electric quadrupole gamma the coefficient α_k has values[3] 2×10^{-6} and 0.11 for 2.5 Mev, $Z=10$ and 0.25 Mev, $Z=96$, respec-

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† Class of 1860 Fellow, 1951–1952.

[1] H. Frauenfelder, Ann. Rev. Nuc. Sci. **2**, p. 129 (1953).

[2] M. Deutsch, Repts. Progr. Phys. **14**, 196 (1951).

[3] Rose, Goertzel, Spinrad, Harr, and Strong, Phys. Rev. **83**, 79 (1951).

tively. The Compton scattering process upon which the polarization depends is less energy-sensitive; in going from 0.25 to 2.5 Mev, the cross section for 90° scattering is reduced by a factor 0.28 and the effect produced in a polarization measuring experiment like the present one (more specifically, the ratio C/B, as defined later, for ideal geometry) is reduced by a factor 0.23. Polarization correlation is thus well suited to cases where internal conversion coefficients are small.

The present experiment investigates the polarization of the gamma ray emitted at 90° to the beta ray which leaves in its first excited state the daughter nucleus (all of which happen to be of even-even type); the parent nuclei involved were Sb^{124}, K^{42}, Rb^{86}, and As^{76}. Beta-gamma directional anisotropy has been previously observed for each of these[1] and polarization-correlation

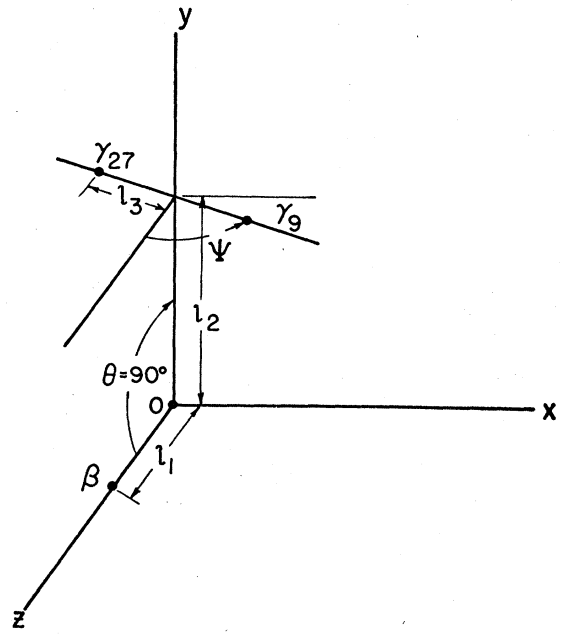

FIG. 1. Schematic diagram of geometry of detectors. $l_1=3.8$ cm; $l_2=7.0$ cm; $l_3=2.2$ cm; diameter of beta crystal, 4.0 cm.

measurements on Sb^{124}, similar to ours, have been reported by Stump,[4] and by Kloepper *et al.*[5] In addition, as a check, measurements were made on Cs^{134}, which has been observed to have no anisotropy.[1]

The gamma-ray polarimeter utilizes the polarization sensitivity of Compton scattering and is similar in design to those developed by Metzger and Deutsch[6] and used by Kraushaar and Goldhaber[7] and others,[4,5] except that its use solely for $\beta\gamma$ correlation reduces the number of scintillation crystals from three to two.

[4] R. Stump, Phys. Rev. **86**, 249 (1952).
[5] Kloepper, Lennox, and Wiedenbeck, Phys. Rev. **88**, 695 (1952).
[6] F. R. Metzger and M. Deutsch, Phys. Rev. **78**, 551 (1950).
[7] J. J. Kraushaar and M. Goldhaber, Phys. Rev. **89**, 1081 (1953).

THEORY

The theory of direction-polarization correlation has been investigated with particular reference to gamma-gamma correlation,[8,9] but the results necessary to the present case may be taken over *in toto*. These results take a particularly simple form when the gammas are dipole or quadrupole, which will be assumed in what follows.

If a gamma ray is observed to be emitted with an angular distribution

$$W(\theta)=1+\alpha_2\cos^2\theta+\alpha_4\cos^4\theta, \tag{1}$$

and, if we define

$$A=[W(180)-W(90)]/W(90), \tag{2}$$

then $A=\alpha_2+\alpha_4$. If now, at $\theta=90°$, we observe the intensities J_θ and J_ϕ of radiation for which the E vector lies in the usual θ and ϕ directions, then we know the following information from Eq. (8) of reference (8):

$$J_\phi/J_\theta=(1+A)/(1-A) \quad (E1, M2) \quad \text{(Yes)},$$
$$J_\phi/J_\theta=(1-A)/(1+A) \quad (E2, M1) \quad \text{(No)}.$$

Here the multipoles to which each alternative applies are indicated; and "yes" "no" refers to the parity change involved in the gamma transition. Thus (for dipoles and quadrupoles) the value of J_ϕ/J_θ at $\theta=90°$ depends not upon multipole order, but only upon parity change and A. If we define

$$B=(J_\phi/J_\theta)-1, \tag{3}$$

then observation of the signs of both A and B determines the parity change uniquely; for we have

$$\begin{aligned} A&=B/(B+2) \quad \text{(Yes)},\\ A&=B/(B-2) \quad \text{(No)}, \end{aligned} \tag{4}$$

and $B<2$ always. Applying the results of Zinnes,[9] this conclusion is not valid for octupole radiation; but octupole radiations have a long enough lifetime[10] ($>10^{-3}$ sec) to make them unlikely in beta-gamma correlation.

The polarization correlation measurement may, of course, be taken for $\theta\neq90°$, and for any quadrupole transitions with $\alpha_4\neq0$. Such measurements could establish the quadrupole, as against dipole, nature of the gamma; but this would already have been established by the fact $\alpha_4\neq0$. But many quadrupole gammas will have $\alpha_4=0$, and in fact $\alpha_4=0$ for any gamma multipole order in beta-gamma correlation unless the order of forbiddenness of the beta is second or higher.[11] If $\alpha_4=0$, then J_θ/J_ϕ has its maximum deviation from unity at $\theta=90°$. All told, there seems little point to measurements at $\theta\neq90°$.

[8] D. R. Hamilton, Phys. Rev. **74**, 782 (1948).
[9] I. Zinnes, Phys. Rev. **80**, 386 (1950).
[10] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).
[11] D. L. Falkoff and G. E. Uhlenbeck, Phys. Rev. **79**, 334 (1950).

APPARATUS

The apparatus used to measure the polarization of the gamma emitted at 90° to the beta in a beta-gamma cascade is indicated in Figs. 1 and 2. The beta and two gamma counters are composed of trans-stilbene crystals and mu-metal magnetically shielded photomultipliers. The beta crystal is 1.6 inches in diameter, 0.020 inch thick, while the gamma crystals are sections of cones 1.0 inch high and 0.7 inch mean diameter. The locations of the centers of mass of the crystals (omitting minor asymmetries) are shown in Fig. 1. The gamma crystals and associated photomultipliers and preamplifiers rotate about the Oy axis as indicated in Fig. 1.

A true triple coincidence between the counters β, $\gamma 9$, and $\gamma 27$ requires that the gamma undergo Compton scattering from one gamma counter to the other; if the gamma is polarized, say, parallel to Oz, then as discussed below the triple rate will be greater for $\psi=90°$, 270° than for 0°, 180°. The pair of gamma crystals thus act as a polarization analyzer; and the basic datum of the experiment is the variation of the true triple coincidence counting rate with ψ, the angle of rotation of the analyzer. Because of the symmetry between $\gamma 9$ and $\gamma 27$, either gamma counter may serve as initial scatterer for the gammas. Geometry is nonideal because $l_3>0$ as well as because of nonzero crystal dimensions.

Below the gamma counters and above the source and beta counter is a plate ($\frac{1}{8}$-in. aluminum, $\frac{1}{8}$-in. Lucite below) which prevents betas from reaching the gamma counters. Surrounding the whole apparatus but not shown in either figure (the supporting ridges on the top and bottom plates appear in Fig. 2) is a thin ($\frac{1}{32}$-in.) aluminum can which serves as a light shield and also serves to contain helium at atmospheric pressure; the helium atmosphere serves to reduce by the factor $Z(\text{He})/Z(\text{air})\approx\frac{1}{4}$ the electron energy at which a given degree of electron scattering in the gas occurs.

The net result of light construction, magnetic shielding, etc., is that there is no observable dependence of single channel gamma-counting rates on ψ except those which are attributable to asymmetry of source location.

ELECTRONICS

A block diagram of the electronics used is shown in Fig. 3. The three scintillation crystals work into 5819 photomultiplier tubes operated at 900 volts and followed by a cathode follower preamplifier, giving output pulses of order 0.1 volt. These pulses are amplified by 35-Mc amplifiers with two separated outputs. Two stages before the output the pulses are passed through a crystal diode limiting circuit which makes the gamma pulses quite uniform in height and makes the betas more so than they would otherwise be; the pulses out of the amplifiers are of the order of 7 volts. These pulses are then clipped with a 0.75-meter, RG7U, clipping cable before going into the coincidence circuit. The latter is a modified Garwin-type circuit with high

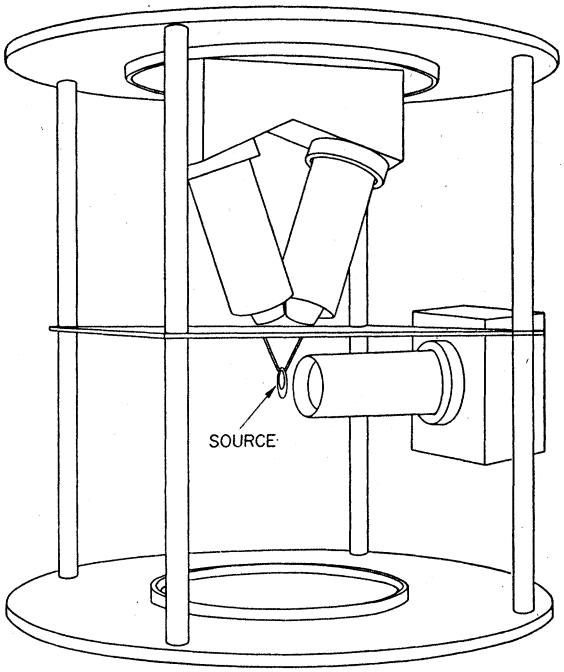

FIG. 2. Schematic drawing of apparatus with helium-and-light shield removed.

stability and high discrimination against doubles (or singles) when counting triples (or doubles); the circuit and its performance characteristics have been described elsewhere.[12] The coincidence circuit output is amplified to the order of 50 volts and then fed to a conventional scaler-discriminator combination.

The resolving time of the coincidence circuit under the above conditions was found to be approximately 2×10^{-8} second, as measured either by use of a delay line in one channel or by observing chance rates. Upward variations of this resolving time, as determined by final discriminator setting, and as made possible by good voltage regulation, were used when an increase in chance/total ratio seemed desirable.

ACCESSORY CALCULATIONS AND EXPERIMENTS

Expected Polarization Effects

As discussed under "Theory," this experiment provides its basic information about the gamma ray in the

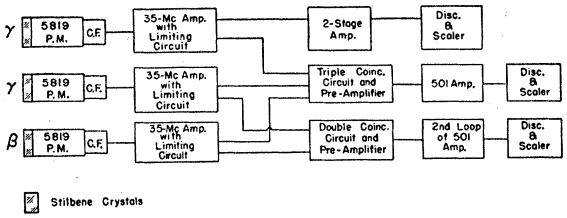

FIG. 3. Block diagram of electronics.

[12] Pipkin, Daubin, Lemonick, and Hamilton, Phys. Rev. **90**, 353 (1953).

$\beta\gamma$ cascade by comparing the signs of the angular correlation coefficient A and of the polarization coefficient B [Eqs. (2) and (3)]. In the geometry of Fig. 1, J_ϕ and J_θ are, respectively, J_x and J_z, J_x and J_z being the intensities of gammas traveling along Oy and with polarization $\mathbf{i}$ and $\mathbf{k}$, respectively. From the preference of the Compton scattered photon to have polarization parallel to that of the incident photon, it is obvious that if $J_x > J_z$ (i.e., $B>0$), the triple coincidence rate will be greatest at $\psi=0, \pi$. Thus, if the relative experimentally observed triple coincidence rate is given by

$$N(\psi)=1+C\cos^2\psi, \tag{5}$$

the signs of C and B are the same.

However, it is desirable to be able to deduce from the observed value of C not only the sign but also the magnitude of B, for comparison with the value of B deduced from the angular correlation coefficient A and Eq. (4). For relating B and C, following Metzger and Deutsch[6] we define a quantity R, the "asymmetry ratio" of the polarimeter, as the value of $N(0°)/N(90°)$ observed when the radiation incident in the polarimeter is linearly polarized in the x direction in Fig. 1 (i.e., $B=\infty$). This definition makes $R>1$. For incident partially polarized radiation described by B, we then have

$$C=B(R-1)/(1+B+R). \tag{6}$$

The asymmetry ratio R is easily calculated for ideal geometry (that is, point gamma counters) and 90° scattering in the polarimeter; in this case it is given by

$$R=(k_0^2+2k_0+2)/k_0^2,$$

where k_0 is the incident gamma energy in units of mc^2. However (at least for low energies), this value of R falls off rapidly as the scattering angle departs from the vicinity of 90°; since for counting rate considerations the polarimeter gamma crystals must be large and close together, the value of R for use in Eq. (6) needs to be determined, at least in part, empirically, as follows.

Calibration of the Polarimeters

A Co^{60} or Cs^{137} source (approximately 20 millicuries) was placed at the center of a lead brick (with a great deal of accessory lead brick shielding); an emergent beam of gammas was collimated by a hole in the lead block $\frac{1}{4}$ inch in diameter, three inches long. This beam travels in the positive x direction in Fig. 1, and three inches from where it leaves the lead it is incident upon a 1-cm^3 stilbene crystal cube which is located at the origin (the usual location of the $\beta\gamma$ source) in Fig. 1. (The linear dimensions of this crystal and the subsequent $\beta\gamma$ sources are comparable hence give rise to similar geometric effects.) The crystal is connected by a Lucite light pipe to the beta photomultiplier which remains in its usual position.

For the ninety-degree Compton scattered gammas of Cs^{137} and Co^{60} ($k_0=0.57$, 0.71, respectively; this same respective order applies throughout this paragraph), the values of $J_z/J_x=1/(1+B)$, as deduced from the Klein-Nishina formula, are 3.7 and 2.1. The values of the coefficient C as experimentally observed with this polarimeter were -0.49 ± 0.03 and -0.34 ± 0.03. These calculated values of B and observed values of C, with Eq. (6), give for the asymmetry ratios of the polarimeter $R=3.60\pm0.5$, 3.63 ± 0.7.

The asymmetry ratio will be dependent upon energy, and one now needs to deduce from the Cs^{137} and Co^{60} data the value of R at other energies. Because of the strong dependence of ideal R upon scattering angle in the polarimeter, the nonideal geometry must be taken into account. This point has been thoroughly discussed by Metzger and Deutsch,[6] whose geometry is very similar to ours and whose notation we adopt in what follows. Our scattering angle δ is 110° by pure geometry, and the effective angle should be somewhat less because of the preference for forward scattering; our crystal counter angular spreads, $\Delta\delta$ and $\Delta\phi$ in scattering angle and scattering azimuth, are comparable with each other and are expected to be approximately 50 degrees. We find that the observed values of R for Cs^{137} and Co^{60} are fitted well by values calculated from the ideal geometry R as modified by taking $\delta=103°$, $\Delta\delta=\Delta\phi=56°\pm10°$; we therefore use these values for nonideal geometry to calculate R as a function of energy. For $k_0=1$, 2, 3, we find $R=2.60\pm0.15$, 1.75 ± 0.05, 1.50 ± 0.04, respectively.

The procedure in analyzing the experimentally observed polarization data will then be as follows. The angular correlation coefficient reported by other workers and corrected by them to correspond to ideal geometry, which we call A_0, needs first to be corrected to the value A which would be observed if one of the detectors in the angular correlation experiment had the size of our beta detector; this means $A=0.82A_0$. Then by use of Eqs. (4) and (6), the values of A, and the above stated values of R, we calculate the predicted value of the polarization correlation coefficient C on each of the two hypotheses concerning gamma parity change; this then is compared with the observed value of C.

Parameters for Angular Dependence of Counting Rates

Discussion so far has been on the basis of only a $\cos^2\psi$ variation of the triple coincidence counting rate $N(\psi)$. Various asymmetries, to be discussed shortly, exist and will give variations with $\cos(\psi-\beta)$, where β is a phase angle not necessarily zero. These asymmetries will also contribute $\cos^2\psi$ terms of arbitrary phase which are always much smaller than the $\cos^2\psi$ terms resulting from polarization effects. Hence finally we analyze all data in terms of the three coefficients α, β, C of the relation,

$$N(\psi)\sim1+\alpha\cos(\psi-\beta)+C\cos^2\psi. \tag{7}$$

Readings of $N(\psi)$ for four values of ψ (0°, 90°, 180°, 270°) suffice to determine these coefficients, as given

by the following relations:

$$\tan\beta=[N(90)-N(270)]/[N(0)-N(180)], \quad -(\pi/2)\leqslant\beta\leqslant(\pi/2); \quad (8a)$$

$$\alpha=[N(90)-N(270)]/(2N_0\sin\beta)=[N(0)-N(180)]/(2N_0\cos\beta); \quad (8b)$$

$$C=[N(0)+N(180)-N(90)-N(270)]/[N(90)+N(270)]. \quad (8c)$$

Here N_0 is the average of N over ψ. The fact that the denominator in Eq. (8c) is not simply $2N_0$ arises from the fact that the omitted constant of proportionality in Eq. (7) is $N_0/(1+\frac{1}{2}C)$.

Discussion of Accessory Angular Dependences

The values of α and β are valuable primarily for a check on reproducibility of data and on the anatomy of the experiment. Relevant angular dependences, other than the polarization $\cos^2\psi$ dependence of the triples, will be summarized briefly in the following paragraphs.

Rotation of the apparatus as a whole, which would show effects of external fields or scattering, produces no α or C in single rates greater than statistics (0.002 in this instance).

The single gamma channels for various sources have values of $|\alpha|$ in the range 0.01 to 0.03; the phase β is such ($\beta\approx0$) that the asymmetry could be caused either by scattering by the beta photomultiplier shield or by the source being displaced from the symmetry axis toward the beta crystal. The former possibility seems ruled out by the fact that when 0.1 inch of aluminum absorber was placed in front of the beta crystal without moving the source (see later discussion of Sb^{124} and As^{76}), changes in $|\alpha|$ of only 0.003 resulted; these aluminum absorbers should have been roughly equivalent (taking into account solid angles and distances) to the photomultiplier shield in ability to scatter gammas into the gamma counters. A source displacement of 0.050 in., caused, for example, by bending of the mica when placing in position, would produce the observed α and β; to this there corresponds $C\approx\alpha^2$ which should be negligible. The observed values of C for single gamma channels averaged 0.005 ± 0.002.

For $\beta\gamma$ doubles the angle β lay in the same range as for gamma singles, but α was increased in magnitude by factors up to two. This is what is expected from the contribution to $\beta\gamma$ doubles by any gamma scattering from the photomultiplier which simultaneously triggers a "beta" count; such scattering could give a negligible contribution to gamma singles, but not necessarily to $\beta\gamma$ coincidences. The relative increases in C and α caused by this phenomenon are known from data taken with 0.1-inch aluminum absorbers in front of the beta counter (see next section); here $|\alpha|$ and C increased to approximately 0.10 and 0.025, respectively. From all this data we calculate an expected contribution to the C for $\beta\gamma$ coincidences of 0.008 ± 0.003 due to scattering from the beta counter. An additional contribution to C is expected from slight residual angular correlation arising from the fact that the separation of the gamma counters makes $\cos^2\theta\approx0.09\cos^2\psi$ instead of zero. The total C thus calculated is in good agreement with that observed.

As to the $\gamma\gamma$ double coincidences, one would expect here an angular dependence which is a simple average of the two single gammas. It turns out, to the contrary, that in α and β the $\gamma27$ dependence appears weighted by at least 2 to 1 over the $\gamma9$ dependence, as if doubles which were initiated in $\gamma27$ were much preferred to those initiated in $\gamma9$. This is probably, although not obviously, related with three incidental facts: the existence of a horizontal crack which bisects the $\gamma9$ scintillation crystal, the apparent lower efficiency of $\gamma9$, and the fact that α for $\gamma9$ singles is some 0.7 as large as for $\gamma27$, as would be the case if only the top half of the $\gamma9$ crystal were sensitive. The values of C fluctuate, in magnitude and sign, from element to element, and are of the same magnitude as the standard deviations in C, about 0.007. Since C has the same sign ($C>0$) for $\gamma9$ and $\gamma27$, as compared to α which reverses sign, we would in any case not expect to see in C any reflection of peculiar weighting of $\gamma9$ and $\gamma27$ in $\gamma\gamma$.

The α and β asymmetries just discussed for singles and doubles do not appear in the triples; with standard deviations in α of order 0.01, the sign of α varies from element to element and in three out of four elements $|\alpha|$ is less than the standard deviation.

These angular dependences of the various channels which have just been discussed seem to be minor and understood, with exception of the unexplained α in the $\gamma\gamma$ doubles, which, however, is not reflected in the triples or in the C for $\gamma\gamma$ doubles. We therefore feel that there will be no errors, beyond statistics, in deducing the gamma polarization from values of C for true triples, calculated according to Eq. (8c) and normalized with respect to $\beta\gamma$ doubles as discussed below.

GENERAL PROCEDURE

Source Preparation

Sources were in every instance prepared by vacuum evaporation onto mica, using a source area 3.3 cm^2 in area and mica thickness approximately 2 mg/cm^2. The active deposit faces the β counter in Fig. 2, and the source is supported from above by two thin (1-mm by 2-mm) Lucite fingers.

Since it is important that there be a minimum of beta scattering, the critical voltage for backscattering was kept as low as possible. This critical voltage V_c, defined by the semiempirical relation,[13]

$$V_c(\text{kev})=1700[Z^2t(\text{g/cm}^2)/A]^{\frac{1}{2}}, \quad (9)$$

is the voltage below which, for a given thickness of

[13] D. R. Hamilton and L. Gross, Rev. Sci. Instr. **21**, 912 (1950).

source and backing, deviations from the beta spectrum Kurie plot will appear. It will be noted that the voltage V_c for the 3 cm of helium between source and beta counter is 39 kev, which is well below the values of V_c for specific sources listed later.

Counting Procedure

As will be apparent from Fig. 3, it was possible to count simultaneously triples and one double channel, or triples and two single channels. (To each of these combinations could have been added also one more single channel; this was not done in practice.) Normally readings of one-half hour apiece at $\psi=0°$, 90°, 180°, 270° were interspersed with readings of chance at 0° (delay lines inserted in one or two channels before the 35-Mc amplifiers), the amount of time being spent on chance readings being dependent upon the chance/total ratio.

The variation of the chance rate with ψ, which must be known in subtracting chance from total, was obtained by composition from the angular dependence of the various double and single rates which give the chance triples; since the single and double rates were much higher than the triples, these single and double angular dependences were always determined much better than was necessary for purposes of chance correction, and served as a useful check on proper operation.

Gamma Scattering by Beta Absorber

In two of the elements used (Sb^{124}, As^{76}) there exist other beta-gamma cascades (with a lower end-point beta component) in addition to the one under investigation. In these cases aluminum absorbers were placed in front of the beta crystal to absorb the low-energy beta component. Triples resulting when these absorbers enable a gamma to fire the beta counter are called "spurious" triples; these should initially increase with absorber thickness and then level off. With an absorber thick enough to cut out all betas, the number and angular dependence of the spurious triples were obtained in each case; from this, the spurious triples for any absorber were deduced and subtracted from total triples.

Normalization of Triple Coincidences

As already noted in the discussion of the angular dependence of the $\beta\gamma$ doubles, the latter may show a $\cos^2\psi$ dependence. This will be reflected in the angular dependence of the triples, which must, therefore, be normalized with respect to the $\beta\gamma$ doubles by subtracting C ($\beta\gamma$ doubles) from C (triples). For the true polarization effects on the triples, $|C|$ and $|A|$ are comparable according to Eqs. (4) and (6); C ($\beta\gamma$ doubles) has magnitude of order 0.01. Thus it turned out empirically that the normalization has not much effect on C for the three cases (Rb^{86}, Sb^{124}, As^{76}) for which a definite polarization effect was observed.

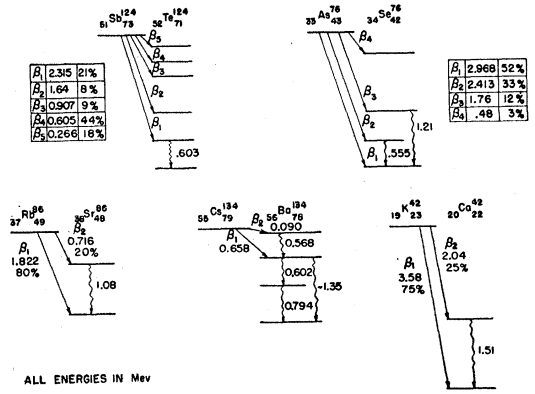

FIG. 4. Decay schemes of nuclides investigated.

RESULTS

The normalized values of C obtained experimentally for each of the five elements under discussion are listed below, with relevant comments. The indicated ranges represent over-all standard deviations; since the chance triples were small compared to true in all cases except arsenic-76, where chance and true were about equal, the standard deviation is approximately that calculated from the total number of true triples. True triple counting rates were several tenths of a count per second in each case. Values of V_c (in kilovolts) are obtained from Eq. (9) using full backing and half source thickness; V_0 is the end point of the beta component in question.

The decay schemes of the five nuclides investigated are summarized in Fig. 4, with data from the NBS compilation[14] as slightly modified by later information;[7] not all the gammas in antimony-124 and arsenic-76 are shown.

All plus-minuses in these results and throughout the paper represent standard deviations.

Cesium-134

Cesium-134 was obtained as an impurity in a Chalk River bombardment of Rb_2CO_3. An evaporated RbCl source (0.9 mg/cm² on 1.09 mg/cm² mica backing; $V_c/V_0=0.33$ for the cesium V_0) was prepared and allowed to decay for a total of five months after bombardment, at which time gamma-ray scintillation spectrometer measurements and observation of rate of decay indicated that (88±3) percent of the $\beta\gamma$ coincidences were due to Cs^{134}. The value of C obtained for this source, without a small correction for rubidium 86, was

$$C=0.009\pm0.013.$$

Antimony 124

Antimony 124 was obtained from Oak Ridge as $SbCl_3$ and $SbCl_5$ and was vacuum evaporated as metal

[14] Way, Fano, Scott, and Thew, *Nuclear Data*, National Bureau of Standards Circular 499 (U. S. Government Printing Office, Washington, D. C., 1950).

to form a source 0.8 mg/cm² thick on 2.2 mg/cm² mica; $V_c/V_0=0.11$.

As is seen from the decay scheme in Fig. 4, the highest-energy beta component is the one which is involved in the most direct correlation with the 607-kev gamma. Data were taken with aluminum beta absorbers of thickness 0.041 and 0.110 inch to remove lower-energy beta components, and with 0.207-in. aluminum to remove all betas and hence to check on spurious triples caused by gamma scattering from beta absorber to gamma counter or by γ-γ correlation.

We estimate that with the 0.110-in. absorber, the relative amounts of the components β_2 and β_3 are 16 and zero percent, respectively; this makes the 0.110-in. absorber sound better than the 0.041-in. But the relative values of the counting rates for these absorbers showed that a large number of the triples observed at 0.110-in. thickness (possibly as many as two-thirds) were spurious. The large size of the spurious-true ratio makes the 0.110-in. data almost meaningless, in spite of the fact that C has the same sign and order of magnitude for true and spurious triples for antimony. (Lest one suspect a common cause here, it is reassuring to observe that for arsenic, C for spurious triples has the same sign as for antimony, but for true triples the opposite sign.) But the same fact (C similar for true and spurious triples) makes the correction of 0.041-in. triples practically independent of how one assumes the spurious triples to depend on absorber thickness. For the 0.041-in. absorber we estimate the spurious triples as 15 percent of true, and obtain finally, for this absorber as corrected for spurious triples,

$$C=+0.147\pm0.012.$$

Potassium-42

Potassium was bombarded at Brookhaven as the carbonate and vacuum evaporated as the chloride. Because of the short life of K^{42}, three sources were used; source thicknesses were 1.1, 4.0, 2.0 mg/cm² on mica backings of 2.2, 2.1, 1.8 mg/cm², giving $V_c/V_0<0.14$ in each case. The half-life of these sources was measured as 12.7±0.5 hours, in agreement with the expected 12.4 hours.

There are no complications here beyond the need for thin sources. The results for the three sources agree within statistics; chance triples are low; the final result is

$$C=-0.003\pm0.015.$$

Arsenic-76

Arsenic was bombarded at Brookhaven as the metal and vacuum evaporated as the metal, 1.5 mg/cm² on 2.3 mg/cm² mica; $V_c/V_0=0.11$. The half-life of the sources was observed to be 25.6±0.4 hours as compared to the expected 26.8 hours.

In the complex decay of arsenic-76, the $\beta\gamma$ correlation under investigation here arises from the beta which goes to the first excited state. Chance rates are high because of the intense beta transition direct to ground, which cannot be absorbed out, and because of the large number of gammas. The correlations were observed with a 0.088-in. aluminum beta absorber, which is calculated to transmit approximately 26 and 6½ percent of β_2 and β_3, respectively; since β_3 is weaker than β_2, as shown in Fig. 4, the β_2 electrons should be about 11 times as abundant as the β_3 after passing through the absorber. Further measurements on angular dependence of triple rate were made with an 0.238-in. absorber which absorbs all betas and gives only the "spurious" triples. Consideration of the range of the Compton electrons in the absorber indicates that the number of spurious triples arising from this source with 0.088 and 0.238 absorbers should be approximately the same; on this basis, the triples from gamma scattering in the 0.088-in. absorber are estimated as 12 percent of the total and corresponding corrections are made.

It should be noted, without going into details, that the process of correcting back to a common time the readings at four different angles for a rapidly decaying source, and then sorting out the various angular dependences, is a complex one when counting rates are comparable for true triples (half-life τ), double-single chance triples (half-life $\tau/2$) and single-single-single chance triples (half-life $\tau/3$). This makes the standard deviation larger than the simple statistics value in the final result,

$$C=-0.114\pm0.035.$$

Rubidium-86

Rubidium was bombarded at Chalk River as the carbonate, vacuum evaporated as the chloride; the active source was 0.9 g/cm² on 2.1 mg/cm² mica, giving $V_c/V_0=0.32$.

The rubidium-86 source was checked with a gamma scintillation spectrometer for the presence of cesium-134, which was found to contribute 16±4 percent of the gammas from the source. With a small correction for the presence of cesium-134, the final value for C obtained was

$$C=-0.060\pm0.019.$$

DISCUSSION

In Table I the observed values of C which have just been listed are summarized. Also listed is A_0, the value

TABLE I. Values of angular correlation coefficient C(obs) and C(pred), as observed in present experiment and as predicted (on basis of parity change "no" for the gamma) from the angular correlation coefficient A_0 reported by other workers for beta-energy discrimination conditions similar to ours.

Nucleus	A_0	C(pred)	C(obs)
Cs^{134}	0.00±0.01	0.00 ±0.003	0.009±0.013
Rb^{86}	0.13±0.01	−0.068±0.005	−0.060±0.025
As^{76}	0.07±0.02	−0.067±0.018	−0.114±0.035
K^{42}	−0.06±0.02	0.022±0.007	−0.007±0.016
Sb^{124}	−0.27±0.04	0.151±0.022	0.142±0.010

of the angular correlation coefficient for ideal geometry, as found by other workers: the values of A_0 are those obtained from integral experiments like ours, or represent averages over that part of the differential spectrum which we used. For cesium-134, A_0 is that of Beyster and Wiedenbeck,[15] and Stump and Frankel.[16] For rubidium-86, A_0 is the integral over the differential spectrum of Stevenson and Deutsch[17] as checked by Ridgway and Pipkin;[18] reference 1 lists a number of other integral results with lower A_0, perhaps caused by source difficulties. For arsenic-76, A_0 is obtained by combining the integral value of Walter, Huber, and Zunti[19] with differential results of reference 18. For potassium-42, we have combined the results of reference 15 and Stevenson and Deutsch.[20] For antimony 124, for which A_0 is sensitive to absorber thickness, we have used the data of reference 15 which is taken for nearly the same absorber thickness as ours.

The values of C predicted from the value of A_0, as discussed under "Accessory Calculations and Experiments" above, and assuming parity change "no" in the gamma transition, are also indicated. If parity change "yes" had been used, the sign of the predicted C would have been reversed and the magnitude slightly altered.

For Cs^{134}, for which no polarization correlation is expected, none is observed. For Rb^{86}, As^{76}, and Sb^{124}, the observed polarization and that predicted on the basis of no parity change in the gamma ray agree very satisfactorily. The comparison of the signs of observed and predicted C is all that is needed to determine the parity change in the gamma transition; the agreement in magnitudes which is apparent in Table I is useful as a check on the experiment and on the details of the radiation and correlation processes.

For K^{42}, an essentially zero polarization is observed; we have no ready explanation for this, although it may be noted that part of the discrepancy corresponds to a discrepancy of 0.006 between the observed and predicted values for C for $\beta\gamma$ doubles, the observed value of the latter having been used in the normalization. If the sign of C (predicted) were reversed, as discussed above, the predicted and observed values would overlap; we do not feel that any significance can be attached to this.

In each of the three cases above with nonzero polarization, i.e., Rb^{86}, As^{76}, and Sb^{124}, $\beta\gamma$ or $\gamma\gamma$ correlation results or both indicate that the first excited level of the daughter nucleus, from which gamma emission occurs, has $I=2$, it being assumed that the ground state has $I=0$ (even-even nucleus). The polarization result, that there is no parity change in the gamma transition, therefore determines that this is an electric quadrupole gamma and that the first excited state has the same parity as the ground state. This is in accord with the systematics of even-even nuclei.[21]

The internal conversion coefficients of the $2-0$ gamma ray have been measured for arsenic-76[22] and antimony-124[23] and agree with our results in describing the gamma as electric quadrupole.

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