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β-γ circular-polarization correlations for first-forbidden β transitions in ^{76}As and ^{124}Sb*†

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The β-γ circular-polarization correlations P_γ associated with the 1.753 MeV and 2.42 MeV β transitions of ^{76}As and with the 2.31 MeV β transition of ^{124}Sb have been measured as an average over the respective energy intervals $E_\beta = 0.56$ to 1.4 MeV; $E_\beta = 1.4$ to 2.1 MeV, and $E_\beta = 1.66$ to 2.31 MeV. Two β detectors, one at an instrument angle $\theta^*_1 = 135°$ and the other at $\theta^*_2 = 150°$, were employed in these measurements. On the assumption that the A_3 term in P_γ is negligible compared to the A_1 term, the experimental data give the following values for the respective P_γ: P_γ (^{76}As: 0.56 MeV $< E_\beta <$ 1.4 MeV, $E_\gamma = 0.559$, $\theta_{\beta\gamma} = 180°) = 0.75 \pm 0.6$, P_γ (^{76}As: 1.4 MeV $< E_\beta <$ 2.1 MeV, $E_\gamma = 1.216$ MeV, $\theta_{\beta\gamma} = 180°) = 0.11 \pm 0.05$, P_γ (^{124}Sb: 1.66 MeV $< E_\beta <$ 2.31 MeV, $E_\gamma = 0.603$ MeV, $\theta_{\beta\gamma} = 135°) = 0.47 \pm 0.07$, and P_γ (^{124}Sb: 1.66 MeV $< E_\beta <$ 2.31 MeV, $E_\gamma = 0.603$ MeV, $\theta_{\beta\gamma} = 150°) = 0.58 \pm 0.08$.

[RADIOACTIVITY ^{76}As; measured $\beta\gamma$ CP, ^{124}Sb; measured $\beta\gamma$ CP.]

I. INTRODUCTION

Nuclear model theorists have recently been devoting considerable effort toward the development of an adequate treatment of anharmonic effects and other features in the collective spectra of doubly even nuclei belonging to the region of the periodic table having neutron numbers ranging from 34 to 48.[1-5] Lecomte *et al.*[4] and references cited therein discuss several of the interesting and peculiar features of the even-even selenium isotopes which are unusual when compared with other isotopes in this region. The work of Ardouin *et al.*[5] suggests that the isotope ^{76}Se with 42 neutrons may be of particular interest in understanding the behavior of these isotopes.

The presence of the 1.216 MeV crossover γ transition between the second 2^+ level of ^{76}Se and its 0^+ ground state can be understood only through the introduction of anharmonic effects in the description of the collective states of this isotope. A measurement of the β-γ circular-polarization correlation P_γ between this crossover γ ray of ^{76}Se and the 1.753 MeV β particle emitted through the ^{76}As decay branch which populates the second 2^+ state of ^{76}Se would supply part of the information needed for a determination of the nuclear matrix elements associated with the 1.753 MeV β transition. Values for the nuclear matrix elements associated with this first-forbidden β transition from the ground state of ^{76}As to the second 2^+ level of ^{76}Se should be of use to nuclear model theorists in their attempts to understand the behavior of the even-even selenium isotopes. For this reason we have undertaken the difficult task of measuring the β-γ circular-polarization correlation between the 1.753 MeV β of ^{76}As and the 1.216 MeV γ of ^{76}Se. An immediate byproduct of this investigation was a confirmation of the results obtained by Smith and Simms[6] for the β-γ circular-polarization correlation for the 2.41 MeV β transition of ^{76}As. A further byproduct of this investigation, resulting from a "confidence run" on ^{124}Sb, was a confirmation of the results of other investigators[7,8] for the β-γ circular-polarization correlation associated with the 2.31 MeV β transition in ^{124}Sb.

The method of forward Compton scattering of γ rays was used to measure the β-γ circular-polarization correlations. The β-γ angular correlation function for first-forbidden β transitions is given by the expression

$$N(W,\theta,\pm 1) = A_0(W) \pm A_1(W)P_1(\theta) + A_2(W)P_2(\theta) \pm A_3(W)P_3(\theta)\,, \tag{1}$$

where W is the total energy of the β particle, θ is the angle between the direction of emission of the β particle and the γ ray, and the $P_n(\theta)$ are Legendre polynomials. The $\pm$ is used for γ's with $\pm$ helicity. Only by using a polarization-sensitive detection method can one obtain information about $A_1(W)$ and $A_3(W)$.

The quantities measured in this experiment are C^+ and C^-, with C^+ being the true β-γ coincidence counting rate with the magnetic field pointed away from the source and C^- being the true β-γ coincidence counting rate with the magnetic field pointed toward the source. (See Fig. 1 and Sec. II.) From the experimentally determined values

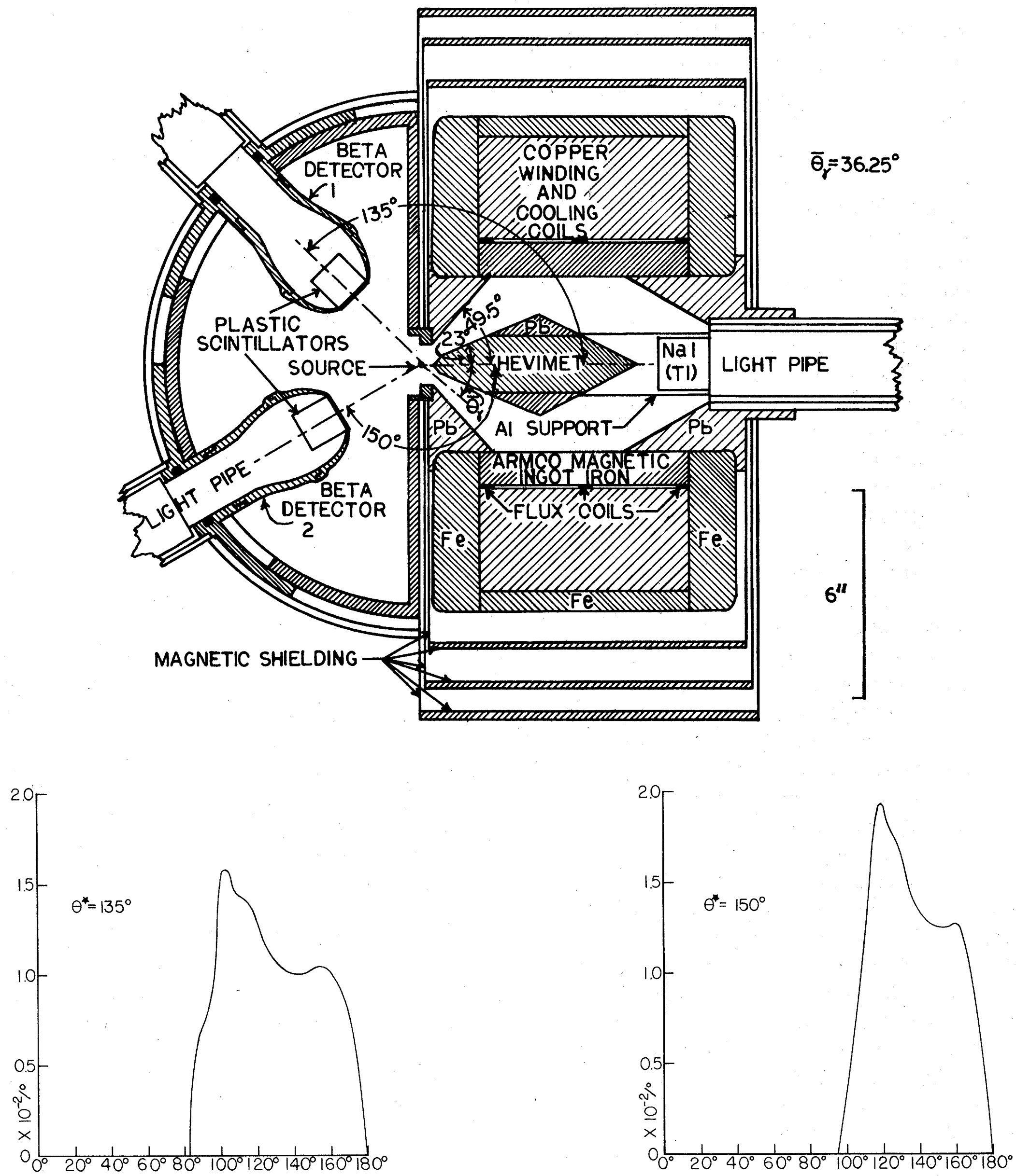

FIG. 1. (a) Polarization analyzer and detectors. The RCA 8575 photomultiplier tubes used with the β and the γ detectors are not shown. The three layers of soft iron shielding surrounding the polarization analyzer magnet served to help reduce the effects of magnetic field reversal on the photomultiplier tubes. Data from the flux coils combined with flux measurements within the cylindrical region enclosed by the magnet were used in the determination of the magnetization of the iron in the scattering region. The region between the source, the β_1-β_2 detectors, and the scattering region in the magnet was evacuated. The axis of the magnet was vertical with the 1.6 mm thick support not only supporting the Pb-Hevimet shield but also serving as a vacuum chamber wall. (b) Relative polarimeter acceptance probability as a function of θ, the angle between the coincident β-γ pair, for the two instrument angles associated with β detectors 1 and 2.

of C^+ and C^- it is conventional to introduce the quantity δ defined as

$$\delta = \frac{C^+ - C^-}{C^+ + C^-} . \tag{2}$$

This quantity δ can be related to the $A(W)$ of expression (1) through the relationship

$$\delta = f \frac{a_1 b_1 P_1(\theta^*) + a_3 b_3 P_3(\theta^*)}{1 + a_2 b_2 P_2(\theta^*)} , \tag{3}$$

which is obtained by methods similar to those employed by others.[9,10] In this relationship

$$a_0 = \int A_0(W)dW, \quad a_1 = \frac{1}{a_0}\int A(W)dW,$$
$$a_2 = \frac{1}{a_0}\int A_2(W)dW, \text{ and } a_3 = \frac{1}{a_0}\int A_3(W)dW. \tag{4}$$

The integrals extend over the β-energy range being observed. The instrument angle θ^* is the angle between the unit vector $\vec{u}_p$ parallel to the magnet axis, pointing from the source to the γ detector, and the unit vector $\vec{u}_\beta$ parallel to a given β detector axis, pointing from the source to the β detector. Dependence on the instrument angle θ^* in place of θ has been introduced by taking advantage of the axial symmetry of the β detectors and the γ-ray polarimeter.

As noted earlier, θ is the angle between the vector $\vec{\omega}_\beta$ in the direction of a β particle which is within the acceptance aperture of a given β detector and the vector $\vec{\omega}_\gamma$ in the direction of a coincident γ ray which is within the acceptance aperture of the γ-ray polarimeter. One may view a rotation of the vector $\vec{\omega}_\beta$ into the vector $\vec{\omega}_\gamma$ as a succession of the three rotations $\vec{\omega}_\beta \to \vec{u}_\beta \to \vec{u}_p \to \vec{\omega}_\gamma$. Using the well-known relationship between the matrix elements of the irreducible representations for a resultant rotation and the succession of rotations which produce the resultant[11] and averaging over the angles around the respective symmetry axes of the given β detector and the polarimeter gives $\overline{P}_n(\theta) = P_n(\theta_\beta)P_n(\theta_\gamma)P_n(\theta^*)$ where θ_β is the angle between $\vec{\omega}_\beta$ and $\vec{u}_\beta$ and θ_γ is the angle between $\vec{\omega}_\gamma$ and $\vec{u}_p$. The $P_n(\theta_\beta)$ and $P_n(\theta_\gamma)$ are absorbed in the b_n which result from numerical integration over the geometry of the experiment. The b_n also involve the polarization-dependent and polarization-independent parts of the Compton scattering cross section, effects of absorption in the iron, contributions due to γ rays attenuated in the shielding and scattered from the magnet (and vice versa), integration over solid angles, counter detection efficiencies, etc. For a given geometry the b_n depend only upon the γ-ray energies. The values obtained for the experimental geometry employed here are given in Table I. Our b_n are essentially equal to I_{nn}/I_{00} where I_{nn} are the quantities employed by Steffen and Frauenfelder,[10] however, we have also included small effects associated with γ-ray penetration of and scattering from the shielding. The fraction of polarized electrons $f = 0.063 \pm 0.002$ was determined from measurements of the magnetization of the iron as a function of current.

TABLE I. Coefficients b_i.

	Energy in MeV			
	0.559	0.603	0.657	1.22
b_i	−0.319	−0.324	−0.337	−0.372
b_2	0.528	0.531	0.527	0.526
b_3	−0.073	−0.078	−0.078	−0.088

For the sake of comparison with results of other investigators we note that the average polarization at an angle θ is defined as

$$\overline{P}_\gamma(\theta) = \frac{\int[N(W,\theta,+1) - N(W,\theta,-1)]dW}{\int[N(W,\theta,+1) + N(W,\theta,-1)]dW}, \tag{5}$$

where the integral is over the observed β-energy range. This can be reduced to

$$\overline{P}_\gamma(\theta) = \frac{a_1P_1(\theta) + a_3P_3(\theta)}{1 + a_2P_2(\theta)}. \tag{6}$$

II. EXPERIMENTAL PROCEDURE

The experimental geometry for the forward Compton scattering circular polarimeter and coincidence counting apparatus is shown in Fig. 1. The apparatus was similar to that used by other investigators for such measurements.[6–8] Note, however, that baffles, similar to those used by some other investigators,[7] were not employed to block out certain azimuthal sectors within the acceptance aperture of the polarimeter. While use of such baffles would have led to an improved angular resolution, this use would also have resulted in greater difficulty in achieving the counting statistics necessary to apply the "stripping procedure" discussed in Sec. III B. The region of the magnet from which the forward Compton scattering takes place was composed of Armco magnetic ingot iron. The cylindrical scattering magnet was enclosed in three iron shields, each magnetically insulated from the other. This shielding reduced the field outside of the magnet by a factor of about 3. In the photomultiplier tube assemblies for the β and γ detectors which are not shown in Fig. 1, the photomultiplier tubes were surrounded by iron and μ metal shields. The light pipes were 33 cm long for the γ detector and 23 cm long for each of the two β detectors.

The effect of reversal of the magnetic field on the coincidence timing signals on the gain of the photomultiplier tubes and on associated electronics was checked. No field-induced change of greater than 0.2 ns could be detected in the relative timing of the β and γ detector signals. The gain of the γ detector was shown to be constant within ±0.05% and that of the two β detectors within ±0.07% under field reversal.

The γ rays directed toward the magnetized iron of the polarimeter were collimated into a conical solid angle having an inner aperture of 23.0° and an outer aperture of 49.5°. The two β detectors had angles between their axes and the axis of the polarimeter magnet of 135° and 150° (see Fig. 1).

The electronics employed for the processing of the signals from the β and γ detectors was of the usual fast-slow coincidence and pulse height analysis type which was interfaced to a Digital Equipment Corporation PDP-8/*I* computer. This electronics employed 13 commercial *EG* and *G* modules (discriminators, coincidence units, linear gate, stretcher amplifier, analog to digital converters, a linear mixer, a pileup gate, and an interface gate). Some minor modifications were made to improve the stability and linearity of some of the commercial units in this system. The computer interface was assembled out of a collection of printed circuit boards. The interface section included singles scalers for the β and γ detectors and a live time counter. The photomultiplier tubes employed were RCA 8575 tubes. All timing signals were taken directly from the photomultiplier anodes. The β analog signals were taken from the anodes while the γ analog signal was taken from the last dynode. For the coincidence circuit, $2\tau = 30$ ns. The γ analog signal was sampled directly by the γ ADC. For the β analog signal a linear gate was opened for 30 ns and the β analog pulse passing through the gate was directed to a stretcher amplifier and from there to the β ADC. For every coincident event the pulse heights from both the β and γ detectors were digitized, read into the computer, and eventually stored on magnetic tape. β counter identification codes were also included.

Periodically, the data acquisition system was switched into a "singles spectrum mode" in which pulse height spectra for each of the individual detectors was rapidly acquired. Successive spectra were compared to check for any drift in gain of the system (electronics and/or photomultipliers). The gain of the γ channel was checked to $\pm 0.05\%$ and that of each of the β channels to $\pm 0.07\%$. If the gain of the γ channel changed by more than 0.25% or that of either β channel by more than 0.3%, the coincidence data taken between the two successive "singles spectrum modes" exhibiting this change were rejected. These rejection criteria were chosen so that any effect on the resulting experimental value of δ would be small compared to the statistical error in the same δ.

Coincidence data were typically taken for approximately 40 minutes or longer. To correct for chance coincidence rates, extra delay was periodically introduced into the γ channel so that true coincidences were impossible. This technique combined with accurate live time data and singles counting rates for each of the detectors taken during the coincidence runs was sufficient to allow correction for chance coincidences and decay effects.

For the ^{76}As experiment, two shipments of the radioisotope were obtained from the International Chemical and Nuclear Corporation. These shipments arrived as $AsCl_3$ in HCl solution. A number of 1 MCi sources (at $t = 0$ for each source) were prepared by drying drops of the solution on a 2.5 cm by 0.5 cm piece of Mylar of 0.04 mm thickness. The source diameter was less than 0.5 cm. A source was used for about ten hours at the end of which time a new source was introduced. Data were taken for approximately six days with each ^{76}As shipment.

The resolution of the analog to digital converters which were employed in the system just described allowed the sorting of the β- or γ-ray pulse heights into 128 bins to each of which was assigned a channel number.

Using the data stored on magnetic tape while running experiments according to the above methods, it was possible to produce γ-ray spectra similar to the one shown in Fig. 2. For this spectrum the number of detected γ events, corresponding to a given γ-ray channel number, which were in true coincidence with β's, corresponding to a given β-ray channel number, were summed over β-ray channels corresponding to any desired energy range. In Fig. 2 this β-ray energy range was

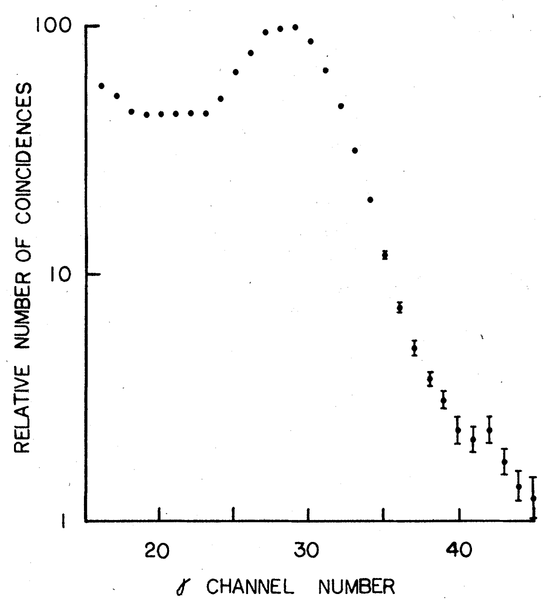

FIG. 2. Sample of true coincidence γ-ray spectrum obtained by summing the γ-ray spectra in coincidence with given β-ray channels over those channels corresponding to a β energy range from 0.5 to 1.4 MeV.

chosen to emphasize the effect of the 1.2161 MeV γ following the 1.76 MeV β of ^{76}As. The β-ray energy range used in summing data for Fig. 2 was 0.5 to 1.4 MeV.

III. ANALYSIS OF THE DATA AND RESULTS

A. Results for the 2.41 MeV β group of ^{76}As

The byproduct result confirming the β-γ circular-polarization correlation measurements of Smith and Simms[6] is easily obtained from true coincident γ spectra similar to that shown in Fig. 2. In this case, however, the data used were those resulting from summation over β channels corresponding to the energy range from 1.4 to 2.1 MeV. (See Fig. 3 for a partial decay scheme for ^{76}As.) Using such true γ coincidence spectra for each of the two β counters employed and for each of the two magnetic field directions the following results were obtained:

$$\delta_1 = -0.0023 \pm 0.0015, \quad \delta_2 = -0.0010 \pm 0.0013. \tag{7}$$

The value of δ_1 is associated with β counter 1 which is located at an angle of 135° relative to the axis of symmetry of the system and the value of δ_2 is associated with β counter 2 which is located at an angle of 150° relative to axis symmetry of the system (see Fig. 1). From these two values of δ, the average value $P_\gamma(180°) = 0.11 \pm 0.05$ for the energy range quoted. This value is to be compared with the value found by Smith and Simms of $P_\gamma(180°) = 0.105 \pm 0.02$. In both cases the seemingly justified assumption that $A_3 \ll A_1$ is used along with the accepted value for A_2 in order to obtain P_γ from the values of the δ.

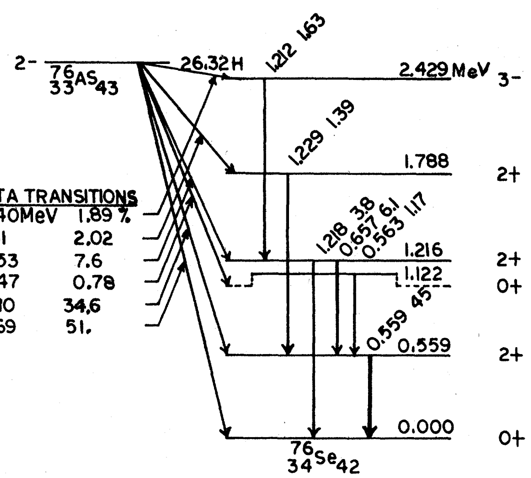

FIG. 3. Partial decay scheme for $^{76}_{33}$As$_{43}$. Information contained and the labeling employed is consistent with that in the Nuclear Data Tables (Ref. 12) except all energies are given in MeV rather than keV and LogFT values for the β transitions are not included.

B. Results for the 2.31 MeV β group of ^{124}Sb

Prior to making the run on ^{76}As, an experiment intended to verify our confidence in our apparatus was carried out. This experiment was undertaken to determine the circular-polarization correlation associated with the 2.31 MeV β transition of ^{124}Sb which has been measured by several observers.[7-9] In our measurement the range of β energy over which the results were averaged was from 1.66 to 2.31 MeV.

The following values of δ were obtained:

$$\delta_1 = -0.009 \pm 0.001, \quad \delta_2 = -0.010 \pm 0.001.$$

On the assumption that $A_1 \ll A_3$ and through use of the expression

$$P_\gamma(\theta^*) = \frac{\delta(\theta^*)}{f b_1} \frac{1 + a_2 b_2 P(\theta^*)}{1 + a_2 P_2(\theta^*)}, \tag{8}$$

which follows from this assumption, the values of P_γ obtained from our values of δ are

$$P_\gamma(150°) = 0.58 \pm 0.08, \quad P_\gamma(135°) = 0.47 \pm 0.07. \tag{9}$$

Our results are to be compared with the values obtained by Steffen and Alexander.[7] For the two angles which were nearest to ours, their values were

$$P_\gamma(155°) = 0.61 \pm 0.06, \quad P_\gamma(140°) = 0.42 \pm 0.06. \tag{10}$$

The value obtained by Camp *et al.*[8] is

$$P_\gamma(146°) = 0.50 \pm 0.05. \tag{11}$$

Figure 4(a) shows a partial decay scheme for ^{124}Sb and Fig. 4(b) displays the angular dependence of $P_\gamma(\theta)$ for all known experimental measurements for the 2.21 MeV β group in ^{124}Sb. It is worth noting that our measurements are in excellent agreement with those of Steffen and Alexander[7] and of Camp *et al.*[8] and further refute the implication from the work of Hartwig and Schopper[9] that P_γ should go negative around 150°.

C. Analysis and results for the 1.753 MeV β group of ^{76}As

Reference to Fig. 2 which is a true coincidence γ spectrum obtained by summing over a β energy range from 0.5 to 1.4 MeV for the ^{76}As data makes it clear that a somewhat more intricate analysis procedure must be employed to obtain information about the values of δ for the 1.216 MeV γ following the 1.753 MeV β. The β energy range which was

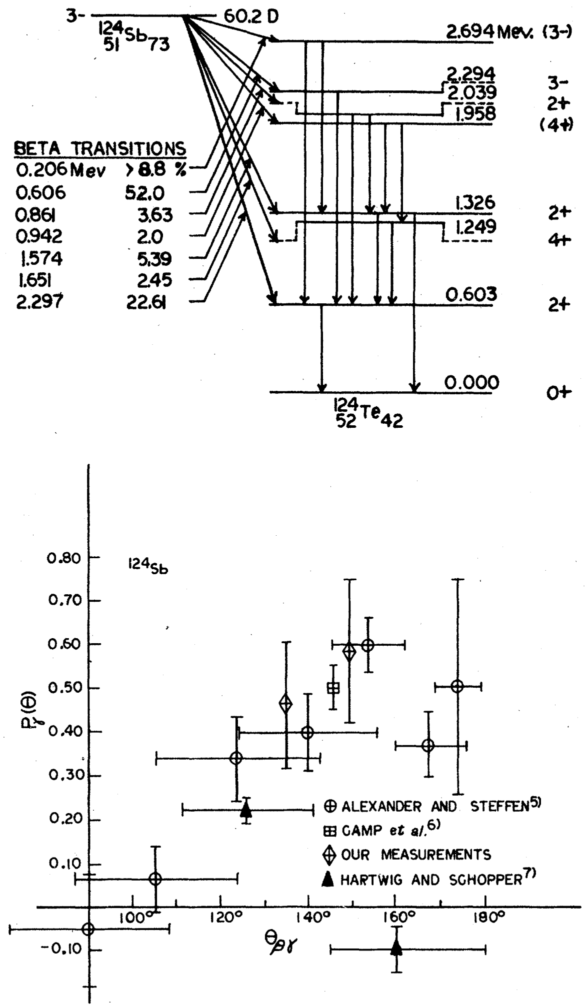

FIG. 4. (a) Partial decay scheme for $^{124}_{51}Sb_{73}$. (b) All know measurements for the β-γ circular polarization, $P_\gamma(\theta)$, in $^{124}_{51}Sb_{73}$. Our values of $P_\gamma(\theta)$ which are plotted here are those obtained through the use of Eq. (8) which assumes that the contribution from the term containing A_3 can be neglected in comparison with the term containing A_1. With this assumption, the value of $P_\gamma(\theta)$ is that to be expected if the "ideal experiment" could be performed to measure $P_\gamma(\theta)$ for a value of the angle θ between the coincident β-γ pair which is equal to the instrument angle θ^* employed in the measurement of the δ used in Eq. (8). Thus the error bars to be associated with the angular positions of our points are those associated with our instrument angles which are too small to show in the figure.

chosen for the spectrum shown in Fig. 2 was one designed to emphasize the effect of this 1.216 MeV γ following the 1.753 MeV β. The peak at channel 29 is due mainly to the 0.559 MeV γ which follows the 2.41 MeV β group, although the 0.657 MeV γ associated with the cascade following the 1.753 MeV β group also contributes. There is no distinct and separate peak due to the 1.216 MeV γ because of its low intensity and the resolution of the γ detector. Thus, some kind of an acceptable "stripping procedure" must be employed in order to extract the effects due to the 1.216 MeV γ.

In order to understand the "stripping procedure" employed in the analysis for the effects of the 1.216 MeV γ, it is useful to discuss briefly the effects, due to magnetic field reversal, which one would expect to observe on the true coincidence γ-ray spectrum for a monoenergetic γ ray. In principle, one would expect to see two changes in the true coincident γ-ray spectrum with field reversal. The first change would be a change in scale (i.e., that resulting from the change in the polarization-dependent part of the Compton scattering cross section resulting from field reversal). Secondly, one would expect to see a change in the shape of the γ-ray coincidence spectrum with field reversal. The extent of this change in shape of the γ spectrum is to some extent under the control of the experimenter at the time of apparatus design. If the difference in scattering angle for the various γ rays, accepted within the aperture of the polarimeter and detected by the γ-ray detector, is kept sufficiently small by proper instrument design, the change in polarization-dependent and polarization-independent parts of the Compton scattering cross section for these various γ rays will be sufficiently small as to eliminate any experimentally observable change in the γ-ray spectrum shape with field reversal. The design of the apparatus employed in these measurements was such as to achieve this end. The fact that this expectation was achieved in reality was demonstrated by the failure to see any noticeable change in γ-ray spectrum shape, with magnetic field reversal, for the true coincidence γ's of ^{76}As when the range of β-ray energies accepted allowed true coincidence contributions from only the 0.559 MeV γ ray.

It is an excellent approximation to assume that the shape of the true coincidence γ-ray spectrum from any monoenergetic γ ray will remain unchanged on magnetic field reversal. Furthermore, it is a reasonably good approximation to assume that the actual true coincident γ-ray spectrum observed from ^{76}As as shown in Fig. 2 is due to a superposition of the effects of two approximately monoenergetic γ rays. These two assumptions, combined with a knowledge of the shape of the scattered γ-ray spectrum for each of these two monoenergetic components, suggest a procedure through which the values of δ associated with each of the two γ rays may be deduced.

A study of the currently accepted decay scheme[12] for ^{76}As combined with the β energy range accepted for the true coincidence spectra shown in Fig. 2 allows one to assume that this resultant spectrum can be considered as a mixture of spectra due to a monoenergetic γ ray of 0.559 MeV combined with a monoenergetic γ ray of 1.216 MeV. The presence of the 0.657 MeV γ ray which is unresolved from 0.559 MeV γ ray has little effect on the argument which follows.

If one divides the combined γ-ray spectra resulting from two monoenergetic γ's into two regions, one emphasizing the effects of the higher energy γ ray and the other using the remaining significant portion of the spectrum, and refers to the lower energy portion of the spectrum as region 1 and the higher energy portion of this spectrum as region 2 one can define the following two quantities:

$$D_1 = N_1^+ - N_1^- \quad D_2 = N_2^+ - N_2^- . \tag{12}$$

In the definitions of these two quantities, N_1^+ represents an integration over region 1 of the γ-ray spectrum with the magnetic field in the positive direction and N_1^- represents an integration over region 1 of the γ-ray spectrum with the field in the negative direction. The quantities N_2^+ and N_2^- have similar meanings. If one designates the lower energy γ with the subscript a and the higher energy γ with subscript b one can also introduce the quantities

$$\begin{aligned} S_a &= \frac{N_{a2}^+}{N_{a1}^+} = \frac{N_{a2}^-}{N_{a1}^-} = \frac{N_{a2}}{N_{a1}} , \\ S_b &= \frac{N_{b2}^+}{N_{b1}^+} = \frac{N_{b2}^-}{N_{b1}^-} = \frac{N_{b2}}{N_{b1}} , \end{aligned} \tag{13}$$

where the N_{a1} represents an integration over region 1 of the γ-ray spectrum resulting from a monoenergetic γ of the lower energy and N_{a2} represents an integration over region 2 of the spectrum from the same monoenergetic γ. N_{b1} and N_{b2} have similar meanings for the spectra of a monoenergetic γ of the higher energy. Since the shape of the γ-ray spectrum will not be altered by field reversal, one may use the values of S_a and S_b obtained from noncoincident scattering experiments using monoenergetic γ rays first of energy corresponding to the lower energy γ and then of energy corresponding to the higher energy γ. With these definitions and a considerable amount of algebra it can be shown that[13]

$$\begin{aligned} \delta_a &= \frac{D_1 S_b - D_2}{N_1 S_b - N_2} , \\ \delta_b &= \frac{D_1 S_a - D_2}{N_1 S_a - N_2} . \end{aligned} \tag{14}$$

In carrying out this procedure region 1 and region 2 of the γ spectrum were chosen as follows: Referring to Fig. 2, the range chosen for region 1 was channel 14 to channel 31 and the range chosen for region 2 was from channel 32 through channel 52.

Using the procedure outlined above and a range of β energies from 0.56 to 1.4 MeV for the ^{76}As spectrum the values of δ for β counter 1 and β counter 2 which we associate primarily with the 1.753 MeV β–1.2161 MeV γ transition sequence are

$$\delta_1 = -0.03 \pm 0.017 \text{ and } \delta_2 = 0.006 \pm 0.014 . \tag{15}$$

Assuming that $A_2 = A_3 = 0$, $P_\gamma(180°) = 0.75 \pm 0.6$ for the 1.216 MeV γ when averaged over the β spectrum range from 0.5 to 1.4 MeV. The same procedure yielded values of δ_1 and δ_2 associated with the 2.41 MeV β–0.559 MeV γ for a β energy range between 0.56 and 1.4 MeV. This energy range lies below the energy range associated with the measurements for this β transition by Simms and Smith.[6] The values of δ obtained are

$$\delta_1 = -0.001 \pm 0.001 \text{ and } \delta_2 = -0.001 \pm 0.001 , \tag{16}$$

which is consistent with the results obtained for the β energy range used by Smith and Simms[6] if allowance is made for the different energy range and the effects of the 0.657–0.559 MeV cascade.

The two monoenergetic γ spectra used to obtain experimental values for the constants S_a and S_b were obtained as follows. In determining S_a, the coincident γ spectrum due to the 0.559 MeV γ of ^{76}As was generated by summing over a β energy range from 1.4 to 2.1 MeV. Choosing this β energy range effectively eliminated contributions from any of the other γ's to the true coincidence spectrum. The constant S_b was determined through the use of the scattered ^{60}Co γ-ray spectrum. It should be noted that while the γ spectrum from ^{60}Co is not, strictly speaking, a monoenergetic γ spectrum, it is composed of two closely spaced γ rays whose average energy differs by only 3% from that of the 1.216 MeV γ of ^{76}As. Further, when the resolution of the apparatus and the energy ranges chosen are considered, no significant error can be expected as a result of using this spectrum for this purpose.

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[1]G. Holzwarth, D. Janssen, and R. V. Jolos, Nucl. Phys. A261, 1 (1976).

[2]G. Holzwarth, and S. G. Lie, Z. Phys. 249, 332 (1972).

[3]S. R. Almoney and G. J. Borse, Nucl. Phys. A171, 660 (1971).

[4]R. Lecomte *et al.*, Nucl. Phys. A284, 123 (1977).

[5]D. Ardouin and R. Tamisier, Phys. Rev. C 12, 1745 (1975).

[6]H. A. Smith and P. C. Simms, Phys. Rev. C 3, 2278 (1971).

[7]P. Alexander and R. M. Steffen, Phys. Rev. 124, 150 (1961).

[8]D. C. Camp, L. G. Mann, and S. D. Bloom, Nucl. Phys. 73, 174 (1965).

[9]G. Hartwig and H. Schopper, Phys. Rev. Lett. 4, 293 (1960).

[10]R. M. Steffen and H. Frauenfelder, *Alpha- Beta-and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (North-Holland, Amsterdam, 1965), Vol. 2, p. 1466.

[11]A. Edmonds, *Angular Momentum in Quantum Mechanics* (Princeton Univ. Press, Princeton, N.J., 1957).

[12]Nuclear Data Sheets 19, 507 (1976).

[13]William Sellyey, thesis (Bryn Mawr College, Bryn Mawr, Pa.), 1974 (unpublished).