Polarization Correlation Measurements on Eu^{154}

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The spins and parities of the 1400- and 1723-kev levels in Gd^{154} are discussed on the basis of the polarization-directional correlation measurements on the 1277–123 and 725–998 kev gamma-gamma cascades following the β decay of Eu^{154}. In the case of the 1277–123-kev cascade, directional correlation measurements and the polarization correlation measurements of the 1277-kev gamma ray are made with liquid and solid sources. An attenuation in the anistropy of directional correlation and in the degree of linear polarization correlation has been observed in both the sources, the attenuation in the solid source being greater. In the 725–998 kev cascade, the polarization of either of the two radiations has been measured in two separate experiments. On the basis of these measurements, the spins and parities of both the 1400- and the 1723-kev levels in Gd^{154} are assigned 2^-. The performance of the apparatus has been checked by measuring the polarization correlations of known cascades in Ni^{60}, Ti^{46}, Pd^{106}, and Sr^{88}.

INTRODUCTION

THE decay of Eu^{154} ($T_{\frac{1}{2}}=16$ years) has been studied by several workers[1–5] and the decay scheme is well established. The level spectrum of Gd^{154} as generated by the β decay of Eu^{154} is reproduced in Fig. 1. The nucleus Gd^{154} which has 90 neutrons lies on the edge of the group of nuclei which show rotational and vibrational spectra characteristic of spheroidal deformation.[6] The 123- and 371-kev levels of character 2^+ and 4^+, respectively, belong to the ground-state rotational band with $K=0$. The levels at 998 and 1130 kev are assigned spins and parities 2^+ and 3^+, respectively, on the basis of conversion coefficient data[2,5] and directional correlation measurements.[7,8] These levels, presumably, are the members of the γ-vibrational band corresponding to $K=2$. The measured directional correlation coefficients[7,8] on the 1277–123- and 725–998-kev cascades can be fitted by various spin assignments to the 1400- and 1723-kev levels. The nature of both the 1277- and the 725-kev γ rays are presumably established as $E1$ from conversion coefficient measurements.[2,5] The present polarization correlation measurements were therefore undertaken to throw more light on the spins and parities of these two levels in Gd^{154}.

EXPERIMENTAL PROCEDURE

The gamma-ray linear polarimeter (Fig. 2) uses the Compton scattering as the polarization-sensitive device. It consists of the directional counter 1 [$1\frac{3}{4}\times2$ in. NaI(Tl) crystal], situated at a distance of 4 in. from the source; and a polarization-sensitive element consisting of a central cylindrical scattering crystal 2 ($1\frac{1}{2}\times1\frac{1}{2}$ in. anthracene), and two side counters 3 and 4 [each of $1\frac{3}{4}\times2$ in. thick NaI(Tl) crystal]. The γ ray γ_2, whose polarization is to be measured, passes through a lead collimator, suffers a Compton scattering in counter

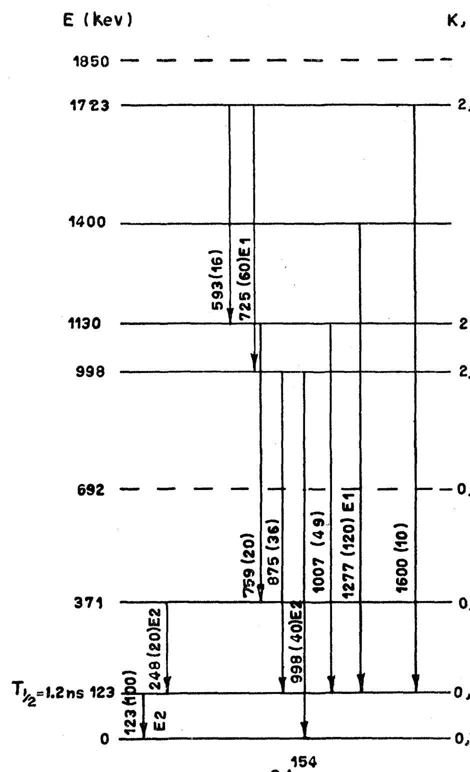

FIG. 1. Level scheme of Gd^{154} as reached from the β decay of Eu^{154}. The intensities quoted in parentheses are taken from references 2–4.

[1] J. M. Cork, M. K. Brice, R. G. Helmer, and D. E. Sarason, Phys. Rev. **107**, 1621 (1957).
[2] José O. Juliano and F. S. Stephens, Phys. Rev. **108**, 341 (1957).
[3] S. K. Bhattacherjee, Shree Raman, and S. K. Mitra, Proc. Indian Acad. Sci. **47**, 295 (1958).
[4] B. S. Dzelepov, N. N. Zhkovsky, V. G. Nedovesov, and G. E. Shukin, Izvestiya Acad. Nauk, Ser. Fiz. S.S.S.R. **21**, 966 (1957).
[5] B. V. Bobikin and K. M. Novik, Izvestiya Acad. Nauk, Ser. Fiz. S.S.S.R. **21**, 1556 (1957).
[6] R. K. Sheline, Revs. Modern Phys. **23**, 1 (1960).
[7] G. D. Hickman and M. L. Wiedenbeck, Phys. Rev. **111**, 539 (1958).
[8] P. Debrunner and W. Kündig, Helv. Phys. Acta **33**, 395 (1960).

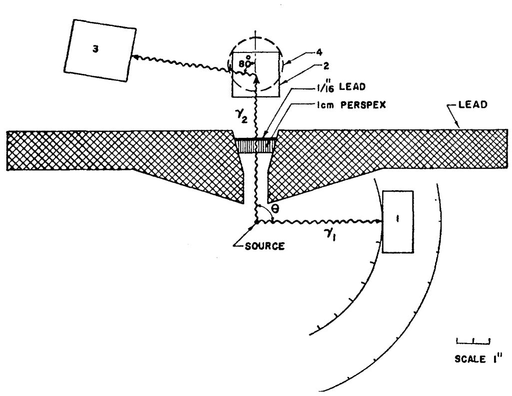

FIG. 2. A diagram of the counter arrangement used in the polarization correlation experiments. Counter 1 is the directional counter; counters 2, 3, and 4 make up the polarization detector, with Compton scattering taking place in counter 2. Counters 3 and 4 are shown in planes parallel and perpendicular, respectively, to the planes defined by the counters 1 and 2. Counters 3 and 4 can be rotated together about the axis of the counter 2. Counters 1, 3, and 4 employ NaI(Tl) scintillation crystals and counter 2 employs an anthracene crystal. Counter 1 can be rotated to change the correlation angle θ.

2, and the scattered gamma ray is detected in either of the side counters 3 or 4; one of them is situated in the plane containing the crystals 1 and 2 and the other in the plane perpendicular to this plane. The counter 2 detects recoil electrons. The mean angle of scattering is $\theta_c=80°$, which is chosen because it is the optimum angle for maximum polarization-sensitivity for the range of γ energies of interest. The angle between the two γ rays γ_1 and γ_2 can be varied. However, most of the experiments are made for $\theta=90°$ since the degree of polarization is, in general, maximum for this correlation angle. The counters 3 and 4 can rotate together about the axis of counter 2, but are fixed relative to each other so that the planes defined by the counters 2–3 and 2–4 are always perpendicular to each other.

For a plane-polarized γ ray of given energy and for a given angle of scattering, the polarization sensitivity of the Compton scattering process is defined by the asymmetry ratio R, which is the ratio of the Klein-Nishina differential cross sections for scattering in the planes perpendicular and parallel to the initial plane of polarization. In the actual experimental situation, the asymmetry ratio R is reduced because of the finite angular spreads of the counters 2, 3, and 4, and becomes the ratio of coincidence rates between 2 and 4 to 2 and 3, for a beam of γ rays incident on the scattering crystal, polarized in the plane defined by the counters 2 and 3.

If p is the degree of polarization of γ_2 (defined as the ratio of intensities of γ_2 polarized in and perpendicular to the plane defined by the two γ rays, γ_1 and γ_2), and if the counter 3 is in the plane containing γ_1 and γ_2, and counter 4 is perpendicular to this plane, then $N_{\parallel}/N_{\perp}=N_{123}/N_{124}=(p+R)/(pR+1)$, where N_{123} is the triple coincidence rate between the counters 1, 2, and 3, and N_{124} is between 1, 2, and 4.

All the crystals were mounted on RCA 6342-A photomultipliers. The photopeak of γ_1 whose polarization was not measured was accepted in a narrow window of the analyzer of counter 1. The recoil electron energy, corresponding to 80° scattering of γ_2, was accepted in the window of counter 2 and the integral counts above a certain bias setting were accepted in the discriminators of counters 3 and 4. The output of counter 2 was taken in coincidence ($2\tau=2$ μsec) with the outputs of counters 3 and 4 separately. Let these coincidences be denoted by N_{23} and N_{24}, respectively. The counters 2–3 and 2–4 act separately as Compton spectrometers. A fast-slow setup was used between the counters 2 and 1, in the conventional way, the fast coincidence resolving time being $2\tau=40$ nanoseconds. The fast-slow coincidence output N_{12} was again taken in coincidence with N_{23} and N_{24} separately in two coincidence circuits ($2\tau=4$ μsec) to give the triple coincidences N_{123} and N_{124}, respectively. N_{23}, N_{24}, N_1, and N_{124} were fed to four mechanical printing counters. The time was recorded on a timer. For a fixed number of triple coincidences N_{123}, a master pulse was delivered by N_{123}—scaler to print the timer and the printing counters recording N_1, N_{23}, N_{24}, and N_{124}. For a preset number of prints, the positions of counters 3 and 4 were interchanged. In the first position, the planes defined by the counters 2–3 and 2–1 are parallel, and in the second position they are perpendicular. Let $S_1=(N_{123}/N_{23})\div(N_{124}/N_{24})$ for the first position and $S_2=(N_{124}/N_{24})\div(N_{123}/N_{23})$ for the second position. Then $N_{\parallel}/N_{\perp}=(S_1S_2)^{\frac{1}{2}}$. This procedure of normalizing the triple coincidences with N_{23} and N_{24} corrects, to the first order, any decentering of the scatterer and the inequalities of the detecting efficiencies for the two counters 3 and 4. The chance coincidences were calculated[9] from the known resolving times of the fast and slow coincidence circuits and the different singles and coincidence rates.

The apparatus was calibrated for R over the photon energy ranges of interest by measuring the polarization correlations of well known cascades in Ni^{60}, Ti^{46}, Sr^{88}, and Pd^{106}. Assuming the theoretical p values and using the experimentally determined $N_{\parallel}/N_{\perp}$, in each of these cases, the R value was extracted. In the case of Pd^{106}, the p value for $0^+(E2)2^+(E2)0^+$ at $\theta=90°$ is infinite, so that one expects $N_{\parallel}/N_{\perp}=1/R$. However, because of the interference due to other cascades in Pd^{106}, this asymmetry was reduced. In order to obtain a value of R, a directional correlation measurement was made with the same energy settings in counters 1 and 2 as was used in the polarization correlation measurement. The A_2 and A_4 coefficients thus obtained were used to calculate p and the R value was extracted from the p value so determined. Figure 3 shows the R value as a function of the gamma-ray energy. The solid line shown in the figure was obtained by integrating the Klein-Nishina formula over the spreads of the crystal dimensions.

[9] P. H. Stelson and F. K. McGowan, Phys. Rev. **105**, 1346 (1957).

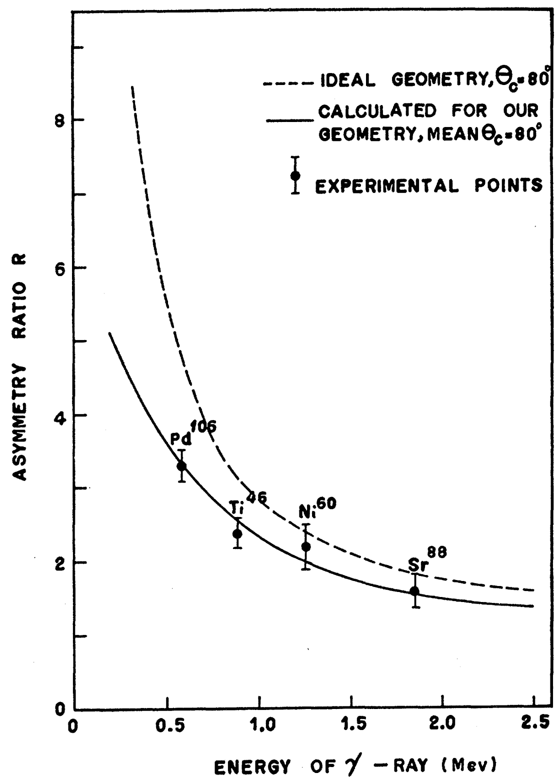

FIG. 3. The asymmetry ratio R as a function of the energy of the γ ray whose polarization is measured.

RESULTS

The Eu^{154} source was obtained from Oak Ridge National Laboratory, by irradiating 95% enriched Eu^{153} in oxide form with thermal neutrons. The source contains about 40% of long-lived Eu^{152} activity. In the present experiment the contributions due to the Eu^{152} contaminations were taken into account.

A. 1277−123-kev Cascade

The 123-kev level has a half-life of 1.2 nsec.[10] In order to find if there was any attenuation in the directional and polarization correlation coefficients due to the extranuclear field in the source, measurements were made with a solid polycrystalline $EuCl_3$ source and with a dilute aqueous solution of $EuCl_3$, contained in a thin-walled Perspex capsule. With these sources, both directional and polarization correlation measurements were made. For the polarization correlation experiment, the 123-kev photopeak was accepted in a narrow window in counter 1 and the polarization of the 1277-kev γ ray was measured by accepting a recoil-electron energy band of 700–1000 kev in counter 2. The results of the directional and polarization correlation measurements on this cascade are reproduced in Table I.

The contribution in the triple coincidences in the

[10] A. W. Sunyar, Phys. Rev. **98**, 653 (1955).

TABLE I. Results of the directional and polarization correlation measurements on the 1277–123 kev γ-cascade in Gd^{154}. R for the 1277-kev γ ray was taken as 1.95.

Source	A_2	A_4	θ	$N_{\parallel}/N_{\perp}$	p
Liquid	0.190 ± 0.012	-0.005 ± 0.018	90°	1.24 ± 0.02	0.50 ± 0.04
			120°	1.13 ± 0.03	0.68 ± 0.06
Solid	0.161 ± 0.012	-0.017 ± 0.018	90°	1.16 ± 0.02	0.63 ± 0.04
			120°	1.07 ± 0.03	0.81 ± 0.06

polarization correlation measurements, due to the 121–1409 kev cascade of Sm^{152} was estimated to be about 5%. From the known spin sequence[11] in Sm^{152}, the correction to the $N_{\parallel}/N_{\perp}$ value was estimated to be less than 1%. Debrunner and Kündig[8] have recently reported measurements on the directional correlation of this cascade with different source conditions. In a liquid source they find $A_2=0.168\pm0.013$; $A_4=0.002\pm0.012$. Hickman and Wiedenbeck[7] find $A_2=0.191\pm0.010$; $A_4=-0.007\pm0.015$ in a liquid source. Our liquid-source values agree well with these measurements. In the solid source, the experimental A_2 value is smaller than that in the liquid source. Similar attenuation is also clearly seen in the polarization correlation measurements. Thus it is established that for this cascade there is an attenuation, due to the extranuclear field, both in the directional as well as in the polarization correlation measurements. By measuring the directional correlation of 248–123-kev cascade in Gd^{154}, Debrunner and Kündig[8] find the attenuation coefficient and correct the A_2 value for the 1277–123 kev cascade. The corrected value quoted is $A_2=0.251\pm0.039$ which is close to the sequence 2(1)2(2)0, indicating that the 1400-kev level has a spin 2.

For a $2^-(E1)2^+(E2)0^+$ cascade, the theoretical p value is 0.4 and for a $2^+(M1)2^+(E2)0^+$ cascade, it is 2.5. The experimental value 0.50 ± 0.04 clearly indicated that if 1400-kev level has a spin of 2, its parity is negative. In Fig. 4, the $p_{90°}$ value is plotted against A_2 with $\delta'=\delta/(1+\delta)$, where δ is the mixing ratio of the higher to lower competing multipoles, as the parameter.[11,12] As can be seen from the figure, the assignments $3^+(83\%\ M1+17\%\ E2)2^+(E2)0^+$ and $1^+(E2)2^+(E2)0^+$ also fit the data. The latter assignment is excluded since it requires an $A_4=-0.75$ in contrast to the experimental value which is zero within the experimental errors. An assignment of 4^- to the 1400-kev level with an $M2+E3$ character for the 1277-kev γ ray also fits the experiment but is excluded on the basis of the measured K-conversion coefficient[5] for the 1277-kev γ ray which is $(0.72+0.07)\times10^{-3}$. The theoretical value[13] for the K-conversion coefficient for an $E1$ transition of the 1277-kev γ ray is 0.7×10^{-3}; its value for an 83% $M1$+17% $E2$ mixture, corresponding to a 3^+ assignment of the

[11] G. T. Wood, Phys. Rev. **116**, 1499 (1959).
[12] C. F. Coleman, Nuclear Phys. **5**, 495 (1955).
[13] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57 ICCK1, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].

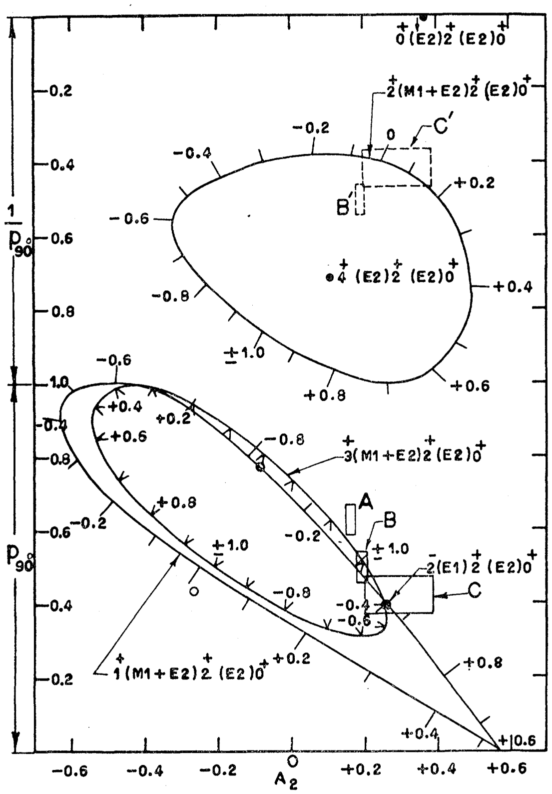

FIG. 4. The degree of polarization, when the polarization of mixed radiation is measured, is plotted for a correlation angle of 90° against A_2 for gamma-gamma cascades having the spin sequence J–2–0, with $\delta'=\delta/(1+\delta)$ as the parameter, where δ is the quadrupole-to-dipole mixing ratio. The necessary formulas were taken from L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953). Markers are placed along the curve to indicate the points for δ' from 0 to ± 1 in intervals of 0.1. Rectangles are plotted to show the experimental limits of the measurements of p and A_2. The rectangles A and B correspond to the 1277–123 kev cascade with solid and liquid sources, respectively. The rectangle C corresponds to the 725–998 kev cascade with a liquid source. The rectangles labeled B' and C' are the mirror images of rectangles B and C, respectively, about $p=1$ axis. By comparing the rectangles B' and C' with the theoretical curves, it is possible to consider the cascades in which the mixed transition has the opposite parity change from the one indicated by the label.

1400-kev level, is 2.2×10^{-3}. This establishes the $E1$ nature of the 1277-kev γ ray and so the 1400-kev level is 2^- in nature.

B. 725–998-kev Cascade

The directional correlation measurements in this cascade have been reported by several workers. Hickman and Wiedenbeck[7] reported the values $A_2=0.213\pm0.025$; $A_4=-0.013\pm0.037$. Debrunner and Kündig[8] reported the values $A_2=0.296_{-0.055}^{+0.090}$ and $A_4=0.035\pm0.036$. These values can be fitted with a spin assignment of 2 for the 1723-kev level. Other spin assignments like 3, 4, 5, and 6 can also fit the correlation coefficients. The higher spin assignments can, however, be excluded on the basis of the measured K-conversion coefficient for the 725-kev γ ray, as will be discussed later. The polarization correlation of this cascade is composed of the following two experiments.

TABLE II. Results of the polarization correlation measurements on the 725–998-kev γ cascade in Gd^{154}. The correlation angle $\theta=90°$.

γ ray whose polarization was measured	$N_{\parallel}/N_{\perp}$	R	p
998 kev	0.70 ± 0.03	2.3	$2.6_{-0.3}^{+0.4}$
725 kev	1.49 ± 0.07	2.9	0.42 ± 0.05

MEASURED POLARIZATION OF 725-KEV γ-RAY

For this experiment the photopeak of the 998-kev γ ray was accepted in a narrow window in counter 1. Here, as well as in the following experiment, the anthracene crystal was replaced by a NaI(Tl) crystal of same dimensions for better energy resolution. The recoil electron band of energy 300–500 kev was accepted in counter 2. Here about 10% of the total coincidences were due to the 725–875-kev γ cascade since a tail of the 875-kev γ-ray photopeak was accepted in counter 1. About 15% of the total coincidences were due to the 593–1007-kev cascade since a portion of the recoil electrons due to the 593-kev γ ray was accepted in counter 2. Since the directional correlation of both the 593–1007-kev[7] and 725–875-kev γ cascades[8] are almost isotropic, not much of an error is made in assuming $N_{\parallel}/N_{\perp}$ for these cascades to be unity. These two corrections on the 725–998-kev cascade were made and the corrected p value is shown in Table II.

MEASURED POLARIZATION OF 998-KEV γ RAY

In this experiment the photopeak of the 725-kev γ ray was accepted in counter 1. The recoil-electron band of energy 450–750 kev was accepted in counter 2. In this experiment about 30% of the total coincidences were due to the 725–875-kev γ cascade because a portion of the recoil electrons due to the 875-kev γ ray was accepted in counter 2. Correction was made for this contribution in the same manner as before. The corrected p value is shown in Table II.

The experimental p values are compared with theory in the parametric plots[12] shown in Figs. 4 and 5. In Fig. 4, the observed p value when the 725-kev γ-ray polarization was measured, is shown. This again fits the $2^-(E1)2^+(E2)0^+$ sequence and also the $3^+(M1+E2)2^+(E2)0^+$ sequence. However, the measured K-conversion coefficient,[2,5] α_K, of the 725-kev γ ray is $(2.4\pm0.4)\times10^{-3}$ as compared to the theoretical value[13] of 1.9×10^{-3} for $E1$. A mixture of 70% $M1$ and 30% $E2$, which also fits the polarization correlation data, requires a value of $\alpha_K=7.6\times10^{-3}$ which is quite different from the experimental value. Thus the 725-kev γ ray is $E1$ in nature and the spin and parity of the 1723-kev level are 2^-. In Fig. 5, the experimental p value when the 998-kev

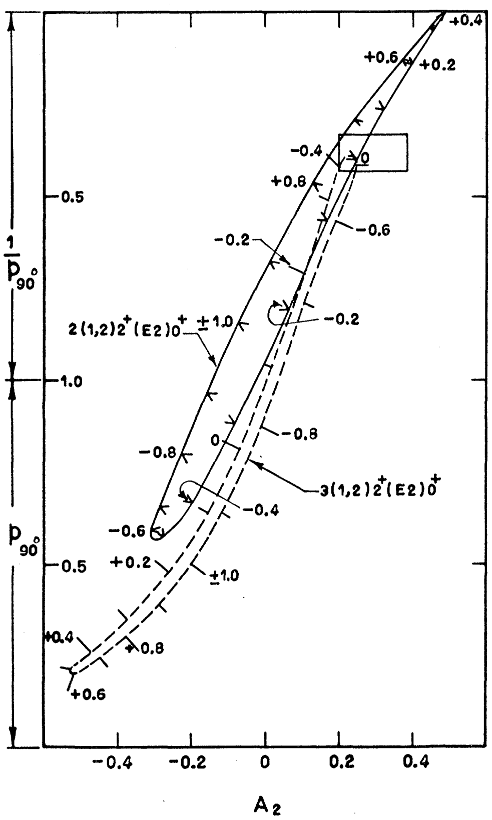

FIG. 5. The degree of polarization, when the polarization of pure radiation is measured, is plotted for a correlation angle of 90°, against A_2 for gamma-gamma cascades having the spin sequence J–2–0. The parameter δ' is the same as in Fig. 4. The rectangle shown corresponds to the measurement when the polarization of the pure $E2$ transition of 998 kev is measured in the 725–998-kev cascade. The limit of $M2$ mixture for the 725-kev γ ray can be seen to be less than 0.5%.

γ-ray polarization was measured is shown. As can be seen, this value also fits the 2^- assignment for the 1723-kev level. One can see from Fig. 4 that the upper limit on an $M2$ mixture in the 725-kev γ ray is about 4% (rectangle C). However, from Fig. 5, this limit is narrowed down to about 0.5%.

DISCUSSION

The nature of the even-parity levels in Gd^{154} has been well understood in terms of the rotations and vibrations of the deformed nucleus.[6,7] There have been reports of the existence of other even-parity levels at 692 kev (0+),[6] at about 800 kev (2+),[14] 720 kev (6+),[14] and another level at 1850 kev.[1,15] The first two levels have been classified as the members of the β-vibrational band and the 720-kev level as belonging to the ground-state rotational band. The presence of these levels, which are presumably weakly populated from the β decay of Eu^{154}, does not alter the conclusions that are drawn from the present experimental results.

The two odd-parity levels of spin 2 in Gd^{154} at 1400 and 1723 kev have different decay properties. The 1400-kev level mainly de-excites to the (0,2+) 123-kev level. The 2^- state at 1531 kev in Sm^{152} also has the same characteristics. Even though a γ transition to the (2,2+) level is observed in Sm^{152}, it is weak compared to the γ transition to the (0,2+) level.[16] These two 2^- levels at 1400 kev in Gd^{154} and 1531 kev in Sm^{152} presumably have the same origin.

On the other hand, the 1723-kev level in Gd^{154} mainly de-excites to the 998- and 1130-kev levels which

[14] D. M. Brink, in *Progress in Nuclear Physics*, edited by O. R. Frisch (Pergamon Press, New York, 1960), Vol. 8, p. 111.

[15] S. Jha, H. G. Devare, M. N. Rao, and G. C. Pramila, Proc. Indian Acad. Sci. **50**, 303 (1959).

TABLE III. Comparison of the ratio of the reduced transition probabilities of the 725- and 593-kev γ rays de-exciting to the 2^+ and 3^+ members of the γ-vibrational band, assuming different K values for the 1723-kev level. The intensities of the γ rays involved were taken from references 2–4.

K	$\frac{B(E1;K,2^-\rightarrow 2,2^+)}{B(E1;K,2^-\rightarrow 2,3^+)}$	Experimental ratio
1	0.5	2.4±0.4
2	2.0	

TABLE IV. Summary of known 2^- levels in even-even nuclei above neutron number 82. E_{2^-} denotes the energy in kev of the 2^- level, E_{2^+} denotes the energy of the 2^+ member of the ground-state rotational band. The fourth column represents the ratio of the reduced transition probabilities of the γ transitions from this level to the 2^+ and 3^+ members of the γ-vibrational band. Cases shown within parentheses are not definite.

Nucleus	E_{2^-}	E_{2^-}/E_{2^+}	$\frac{B(E1;2^-\rightarrow 2,2^+)}{B(E1;2^-\rightarrow 2,3^+)}$	References
Sm^{152}	1531	12.6	···	a
Gd^{154}	1400	11.4	···	
Gd^{154}	1723	14.0	2.4 ±0.4	b
Dy^{160}	1264	14.5	2.5 ±0.2	c
Dy^{160}	1358	15.6	1.05±0.20	c
W^{182}	1189	11.9	···	d
W^{184}	(1150)	(10.4)	···	e
Os^{188}	(1461)	(9.4)	···	f
Th^{228}	1123	19.6	···	g
Cm^{242}	(930)	(22.1)	···	h
Cm^{246}	(840)	(19.5)	···	h
Cf^{250}	(820)	(20.0)	···	h

[a] Reference 16.
[b] Intensities were taken from references 2–4.
[c] G. T. Ewan, R. L. Graham, and J. S. Geiger, *Proceedings of the International Conference on Nuclear Structure, Kingston*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, Canada, 1960), p. 603.
[d] Reference 17.
[e] C. J. Gallagher, Jr., D. Strominger, and J. P. Unik, Phys. Rev. **110**, 725 (1958).
[f] I. Marklund, B. Van Nooijen, and Z. Grabowski, reported at the annual meeting of Swedish Physical Society, June, 1959 (unpublished) and O. Nathan, D. Bes, and S. G. Nilsson (private communication) as quoted in reference 6.
[g] E. Arbman, S. Bjørnholm, and O. B. Nielsen, Nuclear Phys. **21**, 406 (1960).
[h] From Fig. 8 in reference 6.

[16] O. Nathan and S. Hultberg, Nuclear Phys. **10**, 118 (1959).

are the members of the γ-vibrational band via the γ rays of energy 725 and 593 kev, respectively. The transition to the (0,2+) level is also present via the 1600-kev γ ray but its reduced transition probability is about 100 times less than that of the 725-kev γ ray, the 1600-kev γ ray being assumed $E1$. If this 1723-kev level is collective in origin, an assignment of the K value can be made. The experimental ratio of the reduced transition probabilities of 725- and 593-kev γ rays is compared in Table III with theoretical ratios for different K values assumed for the 1723-kev level. As can be seen from Table III, the assignment $K=2$ for this level is clearly favored. Such an assignment explains the relative slowness of the 1600-kev γ transition to (0,2+) level since a transition of $E1$ type is forbidden by the K selection rule. It is interesting to see if any $M2$ mixture, which is allowed by the K selection rule, is present in this γ transition. An identical γ transition of 1189 kev in W^{182} has a 40% $M2$ mixture.[17]

The 2^- levels are found in other deformed even-even nuclei also. Table IV summarizes the presently known 2^- levels occurring in the region of medium-heavy and heavy deformed nuclei. An inspection of this table reveals that such 2^- levels are occurring in regions where there is a shift from a spherical to a deformed nucleus and vice versa. The ratios of the energies of these 2^- levels to the energy of the 2^+ member of the ground-state rotational band (column 3 in Table IV) seem to be grouped into values of about 14, 10, and 20 in the regions of neutron numbers around 90, 110, and 138, respectively; in each region this ratio appears to increase with the increase of deformation.

[17] C. J. Gallagher, Jr. and J. O. Rasmussen, Phys. Rev. 112, 1730 (1958).

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Antishielding of Nuclear Electric Hexadecapole Moments*

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The antishielding factor η_∞ for a possible nuclear electric hexadecapole moment has been calculated for the Cu^+, Ag^+ and Hg^{++} ions, using the Hartree-Fock wave functions for the $3d$, $4d$, and $5d$ electrons involved. It was found that $\eta_\infty(Cu^+)\cong -1200$, $\eta_\infty(Ag^+)\cong -8050$, and $\eta_\infty(Hg^{++})\cong -63\,000$. The implication of these results is discussed.

In a previous paper,[1] we have considered the interaction of a possible nuclear electric hexadecapole (16-pole) moment (HDM) with the ion core surrounding the nucleus. It has been shown that for medium and heavy atoms with closed d shells, the interaction energy of the HDM with the fourth-order derivative terms of the potential due to the ionic lattice (for the case of a crystal) will be considerably amplified by antishielding effects of the same type as have been calculated[2] and observed[3] for nuclear quadrupole moments. The antishielding effect arises from the large hexadecapole moment which is induced in the closed d (and possibly f) shells of the ion core. The induced HDM was written as

$$H_{\mathrm{ind}} = -\eta_\infty H, \qquad (1)$$

where H is the nuclear HDM, and η_∞ is defined as the hexadecapole antishielding factor, in a completely analogous manner to the antishielding factor[2] γ_∞ for the nuclear quadrupole moment.

In the present paper, we wish to report the results of calculations of η_∞ for the Cu^+ and Ag^+ ions, using the Hartree-Fock wave functions which have been obtained for these ions.[4,5] We have found that $\eta_\infty \cong -1200$ for Cu^+ and $\eta_\infty \cong -8050$ for Ag^+. These values are extremely large, even when compared to typical values of $\gamma_\infty(\sim -100)$, and therefore suggest that it may be possible to detect the nuclear HDM for nuclei with spin $I \geqq 2$, by observing the deviation from the relationships between the resonance frequencies which would be expected for a pure quadrupole resonance spectrum.[6]

The predominant contribution to η_∞ for Cu^+ and Ag^+ is due to the $3d \to d$ and $4d \to d$ excitations, respectively, produced by the nuclear H. (Although the stable isotopes of Cu and Ag have spin $I=\frac{1}{2}$ and $\frac{3}{2}$, respectively, we assume the presence of a nuclear

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[3] See, for example, M. H. Cohen and F. Reif, in *Solid-State Physics*, edited by F. Seitz and D. Turnbull (Academic Press, Inc., New York, 1957), Vol. 5, p. 321; T. P. Das and E. L. Hahn, *Nuclear Quadrupole Resonance Spectroscopy* (Academic Press, Inc., New York, 1958).
[4] D. R. Hartree and W. Hartree, Proc. Roy. Soc. (London) A157, 490 (1936).
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