formulated by Brennan and Bernstein[1] has thus been demonstrated with relatively few assumptions about the residual proton-neutron interaction in nuclei. More experimental data, especially on the excited states of odd-odd nuclei, are required to deduce more specific information on the residual neutron-proton interaction. With the modified Nordheim rule as formulated by Brennan and Bernstein we can only exclude dominant high-multipole interactions in the residual neutron-proton interaction, if it is of the general form (1). It seems that most of the regularities found so far could be understood with the assumption that the ratio of triplet to singlet parts in the residual interaction is roughly the same as that of the free proton-neutron interactions.[1,8]

[8] C. J. Gallagher and S. A. Moszkowski, Phys. Rev. 111, 1282 (1958).

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Level Structure of Eu^{153}†

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Gamma rays in Eu^{153} following the decay of Sm^{153} and Gd^{153} have been studied using coincidence and angular correlation methods. Results for the strong transitions are in agreement with the decay scheme given by McCutchen. Measurements were made of spectra of gamma rays in coincidence with the x-ray, 70-kev, and the 97-kev and 103-kev transitions in the decay of Gd^{153}, and with eight energy regions in the decay of Sm^{153}. A number of new, weak transitions were observed in the decay of Sm^{153}, and a consistent decay scheme is proposed. Directional correlation measurements were made on the 70 kev–103 kev cascade from the decay of Sm^{153} and from the decay of Gd^{153}. Possible spin assignments are discussed.

I. INTRODUCTION

THE beta decay of the 47-hour Sm^{153} to Eu^{153} and the electron capture decay of the 225-day Gd^{153} to Eu^{153} have been studied by a number of investigators.[1–25] Figure 1 shows the decay scheme given by McCutchen.[1]

There is general agreement about the levels at 84 kev, 97 kev, 103 kev, 172 kev, and 187 kev. The 70-kev gamma ray has been observed in coincidence with the 103-kev gamma ray in the decay[10] of Sm^{153} and in the decay[1] of Gd^{153}; both transitions[25] are $M1+E2$. The 97-kev gamma ray was first observed by Church and Goldhaber[16] by means of internal conversion measurements on Gd^{153}. This transition[1,21,22] is strongly fed in the decay of Gd^{153}. Recently, Walters *et al.*[15] observed a 97-kev transition with a bent-crystal spectrometer in the Sm^{153} decay with an intensity of less than 5% of the 103-kev gamma ray. The levels at 84 kev and 187 kev, and the corresponding gamma transitions have been observed by Coulomb excitation.[26–28]

The energies of the strong beta components in the Sm^{153} decay have been measured as 803 kev, 698 kev, and 640 kev.[4,8,10,11,13] The 698-kev beta transition has been observed in coincidence with the 103-kev gamma ray, and the 640-kev beta ray has been observed in

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[1] C. W. McCutchen, Nuclear Phys. 5, 187 (1958).
[2] J. W. Mihelich, Phys. Rev. 87, 646 (1952).
[3] K. Siegbahn, Arkiv Fysik 4, 223 (1952).
[4] R. L. Graham and J. Walker, Phys. Rev. 94, 794(A) (1954).
[5] M. R. Lee and R. Katz, Phys. Rev. 93, 155 (1954).
[6] F. K. McGowan, Phys. Rev. 93, 163 (1954).
[7] N. Marty, Compt. rend. 238, 2516 (1954).
[8] N. Marty, J. phys. radium 16, 458 (1955).
[9] B. Anderson, Proc. Phys. Soc. (London) A69, 415 (1956).
[10] V. S. Dubey, C. E. Mandeville, and M. A. Rothman, Phys. Rev. 103, 1430 (1956).
[11] M. C. Joshi, B. N. Subba Rao, and B. V. Thosar, Proc. Indian Acad. Sci. 45A, 390 (1957).
[12] O. Beckman, Nuclear Instr. 3, 27 (1958).
[13] J. M. Cork, M. K. Brice, R. G. Helmer, and R. M. Woods, Phys. Rev. 110, 526 (1958).
[14] A. Klove and A. Storruste, Arch. Math. Naturvidenskab 54, 57 (1958).
[15] T. J. Walters, J. H. Webber, N. C. Rasmussen, and H. Mark, Nuclear Phys. 15, 653 (1960).
[16] E. L. Church and M. Goldhaber, Phys. Rev. 95, 626A (1954).
[17] S. G. Cohen, J. Burde, and S. Ofer, Bull. Research Council Israel 5A, 87A (1955).
[18] S. K. Bhattacherjee and S. Raman, Nuclear Phys. 1, 486 (1956).
[19] A. Bisi, E. Germagnoli, and L. Zappa, Nuclear Phys. 1, 593 (1956).
[20] R. K. Gupta and S. Jha, Nuovo cimento 4, 88 (1956).
[21] N. Marty and M. Vergnes, Compt. rend. 242, 1438 (1956).
[22] M. C. Joshi and B. N. Subba Rao, Proc. Indian Acad. Sci. 46, 430 (1957).
[23] N. M. Antoneva, A. A. Bashilov, B. S. Dzhelepov, and B. K. Preobrazhenskii, Izvest. Akad. Nauk (S.S.S.R.) Ser. Fiz. 22, 135 (1958) [translation: Bull. Acad. Sciences (U.S.S.R.) 22, 134 (1958)].
[24] M. Vergnes, Ann. phys. 5, 11 (1960).
[25] R. L. Graham, G. T. Ewan, and J. S. Geiger, Bull. Am. Phys. Soc. 5, 21 (1960).
[26] C. M. Class and U. Meyer-Berkhout, Nuclear Phys. 3, 656 (1957).
[27] W. H. Johnson, Jr., and A. O. Nier, Phys. Rev. 105, 1014 (1957).
[28] J. de Boer, M. Martin, and P. Marmier, Helv. Phys. Acta 31, 578 (1958).

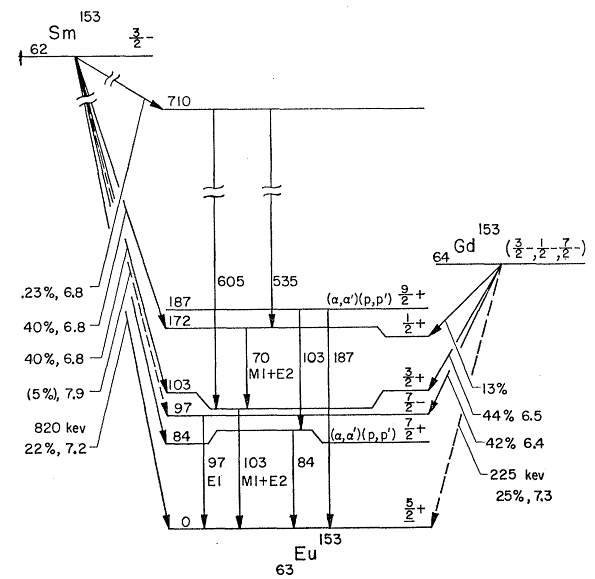

FIG. 1. Decay scheme of Sm^{153} and Gd^{153}, due to McCutchen.[1] The energies are in kev. The numbers after the intensities are log *ft* values.

coincidence with gamma transitions of 70 kev, 103 kev, and 173 kev.[4,8,10]

The half-life of the 103-kev level has been measured as 4×10^{-9} sec,[4,6,24] and the 173-kev level has a half-life of 0.14×10^{-9} sec.[4] McGowan[6] observed that the 97-kev gamma ray is in prompt coincidence with the K-capture x-rays from Gd^{153}. Vergnes[24] obtained a half-life of $\leq10^{-9}$ sec for this level.

There has been uncertainty over the positions in the decay scheme of the 535-kev and 605-kev transitions from the Sm^{153} decay. Dubey *et al.*[10] and McCutchen[1] observed that the 103-kev transition and probably the 70-kev transition are in coincidence with the 535-kev transition. The 103-kev transition was observed to be in coincidence with the 605-kev transition by Dubey *et al.*[10]

Some disagreement also exists over the internal conversion coefficients and the relative intensities of the transitions. Thus, the present coincidence and angular correlation measurements were undertaken in order to resolve some of the previous uncertainties and to study the level structure more completely.

II. EXPERIMENTAL PROCEDURE

Samples of very pure, natural samarium oxide were dissolved in nitric acid and irradiated in a flux of 2×10^{12} neutrons/cm² sec for periods of seven hours in the Ford Nuclear Reactor. Measurements were taken within a period of three and ten days after irradiation. This allowed the 22-minute Sm^{155} and 9.3-hour Eu^{152m} to decay. Immediately after irradiation the 842-kev gamma ray in Eu^{152m} had an intensity of about one-half of the 610-kev transition in Sm^{153}. The half-life of Sm^{153} was followed for 32 days, and only these short-lived impurities were observed.

A sample of gadolinium oxide enriched to 36.2% in Gd^{152} was irradiated for 64 hours in the Ford Nuclear Reactor. Measurements were begun 36 days after the completion of irradiation in order to allow the short-lived Gd activities to decay. The only observed impurities were Eu^{152} and Tb^{160}. The 244-kev gamma ray in Eu^{152} and the 298-kev gamma ray in Tb^{160} each had an intensity of about 8% of the 173-kev transition in Gd^{153}.

A conventional fast-slow coincidence circuit with a resolving time of 30 millimicroseconds was used in the coincidence measurements. Pulses coincident with gamma rays in a selected energy range were fed through a linear gate and recorded on a 256-channel analyzer. The detectors in all cases were 2-in. by 2-in. NaI(Tl) crystals mounted on RCA-6342A phototubes. A Compton shield of 6.4-mm thick lead surrounded by 0.8-mm Cd and 0.4-mm Cu was placed between the detectors in the coincidence measurements. Beta shields of 6.5-mm Teflon were used in front of the crystals, unless otherwise noted.

All of the transitions observed in the Sm^{153} coincidence measurements decayed with the proper half-life. In all cases the accidental spectra were small and were subtracted from the curves shown. The x-ray, 81-kev, 160-kev, and 355-kev gamma rays in Ba^{133} and the 511-kev transition from Na^{22} were used in calibrating the energy in the coincidence measurements.

A fast-slow coincidence circuit with a resolving time of 20 millimicroseconds was used in the directional correlation measurements. Differential analyzers provided energy selection, and lateral lead shields were used to prevent counter-to-counter scattering. Data were taken in a double quadrant sequence at seven angles in each quadrant. The real coincidence rate was corrected for electronic drift. After making a least squares fit,[29] the expansion coefficients were normalized and corrected for finite resolution.[30]

III. RESULTS FOR Sm^{153} DECAY

Gamma-Ray Spectra

Figure 2 shows gamma-ray spectra from the Sm^{153} decay as recorded on a 256-channel analyzer. The spectrum shown in Fig. 2(A) was taken with a Teflon beta shield; a weak source was used at 64 cm from the crystal in order to avoid accidental and real summing of gamma rays in the region of 173 kev. A weaker source at 100 cm from the crystal showed the 173-kev transition better resolved. In order to obtain better statistics on the high-energy radiations, the spectrum shown in Fig. 2(B) was taken with a strong source at 5.7 cm from the crystal

[29] M. E. Rose, Phys. Rev. **91**, 610 (1953).

[30] R. G. Arns, R. E. Sund, and M. L. Wiedenbeck, University of Michigan Research Institute Report 2375-4-T, February, 1959 (unpublished).

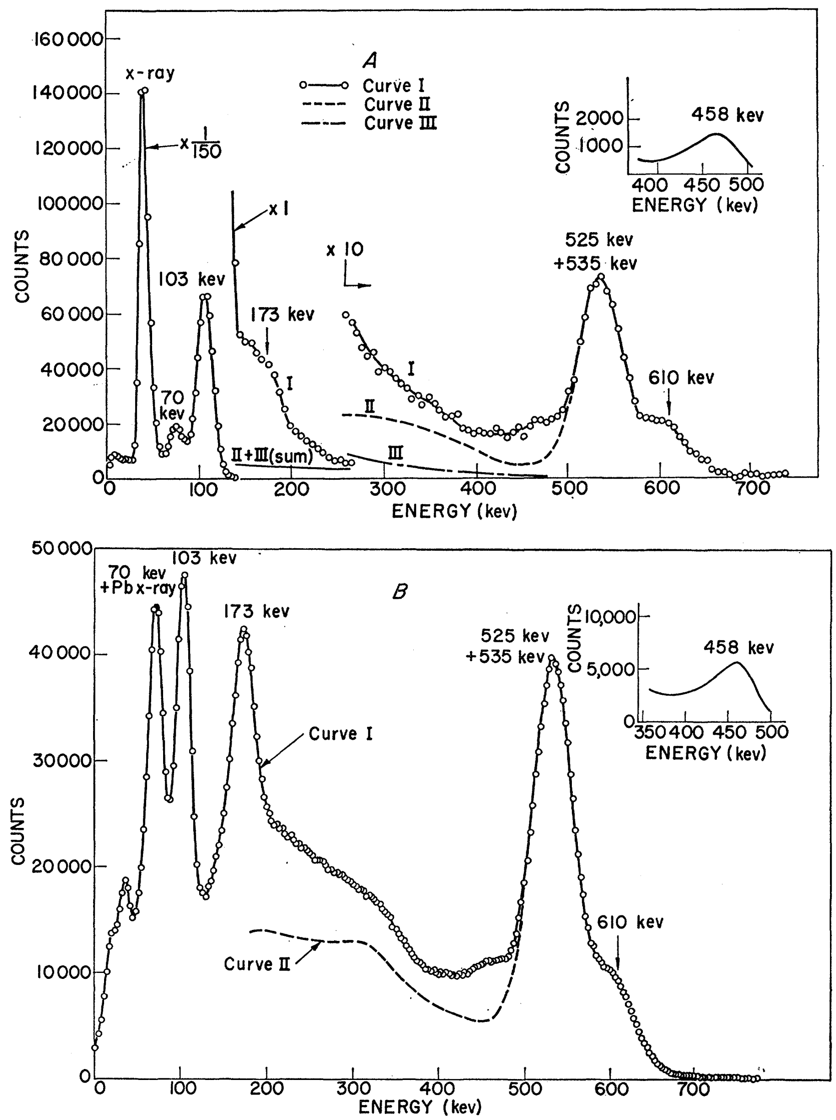

FIG. 2. Scintillation spectra of gamma rays in the decay of Sm^{153}. Curve AI is with the Sm^{153} source at 64 cm from the crystal and with a 6.5-mm Teflon beta shield. Curve BI is with the Sm^{153} source at 5.7 cm from the crystal and with absorbers of 0.084 cm Pb, 0.013 cm W, and 0.203 cm Cd. Curves AII and BII are the photoelectric and Compton distributions for the gamma rays which are in the regions of 530 kev and 610 kev. Curve AIII is the theoretical internal bremsstrahlung. The inserts in A and B show the spectra in the 458-kev region, after subtracting the spectra for the higher energy radiations and the internal bremsstrahlung.

with suitable absorbers. Spectra of Na^{22} and Cs^{137} were taken with the same geometry and absorbers used for Sm^{153} in Fig. 2(A) and 2(B). From these data the photoelectric and Compton distributions were determined for the gamma rays which are in the regions of 530 kev and 610 kev.

The theoretical internal bremsstrahlung was calculated in order to determine its effect in the region above 173 kev, where the gamma transitions are very weak. The result is shown in Fig. 2(A).

Both spectra in Fig. 2 indicate a transition of about 458 kev in addition to the gamma transitions previously reported.

The iodine x-ray escape peak from the 103-kev gamma ray is in the region of the 70-kev transition. In order to determine the intensity of the escape peak, spectra of the 103-kev transition in Se^{81m} were taken after the weak transitions in the 18-minute Se^{81} had decayed for about 200 minutes. The Se used for irradiation was enriched to 97% in Se^{80}. After subtracting the very weak Compton distribution due to high-energy radiations, these spectra were compared with Sm^{153} spectra taken with the same geometry and at the same time as the Se^{81m} spectra. A frontal shield of 6.5 mm Teflon was used in all cases. The spectra are shown in Fig. 3. Corrections were made for absorption, crystal efficiency, and iodine x-ray escape. The relative intensity of the 70-kev gamma ray to the 103-kev gamma ray was calculated to be 0.12 ± 0.03 and 0.13 ± 0.03 at source to crystal distances of 2.54 cm and 10.2 cm, respectively.

Background was subtracted from all spectra. All parts of the Sm^{153} spectra decayed with a 47-hour half-life.

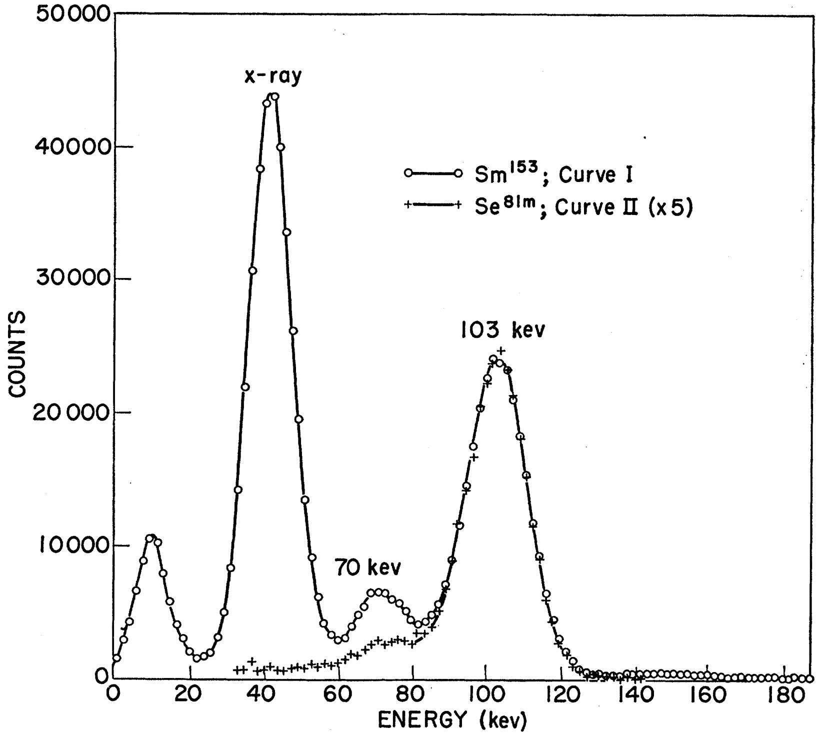

FIG. 3. Curve I is scintillation spectrum of gamma rays in decay of Sm^{153}. The peak at 12 kev is due to the iodine x-ray escape for the Eu x ray. Curve II is scintillation spectrum of gamma rays from decay of Se^{81m}. Both spectra were taken at a source to crystal distance of 2.54 cm.

Coincidence Measurements

Figure 4 illustrates the spectrum of gamma rays in coincidence with the 103-kev transition (89-kev to 116-kev range) from Sm^{153}. The decreased intensity ratio of the 535-kev transition to the 610-kev transition in comparison with the singles spectrum indicates that there is another transition near 535 kev whose intensity is $30\pm10\%$ of the combined intensity. This coincidence run was repeated with the gain of the multichannel analyzer raised. The resulting data, shown in Fig. 5, were used to calculate α_K for the 70-kev gamma ray.

The spectrum of gamma rays coincident with the 173-kev gamma ray (166-kev to 191-kev range) is shown in Fig. 6. Shielding was used in front of both crystals to attenuate the low-energy radiations. Coincidences are shown with gamma rays of 154 kev, 352 kev, and 422 kev. The possibility of the 154-kev transition coming from summing of low-energy transitions was eliminated due to the small number of coincidences at low energies. As will be seen below, this gamma ray along with the peak at 525 kev are mostly due to interference.

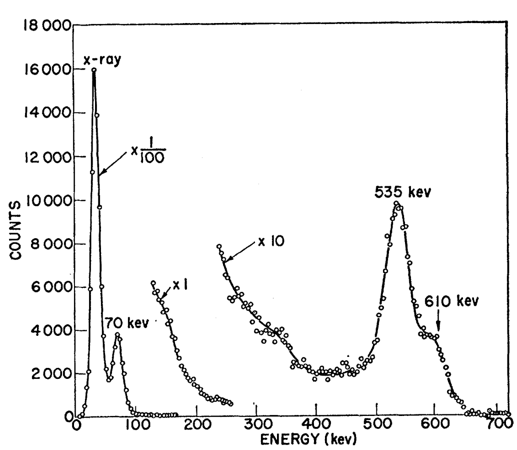

FIG. 4. Gamma rays in coincidence with 103-kev gamma ray (89-kev to 116-kev range) in decay of Sm^{153}.

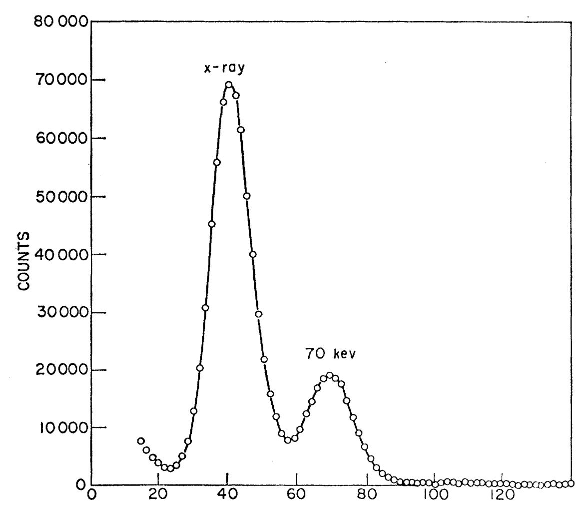

FIG. 5. Gamma rays in coincidence with 103-kev gamma ray in decay of Sm^{153}.

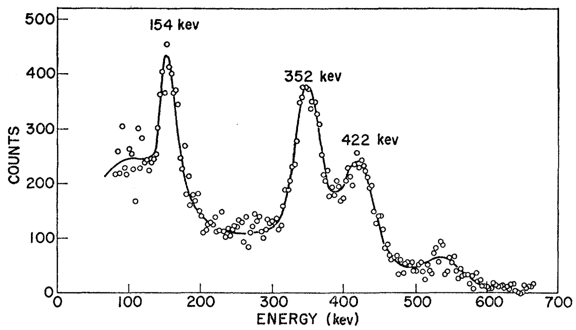

FIG. 6. Gamma rays in coincidence with 173-kev gamma ray (166-kev to 191-kev range). Shielding of 0.084 cm Pb and 0.122 cm Cd on the crystal feeding the multichannel analyzer and of 0.084 cm Pb, 0.013 cm W, 0.076 g/cm^2 Ce, and 0.081 cm Cd on the crystal feeding the discriminator was used.

The spectra of coincidences with the 500-kev to 540-kev range and with the 612-kev to 665-kev range are shown in Fig. 7. These spectra were taken consecutively and are approximately normalized in the 100-kev region. Calibration lines in the coincidence spectra of Ba^{133} showed that there were no energy shifts during the coincidence runs. The 103-kev gamma ray is shown to be in coincidence with the 535-kev transition. A weak coincidence at 154 kev is also shown. No 70-kev coincidence is indicated. The 97-kev gamma ray is in coincidence with the 610-kev transition. This conclusion is supported by the weaker x-ray on this spectrum.

The spectrum of gamma rays coincident with the 458-kev transition (445-kev to 475-kev region) is shown in Fig. 8. A gamma ray at about 67 kev is shown in addition to the x-ray, 103-kev, and 154-kev transitions.

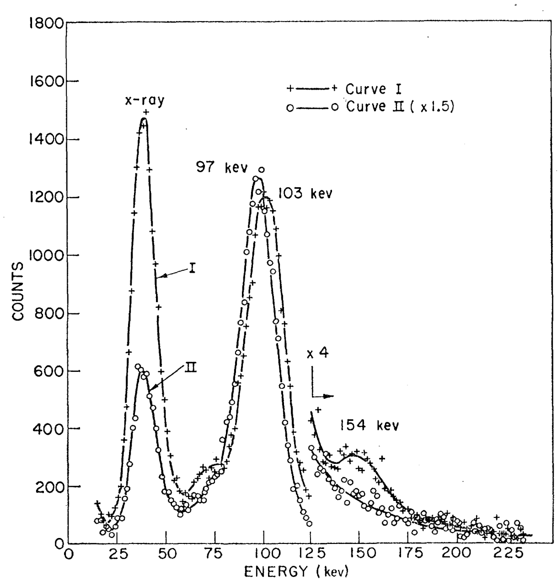

FIG. 7. Curve I is the spectrum of coincidences with the 500-kev to 540-kev region in decay of Sm^{153}. Curve II is the spectrum of coincidences with the 612-kev to 665-kev region in decay of Sm^{153}.

The enhancement of the 67-kev transition and the x-ray is clearly indicated by comparison with the spectrum of coincidences with the 500-kev to 540-kev region.

Figure 9 shows the spectrum of gamma rays in coincidence with the 52-kev to 68-kev range. The 458-kev to 535-kev intensity ratio is considerably enhanced in comparison to the 103-kev coincidence spectrum and to the singles spectrum.

The level structure of Eu^{153} is shown in Fig. 10. The levels at 83 kev, 97 kev, 103 kev, 173 kev, and 191 kev, and the corresponding gamma transitions agree with previous results. The level at 638 kev is based on the 535-kev gamma-ray coincidence with the 103-kev transition; similarly, the 707-kev level is confirmed by the coincidence between the 97-kev and 610-kev transitions. The 352-kev and 422-kev coincidences with the 173-kev transition support the levels at 525 kev and 595 kev, respectively. The proposed 525-kev transition

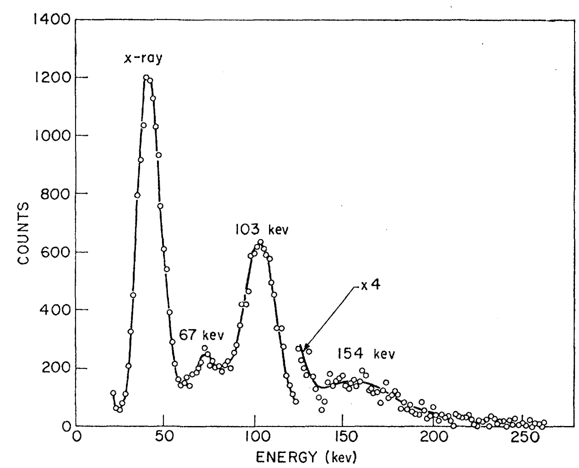

FIG. 8. Spectrum of gamma rays in coincidence with the 445-kev to 475-kev region in decay of Sm^{153}.

to the ground state agrees with the previously discussed conclusion of another transition near the energy of the 535-kev gamma ray.

The spectrum of coincidences with the 173-kev transition shows that the 458-kev gamma ray is not in coincidence with the 173-kev gamma ray, and therefore is not in coincidence with the 70-kev transition. Similarly, the spectrum of coincidences with the 103-kev transition shows that the 458-kev and 103-kev transitions are not in coincidence. The 103-kev gamma ray observed in coincidence with the 445-kev to 475-kev region is from coincidences with the Compton of the 535-kev gamma ray. Since the only gamma rays in coincidence with the 458-kev gamma ray are weak transitions at 67 kev and possibly at 154 kev, the 458-kev transition feeds the ground state. The energy sum of 458 kev and 67 kev agrees with the proposed level at 525 kev. The slight enhancement near 70 kev on the spectrum showing coincidences with the 500-kev to 540-kev region can be

attributed to coincidences with the tail of the 458-kev gamma ray.

The spectrum of coincidences with the 52-kev to 68-kev region support the conclusion that the 458-kev gamma ray is in coincidence with the 67-kev gamma ray. The other peaks on this spectrum are mainly due to coincidences with the 70-kev gamma ray and with the iodine x-ray escape peak of the 103-kev transition.

The position of the 154-kev transition in the decay scheme is supported by the coincidence with the 173-kev transition, 458-kev transition, 525-kev transition, and possibly with the 67-kev transition. It is very unlikely that the 154-kev transition feeds the 638-kev level and the corresponding 535-kev transition, since a level would then exist at 792 kev. Only 803 kev are available between the ground states of Sm^{153} and Eu^{153}. Thus the coincidences between the 154-kev gamma ray and the 500-kev to 540-kev region support the existence of a 525-kev gamma ray. The small number of counts at 525-kev on the spectrum of coincidences with the 173-kev transition (166-kev to 191-kev region) are due to coincidences with the tail of the 154-kev gamma ray.

The weak gamma transitions of 75.4 kev and 89.5 kev from the de-excitation of the 173-kev level and at 14.1 kev, 19.8 kev, and 83.4 kev were observed in conversion electron spectra of Gd^{153} by Graham *et al.*[25] Joshi *et al.*[11] and Marty[7,8] state that the 83-kev level is possibly weakly excited in the decay of Sm^{153}.

The energies of the levels below 173 kev and of the corresponding transitions shown in Fig. 10 are from the internal conversion data on Gd^{153} by Graham *et al.*[25] Similarly, the multipolarities shown were determined by Graham *et al.*[25] from experimental L subshell ratios.

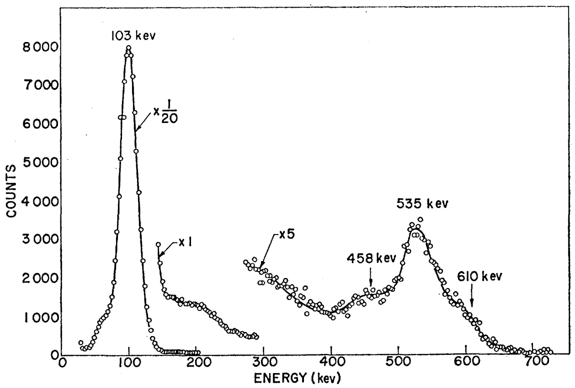

FIG. 9. Spectrum of gamma rays in coincidence with the 52-kev to 68-kev range in decay of Sm^{153}. A 0.122-cm Cd absorber was used in front of the crystal feeding the multichannel analyzer; 0.076 g/cm^2 of Ce was used in front of the crystal feeding the discriminator.

The value of α_K for the 70-kev transition was calculated from the x-ray and 70-kev intensities on the spectra of coincidences with the 103-kev transition. Corrections were made for absorption, crystal efficiency, iodine x-ray escape, and x-ray fluorescence yield. A value of 4.4 ± 0.3 was determined.

Using the α_K value for the 70-kev transition and the singles spectrum, the value of α_K for the 103-kev transition was calculated to be 1.14 ± 0.11. This is a mean for calculations from two spectra at source to crystal distances of 2.54 cm and 10.2 cm. The weak transitions have a negligible effect on these calculations.

The value of α_K for the 103-kev gamma ray was also determined from the x-ray and 103-kev intensities on the spectra of coincidences with the 535-kev transition.

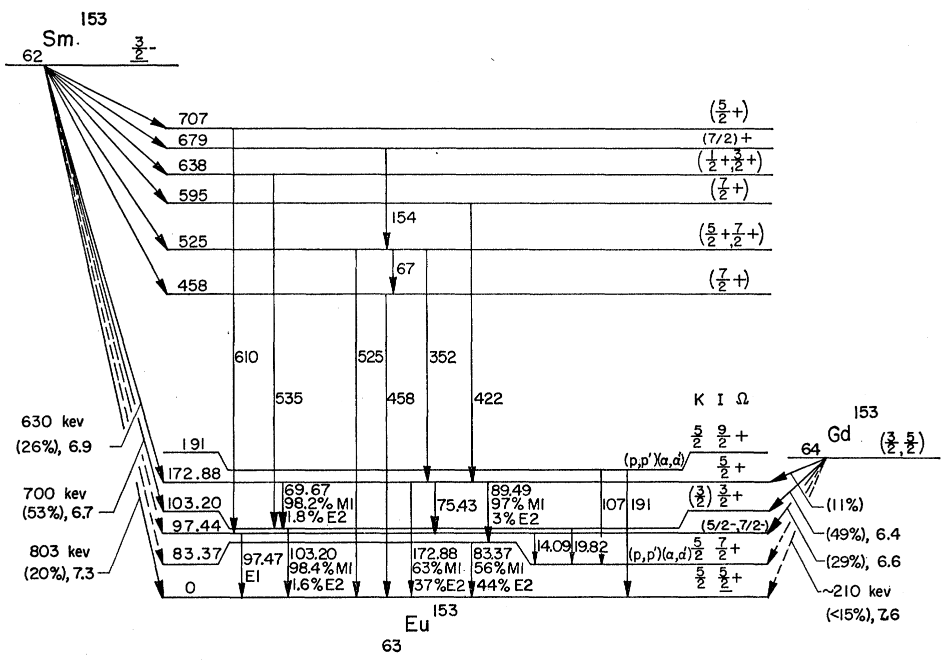

FIG. 10. Sm^{153} and Gd^{153} decay schemes. The energies are in kev. The numbers after the intensities are log *ft* values.

TABLE I. Measured values of α_K for 70-kev, 97-kev, and 103-kev transitions in Eu^{153}.

Author and year	Transitions 70 kev	97 kev	103 kev	Isotope used	Reference
Siegbahn, 1952			0.65	Sm^{153}	3
Graham and Walker, 1954	5.7±1.0			Sm^{153}	4
Lee and Katz, 1954			0.62±0.15	Sm^{153}	5
McGowan, 1954	3.8±0.2		1.14±0.20	Sm^{153}	6
Marty, 1955			1.2 ±0.1	Sm^{153}	8
Dubey *et al.*, 1956	4.4±0.4		1.19±0.15	Sm^{153}	10
Joshi *et al.*, 1957	3.5±1.4		0.69±0.08	Sm^{153}	11
Cohen *et al.*, 1955			1.2	Gd^{153}	17
Bhattacherjee and Raman, 1956			0.67±0.12	Gd^{153}	18
Bisi *et al.*, 1956			0.70±0.03	Gd^{153}	19
Gupta and Jha, 1956			0.61±0.03	Gd^{153}	20
Marty and Vergnes, 1956		0.3 ±0.1		Gd^{153}	21
Joshi and Subba Rao, 1957		0.15±0.04[a]		Gd^{153}	22
McCutchen, 1958		<0.4		Gd^{153}	1
Present measurement	4.4±0.3	$0.36_{-0.07}^{+0.03}$	1.16±0.08	Sm^{153}	

[a] Based on $\alpha_{K-103}=0.69$.

The resulting α_K is 1.18±0.09. The value of α_K for the 103-kev transition determined from the above two methods is 1.16±0.08.

The α_K for the 97-kev gamma ray can be similarly calculated from the spectra of coincidences with the 610-kev transition (612-kev to 665-kev range). In addition to the previously mentioned corrections, the presence of the tail of the 535-kev transition in the 612-kev to 665-kev range was taken into consideration. The calculated value for α_K is $0.36_{-0.07}^{+0.03}$.

The data of various investigators on values of α_K for the 70-kev, 97-kev, and 103-kev transitions are shown in Table I. The α_K measurements listed in the table for the 103-kev transition in the Gd^{153} decay were computed assuming that there is no 97-kev gamma ray. Since both the 97-kev and 103-kev transitions are strong in the Gd^{153} decay, the measurements fall between the actual values of α_K for the 97-kev and 103-kev transitions. No previous direct determination has been made for α_K in the 97-kev transition. However, the present value of $0.36_{-0.07}^{+0.03}$ agrees with the previous calculations made from α_K for the 103-kev gamma ray and from the relative intensities of the 97-kev and 103-kev conversion electrons and gamma rays in the Gd^{153} decay.

Table II gives the theoretical K-shell internal conversion coefficients from the tables of Sliv and Band[31] for the 70-kev, 97-kev, and 103-kev transitions. The experimental $\alpha_K=0.36_{-0.07}^{+0.03}$ for the 97-kev gamma ray shows that this transition is predominantly $E1$. Measurements of the K/L ratio[23,25] and of the L subshell ratios[25] are less conclusive, but are in agreement with this result.

Graham *et al.*[25] have used L-subshell ratios to determine that the 70-kev gamma ray is 98.2% $M1$+1.8% $E2$ and that the 103-kev gamma ray is 98.4% $M1$ +1.6% $E2$. The experimental values of K/L ratios[23,25] and of α_K agree with these assignments.

The total internal conversion coefficients for the 70-kev, 97-kev, and 103-kev transitions were calculated to be 5.1±0.5, $0.41_{-0.08}^{+0.04}$, and 1.38±0.11, respectively. The contributions from the L conversion coefficients were obtained from the data of Sliv and Band.[31]

The relative intensities of the gamma rays from the decay of Sm^{153} are shown in Table III. The intensities of the gamma rays at 70 kev, 103 kev, 173 kev, 422 kev, 458 kev, 525 kev plus 535 kev, and 610 kev were computed from the singles spectra. Corrections were made for crystal efficiency and photofraction, iodine x-ray escape, and absorption. The 352-kev gamma ray intensity was determined from its relative intensity to the 422-kev transition on the spectrum of coincidences with the 173-kev gamma ray.

The 67-kev gamma ray intensity was calculated from the ratio of the 67-kev and 103-kev intensities on the spectrum of coincidences with the 445-kev to 475-kev region. Use was made of the fact that the 535-kev transition feeds the 103-kev level and that about 40% of the total counts in the 445-kev to 475-kev region are due to the Compton of the 535-kev gamma ray. In a similar manner the 154-kev gamma ray intensity was calculated from the spectra of coincidences with the 525-kev transition (500-kev to 540-kev region). A small correction was made to the 154-kev gamma ray intensity to account for the de-excitation of the 525-kev level by the 352-kev and 67-kev transitions, in addition to the 525-kev transition. Because of the branching ratios, much of the 154-kev gamma ray observed on the spectra of coincidences with the 166-kev to 191-kev region can be attributed to coincidences with the Compton of the 525-kev transition.

The intensity limit for the 97-kev gamma ray shown in Table III is from the measurements with a bent-crystal spectrometer by Walters *et al.*[15]

[31] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report, 1956 [translation: Report 57 ICC KL, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].

TABLE II. K-shell internal conversion coefficients.

Gamma-ray energy	Experimental value	Theoretical values[a] $E1$	$E2$	$M1$	$M2$
70 kev	4.4 ± 0.3	0.63	2.8	4.4	51
97 kev	$0.36_{-0.07}^{+0.03}$	0.26	1.2	1.7	15
103 kev	1.16 ± 0.08	0.23	1.1	1.4	12

[a] See reference 31.

Very weak transitions of 14 kev, 19.8 kev, 75 kev, and 89 kev have been observed in the Gd^{153} decay.[25] Since the levels which feed these gamma rays are excited in the decay of both Gd^{153} and Sm^{153}, these weak transitions also occur in the decay of Sm^{153}. The 83.4-kev gamma ray is less than 4% of the 103-kev gamma ray intensity in the Sm^{153} decay.[7,8,11] These gamma rays were not within the limits of observation of the present research, and are therefore not included in the table.

In computing the transition intensity for the 173-kev transition, the theoretical value of α was determined from the tables of Sliv and Band,[31] using a multiple mixture[25] of 63% $M1$+37% $E2$.

The beta transition feeding the ground state has an intensity of 20% and an energy of 803 kev.[4,5,8,10,11,13] The intensities and energies of the remaining beta transitions have been determined from the gamma-ray intensities and energies. The log ft values have been computed using these values.

Directional Correlation Measurements

The directional correlation for the 70 kev—103 kev cascade was measured by accepting pulses in the energy range from 70 kev to 115 kev in both differential analyzers. After correcting for finite resolution, the expansion coefficients from the measurements of the Sm^{153} decay were found to be $A_2=0.005\pm0.007$ and $A_4=-0.007\pm0.011$. The results for the Gd^{153} decay are $A_2=0.006\pm0.010$ and $A_4=-0.007\pm0.016$. Very dilute solutions were used in making both measurements.

The ground-state spin[32,33] of Eu^{153} has been measured to be $\frac{5}{2}$. The deformation parameter of 0.30 results in an assignment[34] to Nilsson orbit 27, which has a spin of $\frac{5}{2}+$. The spin[35] of Sm^{153} has been determined as $\frac{3}{2}$. This is presumably the Nilsson[34] orbit 52, which is the expected ground state for $N=91$ near a deformation of 0.25. Alaga[36] has used selection rules for large nuclear deformations in analyzing the beta transition between the Sm^{153} and Eu^{153} ground states. The log ft value of 7.3 indicates that the transition is hindered first forbidden. This is in agreement with the spin and parity assignments.

[32] J. E. Mack, Revs. Modern Phys. **22**, 64 (1950).
[33] B. Bleaney and W. Low, Proc. Phys. Soc. (London) **A68**, 55 (1955).
[34] B. R. Mottelson and S. G. Nilsson, Phys. Rev. **99**, 1615 (1955).
[35] A. Cabezas, E. Lipworth, R. Marrus, and J. Winocur, Phys. Rev. **118**, 233 (1960).
[36] G. Alaga, Phys. Rev. **100**, 432 (1955).

TABLE III. Relative intensities of the gamma transitions from decay of Sm^{153}. (The intensities have been normalized to the 103-kev transition. The errors on the intensities for the 67-kev, 154-kev, 173-kev, 352-kev, and 422-kev gamma rays are large.)

E_γ (kev)	Gamma-ray intensity	α	Transition intensity
67	0.07		
70	130 ± 20	5.1 ± 0.5	330 ± 50
97	<50		
103	1000	1.38 ± 0.11	1000
154	0.07		
173	1.8	0.35	1.0
352	0.24		
422	0.16		
458	0.5 ± 0.2		
525	1.3 ± 0.5		
535	3.5 ± 0.5		
610	1.1 ± 0.4		

The 83-kev and 191-kev levels observed in Coulomb excitation have been assigned spins[26–28] of $\frac{7}{2}+$ and $9/2+$, respectively, on the basis of the gamma-ray multipolarities and the weakness of the beta transitions feeding these levels from Sm^{153}.

The $M1+E2$ nature[25] of the 103-kev gamma ray indicates that the spin of the 103-kev level is $\frac{3}{2}+$, $\frac{5}{2}+$, or $\frac{7}{2}+$. Since the beta transition feeding the 103-kev level is first forbidden, the spin is further limited to $\frac{3}{2}+$ or $\frac{5}{2}+$.

The $M1+E2$ multipolarity[25] of the 70-kev, 89-kev, and 173-kev gamma rays allows spins of $\frac{5}{2}+$ or $\frac{7}{2}+$ for the 173-kev level. The log ft value of 6.9 for the beta transition feeding the 173-kev level indicates that the spin of this level is $\frac{5}{2}+$.

In interpreting the angular correlation data, the multipolarities[25] of 98.2% $M1$+1.8% $E2$ for the 70-kev gamma ray and 98.4% $M1$+1.6% $E2$ for the 103-kev transition were used. A reasonable error limit of $\pm1\%$ for the quadrupole contents of both gamma rays was used in making the analysis. The A_2 versus Q (quadrupole content) curve for a spin $\frac{3}{2}$ intermediate state and spin $\frac{5}{2}$ ground state has a value of zero at $Q=0.008$. Therefore, the experimental $A_2=0.005\pm0.007$ for the cascade agrees with the spin assignments of $\frac{3}{2}$ and $\frac{5}{2}$ for the 103-kev level and ground state, respectively. In this case, the angular correlation does not limit the spin of the 173-kev level. Therefore the previously concluded value of $\frac{5}{2}+$ for this level is allowed.

One spin sequence which is consistent with previous experimental data, but unlikely, is ($\frac{5}{2}+$, $\frac{5}{2}+$, $\frac{5}{2}+$) for the 173-kev, 103-kev, and ground-state levels. This sequence is ruled out by the angular correlation results.

Therefore, the only sequence allowed by experimental data for the levels at 173 kev, 103 kev, and the ground state is ($\frac{5}{2}+$, $\frac{3}{2}+$, $\frac{5}{2}+$).

Since the 97-kev gamma ray is $E1$, possible spins for the 97-kev level are $\frac{3}{2}-$, $\frac{5}{2}-$, or $\frac{7}{2}-$. The weakness of

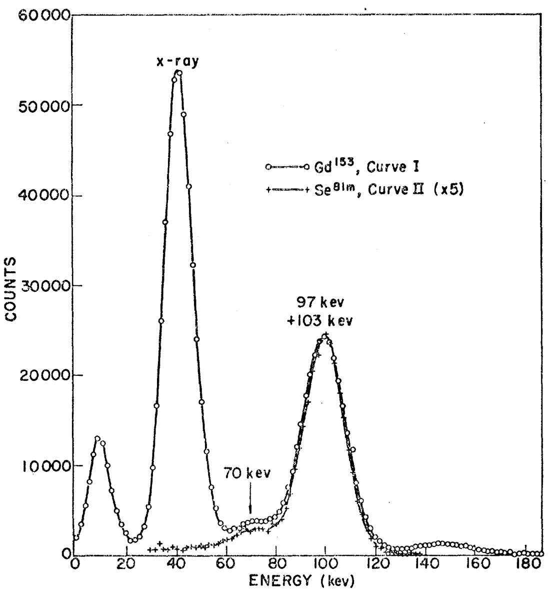

FIG. 11. Curve I is scintillation spectrum of gamma rays in decay of Gd^{153}. The peak at 12 kev is due to the iodine x-ray escape for the Eu x ray. Curve II is the scintillation spectrum of gamma rays from decay of Se^{81m}. The energy axis in curve II is shifted so that the peaks in the region of 100 kev in the Sm^{153} and Gd^{153} spectra correspond. Both spectra were taken at a source to crystal distance of 2.54 cm.

the 97-kev gamma ray from the Sm^{153} decay and the strong intensities of the 97-kev and 103-kev transitions from the Gd^{153} decay indicate that the 97-kev level has spin $\frac{7}{2}-$ or possibly $\frac{5}{2}-$.

The beta transitions feeding the high energy levels have log *ft* values which are first forbidden and first forbidden unique. This information and the relative gamma-ray intensities suggest the spin assignments shown in Fig. 10 for the high-energy states.

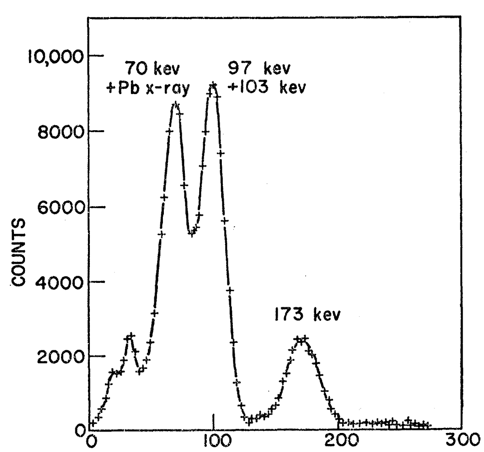

FIG. 12. Scintillation spectrum of gamma rays in decay of Gd^{153}. The spectrum was taken with the Gd^{153} source at 5.7 cm from the crystal and with absorbers of 0.084 cm Pb, 0.013 cm W, and 0.203 cm Cd. A small contribution from Eu^{152} and Tb^{160} impurities was subtracted to obtain the spectrum.

Lee and Katz[5] observed an internal conversion line for the 535-kev transition. A re-interpretation of their data for α_K results in a high order of multipolarity ($M3$, $M4$, $E4$) for the 535-kev transition.[1,8] However, Marty[8] was not able to observe any internal conversion electrons for the 535-kev transition in the presence of the beta rays. The magnitude of the internal conversion coefficient should be rechecked.

IV. RESULTS FOR Gd^{153} DECAY

Gamma-Ray Spectra

Figure 11, Curve I shows the gamma-ray spectrum from the Gd^{153} decay. This spectrum was taken at the same time and with the same geometry and absorbers as the Se^{81m} and Sm^{153} spectra shown in Fig. 3. A comparison of Gd^{153} and Sm^{153} spectra indicates the presence of a strong 97-kev gamma ray in the Gd^{153} decay, in addition to the 103-kev gamma ray and a weak 70-kev gamma ray. The peak at 142 kev in the Gd^{153} spectrum is due to the x ray summing with the gamma rays in the 100-kev region.

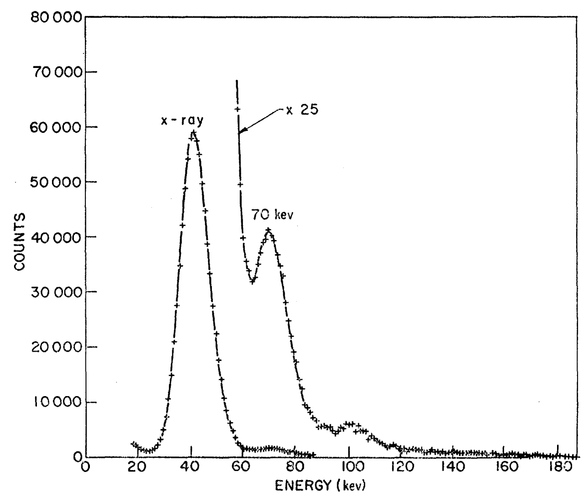

FIG. 13. Spectrum of gamma rays in coincidence with 90-kev to 111-kev region in decay of Gd^{153}.

Curve II of Fig. 11 is the Se^{81m} spectrum with the energy axis shifted so that the peaks in the 100-kev region correspond in the Se^{81m} and Gd^{153} spectra. The very weak Compton distribution from high-energy transitions was subtracted to obtain the Se^{81m} spectrum shown. After making corrections for absorption, crystal efficiency, and iodine x-ray escape, the relative intensity of the 70-kev gamma ray to the 97-kev and 103-kev gamma rays was calculated to be 0.04 ± 0.02 for a source to crystal distance of 2.54 cm. The same result was obtained for a source to crystal distance of 10.2 cm.

Figure 12 shows the gamma ray spectrum taken with a strong source and suitable absorbers. From Fig. 12 and Fig. 2(B) the ratio of the 173-kev gamma ray to

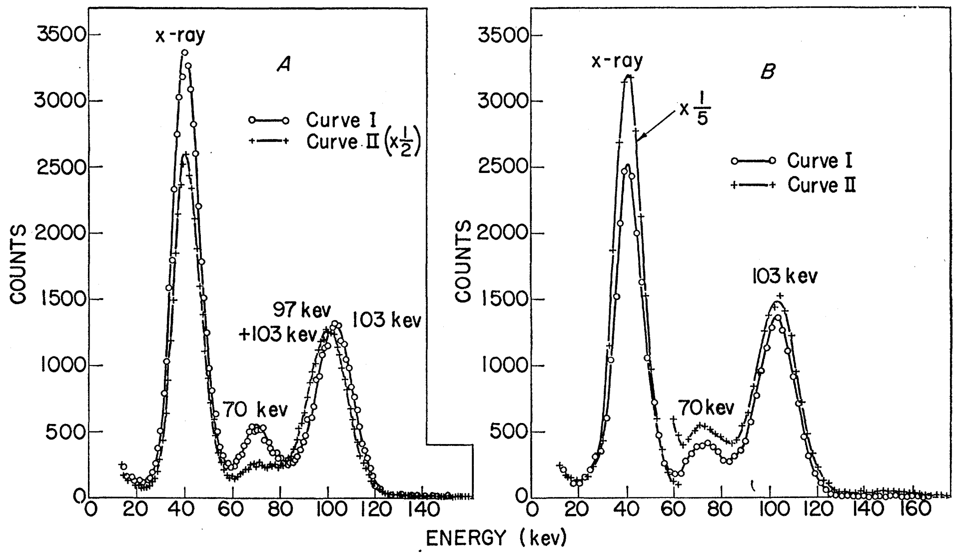

FIG. 14. The spectra of coincidences with the 36-kev to 46-kev region in the decay of Sm^{153} and of Gd^{153} are shown in curves AI and AII, respectively. The spectra of coincidences with the 70-kev to 80-kev region in the decay of Sm^{153} and of Gd^{153} are shown in curves BI and BII, respectively.

the gamma rays in the 100-kev region in the Gd^{153} decay compared to the same ratio in the Sm^{153} decay is 0.37 ± 0.18. This agrees with 0.32 ± 0.18, which is the corresponding ratio for the 70-kev gamma ray and the gamma rays in the 100-kev region.

Coincidence Measurements

The spectrum of gamma rays in coincidence with the 97-kev and 103-kev transitions (90-kev to 111-kev range) is shown in Fig. 13. Peaks are shown at the x ray and at 70 kev. The x-ray coincidence is mainly from the *K*-capture x ray preceding the 97-kev and 103-kev transitions. The small peak at 103 kev is due to coincidences with the tail of the 70-kev transition.

Figure 14(A) illustrates the spectra of gamma rays in coincidence with the x ray (36-kev to 46-kev range) in the decay of Sm^{153} and Gd^{153}. Peaks are shown at the x ray, 70 kev, and 103 kev for the Sm^{153} decay, and at the x ray, 70 kev, 97 kev, and 103 kev for the Gd^{153} decay.

The spectra of gamma rays coincident with the 70-kev transition (70-kev to 80-kev range) in the decay of Sm^{153} and Gd^{153} are shown in Fig. 14(B). Peaks are shown at the x-ray, 70 kev, and 103 kev in both cases. The peaks at 70 kev are due to coincidences with the iodine x-ray escape peak of the 103-kev transition. The large x-ray intensity on the Gd^{153} spectrum is mainly due to *K*-capture x-ray coincidences with the escape peaks of the 97-kev and 103-kev gamma rays.

TABLE IV. Measured values of the intensity ratio of 97-kev gamma ray to the 103-kev gamma ray in the decay of Gd^{153}.

Author	Intensity ratio	Method	Reference
Marty and Vergnes	1.05 ± 0.35	Decomposing scintillation spectrum	21
	$0.9\ \pm0.2$	Intensity ratios in spectra of Sm^{153} and Gd^{153}	21
Joshi and Subba Rao	1 ± 0.1	External conversion spectrum	22
McCutchen	1.74	Xenon counter spectrum	1
Present determination	$0.81_{-0.09}^{+0.17}$	Internal conversion coefficients and electron intensity ratio	

The coincidence measurements on the Gd^{153} decay agree with the previous results[1,25] for the level structure in Eu^{153}, as shown in Fig. 10.

The 97-kev to 103-kev gamma-ray intensity ratio was computed from the *K*-shell internal conversion coefficients and the intensities of the *K*-shell internal conversion electrons of these transitions. Graham *et al.*[25] found the ratio of the *K*-shell electrons for the 97-kev and 103-kev transitions to be 0.253. The ratio of the 97-kev to 103-kev gamma-ray intensities computed in this way is $0.81_{-0.09}^{+0.17}$. A comparison with previously determined ratios is shown in Table IV. In these determinations the 97-kev and 103-kev gamma rays are weakly resolved in both the external conversion[22] and xenon counter[1] spectra. These two spectra[1,22] each had approximately 135 counts at their maxima.

The relative intensities of the gamma rays from the decay of Gd^{153} are shown in Table V. The ratio of the 70-kev gamma ray to 97-kev and 103-kev gamma rays was computed from the singles spectra. The 173-kev intensity was determined from the 70-kev intensity in

TABLE V. Relative intensities of the gamma transitions from decay of Gd^{153}. (The intensities have been normalized to the 103-kev transition. The errors for the 173-kev transition are large.)

E_γ (kev)	Gamma-ray intensity	α	Transition intensity
70	73 ± 37	$5.1\ \pm0.5$	187 ± 83
97	810_{-90}^{+170}	$0.41_{-0.08}^{+0.04}$	482_{-54}^{+83}
103	1000	1.38 ± 0.11	1000
173	1.0	0.35	0.6

Gd^{153} decay and the 173-kev to 70-kev gamma-ray intensity ratio in Sm^{153} decay.

The 14-kev, 19.8-kev, 75.4-kev, and 89.5-kev transitions have intensities which range from about 0.2% to 0.7% of the 103-kev transition intensity, and the intensity of the 83-kev transition is about 1.7% of the 103-kev transition intensity.[25] These gamma rays are not included in the table, since they were not within the limits of observation of the present research.

The decay energy between Gd^{153} and Eu^{153} has been calculated by several investigators from the experimental ratio of L to K capture. The various values obtained for the total disintegration energy range from 186 kev to 225 kev.[18–21] Due to the simplified decay schemes assumed in these determinations and the nature of the calculations, the errors are expected to be large. Using similar techniques, the values calculated for the intensity of the transition to the ground state of Eu^{153} vary from 0% to 25%.[17–20]

The electron capture intensities and log ft values shown in Fig. 10 for the Gd^{153} decay were computed on the basis that the transition to the Eu^{153} ground state has an energy of 210 kev and an intensity of 10%. The gamma-ray energies and intensities were used in these determinations.

V. DISCUSSION

The nuclear deformation[34] changes from 0.16 to 0.30 in going from $_{63}Eu_{88}{}^{151}$ to $_{63}Eu_{90}{}^{153}$. Mottelson and Nilsson[37] attribute this change to the existence of two minima in the curve of nuclear energy as a function of deformation. At neutron number $N=88$ the energy minimum corresponding to the smaller deformation has a value less than the other energy minimum; at $N=90$ the opposite effect takes place. For $N=90$ excited intrinsic states corresponding to the minimum at small deformations may exist. Transitions involving a large change in the nuclear shape would be expected to have a diminished transition probability.

Mottelson and Nilsson[37] suggest that in Eu^{153} the ground state, 103-kev level, and 173-kev level correspond to the larger deformation ($\sim$0.3) and that the 97-kev level has the smaller deformation. The $\frac{3}{2}+$ level at 103 kev may be assigned to Nilsson[34] orbit 33. The state at 97 kev has been assigned a spin of $\frac{7}{2}-$ or $\frac{5}{2}-$ on the basis of experimental data. This state possibly corresponds to Nilsson[34,37] orbit 36 with spin $\frac{5}{2}-$. The weakness of the beta ray feeding the 97-kev in the Sm^{153} decay may be due to the large change in nuclear shape in such a transition.[37]

The 83-kev and 191-kev levels are rotational excitations[38] of the ground state with the expected spin values of $\frac{7}{2}+$ and $9/2+$, respectively.

Several authors[24,37] have suggested that the 173-kev state ($\frac{5}{2}+$) is a rotational level associated with the $\frac{3}{2}+$ 103-kev state in an effort to explain the high intensity of the 70-kev gamma ray relative to the 173-kev gamma ray. However, Graham *et al.*[25] have shown that the experimental reduced transition probabilities do not agree with the theoretical reduced transition probabilities for rotational states based on the proposed K value of $\frac{3}{2}$ for the 103-kev and 173-kev levels.

The ground-state spin of Gd^{153} has not been measured. The log ft values for the Gd^{153} decay feeding the 97-kev and 103-kev levels indicate that Gd^{153} has a spin of $\frac{3}{2}$ or $\frac{5}{2}$. The deformation of Gd^{153} is uncertain, but may be small.[37] Nilsson orbit 57 with a spin of $\frac{3}{2}+$ is a possible assignment.[34,37] In this case the log ft value would indicate a spin of $\frac{5}{2}-$ for the 97-kev state and the transition to this level would be hindered first forbidden, according to the selection rules of Alaga.[36,37] The transitions to the ground state, 103-kev state, and 173-kev state would be hindered allowed.[37] Retardation effects may also exist due to changes in the nuclear deformation.

[37] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Skrifter **1**, No. 8 (1959).

[38] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. **28**, 432 (1956).