The average value obtained for the total energy release, 4.51±0.03 MeV, is consistent with the systematics of disintegration energies in this mass region[10] and is in good agreement with the previously measured value of approximately 4.4 MeV.[3] No estimate of the accuracy of the previous measurement is given by the authors, but an arbitrary error of 0.3 MeV was assigned by the Nuclear Data Group.[10]

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Properties of Gamma Transitions in the Decays of Sm^{153} and Gd^{153} into Eu^{153}†

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The energies and relative intensities of gamma rays produced in the electron-capture decay $Gd^{153} \rightarrow Eu^{153}$ and of the low-energy gamma rays produced in the beta decay $Sm^{153} \rightarrow Eu^{153}$ have been studied with the bent-crystal spectrometer. Two previously unreported gamma rays have been observed at 54.19 and 68.23 keV. These together with a previously reported 151.5-keV gamma transition depopulate a new state at 151.61 keV which we propose as the $\frac{7}{2}^-$, $K=\frac{5}{2}$ level of Eu^{153}. The $M1$ gamma-ray interband branching ratio from the known 173-keV $\frac{5}{2}^+$, $K=\frac{3}{2}$ level and the $E1$ gamma branching ratio from the 151.61-keV level are examined for evidence of band mixing.

INTRODUCTION

THE decays of Sm^{153} and Gd^{153} into Eu^{153} are known to involve three clearly identified intrinsic configurations. These are the $K=\frac{5}{2}^+$ [413] ground-state band, the $\frac{5}{2}^-$ [532] intrinsic level at 97 keV and the $K=\frac{3}{2}^+$ [411] band at 103 keV. A number of conversion-electron lines attributed to decays from a series of unclassified levels in the region 630 to 710 keV have been previously reported.[1,2] In Fig. 1 we present a scheme for the decays of Sm^{153} and Gd^{153} into Eu^{153}. This scheme incorporates the results of some earlier works as well as the new information obtained from the present investigation.

Properties of the excited states of Eu^{153} are of particular interest because of the location of this nucleus at the border of the region of strongly deformed nuclei. Mottelson and Nilsson have been rather successful in interpreting the properties of this decay in terms of the collective model.[3] The apparent change of eccentricity between the [413] and [411] bands on the one hand and the [532] band on the other renders interesting information concerning transitions between these bands.

Various groups have studied the Sm^{153} and Gd^{153} decays examining both internal-conversion and gamma-ray spectra.[1,2,4–8] Recently, Suter *et al.*[2] have made an extensive investigation of the Sm^{153} decay using internal-conversion measurements to obtain transition energies and external-conversion data for gamma-ray intensity values. At present there exists no comprehensive direct measurement of the Eu^{153} relative gamma-ray intensities while there is some contradiction in the intensity data for those gamma rays which have been studied.[4,5,8] A number of weak but unassigned conversion electron lines in the decay from Sm^{153} have been reported.[2]

We have made an accurate determination of the relative gamma-ray intensities in the Sm^{153} and Eu^{153} decays. In addition, we have established a previously unobserved rotational level at 151.61 keV. This level is depopulated by a previously reported[2] 151.5-keV gamma ray and two previously unreported gamma rays at 54.19 and 68.23 keV. A search of the low-energy gamma-ray spectrum failed to reveal any additional gamma rays which might be associated with the several weak but unassigned electron-conversion lines reported in Ref. 2.

SOURCES

Our sources were prepared by encapsulating Sm^{152} (enriched to 99.06%) and Gd^{152} (enriched to 95%) separately in quartz capillaries. These capillaries had

† Work performed jointly under the auspices of the U. S. Atomic Energy Commission and the National Science Foundation.
[1] V. S. Dubey, C. E. Mandeville, and M. A. Rothman, Phys. Rev. **103**, 1430 (1956).
[2] T. Suter, P. Reyes-Suter, S. Gustafsson, and I. Marklund, Nucl. Phys. **29**, 33 (1962).
[3] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Skrifter **1**, No. 8 (1959).
[4] C. W. McCutchen, Nucl. Phys. **5**, 187 (1958).
[5] R. E. Sund and M. L. Wiedenbeck, Phys. Rev. **120**, 1792 (1960).
[6] R. L. Graham, G. T. Ewan, and J. S. Geiger, Bull. Am. Phys. Soc. **5**, 21 (1960).
[7] E. Monnand and A. Moussa, Nucl. Phys. **25**, 292 (1961).
[8] L. Block, W. Goedbloed, E. Mastenbroek, and J. Block, Physica **28**, 993 (1962).

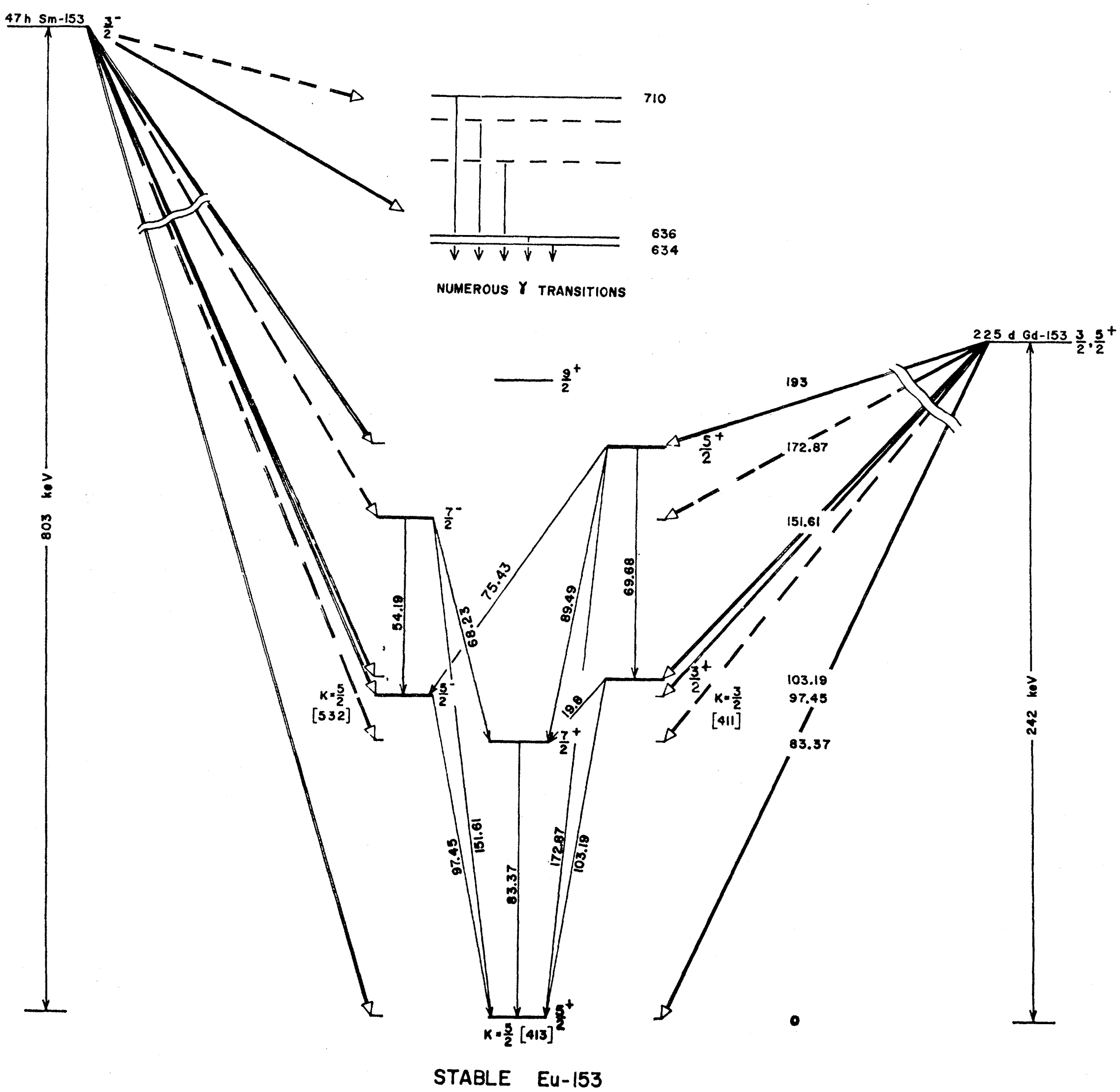

FIG. 1. Decay scheme of Eu^{153}. The 54.19- and 68.23-keV gamma rays have not been previously reported. The proposed level at 151.61 keV is tentatively assigned as a $\frac{7}{2}^-$, $K=\frac{5}{2}$ state. Because of their low intensity we were unable to observe the gamma transitions from the states reported above 600 keV (Refs. 1, 2) with the bent-crystal spectrometer. Neither could we observe the 19.8-keV transition reported by Monnand *et al.* (Ref. 7) because this energy is below the minimum value observable with our spectrometer. The 193-keV $\frac{9}{2}^+$, $K=\frac{5}{2}$ level has been excited by Coulomb excitation (Ref. 12).

an inner diameter of 0.2 mm, an outer diameter of 0.62 mm, and a length of 2.0 cm. The encapsulated isotopes were then irradiated for 3 weeks with a neutron flux of 3×10^{14} in the MTR reactor at Arco, Idaho.

Sm^{153} RESULTS

A 10 Ci Sm^{153} source was formed by single neutron capture on Sm^{152}. The gamma rays from this source with energies >25 keV but <300 keV, were examined on the California Institute of Technology 2-m-radius bent-crystal gamma spectrometer. Energy and relative intensity measurements were made on all lines observed to decay with the 47-h half-life of Sm^{153}. The procedure for making these measurements has been described previously.[9] In addition to gamma rays from the above decay we also observed the longer lived lines associated with the stronger gamma transitions in Gd^{155} and Gd^{156}. Such decays most probably originate through multiple neutron capture on Sm^{154} which is present to 0.48% in our separated isotope.

In Table I we present our gamma-ray energy and relative-intensity results. For comparison we also give the relative-intensity results of Suter *et al.*[2] obtained by photoconversion. Our intensity results do not agree too well with those reported by Suter *et al.* for the 83-, 89-,

[9] P. Alexander and F. Boehm, Nucl. Phys. 46, 108 (1963).

TABLE I. Energies and relative intensities of gamma rays in the decay of Sm^{153}.

Gamma energy (keV)	Relative intensity This measurement	Suter *et al.* (Ref. 2)
54.19±0.02	0.0058±0.0012	...
68.23±0.02	0.0043±0.0013	...
69.68±0.01	17.3 ±1.0	19.2 ±1.2
75.43±0.01	0.61 ±0.04	0.65±0.08
83.37±0.02	0.75 ±0.04	0.58±0.08
89.49±0.02	0.58 ±0.03	0.43±0.06
97.45±0.02	2.63 ±0.13	2.07±0.10
103.19±0.02	100[a]	100 ±3[a]
151.61±0.04	0.032 ±0.005	0.08±0.02
172.87±0.04	0.21 ±0.02	0.33±0.04

[a] Normalized to 100.

97-, 151-, and 172-keV gamma lines. The disagreement is especially large for the 151- and 172-keV lines. On the other hand, our energy values are in remarkably good agreement with those obtained by Suter *et al.* (not shown in Table I) except in the case of the 75.43-keV line for which they find 75.34±0.04 keV. There is also excellent agreement between our energy values and those which have been measured by Graham *et al.*[6]

We observe gamma rays at 54.19 and 68.23 keV which have not been previously reported. From energy-combination principles we assign these transitions together with the 151.61-keV transition first reported by Suter *et al.*[2] to a new rotational level at 151.61 keV. This level could be the $\frac{7}{2}^-$ $K=\frac{7}{2}$ [523] state but is most probably the $\frac{7}{2}^-$ $K=\frac{5}{2}$ level and is so shown in the decay scheme of Fig. 1.

In Table II we compare the values of the moment of inertia parameters for the 3 rotational bands in Eu^{153}. The Eu^{153} $K=\frac{5}{2}^+$ [413] moment of inertia parameter value is 11.91 keV. This may be compared with the value 11.6 keV for the same band in Tb^{159}.[10] The moment of inertia parameter for the $K=\frac{3}{2}^+$ [411] band has a value of 13.9 keV in Eu^{153}, 13.0 keV in Tb^{155}, and 12.2 keV in Tb^{157}.[11] It is not possible to make a similar comparison for the $K=\frac{5}{2}^-$ [532] band in Eu^{153}. Although the [532] intrinsic level appears in Tb^{157} and Tb^{159},[10,11] no rotational excitations on this level have been observed.

From our gamma-ray-intensity data we are able to calculate the beta-decay branching ratios to the low-energy levels in Eu^{153} exclusive of the ground state. It can be seen from Table III that these results are in

TABLE II. Moment of inertia parameters for the 3 rotational bands in Eu^{153}.

	$K=\frac{5}{2}^+$	$K=\frac{5}{2}^-$	$K=\frac{3}{2}^+$
$\hbar^2/2I$	11.91 keV	7.74 keV	13.94 keV

[10] R. M. Diamond, B. Elbek, and F. S. Stevens, Lawrence Radiation Laboratory Report UCRL-10557, 1962 (unpublished).
[11] K. S. Toth and O. B. Nielsen, Nucl. Phys. **22**, 57 (1961).

TABLE III. Beta-decay branching to levels in Eu^{153}.

Level energy (keV)	Beta-decay branching ratio This measurement	Suter *et al.* (Ref. 2)	McCutchen (Ref. 4)	Dubey *et al.* (Ref. 1)
0	...	20	22	22
83	<0.4[b]	<0.3	weak	
97	<1.0[b]	0.8	(5)	
103	46[a]	46	40	38
151	<0.003[b]			
173	31	33	40	40
>600	...	0.14	23	0.06

[a] Normalized to 46.
[b] Because of feeding from unobserved low-energy gamma transitions, only an upper limit can be given.

rather good agreement with those of other authors. According to the data of Suter *et al.*[2] and Dubey *et al.*[1], the intensities of gamma-ray transitions into the three rotational bands of interest from states above 172 keV are so low as not to affect our branching calculation.

A general search of the gamma-ray spectrum was performed from 25 to 300 keV. In regions of special interest the energy spectrum was examined with an accuracy greatly exceeding that possible during the general search. The results of these searches are presented in Table IV. In particular we were not able to observe any evidence of transitions from the 193 keV $\frac{9}{2}^+$ $K=\frac{5}{2}$ level in Eu^{153} which has been observed by Coulomb excitation.[12]

Gd^{153} RESULTS

A 0.6 Ci Gd^{153} source was produced by neutron capture on Gd^{152}. Gd^{153} decays by electron capture into Eu^{153} with a half-life of 225 days. The relative intensities of those gamma lines observed in the decay of Sm^{153} were measured with the Gd source. The results of these intensity measurements are given in Table V together

TABLE IV. Maximum relative intensities of some unobserved gamma rays in the decay of Sm^{153}.

Region searched (keV)	Max. possible gamma intensity[a]
25–100	0.04[b]
100–200	0.15[b]
200–300	0.50[b]
38.3–39.5	0.005[c]
78.6–80.2	0.003[c]
104.0–106.0	0.03[c]
106.0–110.0	0.01[c,d]
171.0–171.4	0.02[c]
189.0–200.0	0.03[e]

[a] Using the same intensity normalization as in Table I.
[b] General search.
[c] Transitions proposed by Suter *et al.* (Ref. 2).
[d] 9/2+, $K=5/2 \rightarrow 7/2^+$, $K=5/2$ transition from 193-keV state (see Ref. e).
[e] $9/2^+$, $K=5/2 \rightarrow 5/2^+$, $K=5/2$ transition seen by Coulomb excitation of state at 193 keV (Ref. 12).

[12] E. M. Bernstein and R. Graetzer, Phys. Rev. **119**, 1321 (1960); C. M. Class and U. Meyer-Berkhout, Nucl. Phys. **3**, 656 (1957); M. Martin, P. Marmier, and J. de Boer, Helv. Phys. Acta **31**, 435 (1958).

TABLE V. Relative intensities of gamma rays in the decay of Gd^{153}.

Gamma energy (keV)	Relative intensity This measurement	Blok *et al.* (Ref. 8)
54.19	<0.1[b]	
68.23	∼0.04	
69.68	8.1 ±0.6	10
75.43	0.26±0.08	
83.37	0.70±0.07	1.4
89.49	0.23±0.07	
97.45	100[a]	100[a]
103.19	72.9 ±3	72
151.61	<0.6[b]	
172.87	<0.6[b]	

[a] Normalized to 100.
[b] The gamma line was too weak to be observed but an upper intensity limit is given.

with the data of Block *et al.*[8] From the relative intensity values of Table V and the gamma-ray branching ratios taken from Table I we have calculated the electron-capture branching ratios to the excited states in Eu^{153}. These are given together with the results of other authors in Table VI.

DISCUSSION

Employing the gamma-ray-intensity data from Tables I and V we have derived the reduced experimental branching ratios into the $\frac{7}{2}+$ 83 keV and $\frac{5}{2}+$ ground-state levels of the $K=\frac{5}{2}$ [413] band from the $\frac{5}{2}+$ $K=\frac{3}{2}$ [411] level at 173 keV and from the $\frac{7}{2}-$ $K=\frac{5}{2}$ [532] level at 152 keV. The values of these ratios are presented in Table VII. These ratios may be interpreted in terms of mixing between the various rotational bands. As a means of comparison the ratios of geometrical coefficients predicted for unhindered transitions between

TABLE VI. Electron capture branching to levels in Eu^{153}.

Level energy (keV)	Electron capture branching ratio This measurement	Blok *et al.* (Ref. 8)	Sund *et al.* (Ref. 5)	McCutchen (Ref. 4)
0	···	9	<15	25
83	≤0.7[b]	2	···	···
97	43[c]	40	29	42
103	49	32	49	44
151	≤0.4[d]			
173	17[a]	17	11	13

[a] Normalized to 17.
[b] Only an upper limit can be given due to the feeding from an unobserved 14-keV ($E1$) gamma transition. The total intensity of the 19.82-keV ($E2$) transition is computed from the data of Monnand *et al.* (Ref. 7).
[c] The feeding from the unobserved 6-keV ($E1$) gamma transition is neglected.
[d] Only an upper limit can be given due to the feeding of an unobserved 21-keV ($E1$) gamma transition.

the same initial and final states are also given in Table VII. Only a lower limit is given for the $M1$ experimental branching ratio as the mixing is[6] $\sim 60\% M1 + \sim 40\% E2$ for the 173-keV transition and $>85\% M1 + <15\% E2$ for the 89-keV transition.

The reduced experimental and simple geometric branching results are seen to disagree by an order of magnitude for the $M1$ transitions while there is no discrepancy in the case of the $E1$ branching ratios. A possible interpretation of these results may be given as follows. Because of their proximity the $K=\frac{5}{2}+$ [413] and $K=\frac{3}{2}+$ [411] bands may be expected to admix. It is possible that the $\frac{7}{2}+$ $K=\frac{5}{2}-\frac{7}{2}+$ $K=\frac{3}{2}+$ admixture[13] is stronger than the $\frac{5}{2}+$ $K=\frac{5}{2}-\frac{5}{2}+$ $K=\frac{3}{2}$ admixture. In this case one might expect an enhancement of the 89-keV transition probability over that of the 173-keV transition. Since the $M1$ transitions are asymptotically hindered ($\Delta\Lambda=2$) the effects of the mixing of the [411] and [413] bands and thus the 89-keV gamma-intensity

TABLE VII. Comparison of reduced experimental and theoretical gamma branching ratios in Eu^{153} from state K_i, I_i to states K_f, I_f and K_f, I_f'.

K_i	I_i	K_f	I_f	I_f'		Branching ratio Experimental	Theoretical[c]
$\frac{3}{2}$	$\frac{5}{2}+$	$\frac{5}{2}$	$\frac{7}{2}+$	$\frac{5}{2}+$	($M1$)	>28.3[a]	2.5
$\frac{5}{2}$	$\frac{7}{2}-$	$\frac{5}{2}$	$\frac{7}{2}+$	$\frac{5}{2}+$	($E1$)	1.5±0.6[b]	1.9

[a] Using the mixing ratio of Graham *et al.* (Ref. 6).
[b] Assumed to be pure $E1$.
[c] Ratio of geometrical coefficients for unhindered transition between levels with the specified I_i, I_f, and I_f'.

enhancement will appear more pronounced than if the transitions were unhindered. Although the $E1$ transitions from the [532] band into the [413] band are also hindered ($\Delta n_z=2$) one would not expect the $E1$ branching ratio to deviate radically from the ratio of the geometrical coefficients given in Table VII. This is due to the lack of admixture between the initial and final bands. It is possible that the $\frac{7}{2}-$ $K=\frac{5}{2}$ level admixes with the $K=\frac{7}{2}-$ [523] intrinsic level predicted[2] to lie at a somewhat higher energy. This possible admixture should have negligible effect on the 68-, 152-keV branching ratio.

ACKNOWLEDGMENTS

The author is indebted to R. Hager and E. Seltzer for their assistance in the measurements and to Professor F. Boehm and Dr. S. Wahlborn for several enlightening discussions.

[13] The $\frac{7}{2}+K=\frac{3}{2}$ level has not been observed experimentally.