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Decay of the Isomer Eu^{152m_2} (96 min)*

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The structure of Eu^{152} is of great interest, since this nucleus is unique in being flanked by two even-even isobars which differ radically from each other in shape: Sm^{152} is strongly deformed while Gd^{152} is spherical. Only two states had previously been known in Eu^{152}: the 13-year ground state (3−) and the 9.3-h isomeric state (0−). A detailed investigation of the decay of a new 96-min isomer, Eu^{152m_2}, has been carried out. This isomer was first reported by Kirkby and Kavanagh, who found two transitions. We have detected a third transition of 18.25 keV (99.9% $M1$+0.1% $E2$). The precise energies, and the spins and parities of three excited states of Eu^{152} were obtained: 89.83 keV (4+), 108.1 keV (5+), and 147.9 keV (8−) (96 min). The half-life of the 4+ state was found to be 4×10^{-7} sec, that of the 5+ state $\lesssim10^{-8}$ sec. A renewed search for an isomeric transition accompanying the decay of the 9.3-h isomer Eu^{152m_1} (0−) was carried out, especially at lower electron energies (7–25 keV) than had hitherto been scanned. This search furnished an upper limit of 0.001% for a transition in the energy range $15\leq E_{\mathrm{IT}}\leq68$ keV, and of ~0.003% for $8\lesssim E_{\mathrm{IT}}\lesssim15$ keV. The cross section for production of the 96-min isomer by pile neutrons is found to be 1/(820±150) of the production cross section of the 9.3-h isomer. Configurations of Nilsson orbitals are proposed for the ground state of Eu^{152} and for three excited states involved in the decay of Eu^{152m_2}, as well as for Eu^{152m_1}(0−). These are consistent with the observed hindrance factors for the electromagnetic transitions.

I. INTRODUCTION

THE level structure of odd-odd nuclei is less well known than those of odd-A and even-even nuclei, because of their greater complexity. Nonetheless, recently several interesting investigations of deformed odd-odd nuclei in the rare-earth region have been carried out. The interpretation of their level schemes[1] was guided by the rapidly accumulating knowledge concerning the parameters of intrinsic states of neighboring odd-A nuclei in terms of Nilsson orbitals,[2] and by the proton-neutron coupling rules for deformed nuclei suggested by Gallagher and Moszkowski.[3] Eu^{152} is one of the most interesting odd-odd nuclei because of the position it occupies in the abrupt transition region between the spherical and the deformed level pattern exemplified by its two isobars Gd^{152} and Sm^{152}, respectively. As will be shown later, it seems possible to interpret the levels of Eu^{152} reported in this article in terms of couplings of Nilsson orbitals. It is hoped that this information may provide a basis for the analysis of the extremely complex data obtained from capture gamma-ray experiments,[4,5] thereby yielding a more complete understanding of the static and dynamic properties of this unique nucleus.

The decay schemes of the 9.3-h isomer and the 13-year ground state of Eu^{152} have been investigated by very many authors.[6] The energy difference between the isomer and the 13-year ground state is estimated to be 50±15 keV, but no isomeric transition ($\lesssim$0.002%) has been found so far.[7] The spin and parity of the 9.3-h isomeric level is of particular importance in connection with the neutrino helicity experiment of Goldhaber,

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[1] C. J. Gallagher, Jr., and V. G. Soloviev, Kgl. Danske Videnskab. Selskab, Mat. Fys. Skrifter **2**, No. 2 (1962).

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

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

[4] O. Schult, Z. Physik **158**, 444 (1960).

[5] O. Schult, Z. Naturforsch. **16a**, 927 (1961); see also J. E. Draper and A. A. Fleischer, Nucl. Phys. **13**, 53 (1959); E. T. Patronis, Jr., and H. Marshak, Phys. Rev. **115**, 1287 (1959).

[6] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Offices, National Academy of Sciences—National Research Council, Washington 25, D.C.), NRC5-6-30 ff.

[7] L. Grodzins and A. W. Sunyar, Phys. Rev. Letters **2**, 307 (1959); see also L. Grodzins, M.I.T. LNS Progress Report, p. 114 1959 (unpublished).

Grodzins, and Sunyar.[8] Although the previous assumption (implied in that experiment) that the 9.3-h isomer is 0− was recently confirmed by the determination of the energy dependence of the β-γ directional correlation,[9] it seemed worthwhile to try again to search for the conversion electron lines of the missing transition in order to determine its multipole order, since the transition energy may be lower than had been assumed. Three techniques for the detection of low-energy electrons have recently been combined in our laboratory: (1) acceleration of electrons before magnetic momentum selection in a Gerholm electron-electron (or electron-gamma) coincidence spectrometer,[10] (2) the installation of a thin counter window in a double-focusing spectrometer permitting the detection of at least 70% of the electrons down to 5 keV, and (3) preparation of very thin sources by evaporation with the help of an electron gun.

While searching for the 9.3-h isomeric transition, for which sources were produced in the Brookhaven Graphite Reactor by neutron capture in natural europium, we observed a new $\sim$11-keV conversion-electron line decaying with a half-life of about 1.5 h. A gamma ray of $\sim$90 keV was also observed with a similar half-life and was found to be in coincidence with the 11-keV conversion-electron line. While these investigations were in progress, an independent observation of a 96$\pm$5-min activity in Eu^{152} was reported by Kirkby and Kavanagh.[11] This activity was produced by two reactions differing from ours, namely, by bombardment of natural europium and of Sm^{154} with 30-MeV protons. Kirkby and Kavanagh observed a conversion-electron line of $\sim$33 keV, identified as the L,M, and N conversion-electron lines of a 38-keV transition, and also a 92-keV gamma ray in cascade with it. Measurement of the K-conversion coefficient of the latter permitted an $E1$ assignment to the 92-keV transition, which was assumed to lead to the ground state. From half-life considerations the authors concluded that the 38-keV transition is $E3$ or $M3$. Hence spin-parity assignments 4+ and 7(−) were made for the proposed 92- and 130-keV levels, respectively.

In the following a re-examination of the decay scheme of the new isomer will be described and an interpretation of the level scheme of Eu^{152} will be attempted.

II. SOURCE PREPARATION

Natural europium oxide was evaporated in an electron-beam evaporator onto a 2-mg/cm^2 Al foil. The evaporated film was estimated by neutron activation to have an approximate thickness of 3–10 μg/cm^2. This estimate was checked by evaluation of the spectral shape of the L-Auger electron lines in a Gerholm spectrometer with 15-kV preacceleration. For the purpose of identification of the new 96-min isomer, several different europium samples and also a sample enriched in Eu^{153} were used.[12]

In order to carry out coincidence experiments between low-energy conversion electron lines, europium oxide was evaporated on a backing of self-supporting carbon film. The approximate thickness of the europium layer was found to be about 5 μg/cm^2 and that of the carbon backing was estimated to be less than 100 μg/cm^2.

The 96-min isomer was produced by irradiating the europium oxide film in the Brookhaven Graphite Reactor for about 30 min. Bombardment within cadmium wrapping was also tried, but discontinued when it was found that the Cd ratios for the 96-min and 9.3-h isomers were approximately equal. For the purpose of identification we shall name the 9.3-h isomer Eu^{152m_1} and the new 96-min isomer Eu^{152m_2}.

III. APPARATUS

A. Electron-Electron (and Electron-Gamma) Coincidence Studies with Preaccelerated Electrons

A Gerholm electron-electron (or electron-gamma) coincidence spectrometer was used for measuring the conversion electron lines, both in singles and in coincidence. In order to observe low-energy electrons, a 15-kV negative potential was applied to a Eu^{152m_2} source.[10] Anthracene crystals were used as electron detectors for both lenses. For $\sim$5-keV electrons emitted from a source with 2 mm diameter, the resolution of the spectrometer is $\sim$2.5% of the momentum of the accelerated electrons. The transmission is $\sim$3% for all energies down to $\sim$2 keV. For electron-gamma coincidence studies, one of the magnetic lenses was replaced by a scintillation spectrometer equipped with a cylindrical NaI(Tl) crystal, $1\frac{1}{2}$ in. in diameter and $1\frac{1}{2}$ in. thick. The coincidence circuit used was of the fast-slow coincidence type with a delay continuously variable over a range of 0.7 μsec. The resolving time of the fast coincidence unit permitted the measurement of half-lives $\gtrsim 2\times10^{-8}$ sec.

B. Double-Focusing Spectrometer

In addition to the Gerholm spectrometer described above, a $\sqrt{2}\pi$ iron-core double-focusing β spectrometer[13] was used for measuring internal conversion electron spectra, when higher resolution was desirable. This spectrometer was equipped with a proportional counter with a gold coated Formvar window approximately 100

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[8] M. Goldhaber, L. Grodzins, and A. W. Sunyar, Phys. Rev. **109**, 1015 (1958).

[9] S. K. Bhattacherjee, S. K. Mitra, and C. V. K. Baba, Phys. Letters **6**, 286 (1963).

[10] K. Takahashi, M. McKeown, and G. Scharff-Goldhaber, Phys. Rev. **136**, B18 (1964).

[11] P. Kirkby and T. M. Kavanagh, Nucl. Phys. **49**, 300 (1963).

[12] At the time of these measurements no highly enriched Eu^{151} was at our disposal.

[13] G. T. Emery, W. R. Kane, M. McKeown, M. L. Perlman, and G. Scharff-Goldhaber, Phys. Rev. **129**, 2597 (1963).

$\mu g/cm^2$ thick with a transmission of ~70% for 10-keV electrons. For the detection of very low-energy electrons this window was replaced by one ~30 $\mu g/cm^2$ thick, with a transmission of ~70% for 5-keV electrons. The rectangular sources used in this spectrometer were about 3 mm wide and 15 mm long. Depending on source thickness, the momentum resolution of the $\sqrt{2}\pi$ spectrometer with such a source is 0.20–0.30% at 32 keV and $\gtrsim 0.35\%$ at 10.3 keV. For the purpose of precise energy calibration of conversion-electron lines, the well-measured Sm^{152} K-conversion electron line of the 121.784±0.007 keV[4,14] transition from 9.3-h Eu^{152m_1} was used as an internal calibration line. This line also served to normalize the intensities of the different runs.

IV. OBSERVATION OF Eu^{152m_2} (96 min)

Figure 1 shows the low-energy electron spectrum above 3 keV from a pile-neutron-irradiated natural europium sample taken with the Gerholm spectrometer at 15-kV preacceleration. The peak at 10.5±0.5 keV which is assigned as the L conversion line of an 18.3-keV transition was found to decay with a half-life of ~1.5 h. A similar initial slope was observed for the decay of the K-LL and K-LM Auger electron peaks, which predominantly decay with a 9.3-h half-life. The yield ratio of the new 1.5-h activity produced in a natural Eu sample and a sample of the same weight enriched in Eu^{153} containing only 5% Eu^{151} was approximately the same as that of the Eu^{151} contents in the two samples.[12] The time-corrected intensity ratios of the 1.5-h, 10.5-keV peak to the well-known 122-keV K-conversion peak for these two runs were found to be equal.

From the same source a weak γ ray of ~90 keV and ~1.5-h half-life was detected in a scintillation spectrometer [Fig. 2(A)].

The 1.5-h decay component of the "K-Auger peaks" led us to suppose the existence of a third transition whose L and M conversion electron lines coincide in energy with the K-LL and K-LM Auger peaks. (Of course, at this point we could not rule out the possibility that the third transition is of sufficiently high energy to be converted in the K shell, giving rise to a 1.5-h K-Auger component. However, it will be shown in Sec. VI that the first assumption is the correct one.)

Our assignment of the 1.5-h activity to a new isomer in Eu^{152} was further supported by the fact that the gamma-ray spectrum following neutron capture in

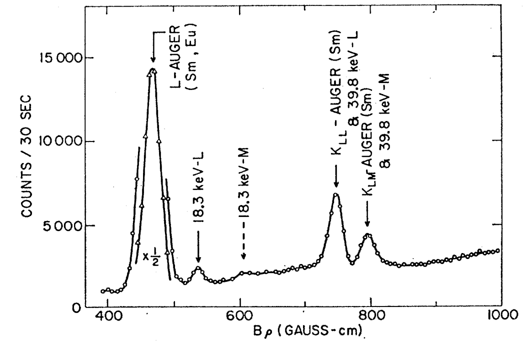

FIG. 1. Low-energy electron spectrum of neutron-irradiated europium source ($Eu^{152m_1+m_2}$). The measurement carried out with the Gerholm spectrometer using 15-kV preacceleration was started about 30 min after the end of a 30-min irradiation.

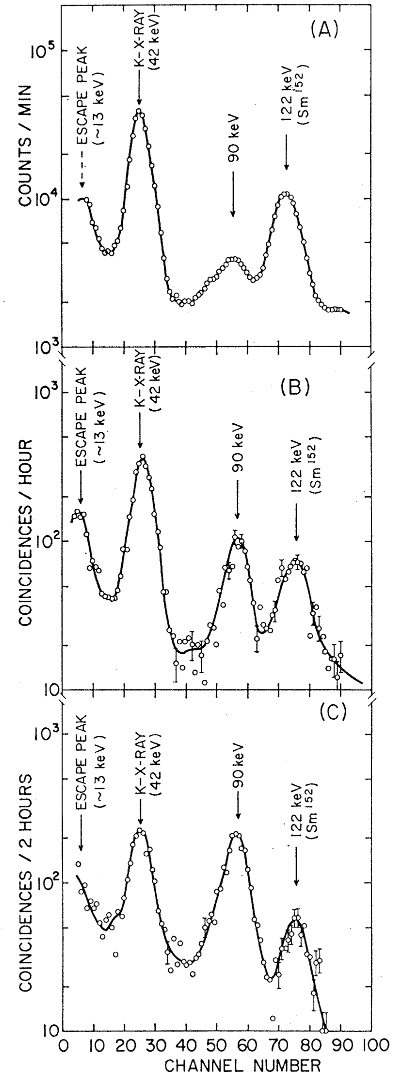

FIG. 2. Gamma-ray spectra from 96-min and 9.3-h Eu^{152} isomers produced by the (n,γ) reaction in Eu^{151} by 30-min neutron irradiation. (A) Singles spectrum taken 30 min after the termination of the irradiation. (B) Photon spectrum in prompt coincidence with L-conversion line of 18.3-keV transition. (Only a small fraction of the K x rays stems from the conversion of the 90-keV γ rays emitted from Eu^{152m_2}. The remainder of the K x rays is partly due to chance coincidences and partly to coincidences with beta rays from the decay of Eu^{152m_1}.) (C) Delayed coincidence photon spectrum triggered by L electrons of 18.3-keV transitions. A delay of 200 nsec was applied to the triggering electron pulses. (Here, again, part of the K x rays and the 122-keV photopeak are due to chance coincidences.) (B) and (C) were taken with the Gerholm gamma-electron coincidence spectrometer with 15-kV preacceleration of the electrons.

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[14] I. Marklund and B. Lindström, Nucl. Phys. 49, 329 (1963).

Eu^{151} contains a strong 90-keV line.[5,15] The recent report on the (96±5) min isomer in Eu^{152} by Kirkby and Kavanagh[11] showed the existence of the isomer and two of its transitions. However, the existence of the 18.3-keV transition discovered by us showed that the decay of the isomer is more complex than these authors had assumed.

V. ELECTRON-GAMMA COINCIDENCES

In order to establish whether there is a cascade relationship between the L conversion electron line of the 18.3-keV transition and the 90-keV gamma ray, electron-gamma coincidence experiments were carried out with the Gerholm coincidence spectrometer using 15-kV electron preacceleration. Figure 2(B) shows the gamma-ray spectrum in prompt coincidence with the 18.3-keV L conversion line. Figure 2(C) shows the coincidence spectrum which was obtained when the pulses of the 18.3-keV L electron line were delayed by 200 nsec. The presence of the 122-keV gamma peak and the K x ray in Figs. 2(B) and (C) is mainly due to chance coincidences. However, it is seen that the 90-keV peak is relatively stronger in 2(C) than in 2(B), indicating that this transition is delayed. By means of a variable delay line, a time spectrum determining the half-life of the 90-keV transition was taken, as shown in Fig. 3. From this it follows that $\tau_{1/2}=(4.0\pm1.0)\times10^{-7}$ sec[16] for the 90-keV state. A similar coincidence relationship and time spectrum were also observed between the 90-keV gamma ray and the electron peaks coinciding with the K-LL Auger and the K-LM Auger lines, which were assigned as the 39-keV L- and M-conversion electron lines (see Sec. VI). By following the decay of the 90-keV photopeak coinciding with the 11-keV conversion electron line, we obtained a half-life $\tau_{1/2}=95\pm10$ min for the isomer in good agreement with Kirkby and Kavanagh.[11]

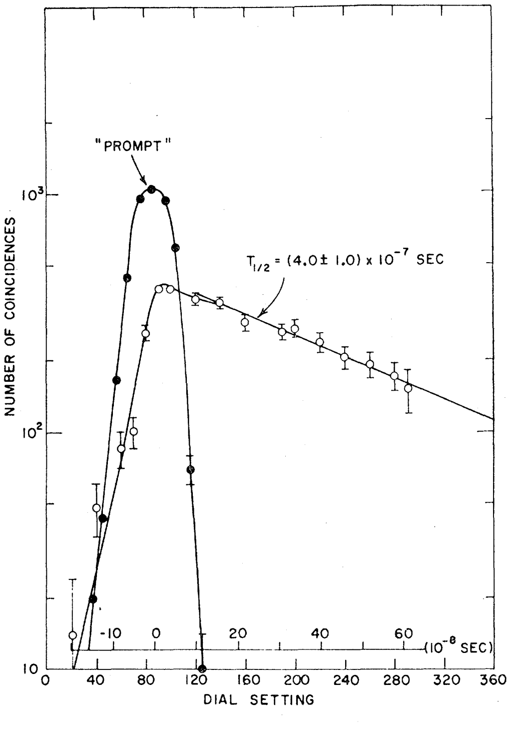

FIG. 3. Time spectrum of coincidences between L conversion line from a 18.3-keV transition and a 90-keV photopeak, determining the half-life of the 90-keV level. The measurement was carried out with the Gerholm spectrometer at 15-kV preacceleration of the electrons.

A K-shell internal conversion coefficient for the 90-keV transition can be directly computed from the spectra shown in Figs. 2(A), (B), and (C). After correction for the intense K x-ray background due to the 9.3-h component, all three curves gave similar values for α_K. However, the delayed coincidence spectrum gave the most reliable value: $\alpha_K=0.30\pm0.05$. This is in good agreement with the value $\alpha_K=0.27\pm0.03$ reported by Kirkby and Kavanagh[11] and leads to the assignment of the multipole order $E1$ for the 90-keV transition. This assignment is supported by our results on the K/L_{tot} conversion-electron ratio described in the following section. The retardation factor for this $E1$ transition is $\sim2.4\times10^6$. Table I summarizes the results on the 90-keV transition. The facts reported above show clearly that the 90-keV transition follows the two other transitions observed in the 96-min isomer and that it is presumably identical with the strong transition observed in the capture gamma-ray spectrum of $Eu^{151}+n$.[5,15]

Using the information on the conversion coefficient for the 90-keV transition and on its multipole-order assignment, we deduced from the initial intensity ratio of the 90-keV (1.5-h) and 122-keV (9.3-h) gamma rays an approximate ratio of activation cross sections of 1:700 for the 1.5-h activity relative to the 9.3-h activity. An improved determination of the activation cross-section ratio is discussed in the following section.

TABLE I. Comparison of the measured values of α_K, K/L_{tot} ratio and $\tau_{1/2}$, for the "90-keV" transition with theoretical values, on which the multipole assignment is based.

		Theoretical[a]		
	Experimental	$E1$	$M1$	$E2$
Transition energy (keV)	89.83 ±0.15	...	...	...
α_K	0.30 ±0.05	0.31	2.0	1.4
$(\alpha_L)_{\text{tot}}$	...	0.04	0.26	1.6
K/L_{tot}	7.2 ±1.0	7.8	7.7	0.88
$\tau_{1/2}$ (sec)	$(0.4\pm0.1)\times10^{-6}$	1.7×10^{-13} [b]	...	...
Retardation factor		2.4×10^6		
Multipole assignment	$E1$			

[a] Values are from *Table of Conversion Coefficients* by M. E. Rose (Ref. 17).
[b] Estimated by using Moszkowski's single-particle formulas ($r_0=1.45\times10^{-13}$ cm).

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[15] A. M. Berestovoii, D. M. Kaminker, and I. A. Kondurov, Zh. Eksperim. i Teor. Fiz. **45**, 892 (1963) [English transl.: Soviet Phys.—JETP **18**, 613 (1964)].

[16] Very recently a measurement has been carried out on the half-life of a 90-keV gamma ray following a high-energy de-excitation gamma ray produced by thermal neutron capture in Eu^{151} (see Ref. 15). The result reported was: 3×10^{-7} sec $\leq\tau_{1/2}\leq1\times10^{-6}$ sec, consistent with our value.

TABLE II. L-shell and M-shell conversion-electron ratios for the 18.25±0.10-keV transition and resulting multipole-order assignment.

	$L_I/L_{II}/L_{III}$[a]	L_I/M_{tot}[b]	Remarks on M-shell ratio[b]	Multipole order assignment
Theoretical values				
$E1$	1.00/0.66/1.17	1.00/0.75	M_I, M_{II}, M_{III}: strong	
$M1$	1.00/0.09/0.02	1.00/0.30	M_I: strongest	
$E2$	1.00/277/404	1.00/150	M_{II}, M_{III}: strong	
$M2$	1.00/0.06/0.58	1.00/0.26	M_I, M_{III}: strong	
$E3$	1.00/70/87	1.00/59	M_{II}, M_{III}: strong	
$M3$	1.00/0.06/6.4	1.00/2.4	M_{III}: strongest	
Observed values	1.00/(0.15±0.05)/(0.15±0.05)	1.00/(0.50±0.15)	M_I, $(M_{II}+M_{III})$, N lines observed	99.9% $M1$+0.1% $E2$

[a] Taken from Ref. 17.

[b] For M-shell conversion coefficients, $Z_{eff}=56$ was used for Eu ($Z=63$) in order to take the screening and finite size effects into account (Ref. 18). The conversion coefficients tabulated by Rose (Ref. 17) were graphically extrapolated to lower energies. The best fit to the experimental value for L_I/M_{tot} is obtained for $Z_{eff}\approx 60$.

VI. INTERNAL CONVERSION-ELECTRON SPECTRA

The presence of two low-energy transitions, one of 18.3 keV and the other of 39 keV, poses the question which of the two is responsible for the isomeric half-life of 96 min. This question may be answered by determining definite multipole assignments for the two transitions. Since the 39-keV conversion electron lines lie very close to some of the K-Auger electron lines, a measurement with fairly high momentum resolution was necessary. Therefore, the conversion-electron spectra for all three transitions were measured with a double-focusing spectrometer at 0.2–0.3% resolution. Because of the relatively short half-life, the measurements were carried out separately for each transition. The 122-keV K-conversion line from the 9.3-h activity served as an internal energy and intensity calibration line.

Figure 4 presents the L and M conversion-electron spectra obtained for the 18.3-keV transition. As seen in the figure, the L_I-conversion line is strongest and the weaker L_{II} and L_{III} lines are of approximately equal intensities. The strongest of the M-conversion lines is the M_I line. The small bump indicated by a dashed arrow in the figure is possibly an $(M_{II}+M_{III})$ composite line. Another small bump is seen at the position of the N-conversion lines (not shown in the figure). The observed value of the transition energy is 18.25±0.10 keV and the relative L- and M-line subshell intensities are given in Table II, together with the theoretical conversion coefficients[17] and the deduced multipole-order assignment for the 18.25-keV transition: $M1$, with an admixture of $\sim$0.1% $E2$. It follows that this transition, unless it is enormously retarded, cannot be responsible for the 96-min isomeric half-life. Following Chu and Perlman,[18] we used for the conversion coefficient for the M-shell $Z_{eff}=56$, although the best fit to the experimental L_I/M_{tot} ratio assuming 0.1% $E2$ admixture is obtained for $Z_{eff}=60$.

We then studied the conversion lines of the 39-keV transition: Even with the double-focusing spectrometer, the 39-keV L-conversion lines were not resolved from the K-LL Auger electron lines of Sm. The observed spectrum is shown in Figs. 5(A), and (B): curve (A) represents a composite spectrum consisting of the K-LL Auger electrons of Sm decaying with a 9.3-h half-life and the L-conversion electron lines of the 39-keV transition decaying with a 96-min half-life. The dashed line in the figure shows the spectrum of pure K-LL Auger electron lines of Sm, which was taken after the 96-min component had decayed. For normalization the K-L_IL_I Auger line at 31.20 keV was used. The energies and relative intensities of the K-LL Auger lines obtained were in good agreement with those reported by Ewan *et al.*[19] Figure 5(B) shows the spectrum obtained by subtracting the contribution of the K-LL Auger lines. It consists of the L_{II} and L_{III} conversion-electron lines of a 39.75 ±0.10-keV transition. The intensity ratio between the L_{II} and L_{III} conversion lines is subject to an uncertainty of the order of 30%. In spite of this ambiguity, the fact that the L_{II} and L_{III} conversion lines are present in nearly equal intensities rules out the possibility that the

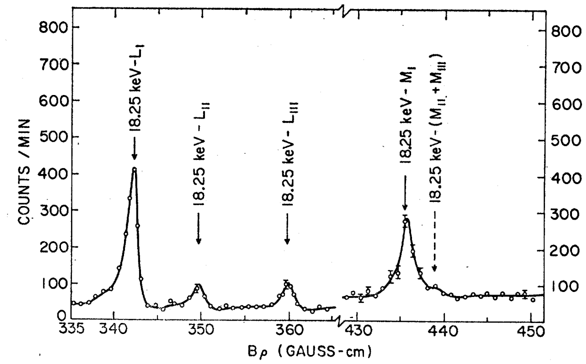

FIG. 4. L-shell and M-shell internal conversion-electron lines of a 18.25-keV transition from a 96-min Eu^{152m_2}, taken with double-focusing spectrometer. The spectrum was corrected for decay after subtraction of the small beta-ray background from Eu^{152m_1}.

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[17] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).

[18] Y. Y. Chu and M. L. Perlman, Phys. Rev. **135**, B319 (1964).

[19] G. T. Ewan, R. L. Graham, and L. Grodzins, Can. J. Phys. **38**, 163 (1960).

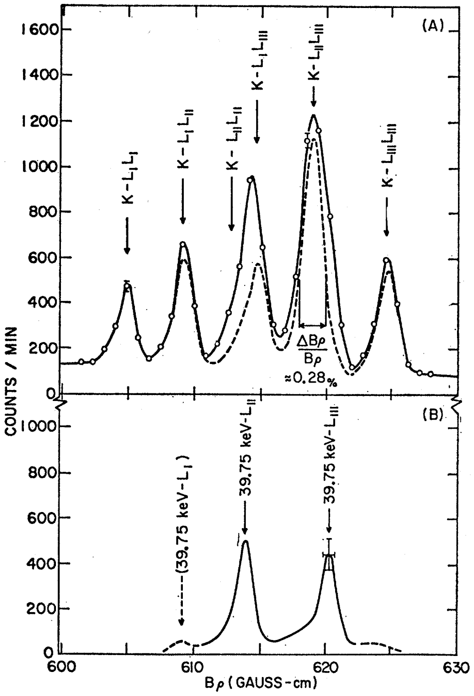

FIG. 5. Electron spectra in the vicinity of the K-LL Auger electrons of Sm (31 keV$\lesssim E \lesssim$34 keV), taken with double-focusing spectrometer. (A) Composite electron spectrum of K-LL Auger electrons of Sm from 9.3-h Eu^{152m_1} and L-shell internal conversion-electron lines of the 39.75-keV transition from 96-min Eu^{152m_2}. The measurement started 20 min after the end of a 70-min bombardment and lasted 37 min. The dashed line shows the spectrum of pure K-LL Auger lines of Sm, taken after the 96-min component had decayed. The K-L_IL_I Auger line at 31.22 keV was used to normalize the intensities of the K-LL Auger electron spectrum. (B) Approximate spectral shape of the 39.75-keV L conversion-electron spectrum, after correcting for the contribution [shown with a dashed line in (A)] from the K-LL Auger lines of Sm. "Cross" shown at the peak of the L_{III} line indicates approximate probable errors for the position and the height of the peak.

transition is magnetic. A faint indication of the unresolved M_{II} and M_{III} shell conversion electron peaks was also observed in the region of the K-LM Auger lines.

TABLE III. L-shell conversion-electron ratios and the $L_{\mathrm{tot}}/M_{\mathrm{tot}}$ ratio for the 39.75±0.10 keV transition and the multipole order assignment.

	$L_I/L_{II}/L_{III}$[a]	$L_{\mathrm{tot}}/M_{\mathrm{tot}}$[b]	Multipole assignment
Theoretical values			
$E1$	1.00/0.43/0.65	3.5	
$M1$	1.00/0.08/0.016	4.7	
$E2$	1.00/46/56	4.3	
$M2$	1.00/0.08/0.35	5.4	
$E3$	1.00/86/100	3.4	
$M3$	1.00/0.09/2.5	4.7	
Observed values	(2±2)/100/(100±30)	$2.7_{-0.2}^{+0.7}$	$E3$

[a] Taken from Ref. 17.

[b] For M-shell conversion coefficients, $Z_{\mathrm{eff}}=56$ was used for Eu ($Z=63$) in order to take the screening and finite size effects into account (Ref. 18). The best fit to the experimental value for $L_{\mathrm{tot}}/M_{\mathrm{tot}}$ is obtained for $Z_{\mathrm{eff}}\approx58$.

No definite intensity ratio for the M subshell lines, however, was obtained. The N-conversion lines could not be well observed, because they were partly obscured. Table III presents a list of experimental results concerning the L and M conversion electron measurements, and compares them with the theoretical values for various multipole orders. As is seen from Table III, the transition of 39.75 keV is either $E2$ or $E3$, since an $E4$ transition of this energy would live considerably longer than 96 min. The retardation factors are $\sim 10^{10}$ and $\sim 10^3$ for $E2$ and $E3$, respectively. Since a retardation factor of $\sim 10^3$ is the most plausible one, the transition is assigned as $E3$. This conclusion is supported by the $L_{\mathrm{tot}}/M_{\mathrm{tot}}$ conversion electron ratio (listed in Table III) obtained by means of an electron-electron coincidence experiment which will be discussed in the following section.

To obtain more precise information on the 90-keV transition, the internal conversion-electron spectrum of this transition was taken. The results are shown in Fig. 6: In addition to the K-conversion line, the L_I line was clearly observed, but not the L_{II} and L_{III} conversion electron lines. The transition energy is now determined to be 89.83±0.15 keV and is in excellent agreement with the very precise value of 89.8505±0.0020 keV given to the strongest line observed in the capture gamma-ray experiment by Schult.[5] A comparison of the intensities of the K and L conversion lines gave a value for the ratio $K/L_{\mathrm{tot}}=7.2\pm1.0$, which is consistent with the $E1$ assignment derived from the K conversion coefficient (Table I).

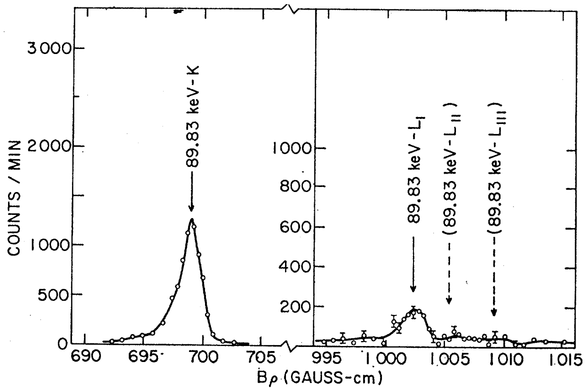

FIG. 6. K-shell and L-shell internal conversion-electron lines of the 89.83-keV transition from 96-min Eu^{152m_2} taken with double-focusing spectrometer.

For these conversion-electron measurements, by means of the double-focusing spectrometer, the 122-keV K-conversion line from the 9.3-h Eu^{152} isomer served as an internal intensity calibration line. The relative intensities of the three transitions in Eu^{152m_2} of 39.75, 18.25, and 89.83 keV, were found to be 1.00: (0.8±0.3): (1.3±0.3). This is consistent with the assumption of a 100% cascade relationship. Since the branching ratio of the 122-keV transition of the 9.3-h Eu^{152} isomer is known to be 13.2%,[6] a comparison of the yield ratio of the 96-min conversion lines to the 122-keV K conversion line gives a production ratio of these two isomers as was already mentioned in Sec. IV. The result is $\sigma_{9.3\mathrm{h}}/\sigma_{96\ \mathrm{min}} = (820 \pm 150)$. The large production ratio suggests a large difference between the spin values of these two isomers.

From our data the branching ratio for beta rays from the 96-min level was found to be $\lesssim 10\%$, in agreement with the result of Kirkby and Kavanagh.[11] Our value is less accurate than theirs ($<5\%$) because of the presence of the strong 9.3-h component in neutron activation.

VII. ELECTRON-ELECTRON COINCIDENCES

Results of the internal conversion-electron measurements described above strongly suggest that the 39.75-keV transition is the isomeric transition, probably $E3$. The L- to M-shell conversion ratio ($L_{\mathrm{tot}}/M_{\mathrm{tot}}$), furnishes a sensitive test for the multipole-order assignment for this transition. Since strong K-LL and K-LM Auger electrons are superimposed on the 39.75-keV L and M lines, a coincidence experiment between the 18.25-keV L-conversion line and the 39.75-keV L- and M-conversion lines seemed desirable. An especially thin evaporated europium film ($\sim 5\ \mu\mathrm{g/cm}^2$) on a backing of self-supporting carbon film, thinner than 100 $\mu\mathrm{g/cm}^2$, was used as source material. Since the energies of the 39.75-keV conversion electrons range from 39 keV down to 32 keV, a foil of this thickness does not appreciably affect the transmission of the electrons. The result of the experiment is shown in Fig. 7 and Table III: a value of the ratio, $L_{\mathrm{tot}}/M_{\mathrm{tot}} = 2.7_{-0.2}^{+0.7}$ was obtained. [The contribution to the K-Auger lines due to the 89.83-keV K conversion is very small ($<0.5\%$) because of the small values of $\alpha_K/(1+\alpha_{\mathrm{tot}}) \approx 0.23$ and of the K Auger yield for europium of 0.09, together with the coincidence reduction due to the half-life of $\tau_{1/2}(89.83) = 4 \times 10^{-7}$ sec.] Because of the limited resolution of the Gerholm spectrometer, the expected weak N-conversion peak is not resolved from the M line of the 39.75-keV transition. However, from the results obtained with the double-focusing spectrometer, the contribution of the N line was known to be small (at most 20% of total M line). The larger positive error in the result is due to the uncertainty caused by the unresolved N-conversion line. This result clearly agrees better with the multipole assignment $E3$ than with $E2$, and therefore supports the assignment made in the previous section. Within the limit of our coincidence circuit ($\sim 2 \times 10^{-8}$ sec) no delayed coincidences between the 39.75- and 18.25-keV transitions were found.

VIII. SEARCH FOR THE ISOMERIC TRANSITION FROM THE 9.3-h LEVEL TO THE GROUND STATE

The search for the isomeric transition between the 9.3-h isomeric level and the 3− ground state was made by using the double-focusing spectrometer and the Gerholm spectrometer. The search was carried out mainly for the electron energy region from 5 to 35 keV, where no detailed measurement had been made previously. No transition was found and we were able to confirm the upper limit for the branching ratio of $\leq 0.002\%$ for the isomeric transition reported by Grodzins and Sunyar.[7] A slightly improved upper limit for the transition intensity ($\leq 0.001\%$, corresponding to a partial half-life $\tau_{\mathrm{IT}} \gtrsim 100$ year) was obtained from the study of electrons with 7 keV$<E<$20 keV, an energy interval which is free of Auger electron lines. This interval corresponds to the transition energy regions $15 \rightarrow 28$ keV (L-conversion electrons) and $55 \rightarrow 68$ keV (K-conversion electrons).

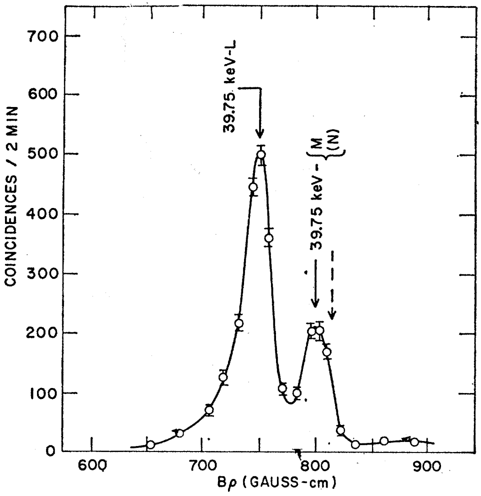

FIG. 7. Conversion-electron spectrum of the 39.75-keV transition coincident with the 18.25-keV L line, taken with electron-electron coincidence spectrometer with 15-kV preacceleration. The source was an evaporated europium oxide film with self-supporting carbon backing. The N line of the 39.75-keV transition is not resolved from the M line.

IX. DISCUSSION OF THE DECAY SCHEME

A decay scheme for the new isomer may now be deduced: We conclude that the 89.83-keV transition leads to the 3− ground state of Eu^{152} for the following reasons: (a) The transition *follows* the other transitions found in the decay of Eu^{152m_2} (Sec. V) and may therefore lead either to the ground state or to the 9.3-h (0−) isomeric state.

(b) The latter possibility appears unlikely because of the following considerations: It was shown in Sec. VI that the 89.83-keV transition is identical with one found in the capture gamma-ray spectrum which occurs in 40% of all neutron captures,[5] while the 9.3-h (0−) state is apparently less populated [there are large discrepancies between the values reported in the literature;

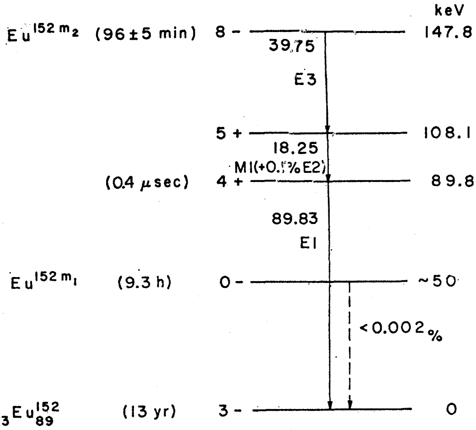

FIG. 8. Proposed decay scheme of Eu^{152m_2} (96 min).

extreme values are $(18\pm4)\%$[20] and $(36\pm1.5)\%$[21] of all captures]. A further argument in favor of the position in the decay scheme suggested for the 89.83-keV transition is based on the fact that the activation cross section for the 96-min state is comparatively very small (see end of this section).

The most plausible spin-parity assignment for the 89.83-keV level is 4+. The half-life of 4×10^{-7} sec corresponds to a hindrance factor of about 2.4×10^{6}. This transition is preceded by the 18.25-keV $M1$ $(+0.1\%\ E2)$ transition, which depopulates a 108.1-keV state, probably 5+, with $\tau_{1/2}\lesssim2\times10^{-8}$ sec. The 96-min isomeric state at 147.8 keV depopulated by the 39.75-keV $E3$ transition is then probably 8−. Since besides these three transitions no other transition with more than 10% branching was observed, the decay scheme of the 96-min isomer shown in Fig. 8 is proposed.

The spin assignments for the 147.8-keV and the 89.83-keV states are supported by the well-known rule[22] that the neutron activation cross section of an isomeric state decreases as ΔI increases. Here ΔI denotes the change in angular momentum between the capturing (compound nucleus) state and the isomeric state. Stolovy[23] reported that the three most prominent resonances in $Eu^{151}+n$ are 3+, while the fourth is 2+. Table IV lists the activation cross sections for four isomeric states in Eu^{152}. As there is considerable disagreement between the values given in the literature, the two sets of values differing most from each other are listed in columns I and II. The values in column II are based on the result of a recent measurement of the thermal neutron capture cross section of Eu^{151}.[24]

As none of the three transitions found in the decay of Eu^{152m_2} has rotational character, it may be assumed that the states populated by the 96-min isomer are all intrinsic states formed by the coupling of a neutron and a proton orbital. Though it is not certain that the level structure of Eu^{152} can be understood in terms of Nilsson orbitals, it seems worthwhile to try to interpret the proposed decay scheme in this manner. According to the Nilsson diagram,[2] the low-lying states in odd proton nuclei at $Z=63$ are $\frac{5}{2}+[413\downarrow]$, $\frac{3}{2}+[411\uparrow]$, and $\frac{5}{2}-[532\uparrow]$. The ground states of Eu^{151} and Eu^{153} are probably $\frac{5}{2}+[413\downarrow]$, while the other orbitals suggested by the Nilsson model are also found in low-lying states. Low-lying $\frac{7}{2}+$ states found both in Eu^{151} (22 keV) and Eu^{153} (83 keV) may be interpreted as $[404\downarrow]$ Nilsson states, which are expected to occur for very small deformations. Possible candidates for orbitals in odd neutron isotopes in the region of $N=89$ are $\frac{3}{2}-[521\uparrow]$, $\frac{3}{2}+[651\uparrow]$, $\frac{5}{2}-[523\downarrow]$, and $\frac{5}{2}+[642\uparrow]$. The ground state of Sm^{151} is $\frac{5}{2}$ (or $\frac{7}{2}$) (−), probably $\frac{5}{2}-[523\downarrow]$, while the ground state of Sm^{153} is $\frac{3}{2}-$, probably $[521\uparrow]$. Possibly the $\frac{11}{2}-[505\uparrow]$ orbital is also present although it has not been observed, probably because its high spin value prevents its population by radioactive decay. Accordingly, the three most probable configurations for the 3− ground state in Eu^{152} are given in Table V, classified as A, B, and C. All three correspond to "deuteron-type coupling" (or the $\Sigma=1$ configuration in the notation of Gallagher and Soloviev).[1] It is seen that none of these configurations corresponds to the coupling of the ground-state spins found in the odd-A nuclei with 63 protons (Eu^{151}) and 89 neutrons (Sm^{151}). It may be, however, that this configuration, with $\Sigma=0$, obtains for the 0− state (classification D in Table V).

The magnetic moment of the ground state of Eu^{152} is known to be $|\mu_{\rm exp}|=1.91$.[25] Though the sign of the magnetic moment is unknown, its magnitude apparently

TABLE IV: Thermal neutron activation cross sections for four isomeric states in Eu^{152}. Columns I and II refer to two different sets of experimental values.

		I		II[d]	
State	ΔI	$\sigma_{\rm act}$ (b)	Ref.	$\sigma_{\rm act}$ (b)	Ref.
3 −	0(1)	6400 ± 500[b]	20	5630 ± 450	21 and 24
0 −	3(2)	1400 ± 300[a]	20	3160 ± 220	21 and 24
4 +	1(2)	3100 ± 100[c]	5 and 20	3520 ± 220[c]	5 and 24
8 −	5(6)	1.7 ± 0.7	Present work, and 20	3.9 ± 1.6	Present work, 21 and 24

[a] This value was obtained by a direct activation cross-section measurement.
[b] Value obtained by subtracting $\sigma_{\rm act}$ (0−) from $\sigma_{\rm capt}=7800\pm200$ b (Ref. 20).
[c] Reference 5 states that the level is populated in 40% of all neutron captures.
[d] The cross-section values in column II are based on $\sigma_{\rm capt}=8790\pm90$ b, given in Ref. 24.

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[20] D. J. Hughes and R. B. Schwartz, BNL 325, 2nd ed., 1958; D. J. Hughes, B. A. Magurno, and M. K. Brussel, BNL 325, 2nd ed., *Supplement Number 1* (1960).

[21] B. Keisch, Phys. Rev. **129**, 769 (1963), reported $\sigma_{9.3\,\rm h}/\sigma_{13\,\rm year}=0.56\pm0.04$; see also W. E. Moore and L. J. Esch, KAPL 2000-8, D.16, 1959 (unpublished).

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[23] A. Stolovy, Phys. Rev. **134**, B68 (1964).

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agrees better with configuration C, since the theoretical value calculated for it in the asymptotic limit is $\mu_{\mathrm{theor}}=+1.7$, whereas the values for configurations A and B are -1.0 and -0.4, respectively. However, the ground state of Eu^{152} may not be sufficiently deformed to warrant the assumption made for these computations.

The $8-$ isomeric state at 147.8 keV can be interpreted as the $\Sigma=0$ state of the $\frac{5}{2}+[413\downarrow]$ proton and the $\frac{11}{2}-[505\uparrow]$ neutron orbitals, which is the only possible configuration for an $8-$ level in this region.

The $4+$ and $5+$ levels at 89.83 and 108.1 keV are probably composed of the same proton orbital $\frac{5}{2}+[413\downarrow]$ coupled with the neutron orbitals $\frac{3}{2}+[651\uparrow]$ and $\frac{5}{2}+[642\uparrow]$, respectively. It follows that the two first steps of the three-step cascade depopulating the isomeric state occur only between different neutron states and leave the proton state unchanged. The configurations suggested for the levels populated by the 96-min isomer are given in Table V, together with that for the $0-$, 9.3-h isomeric level.

(1) If one assumes that the configuration of the ground state is mainly B or C with a small admixture (ϵ) of A (Table IV), the large retardation factor for the 89.83-keV $E1$ transition can be understood as due to an (asymptotically hindered) transition between two neutron orbitals, reduced by ϵ. The two-particle jump between the configuration given for the $4+$ state and configuration B or C is expected to be hindered by an even larger factor.

(2) The $M1$ transition between the $\frac{3}{2}+[651\uparrow]$ and the $\frac{5}{2}+[642\uparrow]$ neutron states is of orbit-flip type and could be somewhat hindered because of $g_l=0$ for the neutron,[26] while the $E2$ transition is expected to be unhindered. No experimental retardation factors for the 18.25-keV transition are known, since only an upper limit of $\sim 10^{-8}$ sec was obtained for its half-life. However, the experimental result that the $E2/M1$ ratio is 10^{-3}, while the theoretical ratio of single particle transition probabilities for $E2$ to $M1$ is $\sim 10^{-4}$, is compatible with the Nilsson model predictions.

(3) According to the configurations given in Table V, the 96-min isomeric $E3$ transition with a hindrance factor of about 2.5×10^3 is an asymptotically hindered transition between the states with the neutron orbitals $\frac{11}{2}-[505\uparrow]$ and $\frac{5}{2}+[642\uparrow]$. The hindrance factor is of the right order of magnitude for a hindered $E3$ transition (see Table X, p. 90 in Ref. 2).

TABLE V. Suggested couplings of the odd proton and odd neutron orbitals in Eu^{152}.

Energy levels (keV)	$I\pi$	Possible configurations p	n	Classification
0 "ground state"	$3-$	$\frac{5}{2}+[413\downarrow]$	$-\frac{11}{2}-[505\uparrow]$	A
		$\frac{7}{2}+[404\downarrow]$	$-\frac{1}{2}-[530\uparrow]$	B
		$\frac{3}{2}+[411\uparrow]$	$+\frac{3}{2}-[521\uparrow]$	C
50±15	$0-$	$\frac{5}{2}+[413\downarrow]$	$-\frac{5}{2}-[523\downarrow]$	D
		$\frac{5}{2}-[532\uparrow]$	$-\frac{5}{2}+[642\uparrow]$	E
89.83	$4+$	$\frac{5}{2}+[413\downarrow]$	$+\frac{3}{2}+[651\uparrow]$	
108.1	$5+$	$\frac{5}{2}+[413\downarrow]$	$+\frac{5}{2}+[642\uparrow]$	
147.9	$8-$	$\frac{5}{2}+[413\downarrow]$	$+\frac{11}{2}-[505\uparrow]$	

X. CONCLUDING REMARKS

As shown in Sec. IX, the existing information on the level scheme of Eu^{152} is compatible with the assumption that this nucleus is deformed. However, as no rotational bands have been found so far, its eccentricity is not known. A more indirect clue is furnished by the ratios of its quadrupole moment to those of the odd-A neighboring Eu isotopes. Alpert[25] reported that $|Q^{152}/Q^{151}|=2.75\pm 0.24$ and $|Q^{152}/Q^{153}|=1.08\pm 0.09$. As it is known[2] that Eu^{151} is not appreciably deformed while two rotational bands, indicating $\delta\approx 0.25$, were found in Eu^{153}, it appears that at least the ground state of Eu^{152} has a deformation similar to that of Eu^{153}. More definite knowledge may be gained by an investigation of the levels of Eu^{152} populated in nuclear reactions, e.g. in thermal neutron capture or charged particle reactions [(d,p), (He^3,p), etc.].

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