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ELECTROMAGNETIC TRANSITION PROBABILITIES IN ^{151}Eu, ^{149}Sm AND ^{147}Sm ISOTOPES

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The half-lives of some excited states in ^{151}Eu, ^{149}Sm and ^{147}Sm isotopes have been measured with a time-to-amplitude converter. Radiations were detected in plastic scintillators mounted on 56-AVP photomultipliers.

The $E1$, $E2$ and $M1$ transition probabilities between low-lying excited states are deduced. The results are compared with the predictions of the single particle and the Nilsson models.

1. *Introduction*

Relatively little is known about particle and rotational states in odd A nuclei at the lower edge of the deformed nuclei region. It was the aim of the present investigation to obtain further informations concerning the level structure of some isotopes belonging to the transition or weakly deformed region. A marked change in nuclear structure occurs between the isotopes ^{151}Eu and ^{153}Eu (88 and 90 neutrons, respectively). ^{153}Eu shows a well-developed rotational structure, while there seems to be no clear rotational pattern in ^{151}Eu.

The states at 243 and 350 keV in ^{151}Eu have odd parity and according to the shell model predictions should have been placed at higher energy. The radiative transition probability as given by Nilsson [2] for deformed nuclei is dependent on the deformation (δ) of the initial and final nuclear states and thus a measurement of the life-time of the level should give an indication of the change in deformation.

The present work brings new experimental data concerning the half-lives of the $\frac{7}{2}^-$ (243 keV) and $\frac{9}{2}^-$ (350 keV) levels in ^{151}Eu.

Moreover, in the course of this investigation the half-lives of the first excited states in ^{151}Eu (22 keV) and ^{149}Sm (22.5 keV) and the life-time of the 197 keV level in ^{147}Sm were reexamined in view of some disagreement among the previously known data.

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2. *Experimental procedure*

2.1. Source preparation

The Gd and Eu activities were produced by irradiating a tantalum target with 660 MeV protons in the JINR Dubna synchrocyclotron and a tungsten target with 26 GeV protons in the CERN synchrotron. The rare earth elements were separated and the Gd and Eu activities purified on an ion-exchange column with Dowex 50 W × 12. After 6 months the aged sample of gadolinium activity with ^{151,153}Gd predominant was again purified chromatographically to get rid of the europium activity. The extracted europium activity (^{147}Eu(25 days) and ^{149}Eu(90 days)) was used for the investigation of the excited states in the respective samarium isotopes.

In the experiments reported in this paper four separated and chromatographically purified samples of Gd and Eu isotopes, obtained in different irradiations of Ta and W target,. were investigated.

2.2. Experimental technique

The experimental set-up includes a time-to-amplitude converter [3] equipped with a pile-up rejection circuit [4] and a circuit providing the pulse-height compensation. Radiations were detected in plastic scintillators mounted on 56-AVP photomultipliers. The gamma rays were detected in a 3 cm × 3 cm Naton-136 organic scintillator, while for detection of electrons a 1 mm thick Naton-136 scintillator was used.

The low energy gamma rays or X_K-rays were detected in Pilot B type scintillators loaded with lead up to 5 and 10%. The best time resolution of the electronic system was 350 ps and slopes of about 50 ps as measured from a prompt coincidence curve with ^{60}Co source.

The gamma ray spectra were investigated with a 1 cm^3 Ge(Li) detector. The resolution of the counter-preamplifier assembly was 3.5 keV for 661 keV gamma rays.

3. *Half life measurements and results*

3.1. The 21.6 keV level in ^{151}Eu

This measurement is motivated by the important role of the 21.6 keV level, especially in Mössbauer effect studies. During the last few years some measurements of the half life of this excited state have been made. There are rather large discrepancies among the published results (*cf.* Table I).

The 21.6 keV level in ^{151}Eu is strongly fed (84%) by an electron capture branch in the decay of the 120 days ^{151}Gd activity (upper part of Fig. 2). The deexcitation of this level takes place by a 21.6 keV $M1$-forbidden transition with an $E2$ admixture of $(0.12 \pm 0.03\%)$ (Refs [5, 6, 7]). The ground state of ^{151}Eu corresponds to the orbit $\frac{5}{2}^+$ [402] if the deformation $\delta = 0.125$ is assumed. The only reasonable assignment to the 21.6 keV level is then $\frac{7}{2}^+$ [404].

The relevant part of the electron and X-ray spectra and the accepted energy gates are shown in the lower part of Fig. 1. For the delayed coincidence measurements use was made of feeding X-rays as well as K 175-conversion electrons and L-conversion electrons from the 21.6 keV transition. For the detection of the L-conversion electrons from the 21.6 keV transition the sources were prepared by depositing the radioactive product on the surface of a thin Naton 136 scintillator.

First, the time correlation between X-rays and L21.6 electrons were measured. In the second experiment the delayed time coincidence spectra between K175 electrons and L21.6 electrons were recorded. The weighted average value from several runs of the two different types of measurements reported here is $T_{1/2} = 10.2 \pm 0.5$ ns (Fig. 1). The delayed curves have been analysed by a least squares fit in a Gier computer.

TABLE I.

Life-times of some excited states in ^{151}Eu and ^{147,149}Sm isotopes

Nucleus	Level energy keV	I^π	$T_{1/2}$ of level [ns]		
			Present work	Other works and method used	
^{151}Eu	21.6	$\frac{7}{2}^+$	10.2 ± 0.5	6.4[a]	Mössbauer effect
				3.4 ± 0.2[b]	K175-(L+M+N)22 del. coinc.
				9.5 ± 0.7[c]	γ 175-L22 del. coinc.
				9.5 ± 0.5[d]	γ175-L22 del. coinc.
				7.5 ± 0.4[e]	K175-(L+M+N)22 del. coinc.
	243	$\frac{7}{2}^-$	0.50 ± 0.03	—	
	350	$\frac{9}{2}^-$	$\leqslant 0.2$	—	
^{149}Sm	22.5	$\frac{5}{2}^-$	7.12 ± 0.11	20 ± 5[h]	Mössbauer effect
				7.6 ± 0.5[e]	$\gamma > 300$-L22 del. coinc.
				6.9 ± 5[f]	$\gamma > 328$-L22 del. coinc.
	277, 350		$\leqslant 0.2$	—	
^{147}Sm	197	$\frac{3}{2}^-$	1.10 ± 0.05	1.31 ± 0.5[g]	$\gamma > 600$-K198 del. coinc.
				1.35 ± 0.10[i]	

[a] D. A. Shirley *et al.*, *Phys. Rev.*, **127**, 2097 (1962).
[b] E. YE. Berlovich *et al.*, *Nuclear. Phys.*, **37**, 469 (1962).
[c] C. C. Kistner *et al.*, *Phys. Rev.*, **32**, 1733 (1965).
[d] D. J. Horen, *Bull. Amer. Phys. Soc.*, **8**, 127 (1963).
[e] E. YE. Berlovich *et al.*, *Izv. Akad. Nauk SSSR* (ser. fiz.,) **28**, 80 (1964).
[f] E. YE. Berlovich *et al.*, *Izv. Akad. Nauk SSSR* (ser. fiz.), **30**, 194 (1966).
[g] E. YE. Berlovich *et al.*, *Izv. Akad. Nauk SSSR* (ser. fiz.), **26**, 221 (1962).
[h] R. Leonard, S. Iha, G. Lang, *Bull. Amer. Phys. Soc.* Ser. II S. No. 1, 85 (1963).
[i] E. Bożek *et al.*, Report No 620/I/PL, IFJ Kraków (1968), *Nuclear Phys.*, **A122**, 184 (1968).

As we see from Table I, our value is in good accordance with the results of Kistner[c)] and Horen[d)] while the other values are a little lower.

Compared with the Moszkowski single particle estimate this value gives a hindrance factor

$$F = \frac{B(M1)_{\mathrm{sp}}}{B(M1)_{\mathrm{exp}}} = 165$$

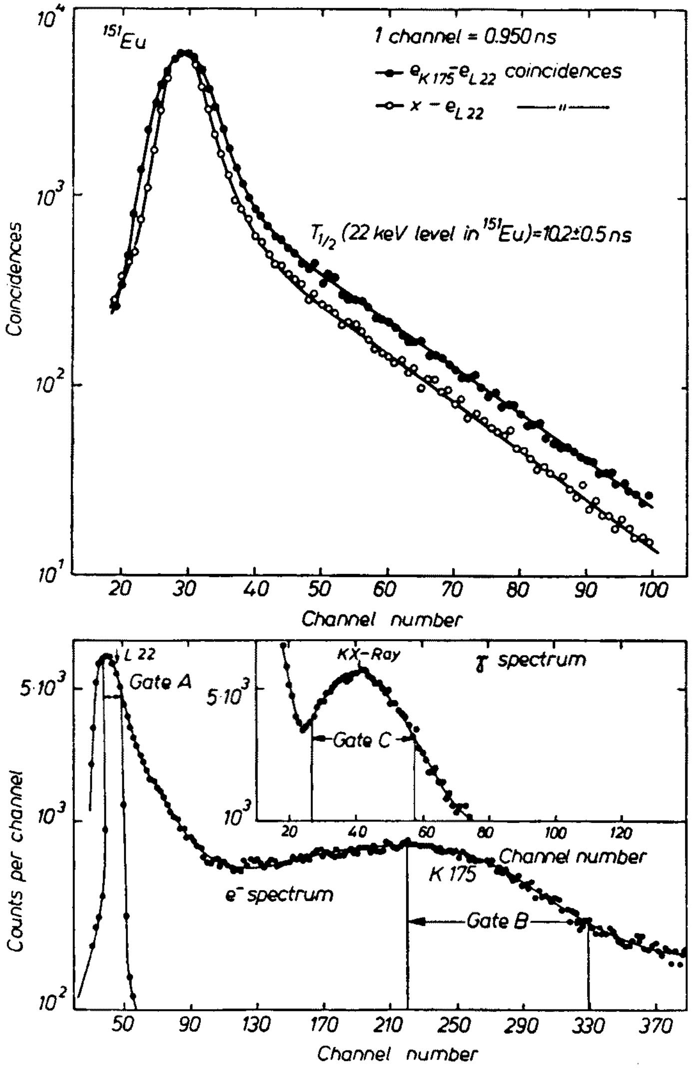

Fig. 1. Measurement of the life-time of the 21.5 keV level in ^{151}Eu obtained for the energy intervals indicated in lower part of figure

3. 2. The 243 and 350 keV levels in ^{151}Eu

A weak E. C. — branch (5.3%) populates the 243.5 keV level which decays mainly by gamma ray of 243.5 keV to the ground state (Fig. 2). The very weak 222 keV transition from this level to the first excited state (21.5 keV) was also observed using the Ge(Li) detector (Table II). The K-conversion coefficient for the 243.5 keV transition ($\alpha_K = 0.024 \pm \pm 0.002$) indicates a $E1$ multipolarity with a possible small $M2$ mixing ($< 3\%$).

The $E1$ character of the γ-transitions from the 243.5 keV level in ^{151}Eu to the ground state, confronted with the other data [5, 8], gives $\frac{7}{2}$ spin and negative parity. The closest Nilsson level with negative parity and suitable spin is the $\frac{7}{2}^-$ [523] orbit which is identified

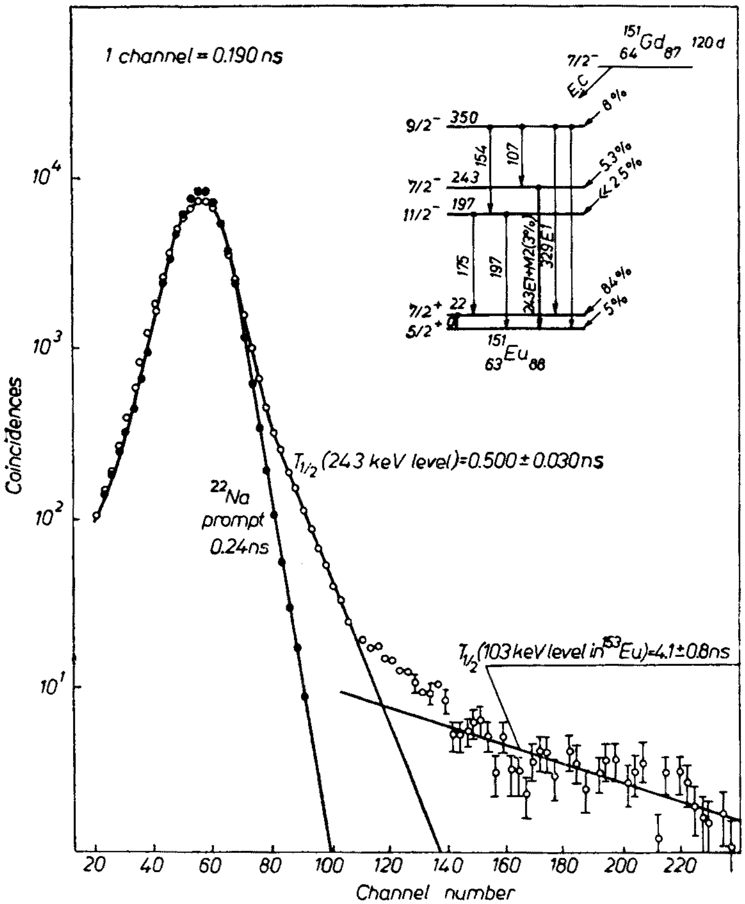

Fig. 2. Delayed coincidence spectrum taken between the X-rays and the γ 243.5 keV lines giving $T_{\frac{1}{2}} = 0.50 \pm 0.03$ ns for the 243.5 keV level. The "tail" in the lower part of the spectrum is due to the life-time of 103 keV level in ^{153}Eu

with the 243.5 keV level. With the present assignment both $E1$ transitions from the 243.5 keV level are forbidden by the asymptotic quantum number n_z.

The spectra of delayed time coincidence between the X-rays and the 243.5 keV γ-transition have been measured. The window in the X-ray channel was the same as in the previous measurement, while the setting in the γ-channel was adjusted to exclude the influence from the 154 keV transition deexciting the 350 keV level in ^{151}Eu and from the 103 keV transitions deexciting the 103 level in ^{153}Eu.

In order to suppress the influence of the 154 keV transitions thin foils of Pb, Cd and Cu were used as filters. With the proper energy setting the prompt coincidence peak from a ^{22}Na source was obtained with a slope of about 0.24 ns.

The measured time coincidence distribution is shown in Fig. 2. The middle part of the right side slope is due to the half-life of 243.5 keV level, while the low intensity "tail" is caused by the 103 keV transition from the ^{153}Eu admixture.

TABLE II

$E1$ transition probabilities in ^{151}Eu

Transition	γ-ray energy (keV)	$M2$ %	Intensity[a]	α_{tot}	$B(E1)_{\text{exp}}$ $[e^2\ \text{barn}]$	$F_M = \frac{B(E1)_{\text{sp}}}{B(E1)_{\text{exp}}}$	$G^2_{E1\text{exp}}$	$F_N = \left[\frac{G^{\text{th}}_{\text{E1}}}{G^{\text{exp}}_{\text{E1}}}\right]$	δ_f	δ_i
$\frac{7}{2}$ [523]$\rightarrow\frac{5}{2}^+$[402]	243.5	<3	94 ± 3	0.026 ± 0.003[b]	$5.83\pm0.7\times10^{-7}$	3×10^4	$3.3\pm0.7\times10^{-5}$	2.5	0.125	0.150
$\frac{7}{2}^-$[523]$\rightarrow\frac{7}{2}^+$[404]	222	low	$\leqslant0.12$	0.054[c]	$>1.1\times10^{-7}$	$<1.7\times10^5$	$>6.3\times10^{-5}$	$<6.2\times10^3$	0.15	0.15
$\frac{9}{2}^-$[523]$-\frac{7}{2}^+$[404]	328	<3	1.2 ± 0.2	0.025 ± 0.003[b]	$>3.7\times10^{-8}$	$<4.9\times10^5$	$>2.1\times10^{-6}$	$<1.8\times10^4$	0.15	0.15

[a] present results based on the Ge(Li) detector measurements,

[b] based on the conversion electron intensity taken from Refs [5, 6],

[c] theoretical value taken from tables of Sliv and Band.

In analysing the result the long lived tail due to the well-known half-life of 103 keV level in ^{153}Eu was subtracted from the delayed curve.

From such an analysis of several measured time distributions a half-life of (0.50 ± 0.03) ns was obtained for the 243.5 keV level in ^{151}Eu. This gives a hindrance factor of 3×10^4 as compared with the Moszkowski estimate.

Also the delayed time coincidence spectra between the X-rays and the 350 keV γ-transition have been measured. It is possible to establish from these measurements a half life less than 0.2 ns for the 350 keV level in ^{151}Eu. Compared with the single particle estimate this gives a retardation factor of $< 5 \times 10^5$.

3. 3. The 22.5 keV level in ^{149}Sm

The 22.5 keV level in ^{149}Sm is fed by an electron capture branch in the decay of the 100 days ^{149}Eu activity (Fig. 3). The deexcitation of this level takes place by a 22.5 keV $M1$ transition with a small $E2$ admixture: $\delta^2 = E2/M1 = 3 \times 10^{-3}$. The highly converted 22.5 keV transition was detected through $L22.5$ conversion electrons in a 1 mm thick Naton 136 plastic scintillator, while the X-rays were detedted in a Pilot B (Pb) scintillator.

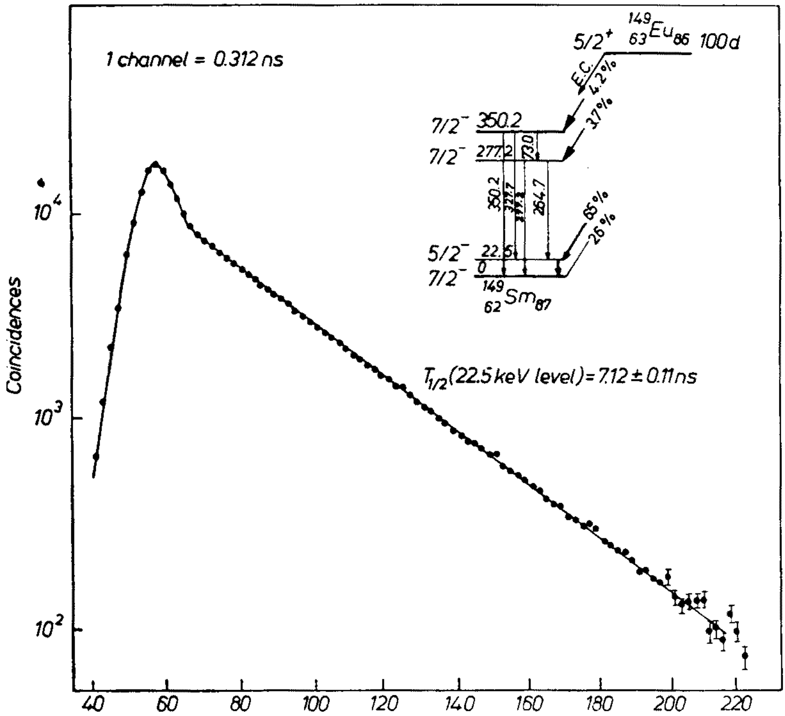

Fig. 3. Delayed coincidence curve taken between X-rays and $L22.5$ conversion electrons giving a half-life of 7.12 ± 0.11 ns for 22.5 keV level in ^{149}Sm

Sixteen delayed time distributions were recorded using four chromatographically purified sources. The time distributions were analysed using the least-squares method. The average result is $T_{1/2} = (7.12 \pm 0.11)$ ns for the 22.5 keV level in ^{149}Sm. Compared with the Moszkowski estimate this gives a retardation factor of 140. Finally, the limit of the life time of the two levels of energy 277 and 350 keV in ^{149}Sm ($T_{1/2} \leqslant 0.2$ ns) was determined from the time correlation between the X-rays and gamma rays of energy 350 and 270 keV.

3.4. The 197 keV level in ^{147}Sm

The 197 level in ^{147}Sm is fed by an electron capture branch (27.7%) in the decay of 24 days ^{147}Eu activity (Fig. 4). Also, the feeding of positrons to this level is known and according to Refs [8] and [9] was found to be 0.13% and 0.38%, respectively.

However, the 197 keV level is rather strongly fed by gamma rays with energies of 601, 857, 880 and 1256 keV. A delayed coincidence measurement utilising the mentioned gamma rays and the K 197 conversion line was performed. As an average value from the analysis

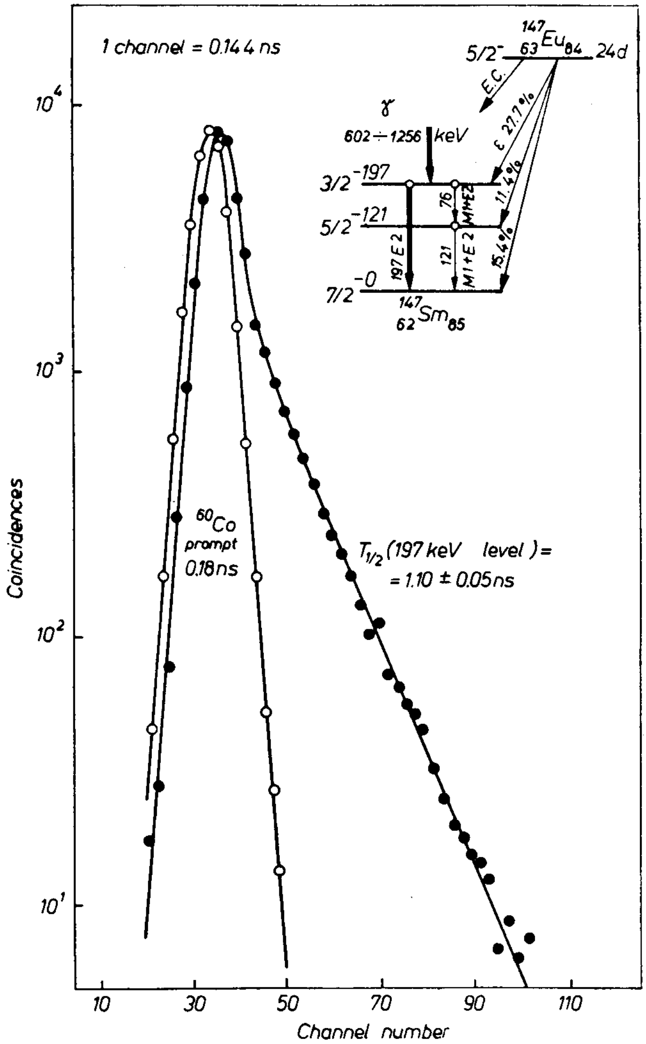

Fig. 4. The γ ray ($E\gamma > 600$ keV) — K197 time correlation giving the half-life of the 197 keV level in ^{147}Sm

of several sets of time distributions we obtain a half-life of $T_{1/2} = 1.10 \pm 0.05$ ns for the 197 keV level in ^{147}Sm. This result is only slightly lower than that of Berlovich *et al.* (Table I). Compared with the Moszkowski estimate our result gives enhancement factor of 9 (including statistical factor S), while the Kisslinger and Sorensen estimate gives for this factor 5.94.

4. *Discussion*

As is seen from Table II, there are large discrepancies between the experimental $E1$ transition probabilities and those estimated by Moszkowski for spherical nuclei.

A more satisfactory approach would be to use a deformed potential, as was done by Nilsson [2].

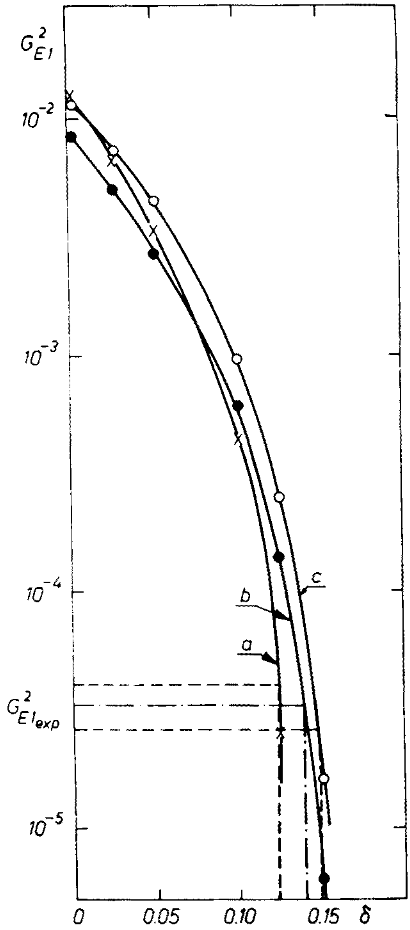

Fig. 5. $G_{E1}{}^2$ factor is plotted as a function of δ for different values of μ.

Curve	a	b	c
ground state	$\mu = 0.500$	0.420	0.500
excited state	$\mu = 0.420$	0.420	0.500

In each case the deformation of the ground state was taken to be $\delta = 0.125$

The ground state of ^{151}Eu corresponds, for a deformation of $\delta = 0.125$ [1], to the orbit $\frac{5}{2}^+$ [402] of the Nilsson diagram, while the higher states $\frac{7}{2}^-$ (243 keV) and $\frac{9}{2}^-$ (350 keV) might be interpreted as the rotational band based on the Nilsson $\frac{7}{2}^-$ [523] orbit. The E1 transition probabilities for the $\frac{7}{2}^-$ [523] $\rightarrow$ $\frac{5}{2}^+$[402] transition were calculated for different

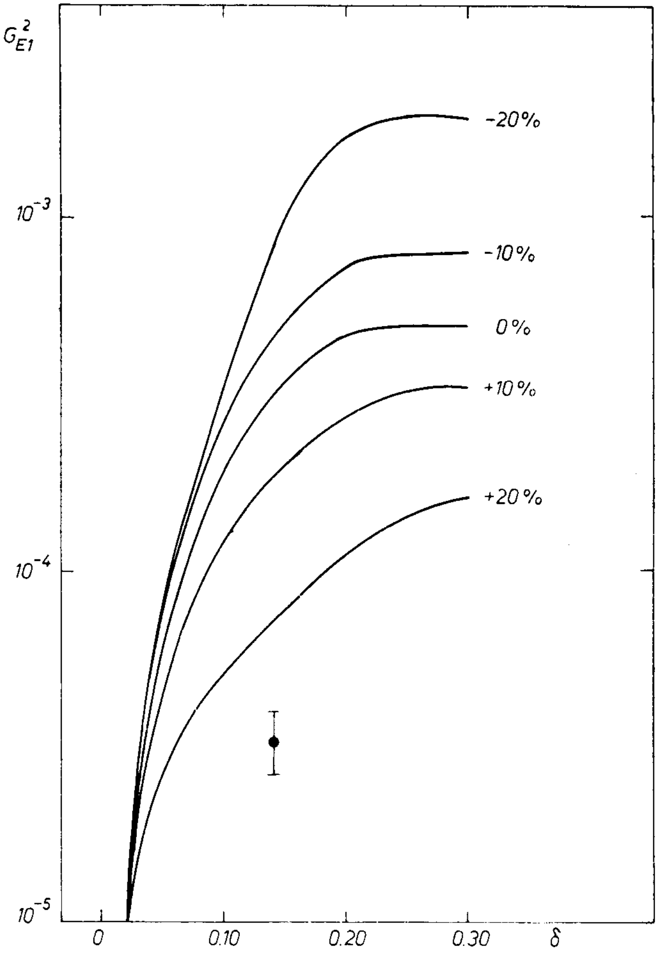

Fig. 6. The theoretical $G_{E1}{}^2$ factor for the $\frac{7}{2}^-$[523]$\rightarrow\frac{5}{2}^+$[402] transition obtained from the Nilsson model (Eq. (35) of Ref. 2) with the same deformation for both levels (0%). For the other curves the deformation of the excited $\frac{7}{2}^-$[523] state has been changed by a given percentage. The experimental value with total probable error is also shown in the graph

values of the deformation parameter using Eq. 35 of Ref. [2] and the wave functions for the two levels were taken from Ref. [10] according to slightly modified version of the Nilsson model suggested recently [11].

In each case the deformation of the ground state was taken to be $\delta = 0.125$; the deformation of the excited state was varied from $\delta = 0$ to $\delta = 0.3$. As we see in Fig. 5, the deformation parameter of the 243.5 keV $\frac{7}{2}^-$ level may lie within the range 0.12 to 0.16. The measured value of the transition probability $G^2_{E1\,\mathrm{exp}}$ thus indicates a small change in the deformation parameter when the 243 keV level decays to the ground state, assuming that the Nilsson model is valid in this case. To see the influence of the change in the deformation parameter on the transition probabilities a numerical calculation with a ±10 and ±20% change in δ for the excited level was made. From the results given in Fig. 6 it is seen that a 10% variation of the deformation of the excited level alters the transition probability by a factor of about two.

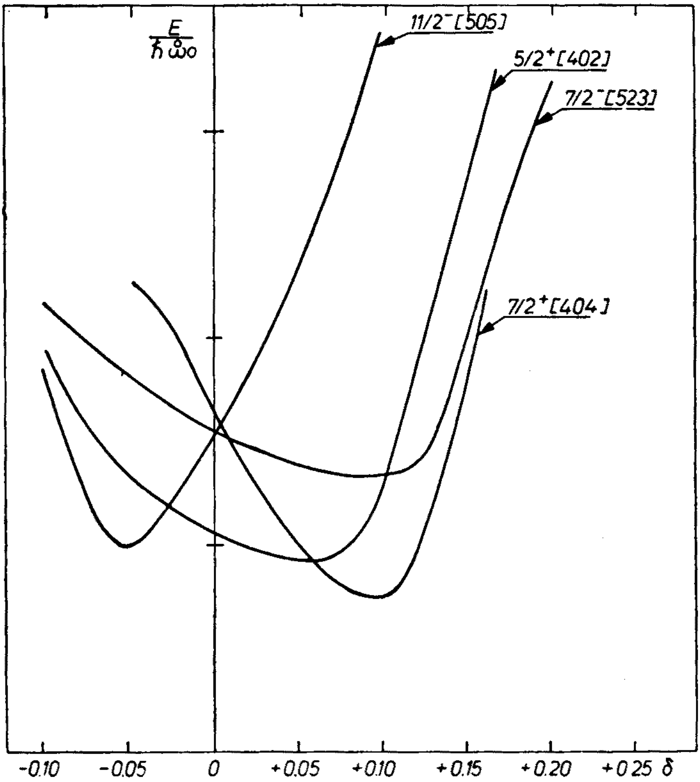

Fig. 7. Equilibrium calculations corresponding to a number of intrinsic configurations in ^{151}Eu. The total energy $\frac{E}{\hbar \mathring{\omega}_0}$ is plotted from an arbitrary level. The ground state configuration corresponds to the orbit $\frac{5}{2}^+$[402] of the Nilsson diagram. The single particle energies were calculated with $\varkappa = 0.0637$, $\mu = 0.600$ for protons, $\mu = 0.420$ for neutrons and $\varepsilon_4 = 0$

This fact can thus hardly explain the deviation between the theoretical and experimental results.

Finally, we have examined the nuclear equilibrium shape in the ground state and excited levels of ^{151}Eu in the same way as was done in Refs [12, 13, 14]. The total energy was computed as a function of the deformation from the equation (26) of Ref. [12]. The nuclear equilibrium shape corresponds to that value of δ for which the total energy has a minimum (Fig. 7). The Coulomb interaction between protons have been neglected in our calculations, as it does not appreciably affect the position of the energy minimum for a particular configuration.

The results of the deformation calculations and the comparison of the experimental and theoretical half-lives presented above suggest that the deformation of the 243 keV state in ^{151}Eu might be higher than in the ground state. It has to be pointed out, however, that the conclusion drawn out from the half-life data is slightly uncertain. This is so because the agreement between the Nilsson model predictions and the experimental results is generally rather poor. It has often been concluded that at least a part of this disagreement is due to the fact that the Nilsson model does not take into account the pairing correlations between the nucleons.

Due to the pairing interaction the electric gamma ray transition probabilities are strongly modified. This modification can be expressed by a pairing factor $R = (U_f U_i - V_f V_i)^2$, which may be calculated on the basis of the superfluid model. The figure obtained would, however, be very uncertain because the pairing factor R contains the difference of two comparable and not very well known products.

Basing on the present measurements the reduced transition probabilities $B(M1)$ have been established and the results have been compared with earlier known data. The hindrance factors calculated relative to the single-particle estimate for the $g_{\frac{7}{2}} \rightarrow d_{\frac{5}{2}}$, $M1$ l-forbidden transitions in odd-Z nuclei (Eu isotopes), and for the $f_{\frac{5}{2}} \rightarrow f_{\frac{7}{2}}$, $M1$ transitions in odd-N nuclei (Sm isotopes) lie within the range 70 to 200. The delay factor F for l-forbidden proton transitions are much lower than the average for other transitions of this type, and the hindrance factor for neutron transitions are higher than usual. There is, however, no evidence of a monotonic decrease of the hindrance factor when approaching the deformation region (see Ref. *b* under the Table I).

Although the Sorensen [15] calculation shows that the quadrupole coupling can explain most of the observed transition rates, in a few cases, particularly for the odd-N nuclei, fast transitions are still unexplained.

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REFERENCES

[1] E. Steichele, P. Kienele, *Z. Phys.*, **175**, 405 (1963).
[2] G. G. Nilsson, *K. Danske Vidensk Selsk.*, *Mat. Fys. Medd.*, **29**, 1 (1955).
[3] J. Jastrzębski, M. Moszyński, A. Zgliński, *Nukleonika*, **11**, 471 (1966).
[4] M. Moszyński, J. Jastrzębski, B. Bengston, *Nuclear Instrum. Methods*, **47**, 61 (1967).
[5] M. P. Avotina *et al.*, *Izv. Akad. Nauk SSSR* Ser. Fiz., **30**, 1304 (1966).
[6] B. Harmatz, T. H. Handley, *Nuclear Phys.*, **81**, 481 (1966).

[7] E. P. Grigorev *et al.*, *Izv. Akak. Nauk SSSR* Ser. Fiz. **32,** 786 (1968).
[8] M. P. Avotina *et. al.*, *Preprint JINR* Dubna, No 2271 (1965).
[9] B. Dzhelepov *et al.*, *Preprint JINR* Dubna, PI 2161 (1965).
[10] M. Zielińska-Pfabé, W. Grochulski, IBJ Report No 854/VII/PL (1967).
[11] G. G. Nilsson, *Proc. of the Lysekil Conference*, 1966.
[12] M. Y. M. Hassan, Z. Składanowski, Z. Szymański, *Nuclear Phys.*, **78,** 593 (1965).
[13] Z. Szymański, *Nuclear Phys.*, **28,** 63 (1961).
[14] A. Sobiczewski, private communication.
[15] R. A. Sorensen, *Phys. Rev.*, **132,** 2270 (1963).