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# New insight in the level structure of $^{153}$Er

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**Abstract.** The high-spin level structure of the $^{153}$Er nucleus has been reinvestigated by in-beam $\gamma$-ray and electron spectroscopy with ($^{14}$N,pxn) reaction. Excitation energies, spin and parity assignments are unambiguously established for the two lowest isomers $T_{1/2} \simeq 380$ ns and $T_{1/2} \simeq 10$ ns. The characteristics of the third one ($T_{1/2} \simeq 250$ ns) at 5.2 MeV are still questionable but its main decay modes are better known. An extension of the level scheme is proposed up to 8.4 MeV.Experimental results have been discussed in terms of shell model multiplets and compared with the other structures observed in $N = 85$ neighbouring nuclei.

**PACS.** 21.10.Pc Single-particle levels – 23.20.Lv Gamma transitions and level energies – 27.70.+q $150 \leq A \leq 189$

## 1 Introduction

High-spin level structures of transitional rare-earth nuclei in the region above $Z = 64$, $N = 82$ have been intensively studied in the recent years. Levels of $^{153}$Er have been observed in three independent experiments [1–3]. Several isomeric states were identified and tentatively interpreted in terms of shell-model configurations. All the measurements established the decay of a $T_{1/2} \simeq 380$ ns isomer at 2.8 MeV. A $T_{1/2} \simeq 250$ ns isomeric state at around 5.2 MeV has been identified by two groups [1,2] and two additional isomers have been reported [2]: a first one ($T_{1/2} \simeq 10$ ns) at an excitation energy of $E_x \simeq 3.0$ MeV and a second one located at around 6.9 MeV with an undetermined half-life.

The lower part of the level scheme below 2.7 MeV is supported by the three above-mentioned independent studies, but discrepancies appear about the position of the first isomeric state identified by all of them. An excited state is set at 2752 keV which deexcites via a $\gamma$-ray of 712 keV. Using an electron spectrometer, Carlen et al. [3] have measured an $\alpha_K$ electron conversion cœfficient for this 712 keV transition which is compatible with M1 or E3 multipolarities. To support the existence of the isomer, the E3 nature was retained with $B$(E3)$\simeq$ 25 W.u.

High-spin levels were more strongly populated in the two other works [1,2] which used the same $^{144}$Sm($^{12}$C,3n) $^{153}$Er fusion reaction at significantly higher incident energies and a second isomer ($T_{1/2} \simeq 250$ ns) was established at an approximate excitation energy of 5.2 MeV. From the observed coincidence relationships of the $\gamma$-rays located between the two isomeric states, it appeared necessary to the authors of [1,2] to set the first isomer not at 2752 keV but at 2752+X keV. According to Horn et al. [1], X=7.5 keV while Foin et al. [2] proposed X$\leq$ 10 keV. Moreover, the two groups [1,2] assigned $I^\pi = 25/2^-$ and $27/2^-$ to the levels at 2752 and 2752+X keV respectively and conjectured that an X keV transition having an M1 multipolarity and inserted between the two states, would explain the long 380 ns half-life.

However, looking in details at the level schemes reported in [1,2], several differences appear between the two isomeric states. In particular, the solution proposed in [2] includes the existence of two unobserved low-energy transitions at 19.0+X keV and 37.5+X keV. The $\gamma$-ray at 19.0+X must be inserted in the strong cascade 910, 363, 746, 418, 349, 356 keV based upon the $21/2^-$ excited state at 2039 keV. In parallel the 37.5+X keV transition is needed to explain the coincidences observed between the two groups of $\gamma$-rays placed below and above the $T_{1/2} \simeq 10$ ns, $I^\pi = 29/2^+$ excited state.

No additional study of this $^{153}$Er nucleus appeared since 1982. Two successive Nuclear Data Sheets compilations have been published on the $A = 153$ chain. Surprisingly, in the first one published in 1990 [4] only the $^{153}$Er level scheme built by Horn et al. [1] has been retained while the second one published in 1998 [5] is based only on the results of our previous study [2]. Therefore, in order to clarify the situation and to have a better understanding

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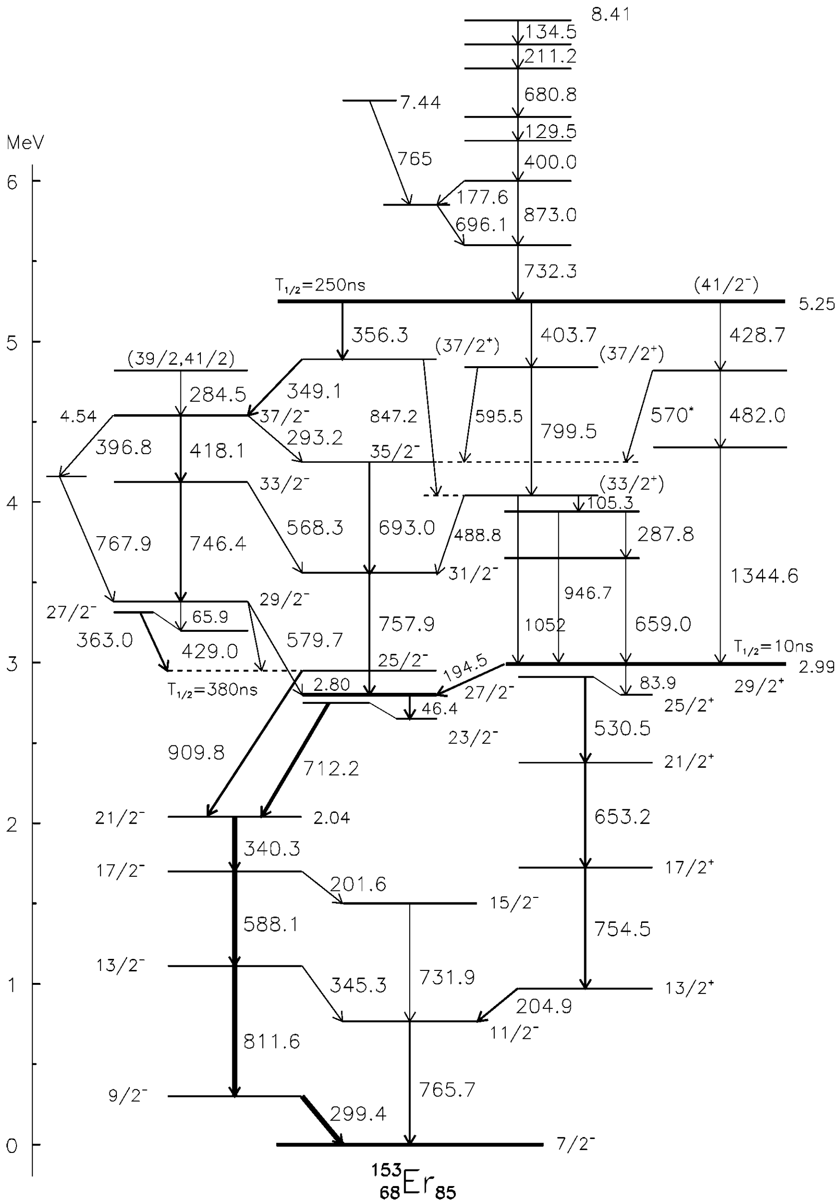


**Fig. 1.** Level scheme of $^{153}$Er. The transitions marked * are seen in coincidence only

of the isomeric states in these $A \sim 150$ transitional rare earth nuclei a complementary study has been undertaken.

## 2 Experimental procedure

In this paper we report on new results obtained using the $^{144}$Sm+$^{14}$N reaction. The $^{153}$Er nucleus has been populated via the $^{144}$Sm($^{14}$N,p4n)$^{153}$Er channel. A $^{14}$N beam of 95 MeV was provided by the Grenoble variable energy cyclotron. Using a 250 $\mu$g.cm$^{-2}$ thin target of $^{144}$Sm isotopically enriched to 87%, deposited on a 470 $\mu$g.cm$^{-2}$ carbon backing, the $^{153}$Er nuclei were produced with a cross-section of 230 mb. The $\gamma$-rays were detected with a modular set-up made of six germanium (80%) Compton suppressed detectors, one X-ray detector and six hexagonal $BaF_2$ detectors [6]. Electrons were measured simultaneously by using an electron guide, the Betatronc [7], equipped with a cooled Si(Li) detector. For the present experiment, electrons emitted in a solid angle of 3% over $4\pi$ and in the $0-1$ MeV energy range were accepted by the selector. The Betatronc axis being perpendicular to the beam, the thin target was placed at 45° with respect to the beam direction. The thickness of the backing was carefully adjusted in order to stop the recoil products and minimize the effect on electron energy resolution. $\gamma$-$\gamma$ and $\gamma$-$e^-$ coincidence events, electron and $\gamma$ singles spectra were collected.

## 3 The level scheme of $^{153}$Er

The proposed level scheme in Fig. 1 mostly supports our previous version [2]. The new sequence 1344.6, 482.0, 428.7 keV confirms the existence of the isomeric state at 5248

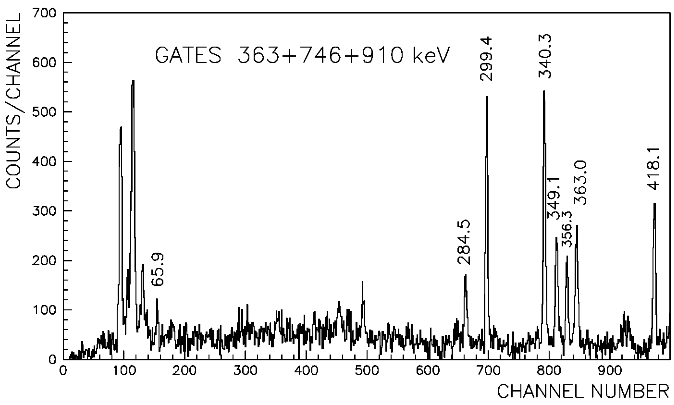


**Fig. 2.** Sum of coincidence spectra gated on the 363, 746 and 910 keV $\gamma$-rays

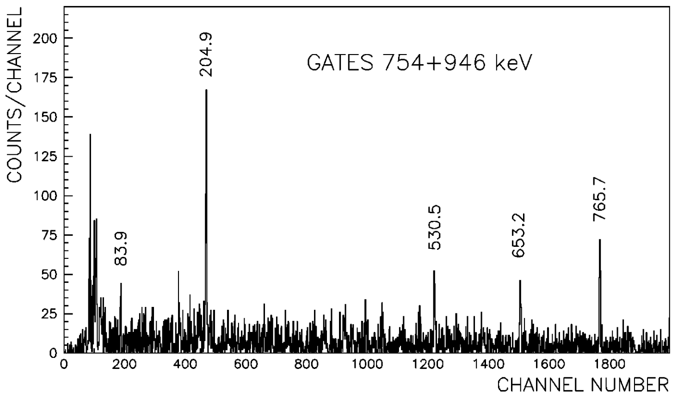


**Fig. 3.** Sum of coincidence spectra gated on the 754 and 946 keV $\gamma$-rays

keV. In addition, from a careful analysis of the coincidence data, the two transitions expected at 19.0+X and 37.5+X keV have been observed at 65.9 and 83.9 keV respectively. The $\gamma$-line at 65.9 keV is in coincidence with those of the sequence 910, 363, 746, 418, 349, 356 keV (Fig. 2) but not with the 429 and 580 keV transitions. The 83.9 keV transition is in coincidence with the $\gamma$-rays belonging to the positive-parity system as shown in Fig. 3.

The characteristics of the $T_{1/2} = 380$ ns isomeric state are fully established by the present work. Its excitation energy previously proposed at 2752+X in [2] is fixed at 2798.1 keV. It decays to the negative-parity states via a cascade of two transitions at 46.4 keV and 712.2 keV. The multipolarity of the isomeric transition whose energy is 46.4 keV was previously reported as M1 [1,2]. From the following arguments, we propose an E2 character for this transition :

- As the 46.4 and 712.2 keV transitions have the same intensity, i.e. 61% of the strongest one [2], a 46.4 keV line should appear in $\gamma$-spectra unless its total internal conversion cœfficients $\alpha_T$ is very large. For such an energy, $\alpha_T(M1) \simeq 4.5$ and $\alpha_T(E2) \simeq 70$. As we never observed any 46.4 keV $\gamma$-ray, a M1 multipolarity is excluded.
- The reduced transition probability for a 46.4 keV transition with $T_{1/2} \simeq 380$ ns is estimated to be $B$(E2)= 1.9 W.u. or $B$(M1)$\simeq 10^{-4}$ W.u. respectively. The $B$(E2) value is in good agreement with those already measured for isomers of $N = 82$ nuclei in this $A \sim 150$ region.

Assuming the isomeric half-life is due to the 46.4 keV transition, the 712 keV $\gamma$-ray cannot have an E3 nature as proposed in [3]. From the present electron data, using the 340 keV E2 transition as normalization, several conversion cœfficients have been estimated. The value $\alpha_K(712) = 0.012 \pm 0.005$ obtained for the 712 keV $\gamma$-ray is in agreement with the one previously reported $(0.0155 \pm 0.0018)$ [3]. It is still compatible with a M1 multipolarity which implies $I^\pi = 23/2^-$ for the 2752 keV excited state. From the E2 character of the 46.4 keV isomeric transition, spin and parity $I^\pi = 27/2^-$ are assigned to the long-lived $T_{1/2} \simeq 380$ ns isomer at 2798 keV.

The dipole character of the 194.5 keV transition [2] requires $I^\pi = 29/2^+$ for the $T_{1/2} \simeq 10$ ns isomeric state at 2993 keV. The newly identified 83.9 keV transition connects this isomer to the lower positive-parity states.

The existence of a third isomer ($T_{1/2} \simeq 250$ ns) reported previously [1,2] is confirmed by the present work. It is characterized by a complex deexcitation mode. About half of the intensity goes to the $21/2^-$ excited state at 2.04 MeV via a cascade of two transitions at 356.3 keV (M2) and 349.1 keV (E1) [2] leading to a $37/2^-$ level at 4.54 MeV whose the deexcitation is fragmented into three branches. The deexcitation of the $T_{1/2} \simeq 250$ ns proceeds also to the $T_{1/2} \sim 10$ ns, $29/2^+$ isomeric state at 2.99 MeV including a new parallel cascade (428.7, 482.0, 1344.6 keV). Spin and parity assignments, $I^\pi = (41/2^-)$, for the 5.25 MeV isomeric state are only tentative, as multipolarities are known only for the strongest $\gamma$-rays [2,3] [and present work].

An extension of the level scheme on top of this third isomer is shown in Fig. 1. The sequence is based on two transitions of 732 and 873 keV as already suggested in [1, 2]. The order of the other transitions is based on transition intensities estimated from $\gamma$-$\gamma$ coincidence data. The highest state observed has an excitation energy of 8.41 MeV.

## 4 Discussion

The $^{153}$Er level pattern exhibits many remarkable similarities with that of the $^{149}$Gd and $^{151}$Dy neighbouring $N = 85$ isotones having $Z \geq 64$, the collective character increasing with the proton number.

The positive-parity yrast structure of the $N = 84$, $^{152}$Er even core (Fig. 4) has been described with the $\nu(f^2_{7/2})$ configuration for levels from $0^+$ to $6^+$ and the $\nu(f_{7/2}h_{9/2})$ one for the $8^+$ isomeric state [8]. A $\pi(h^2_{11/2})_{10^+}$ has been proposed for the $10^+$ while the higher excited levels up to $16^+$ could correspond to the members of a $\nu(f^2_{7/2}) \otimes \pi(h^2_{11/2})_{10^+}$ multiplet [1] as discussed in more details in the frame of shell model calculations [9].

With three neutrons outside of the $N = 82$ closed shell, these $N = 85$ isotones show structures similar to those

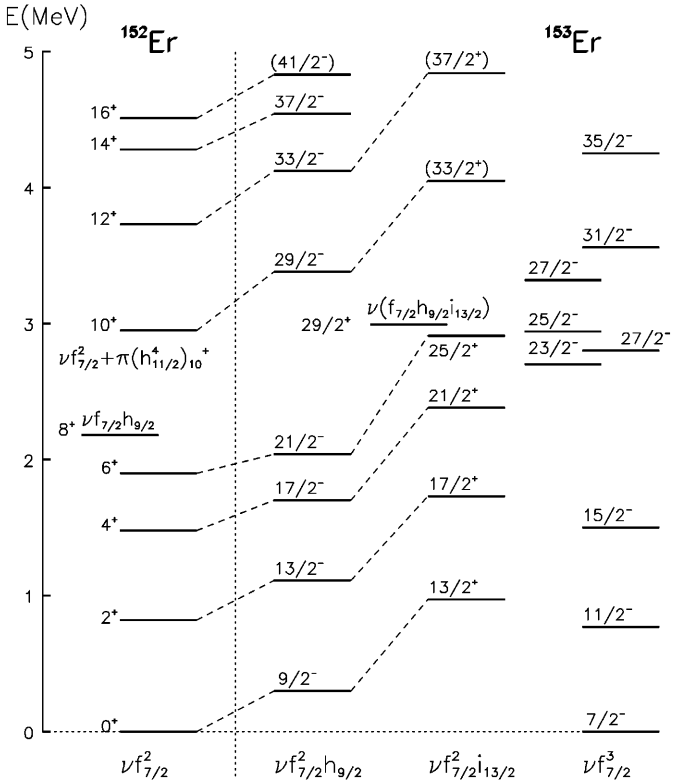


**Fig. 4.** Systematics of the states including the neutron components $\nu f^2_{7/2}$ and $\nu f^3_{7/2}$ in $^{152}$Er and $^{153}$Er nuclei from [1] and present work

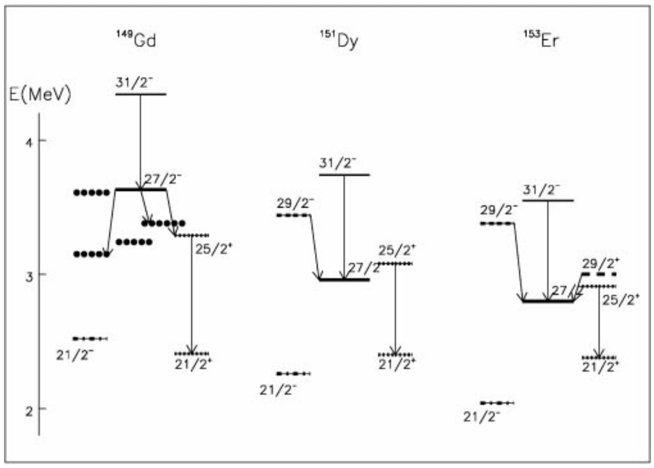


**Fig. 5.** Feeding and decay of the $27/2^-$ isomers in the N=85 isotones $^{149}$Gd, $^{151}$Dy and $^{153}$Er. Energies are taken in [12], [10] and present work

observed in spherical nuclei. Fig. 4 shows a comparison of levels and suggested configurations in $^{152,153}$Er. Single particle excitations in $^{153}$Er, are reproduced by the coupling of the valence neutrons to the $I^\pi = 0^+, 2^+, 4^+, 6^+$ sequence from the $\nu(f^2_{7/2})$ configuration of the $^{152}$Er core nucleus. The $I^\pi = 7/2^-$ ground state of $^{153}$Er has the configuration $\nu(f^3_{7/2})_{7/2}$. The $11/2^-$ and $15/2^-$ excited states are members of the $\nu(f^3_{7/2})$ multiplet. Similarly the $9/2^-$ excited state at 299 keV and the low-energy $13/2^-$, $17/2^-$, $21/2^-$ negative parity states are members of the $\nu(f^2_{7/2}h_{9/2})$ configuration. This description is similar to the one already proposed for the $^{151}$Dy [10] and $^{149}$Gd isotones [11]. In $^{153}$Er, the low-lying positive-parity state at 970.8 keV corresponds very likely to the $13/2^+$ level located at 968 keV in $^{151}$Dy. The $I^\pi = 17/2^+, 21/2^+, 25/2^+$ cascade built upon it is supposed to be described by the dominant $\nu(f^2_{7/2}i_{13/2})$ configuration [10], but a possible mixing with the $\nu(f^3_{7/2}) \otimes 3^-$ excitation is not excluded, as proposed for $^{149}$Gd [11].

In the three $N = 85$ isotones, a $27/2^-$ isomeric state has been identified at 3.63 MeV in $^{149}$Gd [12], 2.96 MeV in $^{151}$Dy [10] and 2.80 MeV in $^{153}$Er (Fig. 5). Though they exhibit very different decay modes inducing different half-lives, they have very likely a similar configuration $[\nu(f^3_{7/2})_{7/2^-} \otimes \pi(h^2_{11/2})_{10^+}]_{27/2^-}$, in agreement with the corresponding $10^+$ excitation energies observed in the even-even cores. The long half-life ($T_{1/2} \sim 380$ ns) observed for this isomer in $^{153}$Er, compared to those measured in the $^{149}$Gd and $^{151}$Dy isotones, is explained by its relative energy position only 46.4 keV above the $23/2^-$ excited state at 2751 keV and 110.7 keV below the $25/2^+$ excited state of the $\nu(f^2_{7/2}i_{13/2})$ multiplet. Its decay is also governed by the configurations of the states involved. From the schematic level structure reproduced in Fig. 5, one sees that the $23/2^-$ excited state in $^{153}$Er presents a specific behaviour. If one notes that the $B$(E2;46.4 keV, $27/2^- \rightarrow 23/2^-$) = 1.9 W.u. for $^{153}$Er is close to the value $B$(E2;63 keV,$10^+ \rightarrow 8^+$) = 0.25 W.u. measured for the $10^+$ isomeric state in $^{150}$Er [13], the $23/2^-$ excited state could correspond to a $\pi(h^4_{11/2})_{8^+} \otimes \nu(f^3_{7/2})_{7/2^-}$ configuration. However, considering the $\nu(f_{7/2}h_{9/2})$ character of the $8^+$ at 2183 keV in $^{152}$Er, a $\nu(f_{7/2}h^2_{9/2})$ configuration cannot be rejected.

At excitation energies higher than 2.8 MeV, the negative-parity states form two distinct level patterns (Fig. 4). The first group with $I^\pi = 27/2^-, 31/2^-, 35/2^-$ corresponds very likely to the members of the $\nu(f^3_{7/2}) \otimes \pi(h^2_{11/2})_{10^+}$ configuration while the second group of states with $I^\pi = 29/2^-, 33/2^-, 37/2^-$ and $41/2^{(-)}$ can be described by the multiplet $\nu(f^2_{7/2}h_{9/2}) \otimes \pi(h^2_{11/2})_{10^+}$.

The description of the positive-parity states is not obvious and the counterparts are missing in the $N = 85$ isotones. The $I^\pi = 29/2^+$, $T_{1/2} = 10$ ns state at 2993 keV can correspond to the alignment of three neutrons from the $f_{7/2}, h_{9/2}, i_{13/2}$ subshells. The existence of a multiplet based upon it with states $I^\pi = 33/2^+, 37/2^+$ is not clearly seen. In the isotone $^{149}$Gd the coupling of $\pi(h^2_{11/2})_{10^+}$ with the $\nu(f^2_{7/2}i_{13/2})$ neutron configuration has been proposed to explain the $I^\pi = 33/2^+$ excited state at 4719 keV which is the basis of a well developped multiplet [12].

The isomer $T_{1/2} \simeq 250$ ns at 5248 keV has very likely $I^\pi = 41/2^-$. It could be interpreted by the $\nu(f^2_{7/2}h_{9/2}) \otimes$

$\pi(h^2_{11/2})_{10^+}$ configuration, similarly to a possible counterpart at 5.63 MeV in $^{149}$Gd.

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