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Reinvestigation of the high spin states in ^{161}Er and enhanced E1 transitions in the N=93 isotones*

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Abstract: High-spin states in ^{161}Er have been studied experimentally using the ^{150}Nd(^{16}O, 5n) reaction at a beam energy of 86 MeV. The relatively enhanced E1 transitions between the $5/2^+$[642] and $3/2^-$[521] bands are observed in ^{161}Er, and the B(E1) values are extracted experimentally. The systematics of the R(E1) values in the $N=93$ isotones are presented. It is found that the strength of the E1 transitions obviously exhibits angular momentum dependence, and the occurrence of the relatively enhanced E1 transitions could be attributed to octupole softness.

Key words: high-spin state, E1 transition, angular momentum dependence, octupole softness

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1 Introduction

Low-energy electric-dipole (E1) transitions observed in nuclei are often strongly hindered, and the B(E1) values observed are typically 10^{-6} Weisskopf unit [1–3]. The small value of the E1 effective charge, relevant nuclear shell structure and pair-correlation effect have been proposed as a possible hindrance mechanism [1, 2]. However, relatively enhanced E1 transitions between two rotational bands with opposite parities in nuclei were observed experimentally [3, 4]. These relatively enhanced E1 transitions are supposed to be related to the octupole softness or deformation [2], which together with quadrupole deformation could lead to an enhanced electric dipole moment [2]. In the presence of octupole deformation, an electric dipole moment is produced in the intrinsic system due to a shift between the mass center of nucleus and the center of electric charge [2].

It is well known that nuclei in the light Ra-Th and heavy Ba-Sm regions exhibit strong E1 transitions, which are attributed to a static octupole deformation or octupole vibration [4]. On the other hand, relatively strong E1 transitions between two rotational bands with opposite parities in the well-deformed odd-A rare-earth nuclei were also reported [3]. Hamamoto et al. [1–3] systematically analyzed the low-energy E1 transitions in this mass region, and pointed out that the enhanced E1 transitions could be explained by taking into account the effect of the particle-octupole-vibration coupling. The E1 transitions connecting the pair of the $3/2^-$[521] and $5/2^+$[642] bands in nuclei with a neutron number around 93 were expected to be enhanced [1]. In fact, a number of strong E1 transitions were observed in the ^{163}Yb [5], ^{159}Dy [6, 7] and ^{157}Gd [8] isotones of ^{161}Er. Therefore, it is very interesting to search for the analogous E1 transitions in ^{161}Er with $N=93$.

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2 Experiment and results

The high-spin states in ^{161}Er were populated via the ^{150}Nd (^{16}O, 5n) reaction. The ^{16}O beam was provided by the HI-13 Tandem Accelerator at the China Institute of Atomic Energy in Beijing (CIAE). The beam energy was chosen to be 86 MeV, at which energy the yields of ^{161}Er were estimated to be large. The target was an isotopically enriched ^{150}Nd metallic foil of 1.5 mg/cm^2 thickness with a 10.8 mg/cm^2 Pb backing to stop the recoiling nuclei. X-γ-t and γ-γ-t coincidence measurements were performed with an array of eleven Compton-suppressed HPGe detectors and one Clover detector. To obtain multipolarity information for γ rays deexciting the oriented states, the detectors were divided into three groups, of which the angle positions (and detector number at that angle) were $\pm 42^\circ$ (5), $\pm 65^\circ$ (3), and 90° (4) with respect to the beam direction. The detectors were calibrated with standard ^{133}Ba and ^{152}Eu sources; the typical energy resolution was 2.0–3.0 keV at full width at half-maximum for the 1332.5 keV line from ^{60}Co. A total of 9.1×10^7 γ-γ coincidence events were recorded in experiment. After gain matching, these data were sorted into a 4k×4k symmetric E_γ-E_γ matrix and two ADO matrixes for off-line analysis. The ADO ratios for the known γ rays observed in this experiment were about 1.4 for stretched quadrupole transitions and 0.7 for stretched pure dipole transitions. Therefore, we have assigned the stretched quadrupole character and stretched dipole character to the transitions of ^{161}Er with anisotropy around 1.4 and 0.7, respectively.

Prior to this work, the rotational bands associated with the $5/2^+[642]$ and $3/2^-[521]$ configurations in

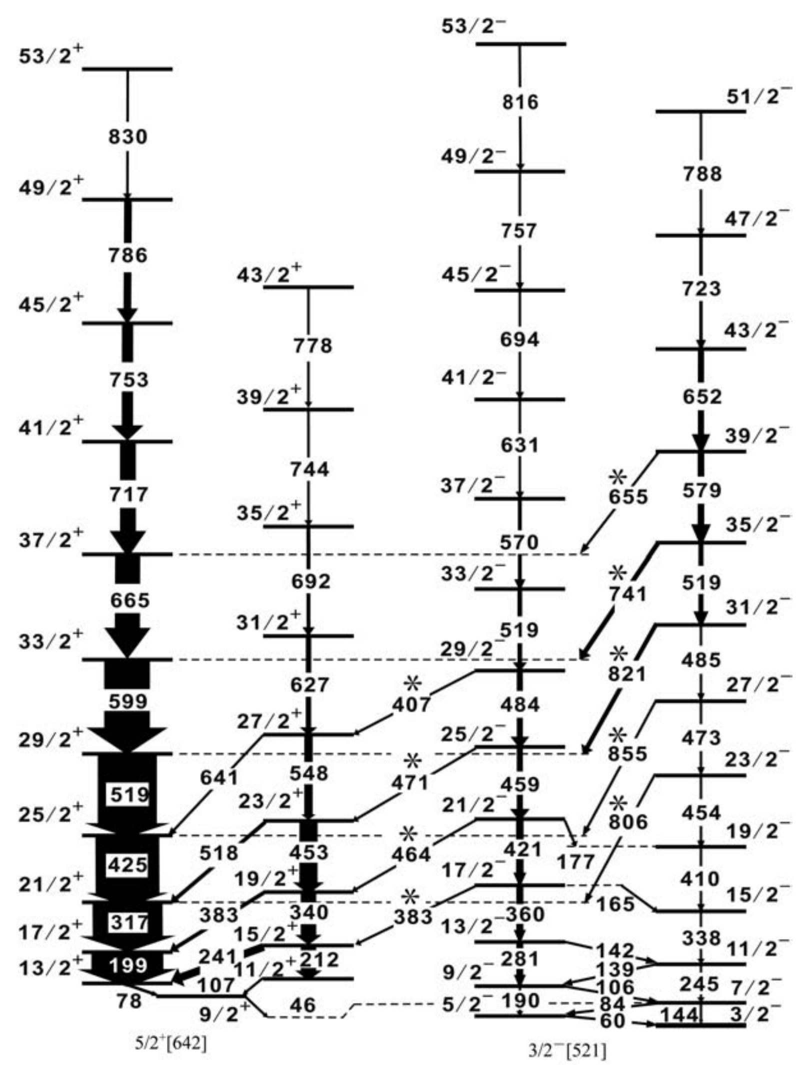

Fig. 1. Partial level scheme of ^{161}Er. The asterisks indicate the observed E1 transitions. The widths of the arrows indicate the relative transition intensities.

^{161}Er were established through decay studies and in-beam spectroscopic work [9–12]. In the present work, based on the analysis of γ-γ coincidence relationships, γ-ray relative intensities and γ-ray energy sums, a new level scheme for ^{161}Er has been proposed and presented in Fig. 1. The previously known $5/2^+[642]$ and $3/2^-[521]$ rotational bands are extended up to $53/2^+$ and $53/2^-$ states, respectively.

Importantly, nine E1 transitions of 382.8, 464.0, 470.5, 406.7, 806.3, 854.5, 821.5, 740.9, and 654.6 keV, linking the negative-parity $3/2^-[521]$ band and the positive-parity $5/2^+[642]$ band, are observed over a wide spin range. In the previous work [11], only the 464.0 and 470.5 keV E1 transitions were identified. Gated spectra showing the existence of the E1 transitions are presented in Fig. 2.

For the $\Delta I = 1$ transitions between the bands built on the $3/2^-[521]$ and $5/2^+[642]$ configurations, the branching ratios, which are defined as

$$\lambda = \frac{T_\gamma(I \to I-2)}{T_\gamma(I \to I-1)}, \tag{1}$$

were extracted for most transitions. Here $T_\gamma(I \to I-2)$ and $T_\gamma(I \to I-2)$ are the γ-ray intensities of the $\Delta I = 2$ and $\Delta I = 1$ transitions, respectively. These intensities are measured in a summed coincidence spectrum gated by the transitions above the state of interest. The branching ratios are used to extract the B(E1) values, which are defined as [13],

$$B(E1) = 7.63 \times 10^{-4} Q_t^2 \langle IK20 \,|\, I-2K \rangle^2 \times \frac{1}{\lambda} \frac{E_\gamma(I \to I-2)^5}{E_\gamma(I \to I-1)^3} (e^2\mathrm{fm}^2), \tag{2}$$

where Q_t is the quadrupole moment, and $E_\gamma(I \to I-2)$ and $E_\gamma(I \to I-1)$ are the $\Delta I = 2$ and $\Delta I = 1$ transition energies, respectively. In the present calculation, a constant quadrupole moment of 7.01 eb is used [10]. The deduced B(E1) values are listed in Table 1.

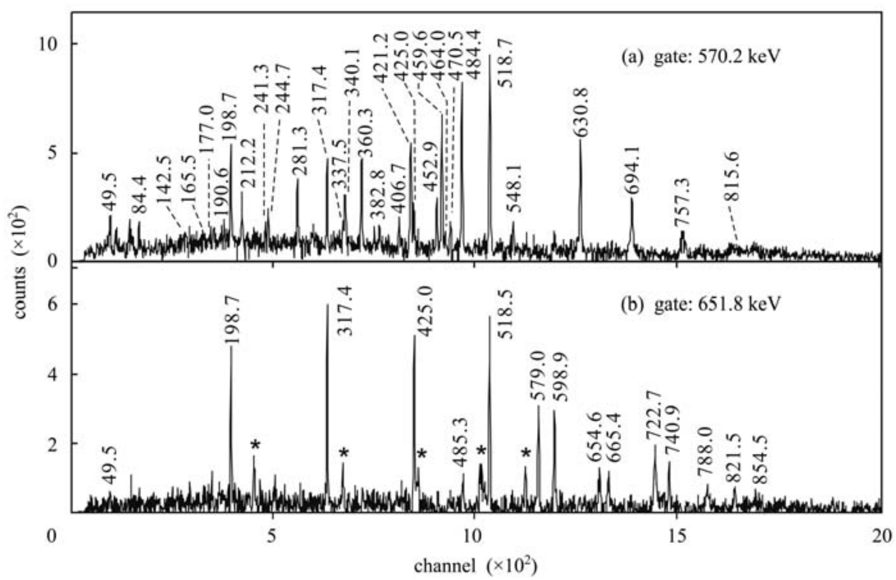

Fig. 2. The γ-ray spectra gated on the 570.2 keV transition (a) and 651.8 keV transition (b). The asterisks indicate the contaminations mainly from ^{162}Er.

Table 1. Experimental λ, B(E1) and R(E1) values obtained in the present work.

E_γ/keV	$I_i^\pi/\hbar$	$I_f^\pi/\hbar$	$\lambda^{a)}$	$B(\mathrm{E1})/(10^{-4}e^2\mathrm{fm}^2)$	$R(\mathrm{E1})/10^{-2}$
382.8	$17/2^-$	$15/2^+$	8.91(13)	1.4(2)	3.8(3)
464.0	$21/2^-$	$19/2^+$	5.85(22)	2.7(6)	4.8(5)
806.3	$23/2^-$	$21/2^+$	1.39(36)	3.2(12)	5.1(9)
470.5	$25/2^-$	$23/2^+$	5.22(15)	4.7(5)	5.9(3)
854.5	$27/2^-$	$25/2^+$	0.63(27)	7.6(20)	7.4(10)
406.7	$29/2^-$	$27/2^+$	5.17(16)	9.8(15)	8.2(6)
821.5	$31/2^-$	$29/2^+$	0.45(22)	13.9(30)	9.6(10)
740.9	$35/2^-$	$33/2^+$	1.05(12)	11.4(14)	8.5(5)
654.6	$39/2^-$	$37/2^+$	2.68(22)	11.3(24)	8.3(9)

a) Branching ratio: $T_\gamma(I\to I-2)/T_\gamma(I\to I-1)$. $T_\gamma(I\to I-2)$ and $T_\gamma(I\to I-1)$ are the relative γ intensities of the E2 and E1 transitions depopulating the same level, respectively.

3 Discussion

In the previous work [10–12], the band properties in ^{161}Er were well studied. The E1 transitions from the $3/2^-[521]$ band to the $5/2^+[642]$ band in ^{161}Er are observed in the present work, and therefore we concentrate on the discussion of the E1 transitions. The occurrence of a relatively enhanced E1 transition is a general phenomenon in the well-deformed rare-earth region [3, 5–8]. Enhanced E1 transitions between the $3/2^-[521]$ and $5/2^+[642]$ bands were observed in the ^{163}Yb, ^{159}Dy, and ^{157}Gd isotones of ^{161}Er [5–8]. The experimental B(E1) values are in the order of or larger than $10^{-4}e^2\text{fm}^2$. Therefore, it is necessary to systematically analyze the E1 transitions in the $N=93$ isotones.

If the Alaga rule holds for the E1 transition, the B(E1) value can be expressed as

$$B(\text{E1})=\{\langle I_\text{i}K_\text{i}1K_\text{f}-K_\text{i}\,|\,I_\text{f}K_\text{f}\rangle M(\text{E1})\}^2, \qquad (3)$$

where M(E1) is the matrix element, and it should be a constant [14]. However, the matrix elements deduced experimentally break this rule, and exhibit angular momentum dependence [14]. Bohr and Mottelson pointed out that the effect of the Coriolis interaction should be considered as an important factor for the angular momentum dependence [14]. They proposed that the B(E1) values follow the generalized intensity relation below [14],

$$\begin{aligned}B(\text{E1}) &= \{M_1+M_2[I_\text{f}(I_\text{f}+1)-I_\text{i}(I_\text{i}+1)]\}^2\\ &\quad\times\langle I_\text{i}K_\text{i}1K_\text{f}-K_\text{i}\,|\,I_\text{f}K_\text{f}\rangle^2, \qquad (4)\end{aligned}$$

where M_1 and M_2 are the I-independent and leading order I-dependent intrinsic E1 matrix elements, respectively. The value of M_2 reflects the Coriolis interaction and/or the probable contribution from the octupole correlation [14]. In order to compare the experimental B(E1) values with Eq. (4), the generalized intensity relation is written as the following formula [14],

$$\begin{aligned}R(\text{E1}) &= \left[\frac{B(\text{E1})/B_{\text{W.U.}}(\text{E1})}{\langle I_\text{i}K_\text{i}1K_\text{f}-K_\text{i}\,|\,I_\text{f}K_\text{f}\rangle^2}\right]^{1/2}\\ &= M_1+M_2[I_\text{f}(I_\text{f}+1)-I_\text{i}(I_\text{i}+1)], \qquad (5)\end{aligned}$$

where, $B_{\text{W.U.}}$(E1) is set as $A^{2/3}/15.5$ [15]. For ^{161}Er, the $B_{\text{W.U.}}$(E1) value is equal to $1.91\,e^2\text{fm}^2$. The R(E1) values are thus calculated and listed in Table 1. The R(E1) values in the N=93 isotones are presented as a function of $I_\text{f}(I_\text{f}+1)-I_\text{i}(I_\text{i}+1)$ in Fig. 3. The R(E1) values obviously exhibit angular momentum dependence. The M_1 and M_2 parameters in Eq. (5) are deduced by fitting the data points before the band crossing with a straight line. It is important to note that the parameter M_2 is not equal to zero. Therefore, there is a substantial mixing between the initial and final states. This admixture could lead to enhanced E1 transitions [14]. The admixture might result from the octupole correlation [14].

In order to have a deeper understanding of the enhanced mechanism of the low-energy E1 transitions in the well-deformed odd-A rare-earth nuclei, a model of one quasiparticle coupled to an axially symmetric rotor was employed to estimate the E1 strength [1–3].

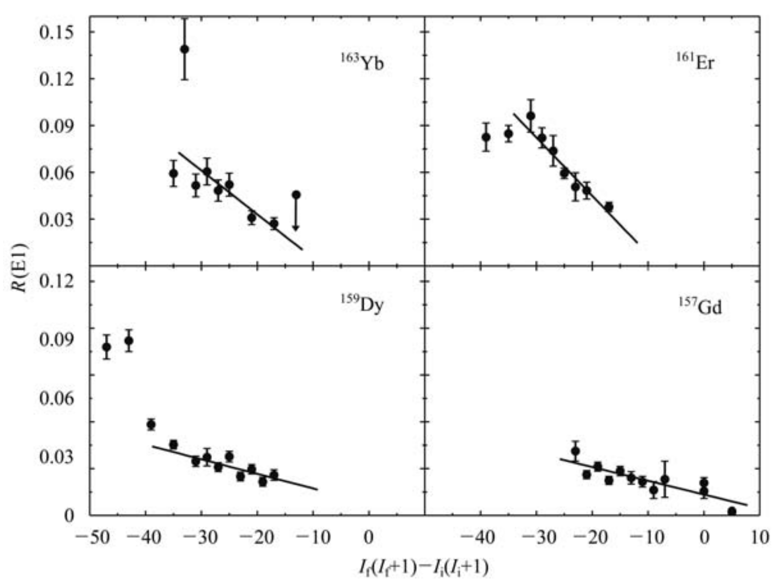

Fig. 3. Experimental R(E1) values as a function of $I_\text{f}(I_\text{f}+1)-I_\text{i}(I_\text{i}+1)$ for the $3/2^-[521]$ band in ^{163}Yb, ^{161}Er, ^{159}Dy, and ^{157}Gd. For ^{163}Yb, the first data point is not used in the fitting since the E1 transition intensity is contaminated by other γ rays.

Although the reasonable values of E1 effective charge, sufficiently large single-particle space, pair-correlation effect, and all important matrix elements of the Coriolis coupling are taken into account in the model, the calculated B(E1) values are at least one order of magnitude smaller than the experimental ones [1, 3]. Since the measured magnitudes of B(E1) values could not be reproduced with the standard E1 transition operator, the following E1 transition operator effectively taking into account the octupole softness was proposed [1, 3],

$$O(\mathrm{E1},\nu) = e_{\mathrm{eff}}(\mathrm{E1}) r Y_{1\nu} + e b_{\nu} r^3 Y_{3\nu}. \quad (6)$$

The second term on the right hand side of Eq. (6) can cause an enhancement of the E1 transition strength. If the parameters b_0 and $b_{\pm1}$ are chosen properly, satisfactory agreement between the measured and calculated B(E1) values can be obtained [1, 3]. However, the b_ν values depend on nuclei, and are sensitive to the pairs of bands studied [2, 3]. Furthermore, the b_ν values necessary for reproducing experimental data could not be obtained using microscopic models [2, 3].

4 Summary

The well-deformed nucleus ^{161}Er was produced in the bombardment of ^{150}Nd target with the ^{16}O projectiles. The previously known $5/2^+[642]$ and $3/2^-[521]$ bands have been extended up to $53/2^+$ and $53/2^-$, respectively. Importantly, nine relatively enhanced E1 transitions from the negative-parity $3/2^-[521]$ band to the positive-parity $5/2^+[642]$ band are observed, and the B(E1) values in ^{161}Er are extracted experimentally. The systematics of the E1 transitions strength between the $3/2^-[521]$ and $5/2^+[642]$ bands in the $N=93$ isotones are presented. It is found that the strength of the E1 transitions obviously exhibits angular momentum dependence, and the relatively enhanced E1 transitions could be attributed to octupole softness.

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