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Search for Entrance- and Exit-Channel Effects and the Suppression of Neutron Emission from the Decay of the Compound Nucleus ^{156}Er*

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Abstract. High angular momentum components have been found in the cross-section for ^{64}Ni + ^{92}Zr $\rightarrow$ ^{156}Er* by gamma-ray spectroscopy. They are expected to influence the known low evaporation neutron multiplicity, which is due to a predicted strong population of superdeformed states. The obtained gamma lines are consistent with a recently proposed level scheme of ^{154}Er obtained by a different reaction. The static and dynamic moments of inertia θ_1 and θ_2 for the Erbium isotopes are calculated. The value of θ_2 agree with cranked structinsky calculations. In the region N = 88 - 102 the moments of inertia are nearly constant in the heavy Er-isotopes, but in the lighter isotopes the moments of inertia are rising with decreasing neutron number. It is instructive to compare the inertial parameter of even isotopes of Erbium with those of Dysprosum isotopes.

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1 Introduction

Some years ago the discovery of superdeformation (SD) in fission isomers of the actinide region [1], still has many open questions. One of them is the well established fact that statistical model calculations systematically overpredict neutron-emission probabilities from some compound nuclei in the rare-earth region [1,2]. This feature seems to be more pronounced for mass-symmetric entrance channels. For example, in the fusion of ^{64}Ni + ^{92}Zr, neutron emission is suppressed [3], such shapes have been found at high spins in both heavy and light rare-earth regions, and due to a shell effect while the reduced Coulomb repulsion further stabilizes the SD shape in the former case, it is the centrifugal force which plays that role at high spins in the latter.

In the present paper, we report on a systematic investigation of the yrast band in even-even ^{156}Er to ^{170}Er [12-20], *i.e.* in a series of Er isotopes ranging from the transitional nucleus ^{156}Er to the well deformed ^{170}Er. New results were reported concerning the alignment and the moments of inertia of the yrast band. For the ν [i $_{13/2}$] configuration in the even-A Er isotopes, it is observed that the inertial parameter decreases with increasing neutron number, and this is probable that a pair of i$_{13/2}$ neutron is being to align in this region.

2 Data Analysis and Discussion

Statistical model calculations over-estimate the experimentally observed average multiplicity of the evaporated neutrons during the decay of the compound nucleus ^{156}Er* formed by the reaction ^{64}Ni + ^{92}Zr [1]. On the other hand, conformity between statistical model calculations and experimental results was established for the number of neutrons evaporated from the same nuclei which, however, had been induced by a different entrance channel ^{12}C + ^{144}Sm [4]. A similar behaviour was measured for the ratio between two-and three-neutron evaporation at a given excitation energy and spin. Statistical model calculations can account for the data in the C-induced reaction, while large deviations are observed at angular momenta above 25 for the Ni-induced reaction [2].

The remarkable neutron suppression of the more symmetric system remains up to the present a puzzling phenomenon which has been proved not to be simply attributed to anomalously large neutron energies, large gamma-decay widths or uncertainties in the location of the yrast line [2,4,5]. The assumption of high angular momentum components in the cross-section for ^{64}Ni + ^{92}Zr $\rightarrow$ ^{156}Er* as an explanation of the observed inhibition of neutron emission [6] could not be supported by the data of a recently performed fusion cross-section measurement and beyond that the evaporation cross-section is not expected to be substantially influenced by such high angular momentum tails [7].

Since none of the above mentioned pictures have supplied consistency with the observed neutron suppression, extraordinary explanations were proposed assuming that a part of the internal excitation energy of the compound nucleus was given by deformation [2,5,7]. Thereby the compound nucleus is supposed to gradually develop from a highly elongated initial shape within a time comparable to neutron emission (10^{-14}–10^{-17} s). The duration of this slow relaxation process could possibly be attributed to either a trapping of the compound nuclei in a superdeformed well [5] or some unknown dynamic mechanism during the deexcitation of the nucleus [7]. Calculations taking superdeformation into account by using elevated yrast lines reduce the deviations between experimental and predicted neutron multiplicity. Moreover, theory predicts for various nuclei in the rare earth region, among them ^{154}Er, the existence of potential minima corresponding to superdeformed shapes and in some of the neighbouring nuclei superdeformed discrete line bands have been discovered [8-10]. However, the observed intensities of the population of superdeformed states in these nuclei affect only about 1% of the concerning evaporation channels, while the strength of transitions in the assumed superdeformed band which ought to account for the neutron suppression in the ^{64}Ni + ^{92}Zr system would have to occupy nearly the entire 2n-channel.

In order to gather more information about the validity of this picture assuming such a strong population of superdeformed states, we carried out an investigation on high spin states in ^{154}Er [3]. It proved to be an excellent tool for clearing data of events which did not originate from the deexcitation of ^{154}Er. Figure 1 shows the coincidence spectrum for selected ^{154}Er γ-rays [3]. We compared therefore our spectrum with a proposed level scheme of the nucleus ^{154}Er [11]. No significant differences between the two systems ^{64}Ni + ^{92}Zr and ^{40}Ar + ^{118}Sn were observed up to at least a state with $I = 36\hbar$. This does not support the above picture in which neutron suppression is supposed to be due to entrance-channel effect.

It is interesting to compare the data in even ^{156}Er to ^{170}Er [13-20] for the observed superdeformed bands. These nuclei have been chosen because they show a large similarity in the structure of the yrast lines. Since these nuclei have been performed at similar excitation energies and angular momenta, these comparisons suggest that the feeding mechanisms in and out the superdeformed bands are similar in these nuclei.

It is instructive to compare the inertial parameters of the even - even Er-isotopes (Figure 2) at spin steps $I = 4, 6, 8, \ldots$ with those of the neighbour isotones Dy nuclei (Figure 3). In this connection it should be remembered that the effective moment of inertia is increased above the core value through the Coriolis coupling between the quasiparticle states and it seems unlikely that it can account for the Er- Dy nuclei staggering of a factor of 2 or more observed in the Er case (Figure 2). Therefore it appears likely that a major contribution comes from a difference in shape between them.

It is now interesting to drive the static and dynamic moments of inertia θ_1 and θ_2 for all the superdeformed bands in $^{156-170}$Er nuclei [13-20]. The energy of the rotor can be expressed either in terms of the angular momentum

$$E_{\text{rot}}(I) = \frac{\hbar^2}{2\theta} I(I+1),$$

or in terms of the rotational frequency, ω,

$$E_{\text{rot}}(\omega) = \frac{1}{2}\theta\omega^2\ .$$

Derivation from rigid-rotor behavior can be expressed as an expansion in $I(I+1)$

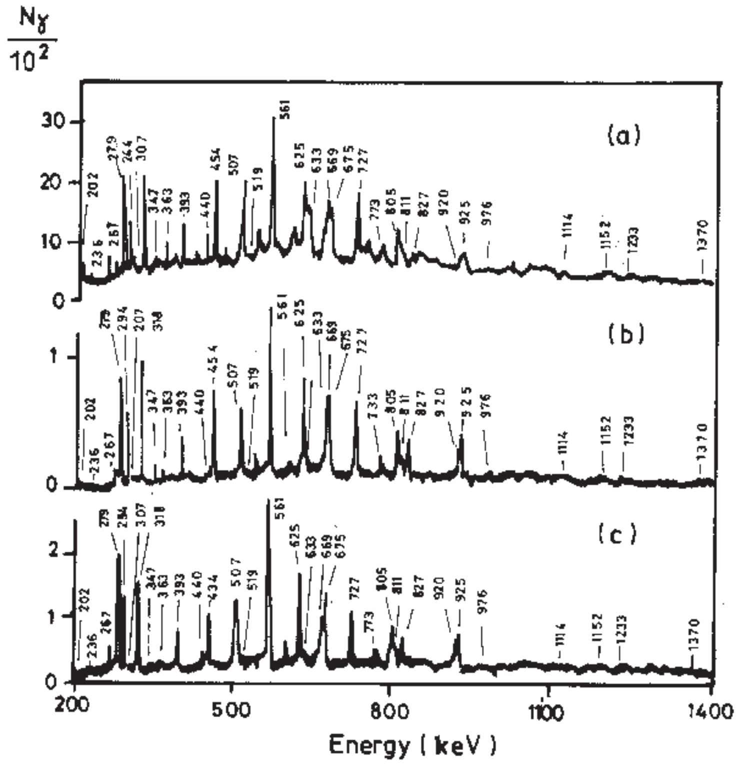

Figure 1. Coincidence spectra for selected ^{154}Er γ-ray ref. [3] (a) total projection; (b) total γ-ray spectrum gated on the scintillator; (c) sum of eight gates corresponding to known transitions in ^{154}Er.

or in ω^2; the relationship between these is just

$$\theta\omega = \hbar I(I+1)^{1/2}\,.$$

To relate ω to rotational transition energy, E_γ, we have

$$\hbar\omega = \frac{E_{\text{rot}}}{I}\,\frac{1}{2}[E_{\text{rot}}(I+1) - E_{\text{rot}}(I-1)] \cong \frac{E_\gamma}{2}\,,$$

where the right side is specifically for the collective stretched $(I+1 \to I-1)$ quadruple transitions. It can also be related to the angular momentum

$$E_\gamma = \frac{\hbar^2}{2\theta}(4I-2)\,, \tag{1}$$

where $\theta = \theta_1$ is the static moment of inertia and is given by the relations

$$\theta_1 = \frac{(2I-1)\hbar^2}{E_\gamma}. \tag{2}$$

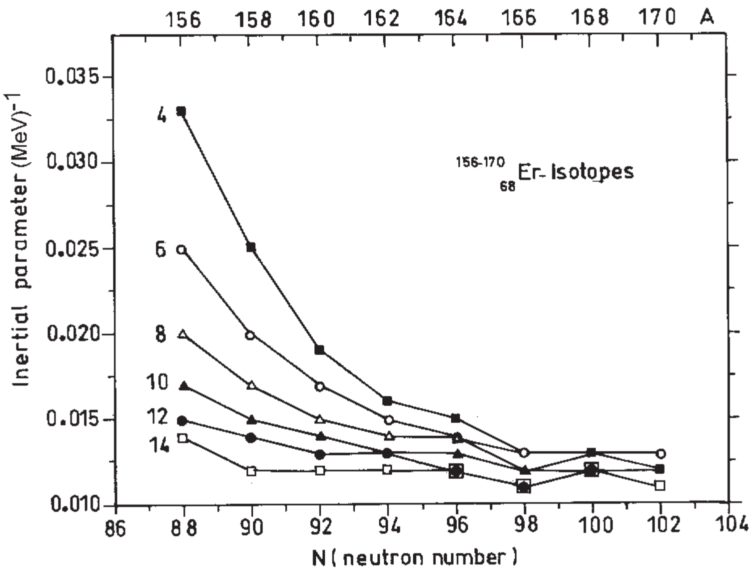

Figure 2. Moment of inertia parameters (MeV^{-1}) as a function of neutron number for isotopes of Erbium ($Z = 68$).

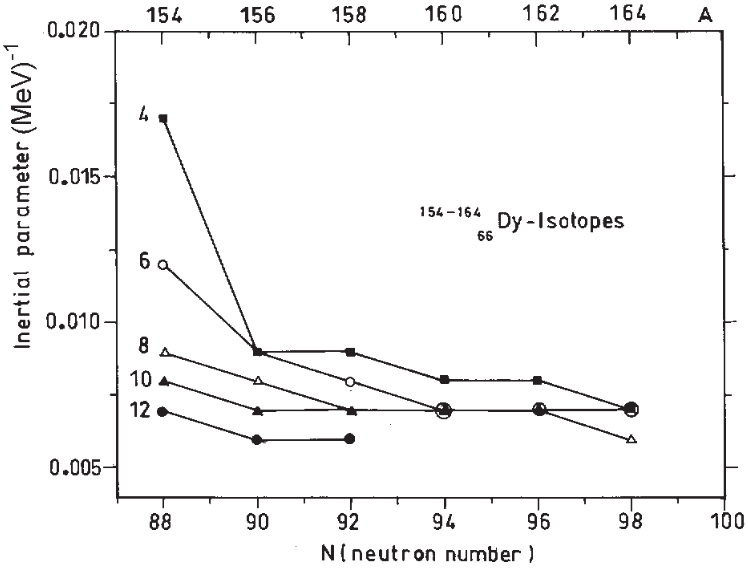

Figure 3. The same as in Figure 2 but for the isotopes of Dysprosum ($Z = 66$).

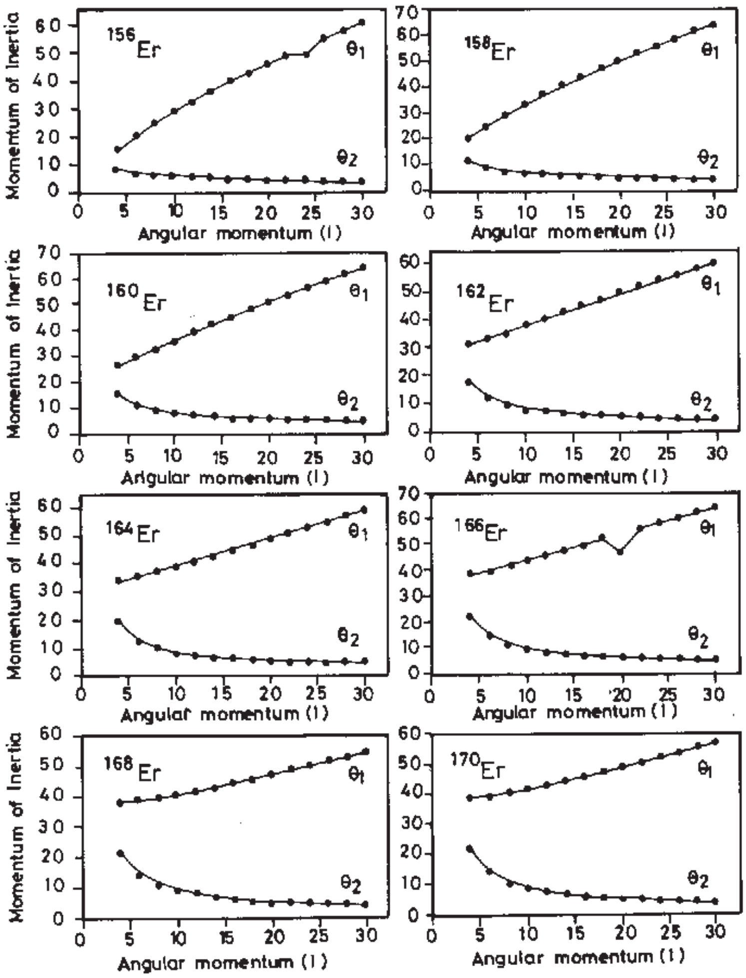

Figure 4. The static θ_1 (MeV^{-1}) and dynamic θ_2 (MeV^{-1}) moments of inertia for the superdeformed band in $^{156-170}$Er nuclei as a function of spin ($\hbar$).

From Eq. (1), an expression is derived for stretched E2-transitions

$$\Delta E_\gamma = \frac{8\hbar^2}{2\theta} - 2E_\gamma \frac{d\ln\theta}{dI}.$$

For a reasonably constant moment of inertia this becomes

$$\Delta E_\gamma = \frac{8\hbar^2}{2\theta},$$

where $\theta = \theta_2$ is the dynamic moment of inertia and is given by

$$\theta_2 = \frac{4\hbar^2}{\Delta E_\gamma}. \tag{3}$$

Equations (2) and (3) used to calculate the static and dynamic moments of inertia for the $^{156-170}$Er nuclei (Table 1) are presented in Figure 4. Similarities as well as striking can be seen. In all nuclei, the values of θ_2 become essentially constant at the highest spin and have values very close to each other. The value measured for θ_1 is somewhat higher and is in agreement with calculations by Chasman, where the drop in the value of θ_2 is due to a smaller deformation. The striking difference in the general behavior of θ_1 and θ_2 should, however, also be pointed out. Furthermore, while θ_1 is seen to increase and θ_2 to decrease with spin. In all nuclei, the shell corrections as a function of spin remain essentially unchanged. An alternative explanation for the decrease invokes residual pairing [9,25].

Table 1. Static θ_1 and dynamic θ_2 moments of inertia for the corresponding spin in the $^{156-170}$Er nuclei

Spin	E_γ	θ_1	θ_2	Spin	E_γ	θ_1	θ_2	Spin	E_γ	θ_1	θ_2	Spin	E_γ	θ_1	θ_2
^{156}Er				^{158}Er				^{160}Er				^{162}Er			
4	460	15.22	8.70	4	344	20.35	11.63	4	266	26.32	15.04	4	229	30.97	17.70
6	541	20.33	7.39	6	440	25.55	9.09	6	375	29.33	10.67	6	334	32.93	11.98
8	606	24.75	6.60	8	513	29.24	7.80	8	459	32.68	8.72	8	427	35.13	9.37
10	657	28.92	6.59	10	573	33.16	6.98	10	531	35.78	7.53	10	506	37.55	7.91
12	704	32.67	5.68	12	623	36.92	6.42	12	590	38.98	6.78	12	577	39.86	6.93
14	744	36.29	5.38	14	668	40.42	5.99	14	644	41.93	6.21	14	638	42.32	6.27
16	781	39.69	5.12	16	708	43.74	5.65	16	691	44.86	5.79	16	694	44.67	5.76
18	815	42.95	4.91	18	744	47.04	5.38	18	734	47.68	5.45	18	745	46.98	5.37
20	845	46.15	4.73	20	778	50.13	5.14	20	774	50.39	5.17	20	791	49.31	5.06
22	874	49.20	4.58	22	808	53.22	4.95	22	810	53.59	4.94	22	835	51.50	4.79
24	961	48.91	4.16	24	838	56.09	4.77	24	845	55.62	4.73	24	875	53.71	4.57
26	927	55.02	4.32	26	865	58.96	4.62	26	876	58.22	4.57	26	913	55.86	4.38
28	951	57.83	4.21	28	891	61.73	4.44	28	907	60.64	4.41	28	948	58.02	4.22
30	974	60.58	4.11	30	916	64.41	4.37	30	935	63.10	4.28	30	983	60.02	4.07
^{164}Er				^{166}Er				^{168}Er				^{170}Er			
4	207	33.82	19.32	4	184	38.04	21.74	4	184	38.04	21.74	4	183	38.25	21.86
6	313	35.14	12.78	6	280	39.29	14.29	6	285	38.60	14.04	6	281	39.15	14.24
8	407	36.86	9.83	8	366	40.98	10.93	8	379	39.58	10.55	8	373	40.22	10.72
10	492	38.62	8.13	10	444	42.79	9.01	10	469	40.51	8.53	10	460	41.30	8.70
12	566	40.64	7.07	12	513	44.83	7.80	12	552	41.67	7.25	12	540	42.60	7.41
14	634	42.59	6.31	14	576	46.88	6.94	14	628	42.99	6.37	14	613	44.05	6.53
16	695	44.60	5.76	16	633	48.97	6.32	16	701	44.22	5.71	16	681	45.52	5.87
18	751	46.61	5.33	18	686	51.02	5.83	18	767	45.63	5.22	18	745	46.98	8.37
20	803	48.57	4.98	20	734	46.32	5.45	20	830	46.99	4.82	20	805	48.45	4.97
22	851	50.53	4.70	22	780	55.13	5.13	22	884	48.37	4.50	22	859	50.06	4.66
24	896	52.46	4.46	24	821	57.25	4.87	24	944	49.79	4.24	24	912	51.53	4.39
26	939	54.31	4.26	26	862	59.17	4.64	26	996	51.21	4.02	26	961	53.07	4.16
28	978	56.24	4.09	28	899	61.18	4.45	28	1047	52.53	3.82	28	1007	54.62	3.97
30	1015	58.13	3.94	30	934	63.17	4.28	30	1093	53.98	3.66	30	1052	56.08	3.80

3 Conclusion

In summary, no confirmative observations due to a strong population of superdeformed states affecting almost the entire 2n-channel of the Ni-induced compound nucleus $^{156}\mathrm{Er}^{*}$ have been seen.

This does not support the idea of the known neutron suppression in the Ni-induced reaction being due to an entrance-channel effect. From the calculations in the studied regions ($N = 88$–102) the moments of inertia are nearly constant in the heavy Er-isotopes, but in the lighter isotopes the moment of inertia is rising with decreasing neutron number. Finally the inertial parameter of even Er-isotopes are compared with those of Dy-isotopes. It seems unlikely that it can be account for the Er-Dy nuclei staggering of a factor 2 or more observed in the Er case.

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