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LETTER TO THE EDITOR

Lifetimes of high spin rotational states

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Abstract. Lifetimes have been measured for Coulomb excited states with $8^+ \leqslant J^\pi \leqslant 12^+$ in even A isotopes of Dy, Er and Yb. A significant retardation in E2 transition rates for the decay of 12^+ states in ^{160}Dy, ^{162}Dy and ^{164}Er is observed.

It is now well established that certain rotational nuclei undergo a sudden increase in their moments of inertia at high spin values. This so-called back-bending effect has recently been reviewed by Johnson and Szymanskii (1973) and Sorensen (1973). Two theoretical approaches have been proposed, one originally due to Mottelson and Valatin (1960) being associated with a phase transition from a superconducting to a normal state, while the other due to Stephens and Simon (1972) involves the decoupling of a pair of neutrons from the core and their alignment in the direction of the rotational axis.

For a full understanding of what is happening in these nuclei it is insufficient to determine the excitation energies of the states alone. Relevant parameters which can supply additional information include nuclear radii, static moments and reduced electric quadrupole transition probabilities.

To date the only published information that exists on the properties of these states, other than their excitation energies, is reduced transition probabilities for ^{158}Er levels derived from lifetime measurements following (HI,xn) reactions (Ward *et al* 1973). Unfortunately, the accuracy of these measurements is limited by the long feeding times (typically several picoseconds) inherent in (HI, xn) reactions.

The advent of heavy-ion beams of sufficient energy has opened up the possibility of Coulomb exciting high spin rotational states, and the large recoil velocities produced by these reactions facilitate the measurement of the lifetimes of such states using Doppler shift techniques. These advantages have been utilized to make a systematic survey of the lifetimes of 8^+, 10^+, and 12^+ states in a number of stable rare-earth nuclei.

Using thick enriched metallic targets high spin states in even Dy, Er and Yb isotopes have been excited with Fe and Kr beams at bombarding energies of 4·14 MeV/nucleon. The bombarding energies used, although close to the Coulomb barrier in these nuclei, were sufficiently low for Coulomb excitation theory to be valid. Singles γ-ray spectra were detected at 0° and 90° with respect to the beam, and lifetimes have been determined from the Doppler-broadened lineshapes observed at 0°. In calculating the lineshapes the electronic contribution to the stopping power was taken from the tabulation of Northcliffe and Schilling (1970) and the nuclear part

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was obtained from the Lindhard model (Lindhard *et al* 1963). Preliminary estimates of the lifetimes were made using recoil particle angular distributions calculated with the multiple Coulomb excitation program of Winther and de Boer (1966) with matrix elements predicted by the simple rotor model. The matrix elements deduced from these lifetimes were then inserted in the Coulomb excitation program and the whole process iterated. The shapes of the angular distributions were found to be only weakly dependent on the matrix elements used. The effect of feeding from higher states was included in the calculations. Fits for lineshapes in ^{166}Er are given in figure 1. In order to check the accuracy of the method an independent measurement of the lifetime of the 8^+ state in ^{166}Er was made using the recoil distance technique, and gave a result of 6·9 ± 0·4 ps compared with 7·45 ± 0·7 ps obtained from the lineshape analysis.

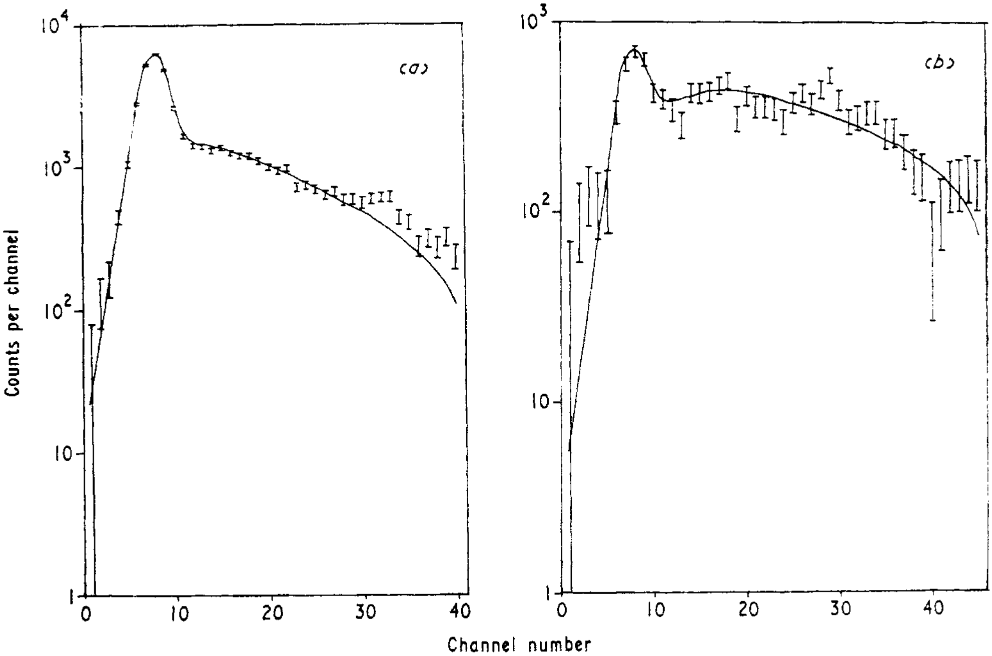

Figure 1. Fitted γ-ray lineshapes taken at 0° for (*a*) $10^+ \rightarrow 8^+$ and (*b*) $12^+ \rightarrow 10^+$ transitions in ^{166}Er.

The data obtained for the decay of 8^+, 10^+ and 12^+ states in Dy, Er and Yb isotopes are given in table 1. In addition results for the decay of the 14^+ state in ^{164}Dy are included. The errors quoted take account of uncertainties in background subtraction and stopping power data, and in all cases are substantially larger than the purely statistical errors. The B(E2) values are expressed as ratios to the predictions of the symmetric rotor model when normalized to the decay of the corresponding 2^+ states.

The values of B(E2) for the decay of 8^+ and 10^+ states are all found to be close to, though on average slightly less than, the rotational predictions. However, in $12^+ \rightarrow 10^+$ transitions some significant deviations from these predictions are observed. The ratio $B(\mathrm{E2})/B(\mathrm{E2})_{\mathrm{rot}}$ for the decay of 12^+ states is plotted as a function of neutron number in figure 2. It is seen that the three nuclei studied with $N \leqslant 96$ have hindered E2 transition rates while the nuclei with $N \geqslant 98$ all have values closer to the rotational predictions.

Table 1.

Nucleus	$8^+ \to 6^+$		$10^+ \to 8^+$		$12^+ \to 10^+$		$14^+ \to 12^+$	
	τ (ps)	$\frac{B(\mathrm{E2})}{B(\mathrm{E2})_{\mathrm{rot}}}$	τ (ps)	$\frac{B(\mathrm{E2})}{B(\mathrm{E2})_{\mathrm{rot}}}$	τ (ps)	$\frac{B(\mathrm{E2})}{B(\mathrm{E2})_{\mathrm{rot}}}$	τ (ps)	$\frac{B(\mathrm{E2})}{B(\mathrm{E2})_{\mathrm{rot}}}$
^{160}Dy	5·9±0·6	0·91±0·09	2·39±0·24	0·92±0·09	1·60±0·17	0·72±0·08	—	—
^{162}Dy	6·7±0·7	0·92±0·09	2·64±0·27	0·86±0·09	1·43±0·14	0·76±0·08	—	—
^{164}Dy	10·6±0·9	0·85±0·09	3·68±0·35	0·89±0·08	1·65±0·16	0·93±0·09	0·96±0·10	0·91±0·09
^{164}Er	4·4±0·4	0·85±0·09	1·55±0·16	0·95±0·10	1·09±0·11	0·68±0·07	—	—
^{166}Er	7·4±0·7	0·86±0·09	2·65±0·26	0·95±0·09	1·25±0·13	1·05±0·12	—	—
^{168}Er	6·2±0·6	0·85±0·09	2·11±0·20	0·85±0·08	0·82±0·09	0·99±0·11	—	—
^{170}Er	5·7±0·6	0·97±0·10	2·04±0·21	0·95±0·10	0·94±0·09	0·91±0·10	—	—
^{170}Yb	5·0±0·5	0·93±0·09	1·56±0·16	1·00±0·10	1·04±0·10	0·81±0·09	—	—
^{172}Yb	5·5±0·6	1·00±0·11	1·76±0·17	1·09±0·11	1·01±0·10	0·85±0·09	—	—
^{174}Yb	6·3±0·6	1·06±0·10	2·48±0·25	0·92±0·09	1·03±0·10	0·98±0·11	—	—

Amongst the nuclei studied level schemes for states with $J^{\pi} > 12^{+}$ are only available for ^{160}Dy (Johnson *et al* 1972), ^{164}Er (Lisle *et al* 1973) and ^{170}Yb (Hartley *et al* 1973) and all are found to exhibit back-bending properties. Although no such information is available for the states of ^{164}Dy and ^{166}Er, the two other $N = 98$ isotones ^{168}Yb and ^{170}Hf have been shown to possess more normal rotational level spectra (Stephens *et al* 1965, Mo *et al* 1972). If ^{164}Dy and ^{166}Er are similar to these, the present data on transition rates for 12^{+} states suggest that the hindrances we observe may be associated with the back-bending effect. In order to put this interpretation on a firmer basis it is important to show that one or more of the nuclei studied, for which $B(\mathrm{E2})/B(\mathrm{E2})_{\mathrm{rot}} \sim 1$ for the $12^{+} \rightarrow 10^{+}$ decay, exhibit normal rotational level sequences.

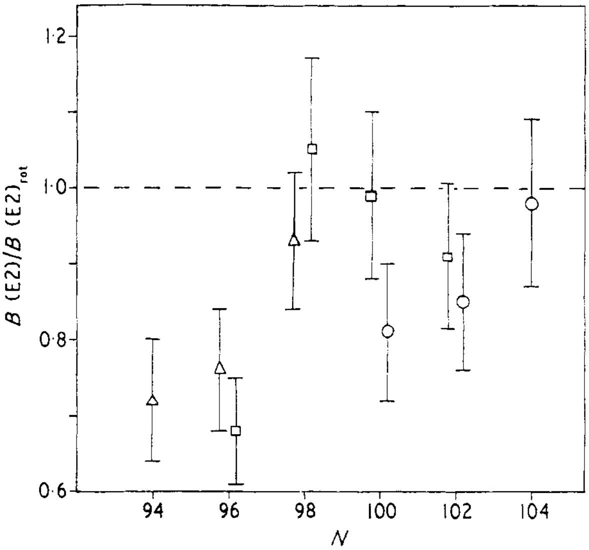

Figure 2. The variation of $B(\mathrm{E2})/B(\mathrm{E2})_{\mathrm{rot}}$ of $12^{+} \rightarrow 10^{+}$ transitions with neutron number N; △ Dy, □ Er and ○ Yb.

If our interpretation is valid the results appear to be broadly in agreement with predictions of the phase transition model. Sorensen (1973) expects considerable retardation of E2 transition rates for states with $12 \leqslant J \leqslant 16$ in strongly back-bending nuclei. This is supported by more detailed calculations of Sano *et al* (1973) for ^{158}Dy in which a 10% retardation is predicted for the decay of the 14^{+} state. In addition similar calculations by Takemasa and Sano (1971) for ^{160}Er suggest that significant retardations may be obtained for the E2 transitions from the 8^{+} and 10^{+} states. In contrast, the Stephens and Simon model, in its present formulation which involves relatively less rearrangement of the internal nuclear structure, is unlikely to cause any substantial reduction in E2 transition rates and does not seem to be in accord with the present measurements. Our conclusions are in contrast to those of Ward *et al* (1973) whose measurements of transition rates in ^{158}Er, albeit with large errors, are consistent with rotational values.

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