

Systematics of $K^\pi = 8^-$ isomers in $N = 74$ nuclei

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An isomer with a half-life of $6 \pm 1 \mu\text{s}$ has been observed in the $N = 74$ nucleus ^{138}Gd , populated following the reaction $^{106}\text{Cd}(^{35}\text{Cl}, p2n)^{138}\text{Gd}$. The isomer decays via a 583 keV $E1$ transition with a hindrance per degree of K forbiddenness, $f_v = 24$. This value is similar to the values measured for the $N = 74$ isotones ^{134}Nd and ^{136}Sm but markedly different from that measured for ^{130}Ba . This suggests that there is some change in structure across the $N = 74$ isotones and possible explanations of this feature are discussed. [S0556-2813(97)00302-6]

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I. INTRODUCTION

Isomeric $I^\pi = 8^-$ states have been observed in the even-even $N = 74$ nuclei, ^{136}Sm [1], ^{134}Nd [2], ^{132}Ce [3], ^{130}Ba [4], ^{128}Xe [5] with half-lives ranging from nanoseconds (Xe) to milliseconds (Ba, Ce). The mode of decay of these states differs, but in ^{130}Ba , ^{134}Nd , and ^{136}Sm they decay by $E1$ transitions to the 8^+ member of the yrast band. The transition rate for this decay varies by four orders of magnitude across these $N = 74$ isotones. A large proportion of this variation is due to the different energies of the $E1$ transitions since, while the energy of the isomeric state is relatively constant as proton number increases, the excitation energy of the yrast 8^+ state decreases sharply. Nevertheless, the underlying transition strength varies by a factor of ~ 40 , a difference yet to be accounted for.

In ^{136}Sm , the properties of the band built on the $I^\pi = 8^-$ isomeric state have been shown [6] to be consistent with a $\frac{7}{2}^+ [404] \otimes \frac{9}{2}^- [514]$, $K^\pi = 8^-$ two quasi-neutron structure. The $E1$ transition from the isomeric state to the yrast band, assumed to have $K = 0$, therefore has $\Delta K = 8$ and is 7 times K forbidden. As Z increases across the $N = 74$ nuclei, the decreasing energy of the first excited state with $I^\pi = 2^+$ indicates [7] that the deformation increases. It might therefore be expected that the K -selection rule governing the $E1$ transition from the isomeric state should be more important for the heavier isotones, leading to a decrease in the transition rate of the $E1$ decay and a corresponding increase in the hindrance. This is *opposite* to what is observed [1]. It is therefore proposed that the variation in the hindrance is due to a change in the underlying structure of either the isomeric states themselves or of the yrast states to which the isomer decays.

In order to get more information on this variation, the $N = 74$ systematics have been extended to the very neutron deficient nucleus ^{138}Gd , the highest- Z even-even nucleus in the sequence which can realistically be studied using stable beam/target combinations and fusion evaporation reactions. The yrast band of ^{138}Gd has been observed previously [8]

and, more recently, side bands were observed in a measurement [9] using the EUROGAM array in conjunction with the Daresbury Recoil Separator. However, no information about decays from isomeric states was available.

II. EXPERIMENTAL DETAILS AND RESULTS

The nucleus ^{138}Gd was populated using the reaction $^{106}\text{Cd}(^{35}\text{Cl}, p2n)^{138}\text{Gd}$ at a beam energy of 150 MeV. The time profile of the ^{35}Cl beam, provided by the 14UD tandem accelerator at the Australian National University, was 2.1 μs on and 99.5 μs off, and this was incident on a 10 mg/cm² enriched (86%) ^{106}Cd target. The other experimental conditions were similar to those used in a recent experiment [1] to study an analogous isomeric state in ^{136}Sm . ^{138}Gd is produced very weakly in the reaction. Statistical model calculations estimate a cross section of 4 mb, 1% of the total fusion cross section, with the main channels being $3p$ (^{138}Sm), $3pn$ (^{137}Sm), and $2pn$ (^{138}Eu) with predicted cross-sections of 20, 58, and 65 mb respectively.

Event matrices of time against γ -ray energy were constructed, and background subtracted time projections for the lowest four ground-state-band transitions in ^{138}Gd were found to have a long-lived component. Figure 1 shows the measured time spectrum for the 221 keV ($2^+ \rightarrow 0^+$) and 384 keV ($4^+ \rightarrow 2^+$) transitions in ^{138}Gd . This decay curve establishes the existence of an isomer with a half-life of $6 \pm 1 \mu\text{s}$.

To deduce the coincidence relationships between γ rays associated with isomers, a γ - γ -time coincidence experiment was performed with the beam chopped to arrive in 1 μs bursts, separated by 17 μs . Events which occurred within the beam bursts were vetoed so that only γ rays observed during "out-of-beam" periods were recorded. Coincident γ rays (time difference ± 20 ns) were sorted into a matrix and spectra gated on the ground-state-band transitions (illustrated in Fig. 2) showed a 583.2 keV transition which was also observed as a delayed transition in the γ -time measurement discussed above. This transition is coincident with those depopulating the 2^+ , 4^+ , 6^+ , and 8^+ levels of the yrast band,

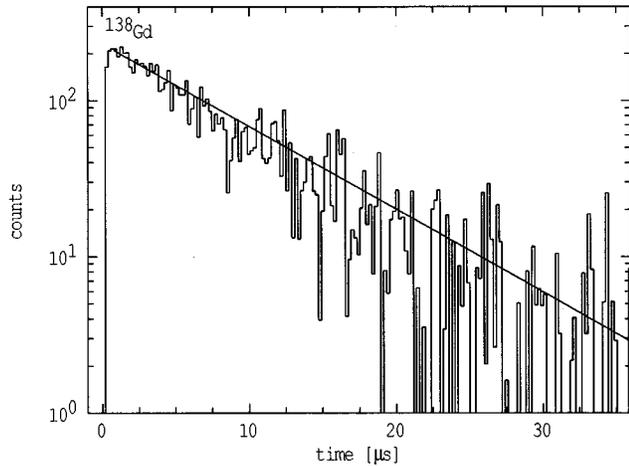


FIG. 1. Time spectrum for the 221 keV $2^+ \rightarrow 0^+$ and 384 keV $4^+ \rightarrow 2^+$ γ -ray transitions in the ground-state band in ^{138}Gd . A fit to the spectrum gives a half-life $6 \pm 1 \mu\text{s}$.

but not the 616 keV transition [9] depopulating the yrast 10^+ level. The 583.2 keV γ ray is therefore placed depopulating an isomeric state at an excitation energy of 2233.1 keV, as shown in the inset to Fig. 2. The absence of any other branches is consistent with $I^\pi=K^\pi=8^-$, which is therefore assumed.

III. ISOMERIC DECAY IN THE $N=74$ ISOTONES

In the ^{136}Sm [1] and ^{138}Gd nuclei, the only observed decay of the 8^- isomeric state is via an $E1$ transition whereas in ^{130}Ba [4] and ^{134}Nd [2], the energy differences are such that $M2$ and $E3$ decays also compete. Details of the decay of each of the states are given in Table I. Column 8 of the table

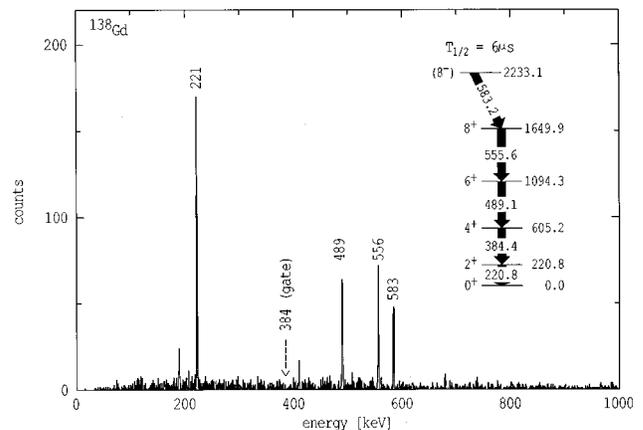


FIG. 2. γ -ray spectrum showing transitions, in coincidence with the 384 keV ($4^+ \rightarrow 2^+$) transition in the ground-state band, in the out-of-beam time region. Inset: Partial level scheme for ^{138}Gd .

shows that there is a jump by a factor of 35 in the Weisskopf hindrance factor (F_W) for the $E1$ branch between ^{130}Ba and ^{134}Nd .

The hindrance per degree of K forbiddenness (f_ν) is listed in column 9 and plotted as a function of Z in Fig. 3. f_ν is defined as $F_W^{1/\nu}$ where $\nu=\Delta K-\lambda$ is the degree of forbiddenness and λ is the transition multipolarity [10]. The value of f_ν for the $\Delta K=8$, 583 keV $E1$ transition in ^{138}Gd is 24.1, similar to the value measured for the analogous transition in the isotones ^{136}Sm ($f_\nu=24.9$) and ^{134}Nd ($f_\nu=26.1$). These values are approximately constant but markedly different from that measured for ^{130}Ba ($f_\nu=43.5$). This is contrary to what would be expected if the heavier $N=74$ nuclei are more deformed and the K -selection rule is correspondingly more rigorous.

TABLE I. Summary of data for the $N=74$ isotones.

Nucleus	$T_{1/2}$	Ref.	$E_\gamma(\text{keV})$	multipolarity	branching ratio	α^a	F_W^b	f_ν
$^{128}_{54}\text{Xe}$	63 ± 12 ns	[5]	204.1	$M1$	58(13)			
			286.5	$E2$	100(13)			
$^{130}_{56}\text{Ba}$	11 ± 2 ms	[4,21] ^c	80.3	$E1$	10(1)	0.4180	293×10^9	43.5
			462.3	$E3$	20(2)	0.0363		
			822.3	$M2+E3$	100(7)	0.0106		
$^{132}_{58}\text{Ce}$	13 ± 2 ms	[3]	797.3	$M2$	100			
$^{134}_{60}\text{Nd}$	410 ± 30 μs	[2]	166.5	$E1$	100(7)	0.0647	8.4×10^9	26.1
			874.0	$M2$	7(2)	0.0123		
$^{136}_{62}\text{Sm}$	15 ± 1 μs	[1]	465.9	$E1$	100	0.0051	5.9×10^9	24.9
$^{138}_{64}\text{Gd}$	6 ± 1 μs		583.2	$E1$	100	0.0034	4.7×10^9	24.1

^aTotal conversion coefficients.

^bWeisskopf hindrance factor $F_W=[T(E1)_{1/2}^\gamma/T(E1)_{1/2}^W]$ [where $T(E1)_{1/2}^\gamma$ is the partial γ -ray half-life, $T(E1)_{1/2}^W$ is the Weisskopf single-particle estimate].

^cUsing the adopted value from Nuclear Data Sheets.

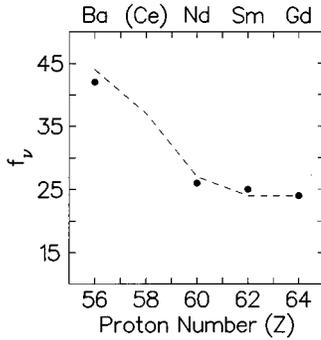


FIG. 3. Systematics of f_v values for observed $E1$ decays from the $K^\pi=8^-$ isomers in the $N=74$ isotones. The line depicts the f_v values which are predicted using the band-mixing calculation outlined in Sec. III A.

A. Rotational K-mixing

In order to investigate the underlying physical processes, we consider first the degree of rotational alignment in the ground-state bands. Figure 4 shows alignments for the $N=74$ Ba, Ce, Nd, Sm, and Gd nuclei [9,11–14], evaluated with the same reference parameters. These data show evidence of a gain in alignment at a frequency of $\hbar\omega \sim 0.35$ MeV, attributed to the alignment of a pair of $h_{11/2}$ protons [15]. Figure 4 suggests that in ^{130}Ba and ^{132}Ce there is a weak interaction between the ground state and s bands which results in a clear backbend. For ^{134}Nd , ^{136}Sm , and ^{138}Gd , however, the alignment gain is less sharp and more complex. The states above and below the backbend in ^{130}Ba and ^{132}Ce are therefore likely to be relatively pure whereas in the heavier nuclei there could be a larger degree of mixing over more states.

In order to try and quantify this difference in the structure of the 8^+ states in the yrast bands, we have attempted to fit

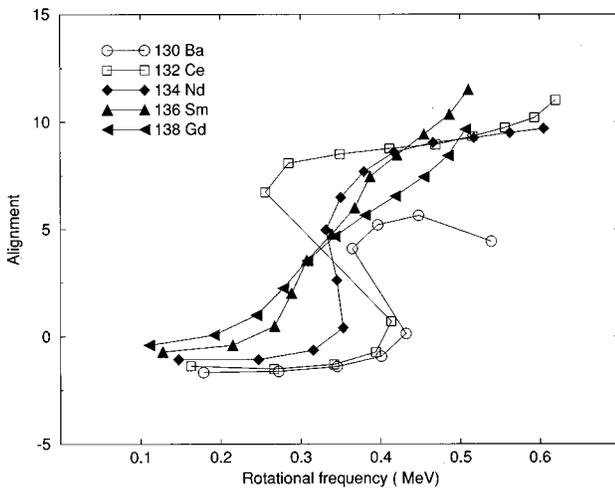


FIG. 4. Experimental alignments for ^{130}Ba , ^{132}Ce , ^{134}Nd , ^{136}Sm , and ^{138}Gd . Harris reference parameters of $\mathcal{I}_0=17.0 \hbar^2 \text{ MeV}^{-1}$ and $\mathcal{I}_1=25.0 \hbar^4 \text{ MeV}^{-3}$ have been used for all five nuclei.

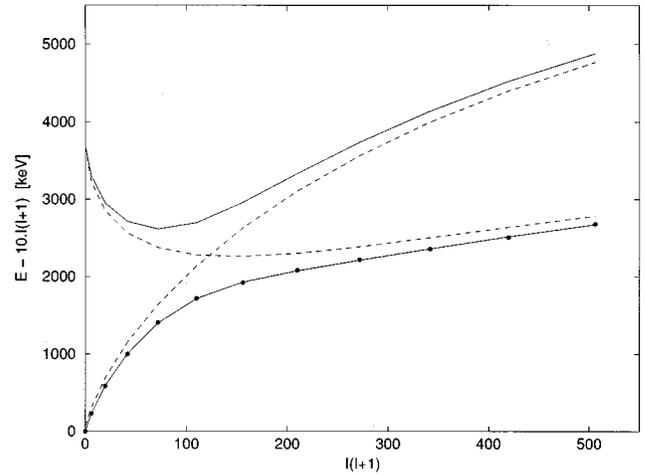


FIG. 5. The results of the two-band mixing calculation for ^{134}Nd . The unperturbed bands are shown as dashed lines and the perturbed bands as solid lines. The dots represent the measured excitation energies of the states in the yrast band.

the observed energies of the states in the yrast band of each nucleus using the prescriptions developed elsewhere (see, for example, Ref. [16]), initially using two-band mixing between a ground and an s band. The unperturbed bands have been parametrized using the variable moment of inertia model [17] and the interaction matrix element was assumed to be spin independent. As an example, Fig. 5 shows the results of the two-band calculation for ^{134}Nd , where the unperturbed bands are shown as dashed lines and the perturbed bands as solid lines. In the case of ^{138}Gd an acceptable fit could not be obtained unless a third band was included, the third band becoming important at spins greater than $12\hbar$. Table II lists the results in terms of the percentage admixture of ground band and s band in the yrast 8^+ states of each of the $N=74$ nuclei under consideration. The results are in qualitative agreement with the inference drawn from the alignment plot, namely that the yrast 8^+ states in ^{130}Ba and ^{132}Ce are relatively pure whereas those in the heavier nuclei contain a sizeable proportion of s -band admixture, largely because of the very large interaction required for the heavier cases.

The ground band is assumed to have $K=0$, and the s band will have a distribution of K values, which can be estimated by assuming the approximation of an expansion using the Wigner d functions for rotation through 90° [18]. The values calculated for the K admixtures will depend on the value of alignment, but the maximum value of $K=8$ admixture (for a pair of $h_{11/2}$ particles coupling to $j=10$) which can be obtained is $\sim 20\%$. Taken with the results of the two-state mixing calculation discussed above and tabulated in Table II, this means that in ^{130}Ba the isomer is decaying to an 8^+ state which contains essentially no $K=8$ component, while in ^{134}Nd the 8^+ state is approximately 4% ($20\% \times 20\%$) $K=8$ configuration. It is thus evident that the $E1$ transition from the isomeric state in ^{134}Nd would not be as hindered as the corresponding transition in ^{130}Ba . The dashed line on Fig. 3 shows the values of f_v calculated assuming the s -band mixing listed in the last column of Table II. The calculations have been normalized to the empirical

TABLE II. Parameters and results of the band-mixing calculations.^a

		band 1 ground	band 2 s band	band 3 ^b	Interaction matrix elements			(amplitude) ² in yrast 8 ⁺	
					V ₁₂	V ₂₃	V ₁₃	% ground	% s band
¹³⁰ Ba	\mathcal{I}_0	6.25	16.9		47			99.4	0.6
	C	6.26	28.9						
	E ₀	5	2833						
¹³² Ce	\mathcal{I}_0	7.54	16.9		135			98.0	2.0
	C	7.00	19.2						
	E ₀	8	3272						
¹³⁴ Nd	\mathcal{I}_0	8.17	22.4		483			80.3	19.7
	C	7.07	16.0						
	E ₀	65	2985						
¹³⁶ Sm	\mathcal{I}_0	7.34	23.0		908			51.3	48.7
	C	7.15	7.95						
	E ₀	309	2373						
¹³⁸ Gd	\mathcal{I}_0	10.6	16.9	22.6	359	29	30	60.5	39.4
	C	4.14	7.95	15.0					
	E ₀	66	1617	3000					

^aEnergies and interaction matrix elements are given in keV. \mathcal{I}_0 is in units of $10^{-3}\hbar^2\text{keV}^{-1}$ and C in $10^6\text{keV}^3\hbar^{-4}$.

^bThe third band is necessary for ¹³⁸Gd but only becomes important at spins greater than $12\hbar$.

f_ν value for ¹³⁸Gd. The degree of agreement is remarkable given the assumptions and it would be of interest to use a more refined method of calculating the K distribution and the admixtures in the various states.

B. Discussion in terms of the structure of the isomeric state

In ¹²⁸Xe and ¹³⁶Sm the configuration of the isomer has been assigned [19,6] as neutrons in the $\frac{7}{2}^+[404] \otimes \frac{9}{2}^- [514]$ orbitals which are near the Fermi surface at prolate deformation. However, in the case of ¹³⁰Ba two possible configurations for the isomeric 8⁻ state have been discussed [20], a two-proton configuration with an oblate shape and a two-neutron configuration with a prolate shape. The authors [20] decided in favor of the neutron configuration in ¹³⁰Ba because a similar state had been seen in ¹³²Ce. However, the observed deviation in the measured f_ν values could also reflect a change in configuration of the observed isomeric state across the region, with the oblate state being observed in ¹³⁰Ba and the prolate state being observed for the higher Z nuclei. This is a realistic possibility since nuclei in this region are known [15] to exhibit γ softness and calculations suggest that for ¹³⁰Ba the potential well has a lower minimum for an oblate shape [20] whereas the opposite is true for ¹³⁶Sm [14]. A small difference in the shape of the potential between the $N=74$ nuclei could be the underlying reason for the observed decay systematics of the isomeric states.

IV. CONCLUSIONS

An isomeric state, proposed to have $I^\pi = K^\pi = 8^-$ has been observed in the very neutron deficient nucleus ¹³⁸Gd. It decays to the yrast structure with a half-life of $6 \pm 1 \mu\text{s}$. The hindrance per degree of forbiddenness for an $E1$ decay is 24.1, close to the values measured previously in the $N=74$ isotones ¹³⁴Nd and ¹³⁶Sm, but considerably lower than that measured in ¹³⁰Ba. Two possible explanations of this phenomenon have been proposed, in terms of the structure and shape of the isomeric state itself and of the yrast state to which it decays. While the results of the calculations outlined in Sec. III A appear to support the band-mixing theory, the fit may be fortuitous and the possibility of shape effects must not be discounted. In order to investigate this more thoroughly it is necessary to confirm the configuration of the isomeric states in these nuclei by examining the bands built on them, or to measure the shapes of the isomeric and ground states.

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