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GROUND STATE BANDS IN HEAVY EVEN-EVEN FISSION PRODUCTS*

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July 1970

We present experimental results on the ground-state bands of heavy even-even nuclei produced in the primary fission of ^{252}Cf . Experimental values for the energy levels and lifetimes range from those typical of spherical nuclei to those associated with permanently deformed nuclei.

- - -

In this letter we present new information concerning the energy levels of very neutron rich even-even isotopes of ^{52}Te , ^{54}Xe , ^{56}Ba , ^{58}Ce , ^{60}Nd , and ^{62}Sm . These results were obtained in a series of experiments on the prompt gamma ray de-excitation of the fission fragments from spontaneous fission of ^{252}Cf . The data, which in some of the cases can be correlated with previously reported results, extend the knowledge about the systematic behavior of collective excitations to neutron rich nuclei far from the beta stability line. The systematics of the energy levels in the ground state bands for the heavier fragments are well fitted using the phenomenological variable moment of inertia model of Mariscotti *et al.*¹ One of the main features of the results is the evidence that the well-known abrupt discontinuity in the ratio E_{4+}/E_{2+} for isotopes with 88 and 90 neutrons reaches its maximum effect in Nd, Sm, and Gd isotopes and becomes much less abrupt in the Ce and Ba nuclei. This smoother transition is similar to the behavior observed for isotopes with $Z > 66$.²

In the experiments x-rays and/or γ -rays were measured in coincidence with pairs of fission fragments. The experimental technique has been described in a previous paper³ and will therefore only be briefly summarized here. In most of the cases the atomic number was determined by observing a coincidence between the characteristic K x-rays and one or more of the γ -rays of the ground state band. The masses of the fragments were calculated from their measured kinetic energies. Direct determination of life times in the region of 0.2-2 nsec were obtained from Doppler shift considerations.

The experimental results are presented in Table I. For each isotope in the table we present two lines of information. The top line contains the experimental energies of the observed levels along with the ratio of the energies of the 4^+ and 2^+ levels, the measured half life of the 2^+ level, the yield per fission of this transition (corrected for internal conversion) and the mean experimental mass associated with the ground state band transitions. Also presented are $BE(2;2 \rightarrow 0)$ values. The second line contains corresponding predicted values. The energies of the 6^+ and 8^+ levels were obtained by interpolation using the standard Mallman plots of E_I/E_2 vs E_4/E_2 ⁴ (I being 6 or 8). The ground state band data used for the curves were obtained from compilations of Mariscotti et al.¹ The predicted half life and $B(E2)$ values are based on the phenomenological variable moment of inertia model.¹ The predicted radiochemical yields are from the calculations of Watson and Wilhelmy.⁵

The following comments explain the bases for the assignments of the levels:

1. Some of the transitions reported here have been observed and identified previously by other methods. The $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions in ^{132}Te were observed by Bergström et al.⁶ following beta decay of fission products

analyzed by an on-line mass separator. This group also reported evidence of the $2 \rightarrow 0$ transition in ^{134}Te . The decay of ^{134}Te has been studied by W. John et al.⁷ who measured delayed γ -rays from fission fragments and reported that the 115 keV transition (tentatively assigned as the $6^+ \rightarrow 4^+$) has a 160 nsec half life and is followed by two cascade transitions of 297 keV ($4 \rightarrow 2$) and 1278 keV ($2 \rightarrow 0$). Our data contain an atomic number identification for this decay and also present transition intensities consistent with their assignment. The $2 \rightarrow 0$ transitions in ^{140}Ba and in ^{142}Ba have been observed by Alväger et al.⁸ following beta decay of mass separated fission products. The $2 \rightarrow 0$ levels in ^{138}Xe , ^{140}Xe , and ^{144}Ce have been observed by Wilhelmy et al.⁹ in studies of transitions following beta decay of unseparated fission products. The rotational band in ^{156}Sm has been observed in the $^{154}\text{Sm}(t,p)$ reaction by J. G. Bjerrgaard et al.¹⁰ They have explicitly identified by means of angular distribution studies only the spin of the 2^+ state; however, the levels of the rotational band of this nucleus as reported here (72 keV, 250 keV, and 518 keV) are in good agreement with their lowest levels (74 \pm 10, 250 \pm 10, 521 \pm 10 keV).

2. Most of the de-excitation of the even-even isotopes is expected to pass through the lowest $2^+ \rightarrow 0^+$ transitions and therefore the yields of these transitions correspond rather well to the calculated isotopic independent yield of these isotopes. The small deviations that appear can be accounted for by uncertainties in the most probable charge (Z_p) of the mass chains which were used in the calculations. With the exception of ^{136}Te , the $2 \rightarrow 0$ transitions from all of the isotopes with calculated independent yields $\geq 1\%$ per fission were found. The above mentioned missing case may be accounted for if there is a sharp decrease in its independent yield as a result of the proximity of the $N = 82$ $Z = 50$ shell. The multipolarity of the $2 \rightarrow 0$ transitions in ^{144}Ba , ^{148}Ce ,

and ^{158}Sm were found by Watson *et al.*¹¹ to be E2 by electron x-ray coincidence studies in prompt decay of ^{252}Cf fragments.

3. The energies of the 2^+ levels and the $4^+/2^+$ energy ratios obey smooth systematics, showing a decrease in the energies and an increase in the ratios with increasing displacement from the $N = 82$ shell. This relationship was used to confirm the level and element assignments when as a result of small internal conversion the x-ray evidence was not available. This approach applies to the case of ^{140}Xe .

4. Higher spin members of the ground state bands have been extracted from γ - γ coincidence data. The intensities of the intra band transitions decrease with increasing spin ($I_2 \rightarrow 0 > I_4 \rightarrow 2 > I_6 \rightarrow 4 > I_8 \rightarrow 6$) in a manner consistent with considerations involving the removal of 6-10 units of angular momentum associated with each fragment; however, these intra band transitions are still the strongest present in the spectrum. This can be seen in Fig. 1 which presents the γ -ray spectrum obtained in coincidence with the 199.4 keV $2 \rightarrow 0$ transitions in ^{144}Ba . Also shown is the γ -ray spectrum of all fragments with experimental masses between 143 and 145. The coincidence spectrum strongly selects the higher spin members of the ground state band. When such a selection was found in which the strongest levels conform to the phenomenological predictions and no other intense lines were present, definite assignments were made.

5. The experimental mean masses associated with the transitions in the even-even isotopes sometimes differ by more than 1 amu from the assigned masses. This can be attributed mainly to the use of average neutron corrections. The average values for a given mass are presumably too small for isotopes that are on the neutron deficient side of the most probable isotope for a given element

and conversely too large for isotopes on the neutron excess side. In some cases we have observed odd mass isotopes of the even Z elements with experimental masses between those of the adjacent even isotopes although the latter are separated by less than 2 amu. There may also be a small smooth systematic error due to the uncertainties in the fragment pulse height to energy calibration procedure.

The data show that the 88-90 neutron discontinuity is smearing out as the proton number decreases below $Z = 60$. This is seen both for the energies of the 2^+ level and the $E4^+/E2^+$ ratio. A plot of the $E4/E2$ ratio of nuclei with $56 \leq Z \leq 70$ is shown in Fig. 2. This figure clearly shows that the maximum effect of the 88-90 neutron discontinuity occurs in the region $60 \leq Z \leq 66$. The nuclei with $N = 92$, $Z = 58$, and $N = 92$, $Z = 68$ have $E4/E2$ ratio and $B(E2)$ values which indicate that they are as rotational as ${}^{152}_{62}\text{Sm}$, which is known to have permanent quadrupole deformation, even though for $Z = 58$ and $Z = 68$ the 88-90 neutron effect is relatively rather smooth. A similar effect has been shown to occur in the 76-80 proton number region¹² where a sharp discontinuity occurs for $106 \leq N \leq 112$ and a smooth behavior was observed outside this region. We can summarize then that the transition from a vibrational spectrum to a rotational one can be either abrupt or smooth depending probably on a delicate balance between proton and neutron pairing correlations. Calculations by Nilsson et al.¹³ and by Ragnarsson and Nilsson¹⁴ indicate that deformation is expected to occur abruptly between 86 and 88 neutrons for the nuclei discussed here. These calculations which are based on the Nilsson model combined with the Strutinsky normalization procedure reproduce the general trend of decreased deformation for nuclei with 88 neutrons on both sides of $Z = 62$.

Another interesting feature of the lowest 2^+ states which are already known or have been established in this experiment is that for any specific even neutron number between 82 and 88 the level energies increase with increasing displacement from the $Z = 50$ shell.

We are grateful to the following persons for their help in this work: Elizabeth Quigg wrote the necessary programs for the PDP-9 computer. Thomas Strong handled the processing of our data using the CDC 6600 computer. Robert Latimer and James Harris electrodeposited the ^{252}Cf sources on our fission detectors. Very useful discussions with John Rasmussen, Frank Stephens, Chin Fu Tsang, and Rand Watson are acknowledged.

FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

Fig. 1. Prompt γ -ray spectrum from ^{252}Cf observed using a 35 cm^3 coaxial Ge(Li) detector a) in coincidence with fragments having experimental masses between 143 and 145, b) in coincidence with fragments having experimental masses between 139 and 149 and also with the 199.4 keV γ -ray ($2 \rightarrow 0$ in ^{144}Ba) detected by a 6 cm^3 planar Ge(Li) detector.

Fig. 2. Systematic behavior of the ratio E_4/E_2 as a function of proton number in the $N = 86-92$ region. \blacktriangle new data from this experiment. The other data is from the Table of Isotopes¹⁵ and Ref. 2.

Table 1. Experimental results and phenomenological predictions for ground state bands.

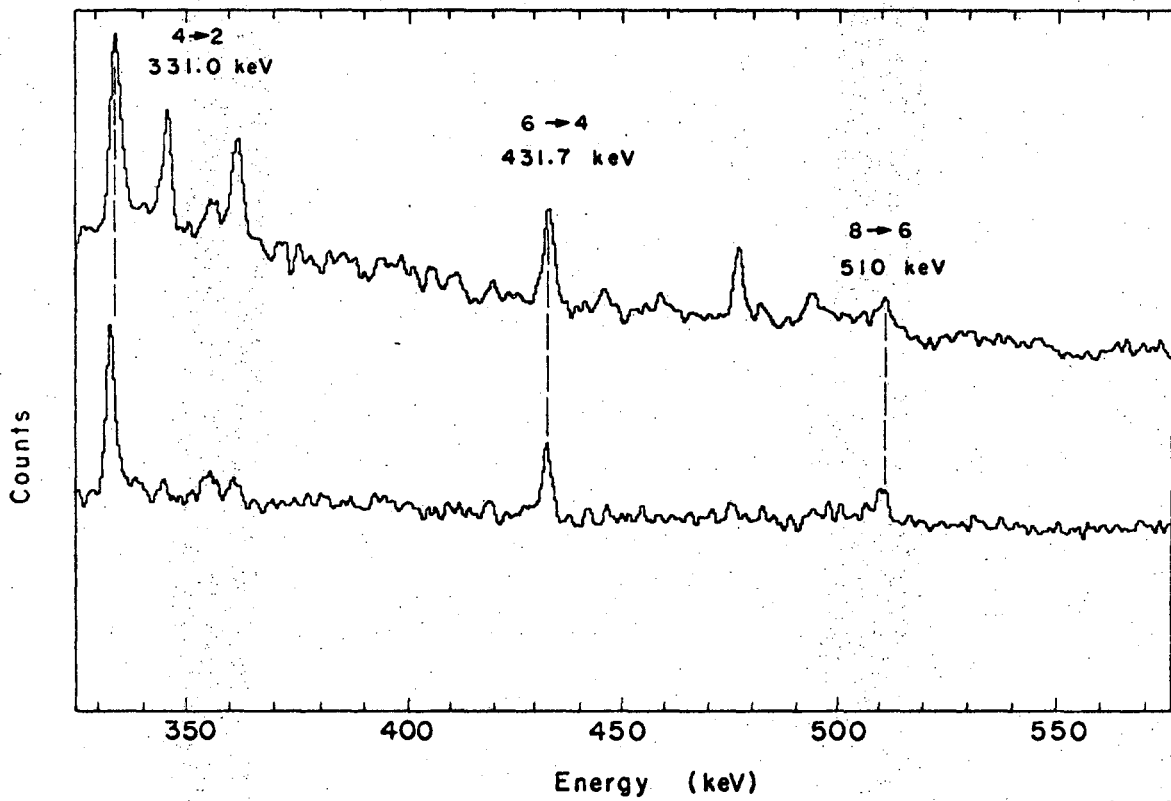
		Energy in keV				E ₄ /E ₂	t _{1/2} (2 ⁺ 0) ^a nsec	Yield %/fis	Mass ^b	B(E2; 2 ⁺ → 0) ^c	
		2 ⁺	4 ⁺	6 ⁺	8 ⁺					exp	s.p.
¹³² Te	exp	974	1964			2.02		~0.2	known		
	pred							0.42	132		3.96
¹⁵⁰ Te	exp	1378	1575	1690		1.23		~1.5 ^d	133.99		
	pred							2.02	134		4.04
¹³⁶ Xe	exp	589.5	1072.9			1.82		2.31	138.28		
	pred							2.25	138		4.21
¹⁴⁰ Xe	exp	376.8	834.7			2.22		1.5	139.23		
	pred			1371	1940		0.04	3.18	140	185	4.29
¹⁴⁰ Ba	exp	602.2						~0.5	known		
	pred							0.2	140		
¹⁴² Ba	exp	359.7	835.4	1467.4		2.32		2.90	142.02		
	pred			1403	1996		0.04	2.08	142	226	4.37
¹⁴⁴ Ba	exp	199.4	530.4	962.1	1472	2.66	0.49	3.60	143.58	314	
	pred			957	1455		0.35	3.33	144	454	4.45
¹⁴⁶ Ba	exp	181.0	514			2.84	0.85	1.01	144.88	277	
	pred			959	1511		0.46	0.78	146	506	4.53
¹⁴⁴ Ce	exp	397.5						~0.2	known		
	pred							0.08	144		
¹⁴⁶ Ce	exp	258.6	668.7	1171		2.59	0.29	1.04	146.40	157	
	pred			1186	1823		0.14	1.24	146	341	4.54
¹⁴⁸ Ce	exp	158.7	454.4	840.9		2.86	0.9 ^m	2.31	147.80	445	
	pred			857	1341		0.70	2.11	148	578	4.61
¹⁵⁰ Ce	exp	97.1	306.1	606.8	983.2	3.15	>0.9 ^m	>0.98	148.84		
	pred			607	976		2.14	0.56	150	956	4.70
¹⁵² Nd	exp	75.9	240.6	487.9	810.0	3.17	>2	>0.6	152.6		
	pred			478	782		2.76	0.99	152	1230	4.78
¹⁵⁴ Nd	exp	72.8	235.2	483.9	812.0	3.23	>2	>0.4	153.5		
	pred			473	781		2.74	0.98	154	1280	4.87
¹⁵⁶ Sm	exp	76	250.2	518		3.29		>0.1	155.8		
	pred			511	863		2.27	0.35	156	1220	4.95
¹⁵⁸ Sm	exp	72.8	240.3	498.5	844.5	3.30		>0.15	157.2		
	pred			495	837		2.32	0.18	158	1280	5.04

^aThe life times were determined from two point decay curves and in principle could be shorter since there is a possibility of hold up from previous transitions. However the cases (denoted by ^m) for which the transition had a measured delayed component with T_{1/2} ≥ 3 nsec were corrected on the basis of the work of W. John et al.⁷

^bIn ¹³²Te, ¹⁴⁰Ba, and ¹⁴⁴Ce no reliable mass calculation was possible due to poor statistics. The γ transitions were known from previous work (see text). In general the calculated masses have a statistical error of less than 0.2 amu.

^cThe B(E2) values are in units of e²cm⁴ 10⁻⁵¹.

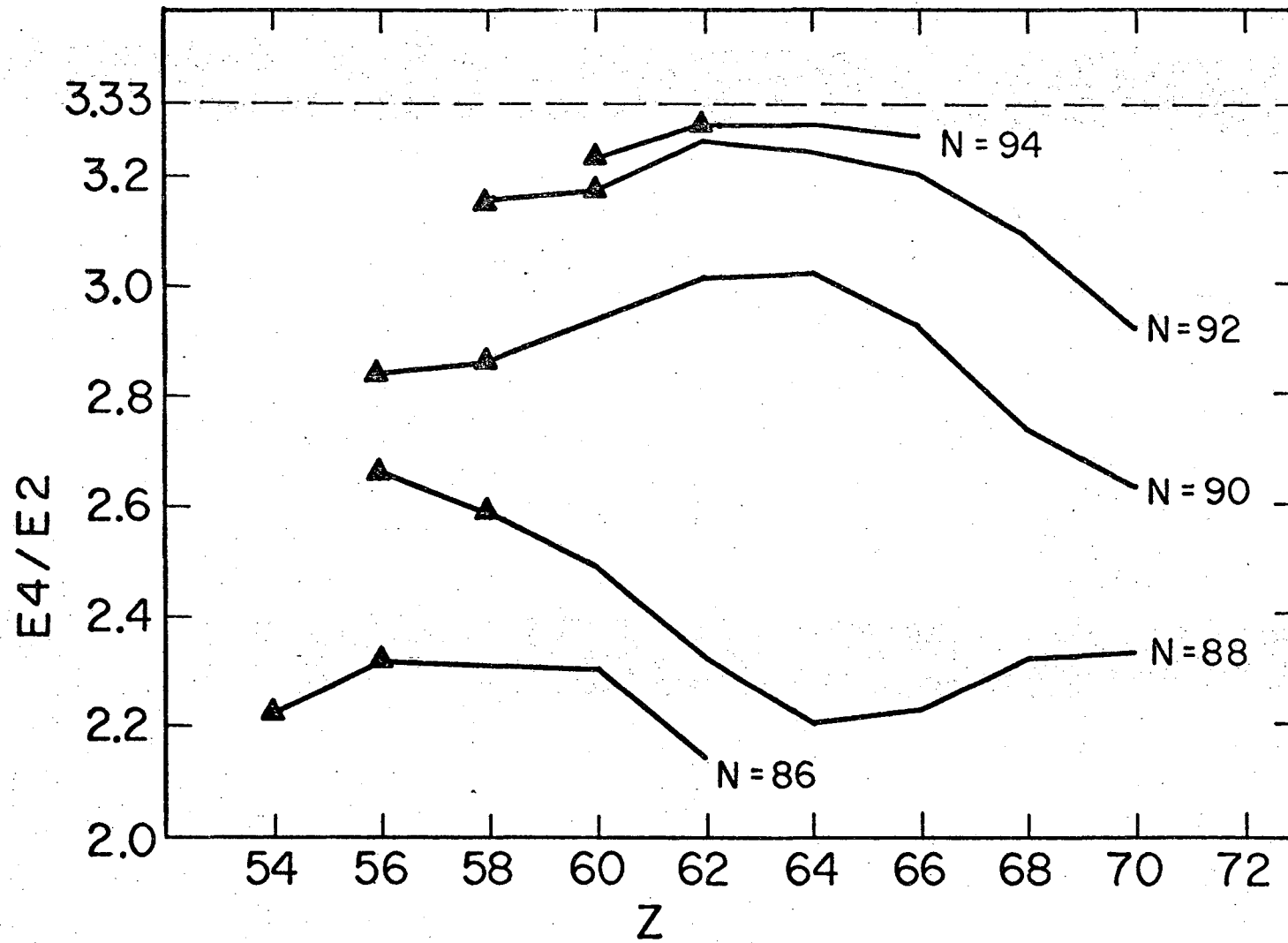
^dThe prompt yield of the 2⁺ state is only ~0.25% per fission. The balance is made up of delayed yield as taken from Reference 7.



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Fig. 1

Fig. 2



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