of (+) and (−) nuclei.

[11]The observed field splittings $\nu_+(1)-\nu_-(1)$ are 97.1 ± 0.6 MHz for K_2MnF_4 and 94.8 ± 0.6 MHz for Rb_2MnF_4. These splittings deviate significantly from the calculated ones, 99.0 and 96.7 MHz, respectively. The finite parallel susceptibility at 1.45°K and ≈47 kG, reducing $\langle S_z \rangle$ of the (+) sublattice and increasing $\langle S_z \rangle$ of the (−) sublattice, could account for the disparity, but the corrections calculated from spin-wave theory are only 0.3 MHz. The origin of this difficulty is not understood, but it will presumably not affect the average frequency of the two NMR branches.

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GROUND-STATE BANDS IN NEUTRON-RICH EVEN Te, Xe, Ba, Ce, Nd, AND Sm ISOTOPES PRODUCED IN THE FISSION OF ^{252}Cf†

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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 β 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, Scharff-Goldhaber, and Buck.[1] One of the main features of the results is the evidence that the well-known abrupt discontinuity in the ratio $E4^+/E2^+$ 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 paper[3] 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 lifetimes 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 $B(E2; 2 \rightarrow 0)$ values. The second line contains corresponding predicted values. The energies of the

Table I. Experimental results and phenomenological predictions for ground-state bands.

		Energy in keV 2+	4+	6+	8+	E4/E2	$t_{1/2}(2\to0)$[a] nsec	Yield %/fis	Mass[b]	B(E2; 2 → 0)[c] exp	s.p.
^{132}Te	exp	974	1964			2.02		~0.2	known		
	pred							0.42	132		3.96
^{134}Te	exp	1278	1575	1690		1.23		~1.5[d]	133.99		
	pred							2.02	134		4.04
^{138}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≈	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≈	>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

[a]The lifetimes were determined from two-point decay curves and in principle could be shorter since there is a possibility of holdup from previous transitions. However the cases (denoted by ≈) for which the transition had a measured delayed component with $T_{1/2} \geq 3$ nsec were corrected on the basis of the work of John, Guy, and Wesolowski, Ref. 4.

[b]In ^{132}Te, ^{140}Ba, and ^{144}Ce no reliable mass calculation was possible as a result of 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.

[c]The $B(E2)$ values are in units of $10^{-51}e^2$ cm^4.

[d]The prompt yield of the 2^+ state is only ~0.25% per fission. The balance is made up of delayed yield as taken from Ref. 4.

6^+ and 8^+ levels were obtained by interpolation using the standard Mallman plots[5] of E_I/E_2 vs E_4/E_2 (I being 6 or 8). The ground-state-band data used for the curves were obtained from compilations of Mariscotti, Scharff-Goldhaber, and Buck.[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.[6]

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 $2^+ \to 0^+$ transitions in ^{132}Te and ^{134}Te were observed by Bergström et al.[7] The

decay of ^{134}Te has also been studied by John, Guy, and Wesolowski[4] who measured delayed γ rays from fission fragments and reported that the 115-keV transition (tentatively assigned as the $6^+ \to 4^+$) has a 160-nsec half-life and is followed by two cascade transitions of 297 keV ($4 \to 2$) and 1278 keV ($2 \to 0$). The $2 \to 0$ transitions in ^{140}Ba, ^{142}Ba, ^{138}Xe, ^{140}Xe, and ^{144}Ce have been reported by Wilhelmy et al.[8] The rotational band in ^{156}Sm has been observed in the reaction ^{154}Sm(t,p) by Bjerrgaard et al.[9]

(2) Most of the de-excitation of the even-even isotopes is expected to pass through the lowest $2^+ \to 0^+$ 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 $2 \to 0$ 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 $2 \to 0$ transitions in ^{144}Ba, ^{148}Ce, and ^{158}Sm were found by Watson et al.[10] 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 intraband transitions decrease with increasing spin ($I_{2\to 0} > I_{4\to 2} > I_{6\to 4} > I_{8\to 6}$) in a manner consistent with considerations involving the removal of 6-10 units of angular momentum associated with each fragment; however, these intraband transitions are still the strongest present in the spectrum.

(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 as a result of the uncertainties in the fragment pulse-height-to-energy calibration procedure.

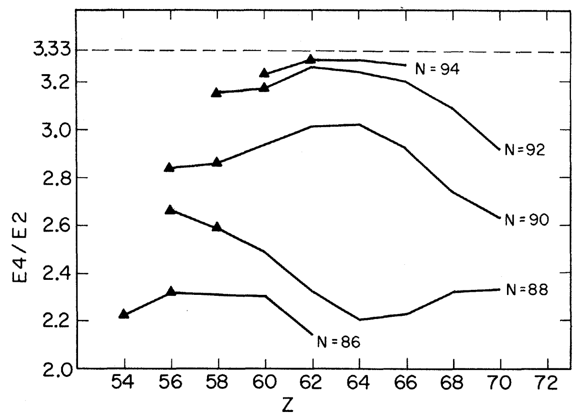

FIG. 1. Systematic behavior of the ratio $E4/E2$ as a function of proton number in the $N = 86$–92 region. Closed triangles are new data from this experiment. The other data are from Refs. 2 and 11.

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. 1. 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 $E4/E2$ ratios and $B(E2)$ values which indicate that they are as rotational as $^{152}_{62}$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 region[12] 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 Nilsson[14] 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 $Z=62$.

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EQUATION OF STATE FOR DENSE NEUTRON MATTER

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A solid-body model for neutron matter is proposed for calculating the equation of state for densities beyond the nuclear density using the Reid soft-core potential for the neutron-neutron interaction.

The equation of state for cold, catalyzed matter has been studied by a number of workers[1-9] for densities of the order of nuclear density ($\rho \sim 3\times10^{14}$ g/cm^3). However the extension of the existing calculations to higher densities is beset with two difficulties: (i) an inadequate knowledge of the nucleon-nucleon interaction at high energies and (ii) the lack of reliable methods for computing the interaction energy of the system at densities higher than the nuclear density. Even if we ignore the first difficulty, the second one is in itself formidable. The methods used in the works cited, generally, are designed for densities near nuclear density and do not work well at higher densities. For example, Cameron and his collaborators[3,4] have studied extensively the properties of neutron stars over a wide range of densities using the velocity-dependent potential of Levinger and Simmons,[10] where the potential energy is calculated only in the first-order perturbation theory. Recently Nemeth and Sprung[7] have calculated the energy of a system of neutrons and protons using the more realistic Reid[11] potential and the reaction-matrix theory of Brueckner and Goldstone. Similar calculations for a system of neutrons have been done by Binder, Pierce, and Razavy[8] and by Wang, Rose, and Schlenker,[9] using different potentials. These calculations are only carried out in the first order of the Brueckner-Goldstone theory; at higher densities than nuclear, higher orders of that theory become important and are almost prohibitively difficult to calculate. It is, therefore, desirable to have a better knowledge of the equation of state at high densities ($\rho \geq 10^{15}$ g/cm^3) to construct more realistic neutron-star models, and even apart from studying the structure of neutron stars, the problem has an intrinsic im-