Deformation of Very Light Rare-Earth Nuclei

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(Received 20 May 1985)

Gamma-ray spectra of neutron-deficient isotopes between cerium ($Z = 58$) and gadolinium ($Z = 64$) have been investigated. New bands of states were identified in many even-even, odd-A, and odd-odd nuclei. This Letter reports results on the ground-state bands in the even-even nuclei ${}^{126}_{58}\mathrm{Ce}_{68}$, ${}^{128,130,132}_{60}\mathrm{Nd}_{68,70,72}$, ${}^{134,136}_{62}\mathrm{Sm}_{72,74}$, and ${}^{138,140}_{64}\mathrm{Gd}_{74,76}$. The systematic trends of deformation are presented and compared with theoretical predictions. The lightest isotopes appear to be axially symmetric rotors with $\epsilon_2 \gtrsim 0.3$.

PACS numbers: 21.10.Dr, 21.10.Ft, 23.20.Lv, 27.60.+j

For nearly 25 years there have been experimental[1] and theoretical[2] indications that the region of atomic nuclei with $Z > 50$ and $N < 82$ should contain nuclei with considerable permanent ground-state deformation. Until now, experimental data[3] have been confined to the periphery of this region. However, theoretical interest has continued[4] and during the last few years new attempts[5-9] have been made to put these predictions on a more quantitative footing with calculations of which isotopes are most deformed, the size and type of deformation, and the manner in which the transition from sphericity (near $Z = 50$ and $N = 82$) to deformation occurs.

Although the center of this deformed region appears to lie beyond the proton dripline (near $N,Z = 64$), most predictions indicate that an area of axially symmetric prolate rotors with $\epsilon_2 \simeq 0.3$ should occur in the lightest particle-bound Nd, Pm, and Sm isotopes. This Letter reports on a series of experiments aimed at extending data far into this region in order to test these estimates of shape.

The most favorable method of production of neutron-deficient exotic nuclei in the $A \sim 130$ region is through compound-nuclear reactions of heavy ions fusing at energies near the Coulomb barrier (~ 4 MeV/nucleon). The bulk of the compound nuclei decay by charged-particle evaporation which leads to production of isotopes closer to stability. To investigate selectively nuclei approaching the proton dripline special detectors are required which allow some selection of reaction channels. In this Letter the isotopic origin of gamma rays was established by measurement of the multiplicities of coincident evaporated particles emitted during compound-nuclear cooling.[10] Standard techniques of gamma-ray spectroscopy were then used to investigate nuclear shapes through the deduction of decay schemes. This technique permits a significant advance in the experimental information on the $A \sim 130$ region which enables us to make the first systematic tests of nuclear-shape predictions.

Targets of 1–3 mg/cm^2 of enriched isotopes on ~ 30-mg/cm^2 Pb backings were bombarded with heavy-ion beams from the Daresbury Laboratory Van de Graaff accelerator. A list of beam and target combinations is given in Table I. Gamma rays were detected in an array of four bismuth-germanium-oxide–shielded germanium detectors[11] placed at 135° to the beam direction. Neutrons were detected in a 1-m^2 array[10] of 37 NE213 liquid-scintillation detectors situated at 0° and subtending a solid angle of 4.7 sr. Charged particles were detected in a Si surface-barrier-detector telescope also at 0°, with a 90-μm ΔE detector and 2000-μm E counter, which subtended 1.0 sr. For each gamma ray the ratio of photopeak intensities in spectra gated by $0, 1, 2, \ldots$ coincident neutrons, protons, or alphas provide a measure of multiplicities of evaporated particles. Complex multiplets of photopeaks in the singles spectra could usually be resolved and analyzed with suitable triple-coincidence selection (e.g., γ-p-n vs γ-$2p$-n). Cross bombardments and changes of relative yield with beam energy provided supporting evidence for assignments. Cas-

TABLE I. Reactions used to populate nuclei in the light rare-earth region.

Beam	Target	Beam energy (MeV)	Compound nucleus	New even-even nuclei produced
^{40}Ca	^{92}Mo	147–200	$^{132}_{62}$Sm$_{70}$	$(2p\,2n)^{128}$Nd; $(\alpha 2p)^{126}$Ce
^{40}Ca	^{96}Mo	175	$^{136}_{62}$Sm$_{74}$	$(2p\,2n)^{132}$Nd
^{40}Ca	^{96}Ru	150–200	$^{136}_{64}$Gd$_{72}$	$(4p)^{132}$Nd; $(\alpha 2p)^{130}$Nd
^{46}Ti	^{92}Mo	205,210	$^{138}_{64}$Gd$_{74}$	$(\alpha 2p)^{132}$Nd; $(2p\,2n)^{134}$Sm
^{48}Ti	^{92}Mo	210	$^{140}_{64}$Gd$_{76}$	$(2p\,2n)^{136}$Sm
^{50}Cr	^{92}Mo	220,230	$^{142}_{66}$Dy$_{76}$	$(\alpha 2p)^{136}$Sm; $(2p\,2n)^{138}$Gd; $(4p)^{138}$Sm
^{50}Cr	^{94}Mo	230	$^{144}_{66}$Dy$_{78}$	$(2p\,2n)^{140}$Gd

cades of transitions were related by γ-γ and particle-γ-γ coincidence data so that the isotopic origin of most bands was highly overdetermined. The nuclei furthest from stability and of most interest are produced through the emission of two protons and two neutrons. For these rare events ($<1\%$ of the fusion cross section) the pattern of neutron detectors firing was examined and events involving adjacent detectors were eliminated to reduce the effect of neutron scattering.

From the reactions listed in Table I a wealth of data have been collected and are undergoing analysis. Some previous misassignments are identified, particularly those of ^{128,132}Nd (Ref. 3 and Choquier, Gizon, and Gizon[12]), which remove the anomalies noted in Ref. 8. This Letter concentrates on the systematic behavior of the even-even isotopes in which states are reported for the first time. We present the energies of the lowest members of these bands in Table II. To demonstrate rigorously that these gamma rays form the normal cascade of stretched $E2$ transitions linking the 0^+-2^+-4^+. . . sequence found in even-even nuclei and to quantify the collectivity of

TABLE II. Gamma-ray energies (in kiloelectronvolts) of the ground-state bands of some new nuclei observed in this work. The ratio of the excitation energy of the first 4^+ state to the 2^+ state is in the last column.

Nucleus	$(2^+ \rightarrow 0^+)$	$(4^+ \rightarrow 2^+)$	$(6^+ \rightarrow 4^+)$	$(8^+ \rightarrow 6^+)$	$(10^+ \rightarrow 8^+)$	$(12^+ \rightarrow 10^+)$	$(14^+ \rightarrow 12^+)$	$(16^+ \rightarrow 14^+)$	$(18^+ \rightarrow 16^+)$	$\frac{E(4_1{}^+)}{E(2_1{}^+)}$
$^{126}_{58}$Ce$_{68}$[a]	170	350	497	608	611	688	679	608	809	3.06
$^{128}_{60}$Nd$_{68}$	134	292	424	530						3.15
$^{130}_{60}$Nd$_{70}$	158	325	455	547	614	664	705	745		3.06
$^{132}_{60}$Nd$_{72}$	213	397	522	580	600	637	687			2.87
$^{134}_{62}$Sm$_{72}$	163	316	418	491	563	640				2.94
$^{136}_{62}$Sm$_{74}$	256	432	535	578	616	678				2.69
$^{138}_{62}$Sm$_{76}$[b]	347	545	686	776	553	356	657			2.57
$^{138}_{64}$Gd$_{74}$	221	385	489	556	616	685				2.74
$^{140}_{64}$Gd$_{76}$	329	508	628	675	827					2.54
	$(\frac{15}{2}^- \rightarrow \frac{11}{2}^-)$	$(\frac{19}{2}^- \rightarrow \frac{15}{2}^-)$	$(\frac{23}{2}^- \rightarrow \frac{19}{2}^-)$	$(\frac{27}{2}^- \rightarrow \frac{23}{2}^-)$	$(\frac{31}{2}^- \rightarrow \frac{27}{2}^-)$	$(\frac{35}{2}^- \rightarrow \frac{31}{2}^-)$	$(\frac{39}{2}^- \rightarrow \frac{35}{2}^-)$	$(\frac{43}{2}^- \rightarrow \frac{39}{2}^-)$		
$^{133}_{61}$Pm$_{72}$	253	430	570	676	742	792	852	917		
$^{135}_{61}$Pm$_{74}$	287	513	658	749	805					
$^{137}_{61}$Pm$_{76}$[b]	337	641	857							

[a] 2-4-6 cascade previously suggested by R. M. Diamond *et al.*, in *Proceedings of the International Conference on Nuclei Far from Stability, Leysin, Switzerland, 1970* (CERN Scientific Information Center, Geneva, Switzerland, 1970).

[b] Cascades identified by W. Starzecki *et al.*, in *Proceedings of the International Conference on Nuclear Physics, Florence, Italy, 1983,* edited by P. Blasie and R. A. Ricci (Tipografia Compositore, Bologna, Italy, 1984).

transitions, further spectroscopic measurements of angular distributions, linear polarizations, and lifetimes will be required and are planned. However, on the assumption that the cascades are the ground-state sequences, several conclusions can be drawn.

The empirical relationship between the energy of the first $J^{\pi}=2^{+}$ state and the $B(E2;2\rightarrow 0)$ in even-even nuclei noted by Grodzins[13] can be used to obtain an expression[14] for mean deformation. We have compared this estimate with deformations extracted from $B(E2;2\rightarrow 0)$ values for Ce[3,15,16] isotopes under the assumption of axial symmetry and a uniform charge distribution. The trend from sphericity (at $N=82$) to deformation ($\epsilon_2>0.25$) is well reproduced, although the values extracted from $B(E2)$'s exhibit more structure, especially in the transition region near $N=74$. The validity of the estimate has been shown in hyperfine studies of Cs isotopes[17-19] where quadrupole and magnetic-moment measurements indicate prolate deformations commensurate with its predictions.

The systematic trends in ϵ_2 extracted from Grodzins's estimate for Ce, Nd, Sm, and Gd are shown in the upper part of Fig. 1. It can be seen that the transition to deformation in the new region is more gradual than in their heavy ($N>82$) counterparts, where deformations extracted from energy-level systematics and $B(E2)$ values[3] increase suddenly near $N=90$. A further difference between heavy and light rare-earth rotors is the influence of the $Z=64$ subshell closure. In the $N>82$ trend to deformation, the Gd nuclei are initially spherical, and then show the most rapid change to deformation at $N=88,90$. Adjacent elements, both heavier[3] and lighter,[17,18] show shape transitions which become more gradual with increasing distance from $Z=64$. In the light rare-earth region this effect does not occur and the transitional behavior

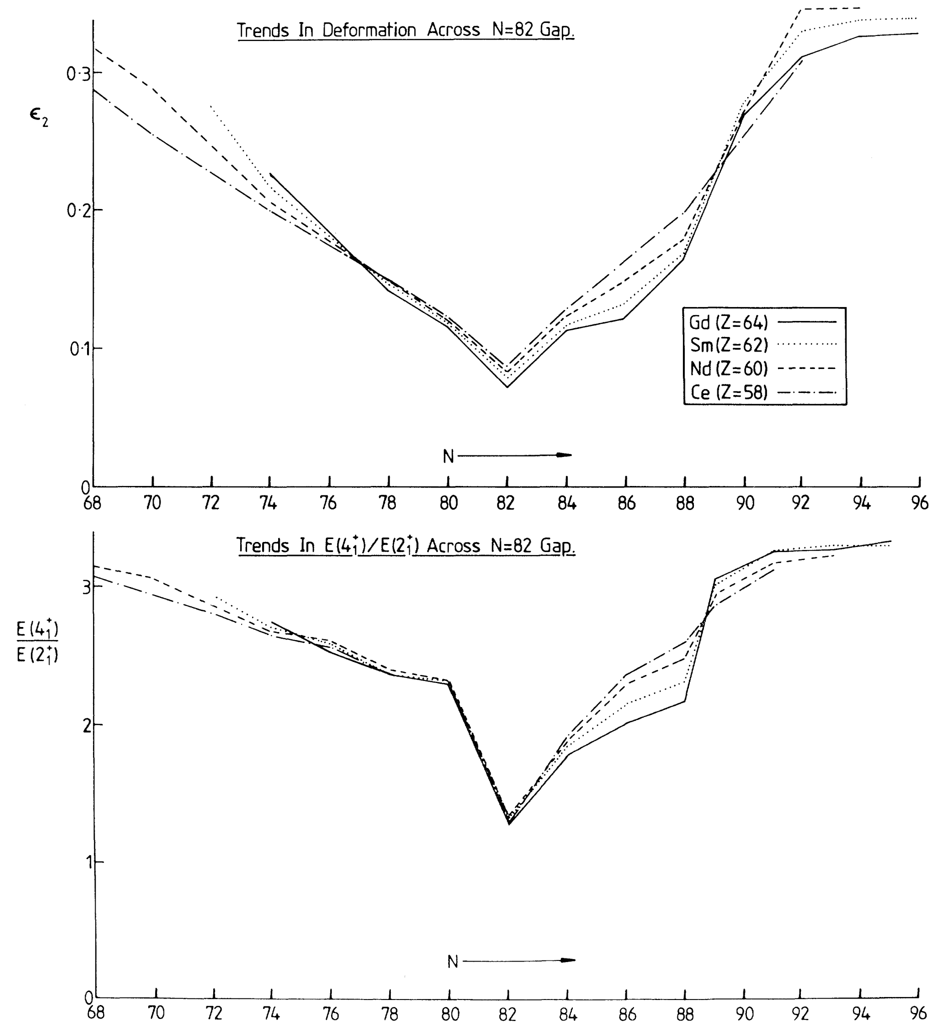

FIG. 1. Upper panel, deformation extracted from the $E(2^{+})$ systematics using Grodzins's formula (Refs. 13 and 14). Lower panel, the ratio of excitation energies of the first 4^{+} and 2^{+} states.

of the elements studies shows little Z dependence.

The ratio of excitation energies of the first 4^+ to 2^+ states is also known to be a guide to the size and type of deformation and is illustrated in the lower part of Fig. 1. For a perfect axially symmetric rotor, this ratio should be 3.33, for a deformed nucleus which is γ unstable it should be 2.5, and for a spherical vibrator, 2.0. The lightest Ce, Nd, and Sm isotopes have $E(4)/E(2) > 3.0$, and are approaching closely the ideal axially symmetric behavior. This is consistent with lifetime and backbending data on light Ce isotopes[15,16,20] which indicate a decrease in the role of γ in lighter nuclei. The high value of this ratio does not appear to support the predictions of extremely γ-unstable shapes in Refs. 4 and 6.

Leander and Möller[7] have emphasized the importance of studying odd-A nuclei in this region. They predict that Pm($Z = 61$) isotopes will show the most rapid shape change near $N = 74$. Stephens *et al.*[14] have found that odd-proton nuclei in the $A \sim 130$ region have decoupled $\pi h_{11/2}$ bands with moments of inertia which reflect the adjacent core deformation. In Table II we have indicated candidates for $\pi h_{11/2}$ decoupled bands in ^{133,135,137}Pm. The Pm isotopes have bands which closely follow the behavior of their Nd isotones; the transition to rotational behavior does not appear markedly more abrupt than in the even nuclei.

Several of the new nuclei have been populated to sufficiently high spin to begin investigation of the systematics of upbending and backbending. Light Ce isotopes are known[15,16] to backbend strongly. Clear evidence[21] has been found that the effect arises from the alignment of a pair of $h_{11/2}$ protons. All of our new measurements to date, both in even-even and odd-A nuclei, indicate that this is a general feature in this region.

The Nd and Sm nuclei have been found to upbend, with the interaction strength between the ground and s bands being strongest in the Sm nuclei. We have extracted interaction strengths of 0.19 ± 0.02, 1.03 ± 0.10, and 1.49 ± 0.30 MeV for the $N = 72$ isotones ^{130}Ce, ^{132}Nd, and ^{134}Sm, respectively, following the prescription of Bengtsson and Frauendorf.[22] A comparison of these values with standard cranked shell-model calculations[15,22] shows a rather poor agreement with the predictions of 0.01, 0.07, and 0.04 MeV, respectively; values which are wrong in relative and in absolute magnitude. We have repeated the calculations with the "modified" Nilsson parameters suggested in Ref. 19 and find that the relative interaction strengths of Ce, Nd, and Sm can be reproduced, but there is still an order of magnitude shortfall in absolute strengths. Clearly, this effect merits further study.

In conclusion, this Letter reports a major advance in knowledge of the $A \sim 130$ region of deformation. Data are presented on eight even-even nuclei which connect previous detailed studies on the periphery of this region to observations of states in nuclei where good axial rotational behavior with quadrupole deformation $\epsilon_2 \gtrsim 0.3$ appears to be well established. The data confirm the general trends in deformation predicted by potential-energy surface calculations. We hope that this Letter stimulates theoretical and experimental interest in this region, as a great deal of work is required to understand the details of the behavior of these nuclei. An intriguing possibility is that the lightest nuclei, with closely spaced neutron and proton Fermi surfaces, may provide an ideal situation to search for evidence of short-range n-p pairing correlations.

This research has been funded by grants from the United Kingdom Science and Engineering Research Council.

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