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Authors

Sheline, Raymond K.
Sikkeland, Torbjorn
Chanda, Richard N.

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OF NUCLEAR DEFORMATION

Raymond K. Sheline, Torbjørn Sikkeland, and Richard N. Chanda

October 24, 1961

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Raymond K. Sheline[†], Torbjorn Sikkeland, and Richard N. Chanda

Lawrence Radiation Laboratory
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The nuclear periodic table has three or possibly four regions where nuclei have been experimentally shown to be deformed, namely $A \approx 19$ to 28 and 150 to 190, $A \geq 222$, and possibly $A \sim 8$. The work presented in this paper gives experimental evidence for an additional region of deformation.

Figure 1 is a schematic representation of the nuclear periodic table in which previously observed regions of nuclear deformation are labeled 2, 4, 5, and 6. Up to $A \approx 40$, the line of beta stability of the nuclear periodic table involves nuclei whose neutron and proton numbers are about the same. Therefore, the first limited regions of deformation, labeled 5 and 6 in Fig. 1, have $N \approx Z$. Above $A \approx 40$, however, the line of beta stability shifts toward a higher neutron ratio. Consequently the neutron and proton shells are somewhat out of phase until one reaches the rare earths and actinides, where extended regions of deformation are observed because the 50 to 82-proton region is approximately in phase with the 82 to 126-neutron region and the 82 to 126-proton region with the 126 to 184-neutron region. On the other hand, though highly neutron-deficient and correspondingly unstable the regions labeled 1 and 3 in Fig. 1, where $N \approx Z$, should contain deformed nuclei. We have concentrated our effort in region 1.

In order to study the energy levels of nuclei in region 1, it was necessary to discover a number of new La and Pr nuclides. We will report here only on those new nuclides whose mass number, half life, and first excited state are relatively certain.

The simplest available method of proving that nuclei are deformed involves the production of odd-odd nuclei whose decay into daughter even-even nuclei gives a characteristic low energy for the first excited state and, if possible, a rotational band built on the ground state with spins $0+$, $2+$, $4+$, $6+$... and ratios of energies to the first excited state $1.0:3.33:7.00$... Accordingly, we have produced the nuclei La^{126} , La^{128} , and La^{130} with half lives of 1.0 ± 0.3 , 6.5 ± 1.0 , and 9.0 ± 1.0 min, respectively.

These La nuclei have been made in a variety of ways (see Table I)†

Table I. Nuclear reactions showing cross bombardments used to produce the nuclides, La^{126} , La^{128} , and La^{130} .

New nuclide	Nuclear reactions	Heavy-ion bombarding energy (Mev)
La^{126}	$\text{In}^{115}(\text{O}^{16}, 5\text{n})\text{La}^{126}$	94
	$\text{Sb}^{121}(\text{C}^{12}, 7\text{n})\text{La}^{126}$	117
La^{128}	$\text{In}^{115}(\text{O}^{16}, 3\text{n})\text{La}^{128}$	65
	$\text{Sb}^{121}(\text{C}^{12}, 5\text{n})\text{La}^{128}$	84
	$\text{Sb}^{123}(\text{C}^{12}, 7\text{n})\text{La}^{128}$	117
La^{130}	$\text{Sb}^{121}(\text{C}^{12}, 3\text{n})\text{La}^{130}$	53
	$\text{Sb}^{123}(\text{C}^{12}, 5\text{n})\text{La}^{130}$	84

using the heavy-ion current of the Berkeley Hilac. A heavy-ion bombarding energy was chosen which would give maximum yield of a desired isotope. This energy (see Table I) was estimated by using Cameron's mass table¹ and by

assuming the average kinetic energy of each emitted neutron to be 4 to 5 Mev.

The reaction products recoiling out of $\sim 1 \text{ mg/cm}^2$ self-supporting targets of In and Sb were caught in a 1.8-mg/cm^2 Pd foil which was then dissolved in hot aqua regia. With Ba as holdback carrier the La activities were precipitated in LaF_3 and the precipitate washed once with dilute HF. The procedure took about 1.7 min from the end of bombardment to the start of counting.

When the same targets were bombarded by ions that produce elements below La in atomic number, the chemical procedure separated only a small fraction of the activity. This suggests that the radiochemical purity of the sample was satisfactory. The purity was also checked by separating some of the La activities carrier-free by elution with ammonium α -hydroxy isobutyrate from a column of Dowex-50 cation-exchange resin.

The mass assignments are also quite definite. In the first place, there is the evidence on the mass numbers from the cross bombardments shown in Table I. In the second place the La^{126} is shown to decay into a species that has a spectrum identical² with that of Ba^{126} . Finally, the La^{130} emits a very strong $356 \pm 4\text{-keV}$ gamma ray. A 359-keV gamma ray is observed³ in the Coulomb excitation of Ba^{130} . To verify the above mass assignments, we are now determining the excitation functions.

The energy levels in the daughter nuclei Ba^{126} , Ba^{128} , and Ba^{130} are used to determine whether or not these nuclei are deformed. The first excited state of the even-even Ba nuclides including Ba^{126} , Ba^{128} , and Ba^{130} are plotted in Fig.2. The lowering of the first-excited-state energy with mass number is similar to that observed in the normal rare earths. A more detailed analysis of these energies is therefore necessary. There are at least three ways to use the first-excited-state energy as a criterion for

deformation. These are (a) a direct comparison between the energy of the first excited state and an $(E_{2+})_{\text{crit.}}$ suggested by Alder et al.,⁴ (b) a determination of an empirical deformation, $\beta_{\text{emp.}}$, from a relationship between $S/S_{\text{rig.}}$ and β ,⁵ and (c) a comparison of $\beta_{\text{Mig.}}$ from the relationship of Migdahl.⁶ These three methods are utilized in Table II, where comparisons are made with other nuclei with similar deformations but from other regions of deformation. A comparison of Ba^{126} , Ba^{128} , and Ba^{130} with other deformed nuclei indicates that Ba^{126} is like W^{186} , Os^{186} , and Ra^{224} . Thus all of these nuclei have a first-excited-state energy less than $(E_{2+})_{\text{crit.}}$ and have very similar $\beta_{\text{emp.}}$ (0.19 to 0.21) and $\beta_{\text{Mig.}}$ (0.15 to 0.18).

Similar statements apply to a comparison of Ba^{128} to Os^{188} and Ra^{222} . On the other hand, both Ba^{130} and Os^{190} seem to be in a transition region. Their first-excited-state energies are each higher than the $(E_{2+})_{\text{crit.}}$, and each has $\beta_{\text{emp.}} = 0.16$ and $\beta_{\text{Mig.}} = 0.12$. Osmium-190 has a rotational band which cannot be fitted well with the simple $I(I+1)$ relationship but is fitted by the nonaxially symmetric rotator model of Davydov and Phillipov.⁷ It seems very probably that Ba^{130} would be very similar in this regard.

In addition to gamma-ray singles spectra, gamma-gamma coincidences were also taken, using standard fast-slow circuitry and, in some cases, a two-dimensional coincidence analyzer. Coincidences were found in each of the La nuclides. The ratio of the supposed second excited state varied from 2.55 in Ba^{130} to 3.13 in Ba^{126} . This agrees very well with the ratios of energies for the first to second and third excited states of the rotational band built on the ground state, which are given in Table II for similarly deformed nuclei. For an axially symmetric rotator, these ratios should be 1.00 : 3.33 : 7.00 : 12.00. However, it must be pointed out clearly that none of the second-excited-state spins have been measured, and the decay-

Table II. Comparisons between the nuclei Ba^{126} , Ba^{128} , and Ba^{130} and nuclei from other regions of deformation.

Nucleus	E_{2+}^a (keV)	$(E_{2+})_{crit.}^b$ (keV)	$\xi/\xi_{rig.}^c$	$\beta_{emp.}^d$	$\beta_{Mig.}^e$	$\beta_{exp.}^f$	Ratios of energies in the rotational band
Ba^{126}	256	279	0.251	0.20	0.16		
Ba^{128}	279	272	0.225	0.18	0.15		
Ba^{130}	356	265	0.172	0.16	0.12		
Gd^{154}	123	200	0.462	0.29	0.25	0.30	1.0:3.02:5.84
Dy^{156}	138	196	0.333	0.23	0.19		1.0:2.93:5.59
W^{186}	124	147	0.273	0.20	0.17	0.24	1.0:3.28
Os^{186}	137	147	0.247	0.19	0.15	0.20	1.0:3.19:6.33
Os^{188}	155	144	0.215	0.18	0.14	0.18	1.0:3.09
Os^{190}	188	142	0.174	0.16	0.12		1.0:2.93:5.60:8.89
Ra^{222}	111	110	0.228	0.19	0.15		1.0:2.79:5.78
Ra^{224}	84.5	108	0.295	0.21	0.18		1.0:2.98
Th^{226}	72.1	106	0.341	0.23	0.20		1.0:3.14:6.33

a. Throughout the Table, energy values are taken from R. K. Sheline, Revs. Modern Phys. 32, 1 (1960) except the values for Ba^{126} , Ba^{128} , and Ba^{130} (reported herein) and Dy^{156} [see E. P. Gregorev and B. S. Dzhelepov, Doklady Akad. Nauk. SSSR 135, 564 (1960)].

b. Values of $(E_{2+})_{crit.} \approx 13\hbar^2/\xi_{rig}$ are given (see Ref. 3). This $(E_{2+})_{crit.}$ is the criterion by which nuclei may be assumed to be spherical [for $E_{2+} > (E_{2+})_{crit.}$] or deformed [for $E_{2+} < (E_{2+})_{crit.}$]. Often the transition is not as abrupt as indicated by the single value.

c. Ratio of $\xi = 3\hbar^2/E_{2+}$ to $\xi_{rig} = 2MAR_0^2/5(1+0.31\beta+..)$ where $R_0 = 1.2A^{1/3} \times 10^{-13}$ cm and $\beta = 1.08/A^{1/3}$.

d. See Ref. 5.

e. See Ref. 6.

f. Experimental deformations calculated from the available values of the transition probabilities for Coulomb excitation.

scheme work is incomplete. The coincidence data thus far available strongly favor a rotational-band interpretation and seem inconsistent with a vibrational interpretation. Nonetheless, a more complete proof of the existence of a rotational band must await complete coincidence analysis.

A trend similar to Fig. 2 for the first excited states of even-even Ce nuclei has also been observed. However, in this case mass assignments and half-lives of the Pr nuclides are not nearly as certain. This evidence does tend to confirm the existence of an extended region of deformation, however. The existence of the region of deformation labeled 1 in Fig. 1 suggests that (a) it should be possible to observe deformed even-even Nd nuclei and possibly also Sm nuclei with presently available heavy-ion beams, and (b) it is certainly feasible to observe a large number of deformed odd-A Ba, La, Ce, Pr, Nd, and Pm nuclides. The observation of odd-A nuclei in this region would be particularly interesting because it would allow assignments of Nilsson orbits in this new region of deformation.

Recent calculations on the equilibrium deformations for nuclei in regions 1 and 3 on Fig. 1 indicate a considerable deformation in each region.⁸ These calculations and this experiment should provide impetus to the observation of deformations in the neutron-deficient actinides, region 3 in Fig. 1. Such experiments might be undertaken by the observation of the α fine structure resulting from decay of even-even nuclei produced from the following types of nuclear reactions: $\text{Pb}^{204}(\text{O}^{16}, 8\text{n})\text{Th}^{212}$ and $\text{Hg}^{196}(\text{Ne}^{20}, 8\text{n})\text{Th}^{208}$.

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FOOTNOTES AND REFERENCES

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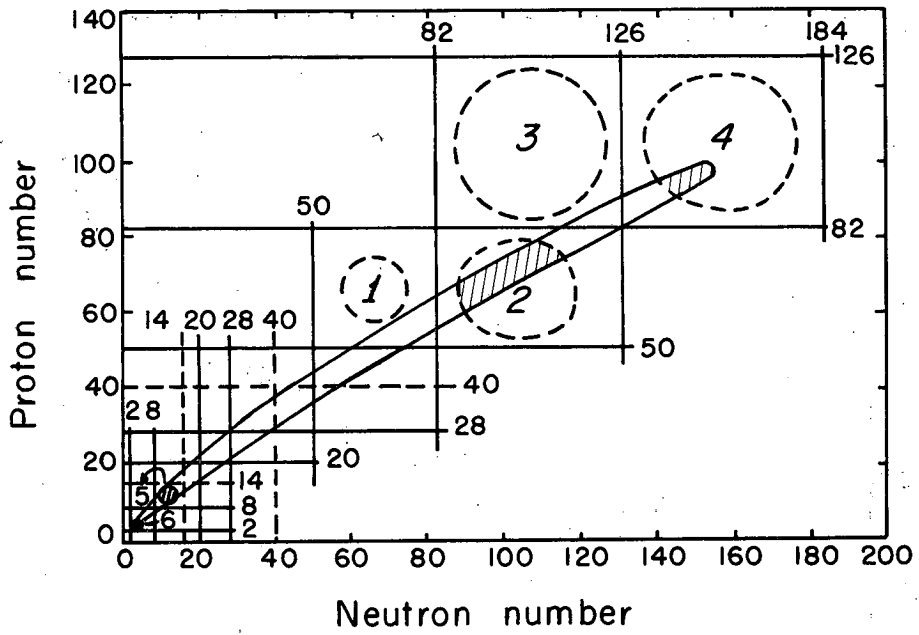
†Summer visitor, on leave from Florida State University, Tallahassee, Florida.

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FIGURE LEGENDS

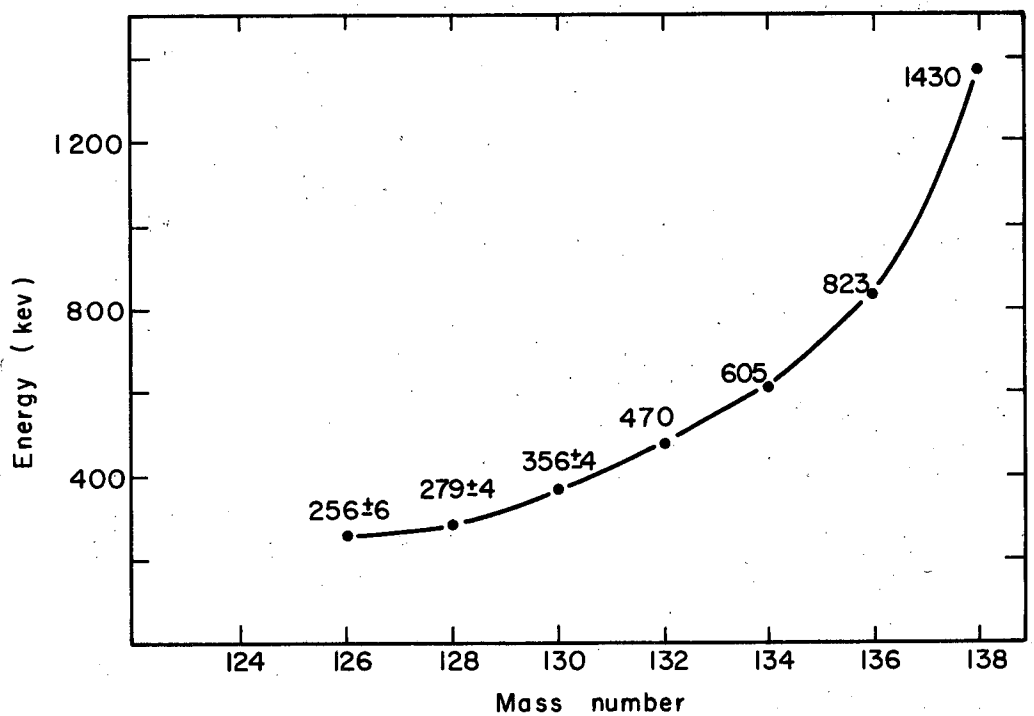
Fig. 1. Schematic representation of the nuclear periodic table showing the neutron (vertical solid lines) and proton (horizontal solid lines) closed shells. The dotted vertical and horizontal lines represent semiclosed shells, which have an effect on regions of deformation. The thin banana-shaped curve approximately encloses nuclei that have been experimentally studied. Regions where nuclei have been experimentally observed to be deformed are indicated with cross hatching. Additional regions where it is reasonable to expect to find deformed nuclei are labeled 1 and 3. This research is concerned with region 1. This figure is patterned after one suggested by E. K. Hyde.

Fig. 2. First excited states of even-even Ba nuclides. The levels in Ba^{126} , Ba^{128} , and Ba^{130} are the results of this research. The dotted lines shows $(E_{2+})_{crit.}$, the dividing point between spherical and deformed nuclei.



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Fig. 2



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Fig. 1

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