The lines in the maser spectrum could be due either to the properties of the glass or to the effect of maser action in a resonant cavity. If the Nd^{+3} ions are in a limited number of well-defined atomic sites in the glass many lines could result,[9] similar to the satellite lines found in red ruby.[6] Alternatively, the lines could be due to the effect of the resonant cavity which gives standing waves only at discrete wavelengths.

The writer gratefully acknowledges the help given by R. Young for making the glass samples, Dr. H. Jupnik for the evaporations, E. Dixon for the studies on various length samples, and F. Hoffman for competent technical assistance during the measurements phase of this work.

[1]A. L. Schawlow and C. H. Townes, Phys. Rev. 112, 1940 (1958).
[2]T. H. Maiman, Nature 187, 493 (1960).
[3]P. P. Sorokin and M. J. Stevenson, Phys. Rev. Letters 5, 557 (1960); IBM J. Research 5, 56 (1961).
[4]W. Kaiser, C. G. Barrett, and D. L. Wood, Phys. Rev. 123, 766 (1961).
[5]I. Wieder and L. R. Sarles, Phys. Rev. Letters 6, 95 (1961).
[6]A. L. Schawlow and G. E. Devlin, Phys. Rev. Letters 6, 96 (1961).
[7]A. Javan, W. R. Bennett, and D. R. Herriott, Phys. Rev. Letters 6, 106 (1961).
[8]E. H. Carlson and G. H. Dieke, J. Chem. Phys. 34, 1602 (1961).
[9]R. C. Vickery and R. Sedlacek, Nature 181, 39 (1958).

EXPERIMENTAL OBSERVATION OF A NEW REGION OF NUCLEAR DEFORMATION*

Raymond K. Sheline,† Torbjørn Sikkeland, and Richard N. Chanda
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received November 20, 1961)

The nuclear periodic table has three or possibly four regions where nuclei have been experimentally shown to be deformed, namely $A \cong 19$ to 28 and 150 to 190, $A \geqslant 222$, and possibly $A \sim 8$. The work presented in this Letter 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 $A \cong 40$, 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 $N \cong Z$. Above $A \cong 40$, 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 $N \cong Z$, should contain deformed nuclei. We have concentrated our effort in region 1.

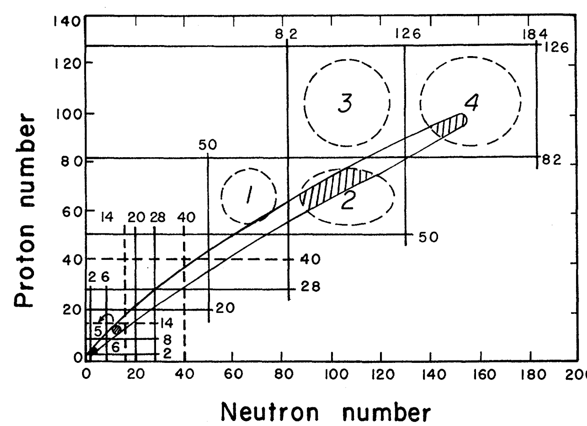

FIG. 1. Schematic representation of the nuclear periodic table showing the neutron (vertical solid lines) and proton (horizontal solid lines) closed shells. The dashed vertical and horizontal lines represent semiclosed shells, which have an effect on regions of deformation. The thin banana-shaped curve 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.

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.

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}	$In^{115}(O^{16},5n)La^{126}$	94
	$Sb^{121}(C^{12},7n)La^{126}$	117
La^{128}	$In^{115}(O^{16},3n)La^{128}$	65
	$Sb^{121}(C^{12},5n)La^{128}$	84
	$Sb^{123}(C^{12},7n)La^{128}$	117
La^{130}	$Sb^{121}(C^{12},3n)La^{130}$	53
	$Sb^{123}(C^{12},5n)La^{130}$	84

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+, ··· 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), 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 table[1] and by assuming the average kinetic energy of each emitted neutron to be 4 to 5 Mev.

The reaction products recoiling out of ~1-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 identical[2] with that of Ba^{126}. Finally, the La^{130} emits a very strong 356 ± 4 kev gamma ray. A 359-kev gamma ray is observed[3] 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

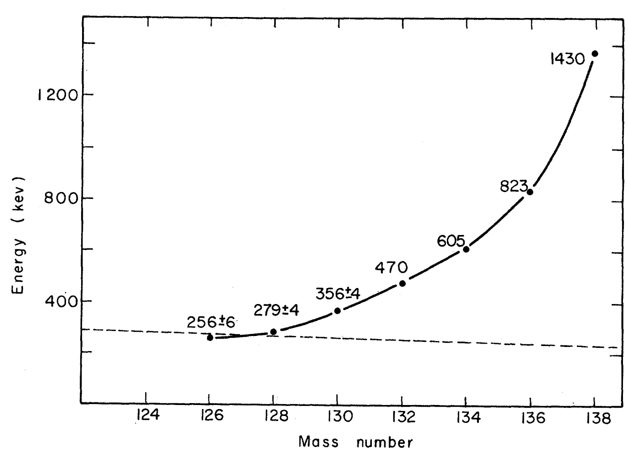

FIG. 2. First excited states of even-even Ba nuclides. The levels in Ba^{126}, Ba^{128}, and Ba^{130} are the results of this research. The dashed line shows $(E_{2+})_{crit}$, the dividing point between spherical and deformed nuclei.

the first excited state and an $(E_{2+})_{crit}$ suggested by Alder et al.,[4] (b) a determination of an empirical deformation, β_{emp}, from a relationship between $\mathscr{I}/\mathscr{I}_{rig}$ and β,[5] and (c) a comparison of β_{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 $(E_{2+})_{crit}$ and have very similar β_{emp} (0.19 to 0.21) and β_{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 $(E_{2+})_{crit}$, and each has $\beta_{emp} = 0.16$ and $\beta_{Mig} = 0.12$. 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 Fillipov.[7] It seems very probable 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 the decay of each of the La nuclides. However, the presence of the 511-kev annihilation radiation tended to obscure coincidence relationships, and it was not possible to fix unambiguously the energy of second and/or third excited states in the Ba isotopes. However, if one makes the simplest assumptions with the coincidence data, the results strongly favor a rotational band interpretation, and are inconsistent with a vibrational interpretation. Ratios of the supposed second excited states are similar to those in Column VIII of Table II. Nonetheless, none of the spins of the supposed second excited states has been measured. Consequently, a satisfactory proof of the existence of rotational states 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

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)	$\mathscr{I}/\mathscr{I}_{rig}$ [c]	β_{emp} [d]	β_{Mig} [e]	β_{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. Grigor'ev and B. S. Dzhelepov, Doklady Akad. Nauk S.S.S.R. 135, 564 (1960); translation: Soviet Phys. –Doklady 3, 1243 (1961)].

[b] Values of $(E_{2+})_{crit} = 13\hbar^2/\mathscr{I}_{rig}$ are given (see reference 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 $\mathscr{I} = 3\hbar^2/E_{2+}$ to $\mathscr{I}_{rig} = (2MAR_0^2/5)(1+0.31\beta+\cdots)$, where $R_0 = 1.2A^{1/3}\times10^{-13}$ cm, $\beta = 1.08/A^{1/3}$, and MA is the nuclear mass.

[d] See reference 5.

[e] Values of β_{Mig} are determined from $\mathscr{I} = (2MAR_0^2/5)(2.33\beta_{Mig} - 0.1)$ (see reference 6).

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

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 the decay of even-even nuclei produced from the following types of nuclear reactions: $Pb^{204}(O^{16}, 8n)Th^{212}$ and $Hg^{196}(Ne^{20}, 8n)Th^{208}$.

We are grateful particularly to Albert Ghiorso for his encouragement and help in all phases of this research, to Daniel O'Connell for the targets, to Roberta Garrett, Suzanne Hargis, and Beverly Isaacs for help with the chemistry and plotting, to the Hilac crew for their help during bombardments, to Charles A. Corum for the design of the target assembly, and to Almon E. Larsh, Alfred Wydler, and William Goldsworthy for help with the electronics.

---

*Work supported by the U. S. Atomic Energy Commission.

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

[1]A. G. W. Cameron, Atomic Energy of Canada Limited Report AECL-433, 1957 (Chalk River Report CRP-690) (unpublished).

[2]M. I. Kalkstein and J. M. Hollander, Phys. Rev. 96, 730 (1954).

[3]L. W. Fagg, Phys Rev. 109, 100 (1958).

[4]K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. 28, 432 (1956).

[5]B. Elbek, in Proceedings of the International Conference on Nuclear Structure, Kingston, Canada, 1960, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, 1960), p. 601; N. K. Glendenning and J. Sawicki, Lawrence Radiation Laboratory Report UCRL-9178, 1960 (unpublished). The parameter β_{emp} is an empirical relationship between $\mathcal{I}/\mathcal{I}_{rig}$ and β.

[6]A. B. Migdahl, Nuclear Phys. 13, 655 (1959).

[7]A. S. Davydov and G. F. Fillipov, Nuclear Phys. 8, 237 (1959).

[8]E. Marshalek, L. Person, and R. K. Sheline, Lawrence Radiation Laboratory (unpublished work).