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**J.A. Becker, E.A. Henry, S.W. Yates,
T.F. Wang, and A. Kuhnert
Lawrence Livermore National Laboratory**

**M.J. Brinkman and J.A. Cizewski
Rutgers University**

**M.A. Deleplanque, R.M. Diamond F.S. Stephens,
F. Azaiez, W. Korten, and J.E. Draper
Lawrence Berkeley Laboratory**

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J. A. Becker, E. A. Henry, S. W. Yates, T. F. Wang, and A. Kuhnert
*Lawrence Livermore National Laboratory,
Livermore, California 94550*

M. J. Brinkman and J. A. Cizewski
Rutgers University, New Brunswick, New Jersey 08903

M. A. Deleplanque, R. M. Diamond, F. S. Stephens,
F. Azaiez, W. Korten, J. E. Draper
*Lawrence Berkeley Laboratory,
Berkeley, California 94720*

A γ -ray cascade in ^{191}Hg of 12 members with average energy spacing 37 keV and $Q_t = 18(3)\text{eb}$ was reported by Moore, and coworkers in 1989. This was the first report of very elongated nuclei (superdeformation) in this mass region. Since then, some 25 γ -ray cascades have been observed in 11 (slightly neutron deficient) Hg, Pb and Tl nuclei. The bands have similar dynamic moments-of-inertia. Some nuclei exhibit multiple bands, and the backbending phenomena has been observed. Level spins can be obtained from comparison of transition energies to rotational model formulas. Selected bands (in different nuclei) have equal transition energies (within 0.1%). Alignment in integer multiples of $\hbar$ has been observed. Properties of these bands will be described.

I. INTRODUCTION

Very elongated or "superdeformed" (SD) nuclei have been known for some time among the heavy nuclei. These are the 34 fission isomers found in the actinide and transactinide region of the nuclear chart, initially discovered in 1962^{1,2} and explained in 1967.^{3,4} A fission isomer is the prototypical shape isomer. The fission isomers, characterized as a prolate ellipsoid, have major/minor axis ratio $c/a \sim 2/1$. They have lifetimes ranging from 10^{-8} to 10^{-3} s and excitation energies of a few MeV relative to the nuclear ground state. Rotational bands with the fission isomer as bandhead have been reported. Further references and detail have been given in a recent review of the fission isomers by Poenaru, *et al.*⁵ These phenomena can be understood in terms of the "double humped" barrier. The fission isomer is a quasi-stationary state whose wave function is concentrated in a deep secondary minimum (II) or "pocket" in the nuclear potential energy surface. Decay is possible either to states of normal deformation (I) or to fission. The isomerism comes about because of the extreme change in shape required of a $II \rightarrow I$ transition and because of the height of the outer fission barrier.

The explanation of the fission isomers suggested that relatively deep secondary minima might exist in nuclei in other regions of the nuclear chart. Early experimental efforts mounted in an effort to locate the analog of fission isomers in other regions of the periodic table where fission is forbidden were unsuccessful. Examples of such studies are those of Bjørnholm, *et al.*,⁶ Ruddy and Alexander,⁷ and Butler *et al.*⁸ These experiments are very difficult because of the expected low formation probability for class II states. New accelerator technology and modern Ge detector arrays offer a possibility of finding shape isomers in other regions of the periodic table. Heavy-ion reactions can be used to populate SD rotational bands at high angular momenta. The experimental signal is a high multiplicity γ -ray cascade with a regular energy spacing characteristic of a very deformed rotating nucleus.

Modern Ge detector arrays have a number of features which make it possible to isolate the cascade γ radiation of a SD band from the background radiation produced by 99% of the reactions. The Ge detectors have excellent energy resolution, are relatively efficient, have Compton suppression shields to enhance the peak/total ratio, and may have an inner 4π ball of Bismuth Germanate (BGO) for multiplicity and sum-energy selection. The large number of Ge detectors makes it possible to emphasize the high multiplicity of the SD cascade in the data analysis (*e.g.* study triple coincidence events).

In 1986, superdeformation at high angular momentum was found⁹ in ^{152}Dy . The nucleus was populated in the fusion-evaporation reaction $^{108}\text{Pd}(^{48}\text{Ca}, 4n)^{152}\text{Dy}$, at $E(^{48}\text{Ca}) = 205 \text{ MeV}$. Reaction γ -rays were detected in a Compton suppressed array of 12 Ge detectors, TESSA3. The experimental signal was a rotational cascade of 19 γ -rays with constant energy difference of 47 keV. The in-band transition rates are very enhanced: $Q_t = 19(3)eb$, $[B(E2) \sim 2660 \text{ Wu}]$. The corresponding major/minor axis ratio is 2/1. The $A \sim 152$ region is being actively explored and there are now ~ 10 nuclei which support SD bands. Another region is located near ^{132}Ce , where Nolan *et al.*¹⁰ first found superdeformation in 1985. While the SD cascade proceeds down to the band head (where it has been studied) in the fission isomers, the γ -ray cascades of the SD bands in the $A = 152$ or 132 region terminate abruptly near spin 24 (^{152}Dy).

II. SUPERDEFORMATION IN THE ^{194}Hg REGION

Recent calculations have emphasized the neutron deficient Hg isotopes as a promis-

ing area of the nuclear chart to look for very deformed nuclei. Chasman¹¹ made detailed predictions in the framework of the cranked Strutinsky model, using a Woods-Saxon potential for neutrons and protons. Chasman suggested that the lighter Hg isotopes were good candidates for an experimental search for superdeformation. The heavy-ion group at Argonne, motivated by these calculations, began a search for superdeformation in 1989.

Self-consistent mean-field calculations have been undertaken by Weiss, Krieger, Bonche and their collaborators.^{12,13} They have the capability of fully microscopic 3-D Hartree-Fock calculations.¹² The nucleon-nucleon interaction is a Skyrme interaction (SKM*) which best describes the fission barrier data, together with a simple seniority pairing potential. Calculations successfully reproduce the shape of the potential barrier for ²³⁰Th. The calculated energy surfaces show deep secondary minima in the Os and Hg nuclei at zero spin.¹³ The minima are deep enough to support a meta-stable spin 0 state in the second well. The nucleus ¹⁹⁴Hg was singled out as a good experimental candidate for observation of shape isomerism. Similar calculations have been done by Girod, *et al.*¹⁴ Motivated by these calculations, the LLNL-LBL-Rutgers collaboration began experiments at the LBL 88-INCH Cyclotron Facility with the detector array HERA in August 1988.

Superdeformation in the $A \sim 194$ region was first reported by Moore and coworkers¹⁵ in ¹⁹¹Hg in July 1989. They produced ¹⁹¹Hg in the ¹⁶⁰Gd(³⁶S,5n) reaction at $E(^{36}\text{S}) = 172$ MeV. The experimental signal consisted of a quadrupole γ -ray cascade of 12 members, with average energy spacing 37 keV. The average quadrupole moment $Q_i = 18(3)eb$ corresponds to $c/a \sim 1.65/1$. Soon after the ¹⁹¹Hg announcement, two collaborations^{16,17} announced (in back-to-back papers) observation of a SD band in ¹⁹²Hg. Strong experimental efforts at major laboratories quickly identified a number of SD cascades in this region. All nuclei were populated in heavy-ion fusion-evaporation reactions and in each case the rotational band signature observed in Ge detector arrays. Residual nucleus identification has been made through various combinations of cross-bombardment techniques, excitation function behaviour, and coincidence relationships with known γ -rays in the residual nucleus. There are now some 25 SD cascades known in 11 Fg, Tl, and Pb nuclei. Fig. 1 illustrates those nuclei where SD bands have definitely been observed in the $A = 194$ region. A reference list has been presented.^{18,19}

The SD bands of this region have a similar moment of inertia. The values of $\mathcal{J}^{(2)}$ start at $\sim 100\hbar^2/\text{MeV}$ and increase smoothly by $\sim 20\%$ over ~ 30 units of $\hbar$. The population pattern is similar to the $A \sim 152$ region, a slow intensity build up with decreasing spin and excitation, a plateau region, and a sudden depopulation over one or two transitions to states of normal deformation. In the $A \sim 194$ region, however, the γ -ray cascade includes low-energy transitions. Therefore cascade γ -ray energies can be fit to rotational model formulas to extract level spin.^{18,20} For example, the 214.6-keV transition in ¹⁹²Hg has been identified as an $I = 10 \rightarrow 8$ transition, and the ¹⁹⁴Hg 262.5-keV transition is an $I = 13 \rightarrow 11$ transition. Thus the SD cascades terminate at low spin in the $A = 194$ region. Bonche, *et al.*²¹ have offered an explanation for the sudden depopulation. The excitation of the SD bands is not accurately known, because the linking transitions to states of normal deformation have not been observed.

The energy spectrum of a rotational band is given by $E = \hbar^2/(2\mathcal{J}) \cdot I(I+1)$, and therefore E_γ for an $I \rightarrow I-2$ transition is $E_\gamma(I \rightarrow I-2) = \hbar^2/(2\mathcal{J}) \cdot (4I-2)$. The constant change in E_γ for adjacent transitions is $\Delta E_\gamma = 8\hbar^2/(2\mathcal{J})$. Fig. 2 illustrates these points for three SD cascades. Nuclei with more than one SD band have been found: Fig. 2(b,c) illustrates the energy spectrum of two of the three SD cascades known^{22,23} in ¹⁹⁴Hg. These two are interpreted as signature partners because of their

relative energy spacing. It can be seen from the figure that the γ -ray transition energies of ^{192}Hg are equal, within 1 keV, to the γ -ray energies of the ^{194}Hg cascade illustrated in Fig. 2(b). There are other cases of the energy equivalence in this mass region and in the $A = 152$ region,²⁴ but it is a more general phenomena in the $A \sim 194$ region. The precision of this energy equivalence, a remarkable phenomena, is not understood at the present time and the subject of intense theoretical activity.

Alignment (the difference in angular momentum as a function of rotational frequency) can be calculated if level spin is known. Fig. 3 illustrates the alignment of the excited bands in ^{194}Hg relative to ^{192}Hg . At higher frequencies, the difference in angular momentum is $1.00(4)\hbar$. Furthermore the transitions in ^{192}Hg line up with the odd-spin ^{194}Hg SD cascade. This completely unexpected association appears to be a common feature in the $A \sim 194$ region. Further discussion and interpretation in terms of pseudospin symmetry have been put forward.^{25,26}

III. SUMMARY

A new region of superdeformation has been located near $A = 194$. The first evidence was reported in July 1989, and since then new experimental reports have come quickly. Presently 25 cascades have been identified in 11 nuclei. The limits of the region of elongated nuclei are not well defined. There are similarities with the $A = 152$ region exist, however two are two major differences: near $A = 194$, the bands extend to low spin ($8-12\hbar$), and they have very similar moments of inertia, $\mathcal{J}^{(2)}$. Multiple bands have been found in several nuclei, and the first instance of back bending has been located.²⁷ Energies of γ -ray transitions are extraordinarily similar between selected bands, well beyond what is expected from $A^{5/3}$ scaling. Present experimental activity is near the sensitivity limit of current detector arrays. Studies with the next generation of detector arrays will undoubtedly yield exciting details of elongated nuclei.

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FIG. 1. Fragment of the nuclear chart illustrating the location of superdeformation in the $A = 194$ region. References are given in *e. g.*, Becker, *et al.*

FIG. 2. Energy spectra of (a) ^{192}Hg ; (b) and (c) $^{194}\text{Hg}^*$. All spectra are double-gated(triple coincidence). Gate details are in Stephens, *et al.*²⁵

FIG. 3. Alignment of $^{194}\text{Hg}^*$ bands 2 ($\bullet$) and 3 ($\blacksquare$) relative to ^{192}Hg vs rotational frequency($E_\gamma/2$).

Permanent Address: University of California, Davis, CA 95616

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188Hg	189Hg	190Hg	191Hg	192Hg	193Hg	194Hg
1	1	1	3	1	4	3
188Pt	189Pt	189Au	190Au	193Tl	194Tl	195Tl
2	2	6	2	2	2	1
194Pb	196Pb					
1	1					

Fig. 1

Fig. 2

Fig. 3

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