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Superdeformation in the Hg-Tl-Pb Region

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ABSTRACT

Superdeformation in the Hg-Tl-Pb region is discussed, with concentration on the experimental results. At least twenty-five superdeformed bands are known in this region, providing much new data to test theoretical calculations.

I. Introduction

The phenomenon of superdeformation has been recently identified in the region of the neutron deficient mercury, thallium, and lead nuclei. Superdeformation was first identified in the actinide nuclei nearly thirty years ago when Polikanov et al.¹ observed delayed fission from ^{242}Am . Experiments at the time showed that the fission isomers were neither of the ordinary "high spin" type, nor caused by small transition energies. The idea of shape isomerism was advanced to explain these nuclear states. In this view, the shape isomer is a state of the nucleus at an extreme deformation. Consequently, decay to normal nuclear states with little or no deformation is inhibited by the dramatic shape change required, and isomerism results. With the incorporation of shell effects into the liquid drop description of nuclear potential energies, deformed minima arose naturally in calculations and provided a theoretical basis for shape isomerism². Theory predicted that secondary minima exist in the

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potential energy surface of nuclei in many regions of the nuclear chart, but additional examples of shape isomerism were found only in the actinides.

This situation changed dramatically in 1986 when Twin et al.³ observed a cascade of seventeen gamma rays in ^{152}Dy data obtained with a heavy-ion reaction. They showed that these gamma rays were mutually coincident with each being about 47 keV from its neighbors. They recognized that this band was the signature of a rapidly rotating nucleus with a large prolate deformation. They established that the axis ratio is 2:1 for ^{152}Dy , as it is in the actinide nuclei. Soon high spin superdeformation was identified in other nuclei near $A = 150$, as well as $A = 135$. Recently superdeformation has been identified in the $A = 142$ region, and in the Hg-Tl-Pb region where the axis ratio is about 1.65:1. The rapid accumulation of experimental data has been accompanied by intense theoretical effort. Though significant understanding of nuclei at a large deformation is emerging, many unanswered questions remain. A partial list of properties necessary to characterize nuclei at large deformation includes: extent of the region in Z and N , excitation energy of the superdeformed (SD) states with respect to the ground state, spins and parities of the SD band members, level lifetimes, band depopulation, moments of inertia, the population mechanism, and the systematics of and relationships between the SD bands. In this paper, we review the experimental results for some of these properties for nuclei in the Hg-Tl-Pb region.

II. A Typical Superdeformed Band in the Hg-Tl-Pb Region

Superdeformed bands have been identified in data from heavy-ion reactions accumulated with large multidetector arrays such as HERA located at the 88-Inch Cyclotron facility at the Lawrence Berkeley Laboratory. These arrays are particularly effective for the study of events with a high gamma-ray multiplicity. The SD band in ^{192}Hg is typical of those found in the region (Fig. 1). The band consists of eighteen levels connected by seventeen gamma rays with energies ranging from about 200 to 800 keV. The energy spacing between gamma rays is about 30 keV near 800 keV, and increases to about 40 keV near 200 keV. The transition intensity gradually increases as the gamma-ray energy decreases, and reaches a maximum near the middle of the sequence. This maximum intensity is sustained down to the one or two lowest energy gamma rays. Then the intensity drops precipitously, and the gamma-ray sequence ends. These gamma-ray energy and intensity patterns are followed by almost all SD bands in the region. The ^{192}Hg SD band is atypical in one respect. It is populated relatively strongly, with about 2% of reactions that make ^{192}Hg resulting in population of the SD band. Many SD bands in the region are populated much more weakly, some as much as a factor of ten less.

Fig. 1 Spectrum of the ^{192}Hg SD band gamma rays gated by the 496-keV gamma ray. Low-lying yrast transitions in ^{192}Hg are labeled by spin and parity, and ^{193}Hg gamma rays are indicated by an asterisk. (From ref. 5).

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

Fig. 2 Nuclei in the Hg-Tl-Pb region where SD bands have been identified. The number in the upper left corner indicates the number of SD bands known in each nucleus.

III. Extent of the Region of Superdeformation

At least twenty-five SD bands have been identified in eleven nuclei in the Hg-Tl-Pb region⁴⁻¹⁵ (see Fig. 2). Many of these nuclei exhibit multiple bands. Much of the current research activity around the world is concentrated on defining the limits of this region of superdeformation. Searches have been made in ¹⁸⁸Hg (ref. 16), ¹⁹⁰Au (ref. 17), and ¹⁸⁹Pt (ref. 18) but no SD bands have been identified in these nuclei. All the more neutron rich nuclei in this region that have been studied in sufficient detail with heavy-ion reactions have been shown to possess SD bands. No results for nuclei with $Z > 82$ have been reported, although studies of Bi, Po, and Ra nuclei are planned or underway. Many nuclei that are predicted to be superdeformed can not be produced by currently available target-projectile combinations.

IV. Spin of Superdeformed Band Members

The spin of the SD band members is an important property that so far has been established only indirectly, except for several actinide nuclei. However, the regular pattern of the gamma-ray sequence immediately suggests that the SD bands are rotational in nature. The gamma rays of several strongly populated SD bands in the Hg-Tl-Pb region have been shown to be quadrupole transitions. Thus the level energies for these bands can be given by the rotational formula:

$$E_I = (\hbar^2/2\mathcal{J})[I(I+1) - K^2] + E_0. \quad (1)$$

As can be seen from the spectra, the spin of a given level is also a smooth function of the gamma-ray energy. Following Harris¹⁹, we have expanded the level spin as a function of rotational frequency:

$$I^* = 2\alpha\omega + 4/3\beta\omega^3 + \dots, \quad (2)$$

where $I^* = \sqrt{I(I+1)}$, I is the spin, and α and β are the inertial parameters, and $\hbar\omega = E_\gamma/2$ is the rotational frequency²⁰. A series of such equations is generated, one for each level, with spin values increasing by $2\hbar$ with each transition. A least squares fit to this set of coupled equations yields I_f , the spin of the lowest level, as well as α and β . This method to determine spin of SD band members is effective in the Hg-Tl-Pb region because the gamma-ray sequence extends to low energies, where a change of one unit of angular momentum has a large affect on the level energy and the gamma-ray energy. This is in contrast to the $A = 150$ region, where gamma-ray sequences end at higher energy and the method cannot

Table 1. Results of least squares fits to eqn. 2 for sixteen superdeformed bands. The bands are identified by the nuclide and the energy of the lowest-energy band transition. Band energies were first fit with I_f , α , and β as free parameters. I_f was then fixed to the nearest integer or half integer (given here) and α and β fit again. The results of the final fits are tabulated here.

Nuclide	E_γ	α ($\times 10^{-2} \hbar^2/\text{keV}$)	β ($\times 10^{-8} \hbar^2/\text{keV}^3$)	I_f
^{190}Hg	360.0	4.129(3)	8.51(6)	14
^{191}Hg	350.6	4.444(5)	6.48(10)	29/2
^{192}Hg	214.6	4.366(2)	9.03(8)	8
^{194}Hg	254.3	4.430(1)	8.49(4)	10
^{194}Pb	169.7	4.398(4)	8.33(16)	6
^{196}Pb	215.8	4.363(5)	6.13(14)	8
^{191}Hg	292.0	4.713(3)	5.21(8)	25/2
^{191}Hg	311.8	4.709(4)	6.14(9)	27/2
^{193}Hg	293.6	4.663(7)	6.45(18)	25/2
^{193}Hg	234.5	4.662(8)	6.37(25)	19/2
^{194}Hg	201.2	4.677(2)	6.23(8)	8
^{194}Hg	262.5	4.682(4)	6.38(11)	11
^{193}Tl	228.1	4.777(5)	5.07(2)	19/2
^{193}Tl	248.3	4.773(4)	5.92(11)	21/2
^{194}Tl	268.0	4.988(5)	4.08(14)	12
^{194}Tl	240.5	4.767(8)	5.30(19)	10

distinguish between similar spin values for the lowest band member.

As a result of our fitting procedure, we know that many of the SD bands in the Hg-Tl-Pb region are depopulated completely near spin 10 (See Table 1). In ^{194}Pb the SD band is observed down to spin 6. Since the spins of the SD band members can be known with confidence now, important quantities such as the kinematic moment of inertia and the spin alignment can be determined. In cases where the population of low-lying yrast states can be observed, an approximate constraint on the number of gamma-rays present in the cascade from the SD band is established. In addition, the fitting procedure provides values for inertial parameters that can be used to compare different SD bands.

Fig. 3 ^{194}Hg normal levels (solid symbols) and SD band levels (open circles) plotted as a function of spin. The SD band becomes yrast at about spin 34. As a result, the SD spin-0 bandhead (unobserved) has an excitation energy of about 4 MeV.

V. Excitation Energy of Superdeformed Bands

An important, and as yet unresolved, question about SD bands is their excitation energies relative to the ground state. The precise way to determine a band's excitation energy is by identifying the gamma rays that connect the levels in the SD band to the normal levels in the nucleus. These connecting transitions have not been identified so far (except possibly in ^{191}Hg , an observation as yet unconfirmed). To gain insight into the excitation energy of SD bands in these nuclei, we have made the usual assumption that the SD band becomes yrast at the transition which exhibits half the maximum band intensity. In ^{194}Hg that transition connects levels with spins 36 and 34. In order to improve our knowledge of the yrast sequence of normal states in ^{194}Hg , we have extended the known level scheme up to approximately spin 34. A reasonable positioning of the spin 34 SD band member relative to the normal states of about the same spin results in the spin 10 SD band member being about 2.2 MeV above the lowest 8+ level (see Fig. 3). The spin-0 SD bandhead is then found by extrapolation to be about 4 MeV above the ground state. The three-dimensional microscopic Hartree-Fock calculations of Bonche et al.²¹, which yield a SD minimum that is 4 to 5 MeV above the ground-state minimum, are in agreement for our estimate of the excitation energy for the SD bandhead in ^{194}Hg .

Fig. 4 Intensity remaining in the SD band as a function of level spin for some bands in ^{192}Hg , ^{193}Hg , ^{194}Hg , and ^{194}Pb . For ^{194}Hg , the intensity plots are for the yrast SD band (solid curve), and one of the excited bands (dashed curve).

VI. Depopulation of Superdeformed Bands

The intensities of the transitions in the all SD bands in the Hg-Tl-Pb region follow the same general pattern of an increase as the gamma-ray energy decreases until a maximum is attained about midway through the band, followed by a rapid decrease in intensity for the one or two lowest energy transitions. The SD bands are completely depopulated before the bandhead is reached. This observation is understood conceptually as competition between in-band and out-of-band transitions. However, detailed understanding of band depopulation is only beginning to emerge and probably involves the density of states, mixing of SD and normal states, a decrease of transition rates within the SD band, the influence of octupole and higher multipole degrees of freedom, and other phenomena.

Fig. 4 summarizes the depopulation of the SD bands as a function of level spin for ^{192}Hg , ^{193}Hg , ^{194}Hg (two bands) and ^{194}Pb . The intensity of all of these bands has decreased to below detectable limits by the time the gamma-ray cascade has reached levels in the spin range of 6 to 12. The SD band in ^{194}Pb is observed down to the spin 6 level, the lowest spin

Fig. 5 Level scheme of ^{194}Pb , including the SD band at about 5 MeV of excitation. The transition intensities at the right of the gamma-ray arrows are normalized to 100 for the maximum intensity of the SD band. Intensity values are preliminary.

observed in an SD band outside the actinide region. On the basis of energy alone, the quadrupole transition rates for the lowest-energy gamma rays observed in these bands differ by about an order of magnitude or more, if all other factors are equal. Particularly interesting is ^{194}Hg where the most strongly populated (yrast) SD band is depopulated at spin 10, while a more weakly populated (excited) band is depopulated at spin 8. Theoretical calculations of Bonche et al.²² are beginning to reproduce general band depopulation patterns such as the ones exhibited by these nuclei. However, detailed understanding of band depopulation will be necessary in order to predict with confidence the existence of shape isomers in this region.

In some even-A nuclei with few low-lying isomers, the feeding of normal yrast states can be measured, even if the connecting transitions can not be observed. Fig. 5 depicts a portion of the ^{194}Pb level scheme including the SD band. The maximum intensity of the band is taken as 100 units. The intensity of the lower SD band transitions and the normal states in coincidence with the band are indicated. Those transitions for which the intensity is not given cannot be observed and an upper limit on their intensity is about 20 units. The intensity of the $4^{+}\text{--}2^{+}$ and $2^{+}\text{--}0^{+}$ transitions is about 80 units, indicating that up to 20 units of the intensity may go through the 9^{-} , 10^{+} , 11^{-} , or 12^{+} isomers and could not be detected in thin target experiments. Most of the intensity that is observed goes through the $5^{-}\text{--}4^{+}$ transition. If the SD band in ^{194}Pb has positive parity as would be expected, this observation indicates that E1 decay from the SD bands in this region may populate low-lying negative-parity levels directly. The importance of the octupole degree of freedom in the decay of the SD bands could be assessed once the E1 transition rates are measured. Cullen et al.¹³ have suggested that octupole deformation may play a role in the decay of one SD band to another in ^{193}Hg .

This work is supported in part by the U. S. Department of Energy under Contract No. W7405-ENG-48 (LLNL), the SDIO/IST (LLNL), in part by the U. S. Department on Energy under Contract No. DE-AC03-76SF00098 (LBL), and in part by the National Science Foundation (Rutgers).

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