Conf 9210367--2

SUPERDEFORMATION IN THE MASS 190 REGION

T. L. Khoo, T. Lauritsen, Y. Liang, M. P. Carpenter,
R. V. F. Janssens, I. Ahmad, P. B. Fernandez, R. G. Henry,
E. F. Moore, F. Soramel, F. L. H. Wolfs
Argonne National Lab., 9700 S. Cass Ave., Argonne, IL 60439

Ph. Benet, I. G. Bearden, B. Fornal, P. J. Daly
Purdue University, West Lafayette, IN 47907

K. B. Beard, U. Garg, D. Ye
University of Notre Dame, Notre Dame, IN 46556

M. W. Drigert
Idaho National Engineering Lab., Idaho Falls, ID 83415

ABSTRACT

The steps in the formation of superdeformed bands are described. The hot compound nucleus cools and is trapped within the superdeformed secondary minimum, becoming a cold system executing periodic motion (rotation), before suddenly heating up in the process of decaying to the normal yrast states.

1. Introduction

There is a growing interest in the physics of mesoscopic systems, which have a finite number of particles and are, hence, neither microscopic or macroscopic. New fields of research have blossomed in the study of metal clusters, buckyballs, cold trapped ions and small systems in condensed matter physics, such as quantum dots. The nucleus is, of course, the prototypical mesoscopic system. Thus, our studies reveal information not only about the structure of the nucleus but also about mesoscopic physics in general.

The superposition of microscopic shell structure and macroscopic liquid drop properties can produce well-defined pockets in the potential energy surface at large deformation and lead to the occurrence of highly elongated superdeformed (SD) nuclei - see Fig. 1. The SD secondary minimum is generally an excited minimum, or false vacuum, above the normal ground state, or true vacuum. It is believed that a false vacuum was responsible for the inflation phase of the big bang, during which an extremely rapid expansion of the universe occurred. The SD minimum, a pronounced well which is several MeV deep, thus, provides an opportunity to study physics in a false vacuum, as well as the mechanisms for falling into and out of the false vacuum. The yrast states in the SD pockets, as well as the first few low-lying states (refer to Fig. 1), give rise to SD bands which emit the well-known sharp equally-spaced E2 γ rays. With increasing excitation energy the level density increases

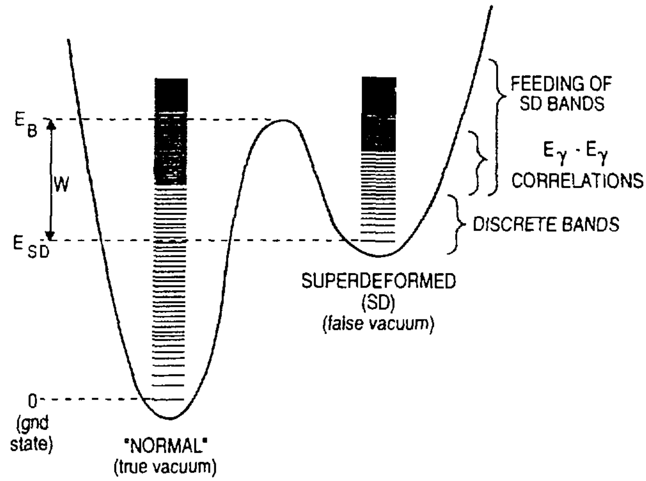

Fig. 1. Schematic potential energy surface, showing the secondary SD minimum above the minimum corresponding to normal states of smaller deformation. Different methods are indicated for studying SD states at various excitation energies in the SD well.

and leads to a quasicontinuum of bands which can be observed as ridges in E_{γ}-E_{γ} matrices (see, for example, Ref. 1). As the excitation energy approaches the top of the barrier separating SD states from normal ones, not only does the level density increase, but mixing between the two classes of states also grows. Normal states are here defined as the entire family of states which are not localized around the SD minimum in deformation space. The excited SD states can be investigated through the feeding of SD bands.

The feeding and decay of SD bands involves large amplitude motion, with very dramatic rearrangements of nuclear shape and structure, as depicted in Fig. 2. The fusion of two heavy ions leads to a hot compound nucleus. Even after cooling by neutron emission, the compound nucleus is still sufficiently hot that thermal fluctuations leads to sampling of a large variety of shapes in the β-γ plane, before it is finally trapped in the SD well. The decay from the SD pocket involves a change from a very elongated prolate shape, with the angular momentum perpendicular to the symmetry axis, to oblate shapes, where the angular momentum is either aligned perpendicular to or along the symmetry axis.

In the following, we shall discuss the main step in the chronology connected with SD bands; into, in and out of the SD minimum. Many of the results reported here are from experiments on ^{192}Hg and were performed using the Argonne-Notre Dame γ facility and ATLAS, the Argonne accelerator system.

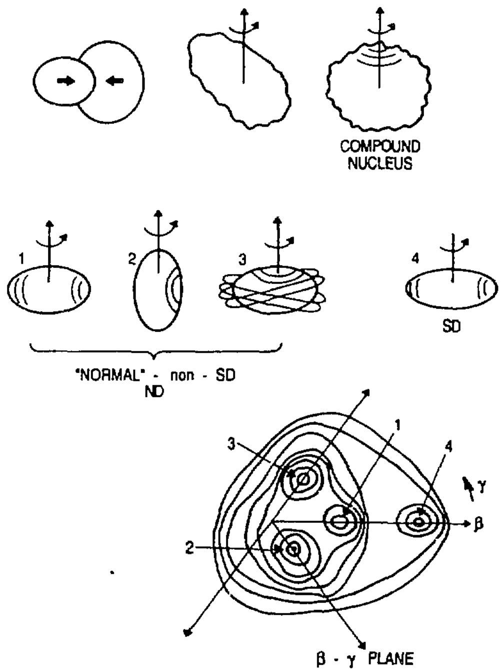

Fig. 2. Illustration of various shapes encountered, starting from the moment of fusion, and their localization in the beta-γ plane. At high temperature, fluctuations cause sampling of an assortment of shapes, some shown in the middle row. The SD shape is established after trapping in the SD minimum. When a SD nucleus decays, a major shape rearrangement usually results in oblate shapes (2 and 3).

2. Into the SD Minimum-Feeding SD Bands

Neutron emission cools the nucleus to the so-called entry region, which lies about one binding energy above the yrast line. Further cooling occurs with emission of statistical γ rays, and angular momentum is removed by stretched E2 transitions. At high excitation energy, the nuclear shape is not well-defined as mixing between SD and normal states leads to exchanges between the two classes of states. When the γ cascade reaches below the barrier, trapping in either the SD or normal well increases. The bulk of E2 γ rays are emitted by the SD nucleus below the top of the barrier. This is illustrated in Fig. 3 by typical cascades generated by a model (Ref. 2,3), involving Monte Carlo simulations, which is able to account for all the observables connected with feeding of SD bands, including: band intensities, variation of intensity with spin, entry distributions (Ref. 2,3) leading to formation of SD bands and quasicontinuum spectra of γ rays leading to the SD band.

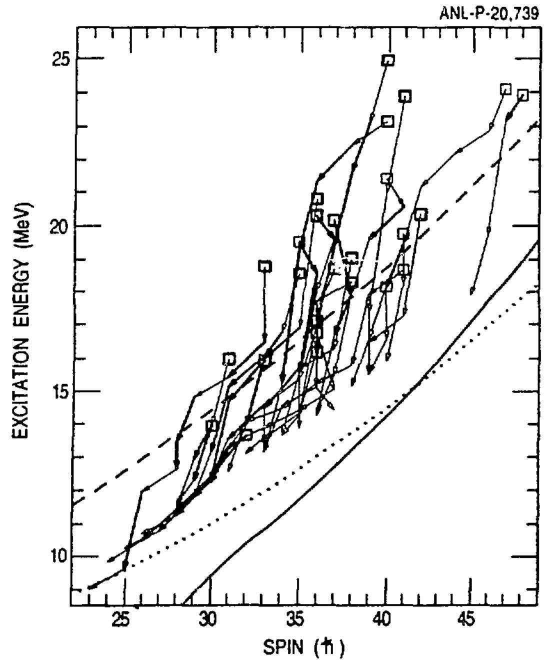

Fig. 3. Samples of 25 cascades which populate SD bands. Transitions are denoted by thick lines when the initial shape is normal and by thin lines when it is SD. Thick or thin squares indicate either normal or SD shapes, respectively, at the starting point of a cascade. The normal (solid line) and SD (dotted line) yrast lines are shown, as well as the barrier separating the two classes of states (dashed line).

Figure 4 shows the spectrum of quasicontinuum γ rays coincident with SD lines. (A correction for detector response has been applied and sharp intraband lines and γ rays following the SD band decay have been subtracted.) The prominent peak arises from stretched E2 γ rays preceding the band. A Maxwellian-like spectrum is also apparent, which must contain both the statistical γ rays preceding the SD band, as well as the decay γ rays. A spectrum has been obtained from our model, which reproduces well the shape of the E2 peak, but not the overall multiplicity - see Fig. 4. When the cascade reaches near the bottom of the SD well, trapping is complete and further γ emission gives rise to sharp lines which have the characteristic picket-fence pattern of almost equal spacing.

3. In the SD Well - the SD Bands

The dynamic moments of inertia $J^{(2)}$ can be deduced from the spacings. Figure 5 shows $J^{(2)}$ as a function of rotational frequency for all known SD bands in the mass 190 region. A striking feature is that

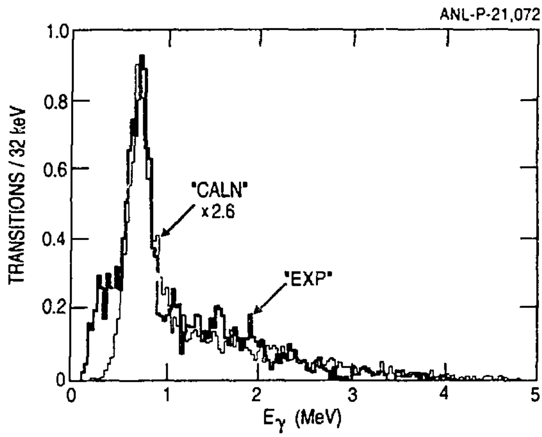

Fig. 4. Thick line: measured spectrum of quasicontinuum transitions coincident with SD lines in ^{192}Hg (after correction for detector response), which includes both the γ rays feeding and decaying from the SD band. Thin line: spectrum of only feeding transitions from Mónte Carlo simulations, multiplied by 2.6.

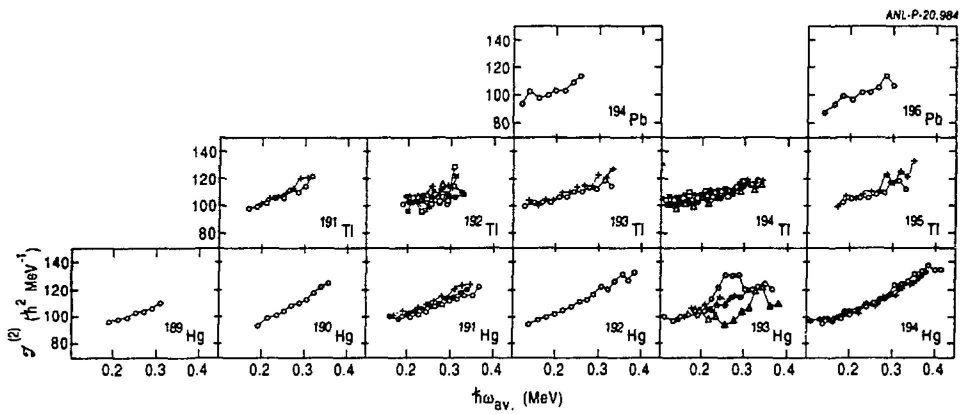

Fig. 5. Dynamic moments of inertia as a function of rotational frequency ($E_\gamma/2$) of all known SD bands in the A=190 region. Note the general rise with frequency. Data are complied from work done at many laboratories; a partial list of references may be found in Ref. 6.

$J^{(2)}$ increases with frequency for all bands. Cranked shell model calculations (e.g. Ref. 4) suggest that this rise is due to alignment of both protons and neutrons from N=6 and N=7 shells (which are two major shells higher in spherical nuclei). Alignment implies that pair correlations are still present despite the large deformation and angular momentum. If the aligning N=6 and 7 orbitals are blocked, there should be no alignment. This indeed is observed (Ref. 5) in a pair of SD bands in the odd-odd nucleus ^{192}Tl (see Fig. 6), thereby providing support for the above interpretation. The cranked shell model calculations provide good indications of the orbitals which are near the Fermi surface at large deformation (β~0.50), but there are still many open problems to be solved before a complete description of SD bands is achieved.

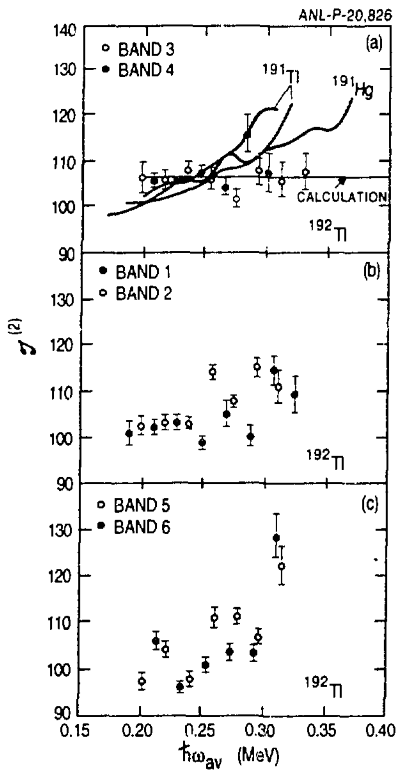

Fig. 6. Dynamic moments of inertia of the 6 SD bands found in ^{192}Tl. Bands 3 and 4, the only examples of constant $J^{(2)}$ in the A=190 region, show that occupation of the N=6 proton and N=7 neutron orbitals block the alignment responsible for the generally increasing $J^{(2)}$ in all other cases in the A=190 region (see Fig. 5).

Perhaps the most striking revelation from SD bands is that there are bands in adjacent nuclei, differing by one or two nucleons, which exhibit transition energies which are equal within 1 part in 500. There are also cases where the line energies in an odd-A nucleus lie almost exactly at the 1/4 and 3/4 points of the interval between SD transitions in an adjacent even-even nucleus. These degeneracies, which are highly unusual in nuclear physics, occur in both the A=150 and 190 regions for SD bands. Identical bands are discussed in, e.g., Ref. 6. Examples have now been also found[7,8] for nuclei with smaller deformation. It is clear that one requirement for this unexpected phenomenon is identical moments of inertia in nuclei with different masses and where pairing is expected to be quite different. The physics giving rise to either identical moments of inertia or identical γ energies is still not identified. It would be exciting if the cause is an underlying symmetry, which has yet to be identified.

4. Out of the SD Minimum -- Decay of the Bands

When sharp rotational transitions are emitted, the nucleus is a cold rotating system which is near the minimum of the SD well. However, as the angular momentum decreases, the excitation energy above the normal yrast line increases, so that the SD state is embedded in a sea of normal states with increasing level density (see Fig. 7). Suddenly - very suddenly indeed - the band disappears, around spin 10 and 25 in the A=190 and 150 regions, respectively. The SD band, which may have emitted an impressive series of 20 consecutive transitions up to this point, disappears without a trace! Searches for the decay γ rays have found them to be very elusive.

The likely cause for the decay is that a SD state mixes with the underlying continuum of normal states. A calculation (Ref. 3) on this mixing, using a model first introduced by Vigezzi et al. (Ref. 9), suggests that: (a) the SD well has a depth of 0.5-1.3 MeV at the point of decay; (b) the sudden decay requires a well depth which changes with spin (at a rate of $dW/dI \sim 0.25$ MeV/$\hbar$); and (c) the mixing is with only a few of the adjacent normal states (the spreading width of the SD state is only 0.03 times the average separation between normal states). Thus, the decaying SD state is still very narrow. It is expected to lie about 3.3-4.3 MeV (Ref. 2,3) above the normal yrast line.

Since the decay occurs through the admixed components of normal states, the decay pattern should be that of a highly excited normal state. This decay should be largely statistical, with a quasicontinuous spectral distribution. Superimposed on this should be sharp lines below about 1 MeV from the vicinity of the normal yrast line, as well as broad clusters of lines near the maximum energy available for decay. These are features we predict for the decay γ rays. If they are indeed so widely dispersed in energy, they would be hard to detect.

Figure 4 contains the spectrum of transitions which both populate and depopulate the SD band in ^{192}Hg. It contains a prominent E2 peak from the transition feeding the SD band, as well as a Maxwellian-like component which must contain both the statistical γ rays feeding the band and the decay γ rays. The spectrum of only feeding γ rays is calculated in our model and is also shown; it exhibits both the E2 peak

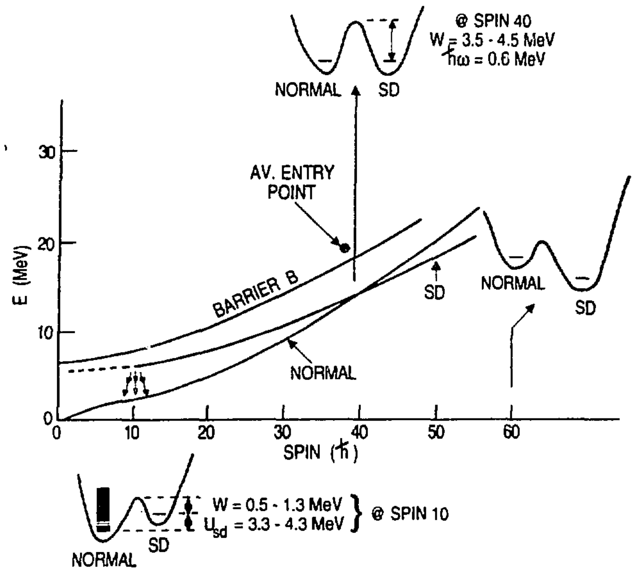

Fig. 7. Summary of some information on feeding and decay of SD states. Energies of normal and SD yrast lines in ^{192}Hg, and of the barrier separating normal and SD states are given. The SD band excitation energy shown here is deduced from the feeding process. Typical well depths at different spins are shown (but not to scale).

and statistical γ rays. (There is, however, a discrepancy between the multiplicities of the experimental and calculated E2 peak.) The calculated spectrum shows little yield below 0.5 MeV, whereas the experimental spectrum still contains some strength here. We suggest that this difference, and other dissimilarities between spectra such as those shown in Fig. 4, may be used to extricate decay γ rays from feeding transitions. However, the experimental spectrum in Fig. 4 suffers from low statistics, particularly at high energy. Furthermore, since it was obtained by setting only single gates on a few "clean" lines, there is danger of contamination camouflaging as the sought-after decay γ's. A reliable search for the decay spectrum must await data from the next generation of γ-ray arrays, such as EUROGAM and GAMMASPHERE.

5. Summary

There are several fascinating steps in the formation of SD bands. First, there is cooling of a hot compound nucleus, where shapes are not well-defined because of shape fluctuations. Second, the SD shape begins to take form after trapping in the SD well begins about 1 MeV below the barrier. Trapping is complete when the cascade reaches near the bottom of the well. Isolated by the barrier from normal states, which may have high density, the SD nucleus executes ordered periodic motion and emits a characteristic rotational spectrum. Third, when the density of normal states becomes sufficiently high, the SD state eventually mixes weakly with a few of them. The small admixture of normal states, together with a quickly decreasing intraband transition rate, leads to a complete disappearance of the SD band. The cold ordered system suddenly becomes chaotic and emits, we predict, a statistical (thermal) spectrum. Fourth, there is rapid cooling to the normal yrast line and sharp lines are again emitted in the final yrast cascade to the ground state. But the striking regularity of the spectrum from the false vacuum is not recovered.

6. Acknowledgement

This work was supported by the U.S. Department of Energy, Nuclear Physics Division, under contract W-31-109-ENG-38.

7. References

1. B. Herskind, T. Døssing, N. Nica, S. Leoni, A. Bracco, R. A. Broglia, E. Vigezzi and M. Matsuo, *Proc. of Int. Seminar on the Frontiers of Nuclear Spectroscopy, Kyoto, Japan 21-24 October 1992.*

2. T. Lauritsen, Ph. Benet, T. L. Khoo, K. B. Beard, I. Ahmad, M. P. Carpenter, P. J. Daly, M. W. Drigert, U. Garg, P. B. Fernandez, R. V. F. Janssens, E. F. Moore, F. L. H. Wolfs and D. Ye, *Phys. Rev. Lett.* 69 (1992) 2479.

3. T. L. Khoo, T. Lauritsen, I. Ahmad, M. P. Carpenter, P. B. Fernandez, R. V. F. Janssens, E. F. Moore, F. L. H. Wolfs, Ph. Benet, P. J. Daly, K. B. Beard, U. Garg, D. Ye and M. W. Drigert, *Proc. INS International Symposium on Rapidly Rotating Nuclei, October 21-24 1992, Tokyo.*

4. M. P. Carpenter, R. V. F. Janssens, I. Ahmad, P. B. Fernandez, T. L. Khoo, F. L. H. Wolfs, D. Ye, K. B. Beard, U. Garg, Ph. Benet, R. Wyss, W. Satuła, W. Nazarewicz and M. A. Riley, *Phys. Lett.* B240 (1990) 44.

5. Y. Liang, M. P. Carpenter, R. V. F. Janssens, I. Ahmad, R. Henry, T. L. Khoo, T. Lauritsen, F. Soramel, S. Pilotte, J. M. Lewis, L. L. Riedinger, C.-H. Yu, U. Garg, W. Reviol, and I. G. Bearden, *Phys. Rev.* C46 (1992) R2136.

6. R. V. F. Janssens, and T. L. Khoo, *Ann. Rev. Nucl. Part. Sci.* 41 (1991) 321.

7. I. Ahmad, M. P. Carpenter, R. R. Chasman, R. V. F. Janssens and T. L. Khoo, *Phys. Rev.* C44 (1991) 1204.

8. C. Baktash, J. D. Garrett, D. F. Winchell and A. Smith, *Phys. Rev. Lett.* 69 (1992) 1500.

9. E. Vigezzi, R. A. Broglia and T. Døssing, *Phys. Lett.* B249 163 (1990).