C. SUPERDEFORMATION AND OTHER SPECTROSCOPY TOPICS

Studies of the properties of nuclei under extreme conditions, and in particular, of superdeformed nuclei remain a topic of intense investigation within the Division. Over the last few years, research has emphasized the properties associated with the decay out of superdeformed bands, and searches for hyperdeformation. Other efforts utilizing gamma-ray spectroscopy techniques are also summarized here.

c.1. A Superdeformed Band in the N = Z Nucleus ^{36}Ar

(R. V. F. Janssens, M. P. Carpenter, D. Seweryniak, C. E. Svensson,* A. O. Macchiavelli,* A. Juodagalvis,† C. Baktash,‡ R. M. Clark,* M. Cromaz,* M. A. Deleplanque,* R. M. Diamond,* P. Fallon,* M. Furlotti,§ A. Galindo-Uribarri,‡ G. J. Lane,* I. Y. Lee,* M. Lipoglavsek,‡ S. D. Paul,‡ D. C. Radford,‡ D. G. Sarantites,§ F. S. Stephens,* V. Tomov,§ K. Vetter,* D. Ward,* C. H. Yu,‡ I. Ragnarsson,† and S. Aberg†)

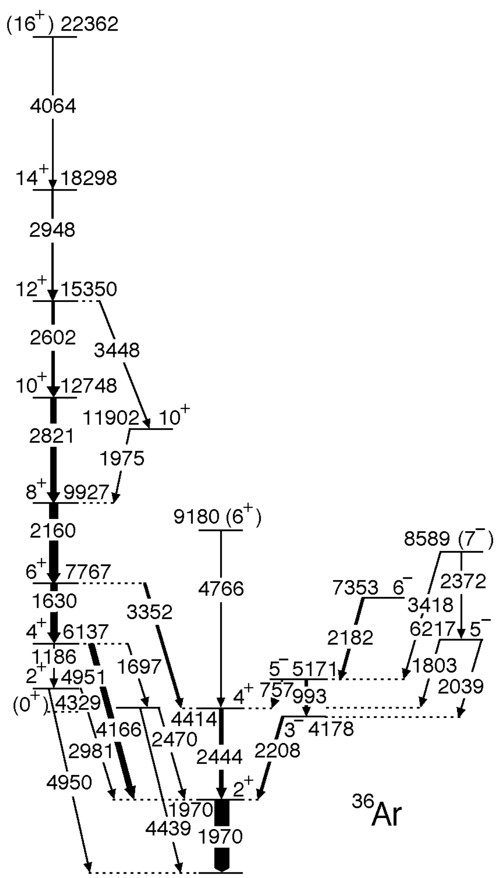

Fig. I-46. Partial decay scheme for ^{36}Ar showing the superdeformed band (left). Transition and level energies are given to the nearest keV.

With the Gammasphere spectrometer and the microball array, a superdeformed band has been identified in the N = Z nucleus ^{36}Ar following the ^{28}Si(^{16}O, 2α) reaction at 75 MeV. The band is firmly linked to known low-spin states in this nucleus: the relevant level scheme is shown in Fig. I-46. The band is observed to its presumed termination (spin 16). Deformed mean field and spherical shell model calculations lead to a configuration assignment in which four fp-shell orbitals are occupied. This band involves the cross-shell correlations typical of rotational motion in heavier nuclei, while the number of active particles remains sufficiently small to be confronted with the spherical shell model. The latter calculations support the $(fp)^4$ assignment, but suggest that the entire sd-shell is also essential for the full description of this band. Hence, ^{36}Ar provides an ideal case to investigate the microscopic origin of collective rotation in nuclei. A paper reporting these results has recently been submitted for publication[1]. In addition, an experiment to determine the lifetimes of the superdeformed states, to deduce the associated deformation (predicted to be $\varepsilon_2 \sim 0.4$) and to characterize the transitions linking the new cascade to the low-lying level structure has also been performed recently. The analysis of the latter experiment is underway.

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[1]C. E. Svensson *et al.*, submitted to Phys. Rev. Lett.

c.2. Decay Out of the Doubly Magic Superdeformed Band in the N = Z Nucleus ^{60}Zn

(M. P. Carpenter, G. Hackman, R. V. F. Janssens, P. Reiter, D. Seweryniak, C. E. Svensson,* D. Rudolph,† C. Baktash,‡ M. A. Bentley,§ J. A. Cameron,* M. Devlin,¶ J. Eberth,|| S. Flibotte,* A. Galindo-Uribarri,‡ D. S. Haslip,* D. R. LaFosse,¶ T. J. Lampman,* I. Y. Lee,** F. Lerma,¶ A. O. Macchiavelli,** J. M. Nieminen,* S. D. Paul,‡ D. C. Radford,‡ L. L. Riedinger,†† D. G. Sarantites,¶ B. Schaly,* O. Thelen,|| H. G. Thomas,|| J. C. Waddington,* D. Ward,** W. Weintraub,†† J. N. Wilson,¶ C. H. Yu,‡ A. V. Afanasjev,†‡‡ and I. Ragnarsson†)

Investigations throughout the chart of the nuclides have led to the observation of many superdeformed (SD) rotational bands in the A ~ 190, 150, 80 and 60 nuclei. Although it has been relatively straightforward to observe the long cascades of rotational transitions in these bands with modern γ-ray arrays, discrete transitions connecting SD bands to states in the first well have been more difficult to identify. As a result, the excitation energy, spin, and parity of levels in these superdeformed bands are unknown. Recently, significant progress has been made in studying the decay out of SD bands in the A ~ 190 region where the observation of linking transitions in ^{194}Hg[1] and ^{194}Pb[2] has led to definite quantum number assignments for SD states in these nuclei. In addition, a consistent description of the decay out process in A ~ 190 SD bands in terms of a statistical process governed by the weak mixing of SD states with a ``sea" of hot ND states has been developed[3]. The nature of the decay out process for SD bands in other mass regions remains an open question.

Recently, an SD band in ^{60}Zn built on the SD shell gaps at *N*,*Z* = 30 has been identified for the first time from data taken with the Gammasphere array. Two different experiments were conducted. In the first experiment, a 125-MeV ^{28}Si beam from the 88-Inch Cyclotron at Lawrence Berkeley National Laboratory accelerated onto a ^{40}Ca produced ^{60}Zn via the 2α channel. In the second experiment, a 134-MeV ^{32}S beam provided by the ATLAS facility at Argonne impinging onto a ^{40}Ca target produced ^{60}Zn via the 3α channel. In both experiments, evaporated charged particles were detected with the Microball, a 4π array of CsI scintillators, in order to isolate weak reaction channels.

From the analysis of these data, a previously unknown rotational band was found consisting of 11 transitions. The quadrupole moment, Q_t of the band was measured to be 2.75 ± 0.45 *e*b. The corresponding quadrupole deformation of 0.47 ± 0.07 confirms the SD character of the band. Of equal interest is the observation of linking transitions connecting the SD band to the yrast line, thus establishing the spins, parities and excitation energies of the SD states. Unlike the A = 190 region where linking transitions are found to have dipole character, these transitions in ^{60}Zn are dominated by $\Delta I = 2$ E2 transitions, indicating that the decay-out process in ^{60}Zn differs substantially from that observed in the A ~ 190 region.

A paper reporting the results from these two experiments was published this past year in Physical Review Letters[4].

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*McMaster University, Hamilton, Ontario, †Lund University, Sweden, ‡Oak Ridge National Laboratory, §Staffordshire University, United Kingdom, ¶Washington University, ||University of Cologne, Germany, **Lawrence Berkeley National Laboratory, ††University of Tennessee, ‡‡Technical University of Münich, Germany

[1] T. L. Khoo *et al*., Phys. Rev. Lett. **79**, 1233 (1996); G. Hackman *et al*., Phys. Rev. Lett. **79**, 4100 (1997).
[2] A. Lopez-Martens *et al*., Phys. Lett. **B380**, 18 (1996).
[3] R. G. Henry *et al*., Phys. Rev. Lett. **73**, 777 (1994).
[4] C. E. Svensson *et al*., Phys. Lett. **82**, 3400 (1999).

c.3. Level Structure of ^{94,95,96}Tc at High Spins and Shell-Model Calculations

(R. V. F. Janssens, M. P. Carpenter, T. L. Khoo, T. Lauritsen, S. S. Ghugre,*
B. Kharraja,* U. Garg,* W. F. Mueller,† W. Reviol,† L. L. Riedinger,†
and R. Kaczarowski‡)

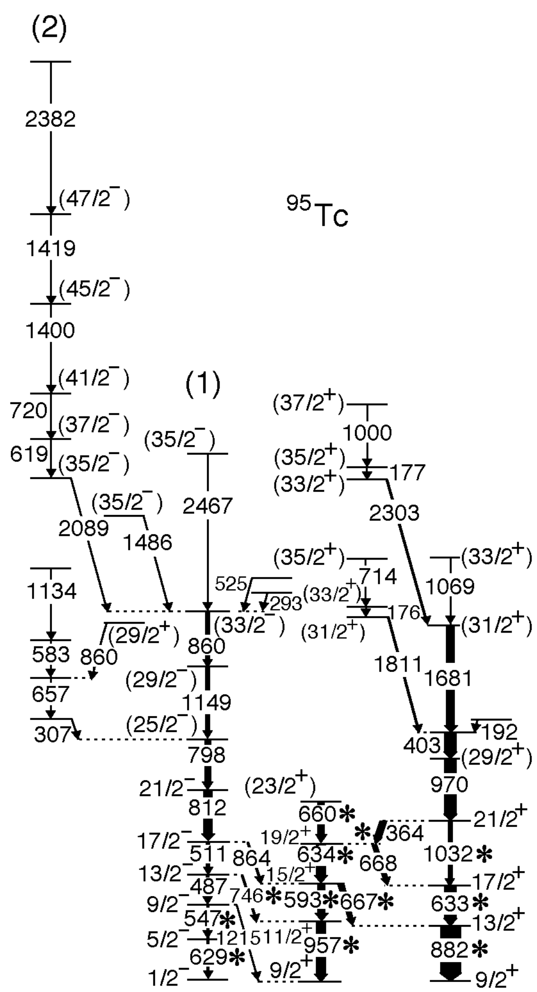

*Fig. I-47. Level scheme for ^{95}Tc as established from the present study. The previously-known transitions are indicated by a * sign.*

High spin states in the ^{94,95,96}Tc (N = 51, 52 and 53) nuclei have been investigated using the ^{65}Cu + ^{36}S reaction at a beam energy of 142 MeV with the Gammasphere spectrometer. More than 60 new transitions have been identified and placed in their respective level schemes, which now extend up to spin ~ 22 $\hbar$ and excitation energies Ex ~ 12 MeV. The ^{95}Tc scheme is given as an example in Fig. I-47. Spherical shell-model calculations have been performed using different model spaces. A restricted model space, using ^{88}Sr as the core and the proton (p1/2, g9/2) and neutron (d5/2, s1/2) valence orbitals, reproduces the experimental excitation energies up to spin 14 $\hbar$. The higher-angular-momentum states are dominated by the excitation of a g9/2 neutron across the N = 50 magic core, as indicated by large-basis shell model calculations. A paper summarizing these results has recently been published[1].

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[1]S. S. Ghugre *et al*., Phys. Rev. C **61**, 024302 (2000).

c.4. Recoil-Distance Lifetime Measurements in ^{96,97,98}Ru: Search for Onset of Collectivity Above the N = 50 Shell Closure (R. V. F. Janssens, I. Ahmad, M. P. Carpenter, T. L. Khoo, T. Lauritsen, B. Kharraja,* S. S. Ghugre,* U. Garg,* H. Jin,* W. F. Mueller,† W. Reviol,† L. L. Riedinger,† R. Kaczarowski,‡ E. Ruchowska,‡ S. Fischer,§ W. C. Ma,¶ and I. M. Govil||)

Lifetimes of high-spin states in the N = 52-54 Ru nuclei have been investigated using the recoil-distance Doppler-shift technique for low- and moderate-spin transitions. The data were collected in coincidence mode at the Argonne-Notre Dame BGO gamma-ray facility using ^{65}Cu(^{36}S,p2-4n) reactions with 142 MeV beams from ATLAS. Lifetimes were obtained for both the positive and negative parity states in the even Ru isotopes. In the odd isotope, lifetimes could only be measured along the yrast line. The main purpose of the experiment was to investigate whether the observed E2 "band-like" cascades seen in these nuclei[1] are of collective nature. The deduced transition probabilities B(E2) and B(M1) do not exhibit the enhancement that would be expected for collective behavior. Rather, good agreement with shell model calculations was found. The data have recently been published[2].

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*University of Notre Dame, †University of Tennessee, ‡Soltan Institute for Nuclear Studies, Swierk, Poland, §DePaul University, ¶Mississippi State University, ||Panjab University, Chandigarh, India

[1]B. Kharraja *et al*., Phys. Rev. C **57**, 83 (1998).

[2]B. Kharraja *et al*., Phys. Rev. C **61**, 024301 (2000).

c.5. Search for Hyper-Deformation in the A = 150 Region (T. Lauritsen, I. Ahmad, M. P. Carpenter, C. Davids, R. V. F. Janssens, T. L. Khoo, C. J. Lister, P. Reiter, A. A. Sonzogni, S. Siem, J. Uusitalo, I. L. Wiedenhöver, A. Korichi,* H. Amro,† S. M. Fischer,§ F. Hannachi,* and A. Lopez-Martens‡)

Several attempts have been made to experimentally verify the existence of a hyper-deformed (HD) minimum in the nuclear potential energy surface. Such a minimum, created by shell effects and stabilized by rapid rotation, has been predicted by a number of theorists[1,2], and is calculated to become yrast at very high spins (> 70 $\hbar$).

Searches for the discrete band transitions emitted while the nucleus is trapped and cold in this minimum have been unsuccessful[3-5]. It is likely that the nucleus never gets cold enough over a sufficiently long time period for a cascade of closely spaced discrete gamma rays to be emitted. The only evidence that we therefore may get for the existence of the HD minimum is from the gamma rays emitted while the nucleus is relatively hot in this minimum. In that case, because the level density is high and there are many bands, a quasicontinuum (QC) of gamma rays are emitted which will exhibit characteristic ridges in a gamma-gamma matrix or planes in a gamma-gamma-gamma cube. The first hints of evidence for HD were indeed found in QC spectra (of ^{153}Dy[6-7]).

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[1]Dudeck *et al*., Phys. Rev. B **211**, 252 (1988).

[2]Chasman, Phys. Lett. **B302**, 134 (1993).

[3]LaFosse *et al*., Phys. Rev. C **54**, 1585 (1996).

[4]LaFosse *et al*., Phys. Rev. Lett. **74**, 5186 (1996).

[5]J. N. Wilson *et al*., Phys. Rev. C **56**, 2502 (1997).

[6]Galindo-Uribarri *et al*., Phys. Rev. Lett. **71**, 231 (1993).

[7]Lunardi *et al*., Proceedings from the Conference on Nuclear Structure at the Limits, ANL, July 22-26, 1996, p. 29 and Lunardi *et al*., Heavy Ion Physics **6**, 241 (1997).

A new search for hyper-deformation was performed with Gammasphere (GS) coupled to the Fragment Mass Analyzer (FMA). ^{80}Se at 340 MeV impinged on two stacked ^{76}Ge targets. The 4n reaction channels populated ^{152}Dy at very high spins (~70-80 $\hbar$). The FMA coupled to Gammasphere (GS) provides a unique opportunity to optimize the experimental conditions at which the weak HD signal in a strong channel can be extracted. With the FMA it is possible to study reaction channels at much higher spins than usual -- and still get clean spectra -- by populating the channels at much higher bombarding energies than their optimum. The strong competition from fission and other reaction channels at these extreme spins can be overcome by the mass gating of the FMA!

The number of gamma cascades that pass through the HD minimum is probably very small. Thus, one must think of ways to extract the very weak signal from these cascades from the overwhelming number of gamma cascades that do not pass through the HD minimum. One way is to selectively gate on very high spin and relatively low energy entry points (H,K) of a reaction channel. The HD minimum will only be low in energy at very high spins, thus, such a gating should further enhance the HD signal. GS without the heavy-mets mounted in front of the BGO Compton shields is a ≈72% efficient calorimeter. This allows us to efficiently place gates on the sum-energy and multiplicity (~spin) at which the residues are created.

In essence, the performed experiment was tailored to use the Fragment Mass Analyzer (FMA) to cleanly tag on the residues that are populated at high spins; but against all odds survived fission!

The data from this experiment has now been partially analyzed. Figures I-48 and I-49 show diagonal cuts of mass gated (A = 152) gamma-gamma matrices -- with cut parameters identical to those used in Ref. 6. As can be seen, no HD signal is observed. Furthermore, the SD ridges are clearly seen in Fig. I-49 - whereas that is not the case in Ref. 6. This data analysis is still ongoing and the data in Figs. I-48 and I-49 were not HK gated. Preliminary analysis where this energy and spin (HK) gating is used has so far not produced hints of the reported[6] 30 keV HD ridges.

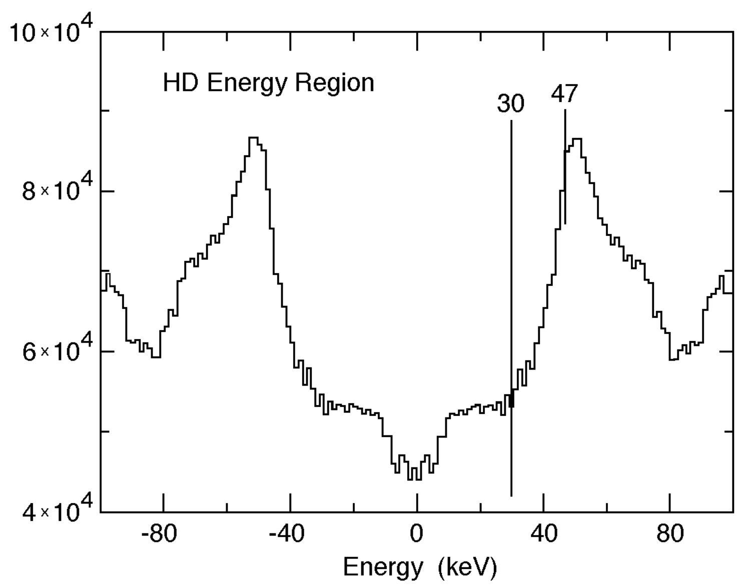

Fig. I-48. Diagonal projection of a gamma-gamma matrix with mass gated (A = 152) data from this experiment. The projection parameters are the same as in Ref. 6 panel a (i.e., the HD region of [6]).

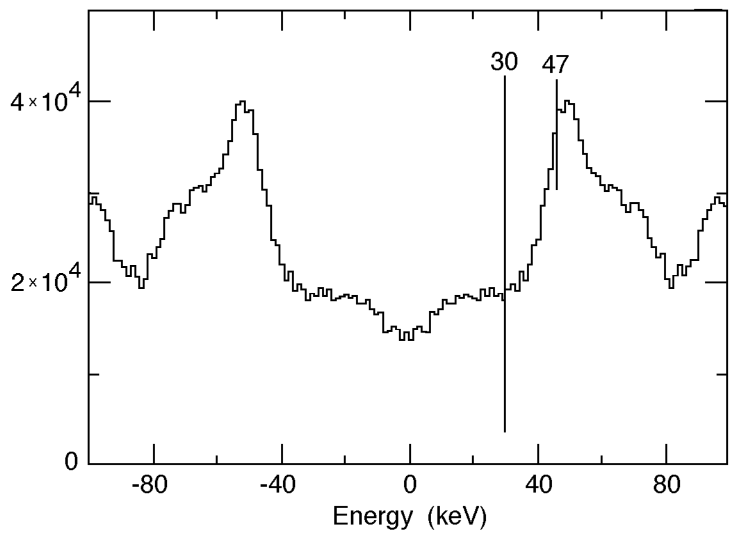

Fig. I-49. Diagonal projection of a gamma-gamma matrix with mass gated (A = 152) data from this experiment. The projection parameters are the same as in Ref. 6 panel b (i.e., the SD region of [6]).

c.6. Quasicontinuum and Discrete Gamma Rays Linking Superdeformed Bands in ^{151,152}Dy (T. Lauritsen, I. Ahmad, M. P. Carpenter, C. Davids, J. P. Greene, R. V. F. Janssens, T. L. Khoo, F. G. Kondev, C. J. Lister, S. Siem, A. Sonzogni, R. C. Vondrasek, I. L. Wiedenhöver, A. Korichi,* H. Amro,† T. Døssing,§ F. Hannachi,* B. Herskind,§ and A. Lopez-Martens‡)

With the possible exception of ^{149}Gd[1], no firm transitions have been found which link the decaying superdeformed (SD) states to the normal (ND) states in the A = 150 mass region. Thus, the spins and excitation energies of the many SD bands in this mass region have not been experimentally determined. A preliminary analysis, based on data from a Gammasphere (GS) experiment in 1998, of (QC) gamma rays in coincidence with the yrast SD bands in ^{151,152}Dy has been performed. The analysis reveals that the spectra of decay QC gamma rays are very different from what is seen in the A = 190 region! No high energy statistical component is seen; rather an excess strength at low energy is observed, see Fig. I-50. This could indicate that the decay of SD bands in the A = 150 region is different from the decay of SD bands the A = 190 region.

Due to the scope and goals of the experiment in 1998, the data set was marginal for the extraction of the QC in coincidence with the SD bands. Thus, a new long run, optimized for the QC analysis, was proposed and accepted by the ATLAS PAC. ^{80}Se at 320 MeV impinged on two stacked ^{76}Ge targets mounted on the Gammasphere target wheel. The 5n,4n reaction channels populated ^{151,152}Dy at optimum energies to populate the SD bands in these residues. The large area fragile stacked germanium targets for the target wheel required significant target developments. Due to the almost symmetric reaction, the transmission of the ^{151,152}Dy were detected in the FMA with as high efficiency as possible. The new analysis of the QC from this dedicated experiment is still ongoing.

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[1] Ch. Finck, Phys. Lett. **B467**, 15 (1999).

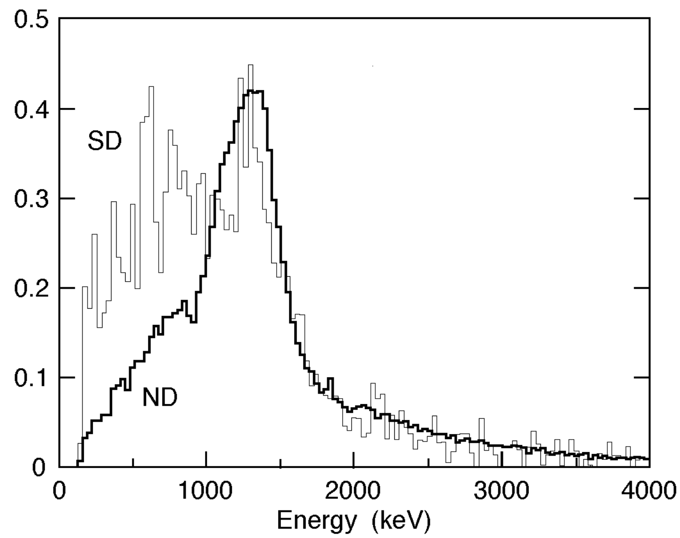

Fig. I-50. Quasicontinuum when double gates are place on ND gamma rays (thick line) and when triple gates are place on SD gamma rays (thin line). Both spectra have been corrected for detector efficiency, corrected for summing effects, unfolded and normalized to the same number of gamma cascades.

However, the new dataset has already revealed a number of high energy one-step primary transitions linking the yrast SD band in ^{152}Dy to the ND states the band decays into! Figure I-51 shows some of these lines. In particular, the 4014 keV line is promising. Figure I-52 show spectra where gates have been placed on the two strongest one-
step primary transitions, 4014 and 2895, and any combination of two SD lines. It is clearly seen that the spectrum gated on the 4014 one-step primary transitions does not include the 647 keV line, establishing that the decay of the SD band via this line is from the level feed by the SD 693 line and it feeds into the level feed by the 221 ND transition. However, from this dataset it probably cannot be determined if the decay proceeds via any intermediate states. The 2895 keV transition most likely comes from the SD level feed by the 647 keV line and eventually feeds into the ND level feed by the 541 keV line. The 2895 keV transition is not as clean as the 4014 keV line since it has a larger background. The intensities of the 4014 keV and 2895 keV one-step primary transitions are only 0.4% and 0.3%, respectively, of the intensity of the SD band.

The analysis of the one-step primary is still ongoing; but it is clear that it will be necessary to gather more statistics to finally be able to link the yrast SD band in ^{152}Dy. A new, much longer run will be proposed to the LBNL PAC when Gammasphere is moved back to Berkeley in the spring of year 2000.

The 4014 keV line allow us to determine that the SD level feed by the 693 keV SD line has an energy of at least 11,675 keV and probably a spin around 26 $\hbar$.

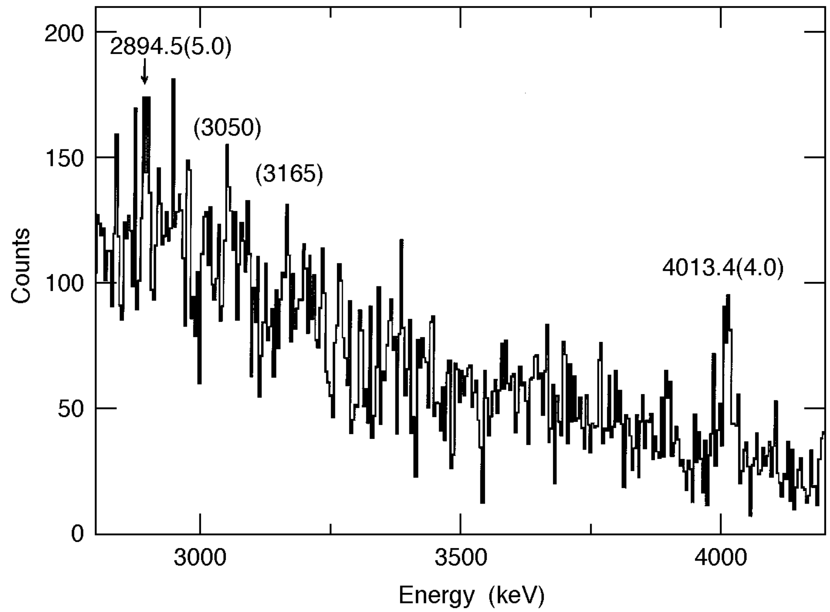

Fig. I-51. The high energy end of a spectrum where gates have been placed on three clean SD lines from the yrast SD band in ^{152}Dy. Further analysis indicates that the 4014 keV line is from the level fed by the SD 693 line and it feeds into the level fed by the 221 ND transition. It is, however, not clear from this dataset if the decay proceeds via any intermediate states. The data analysis is still ongoing.

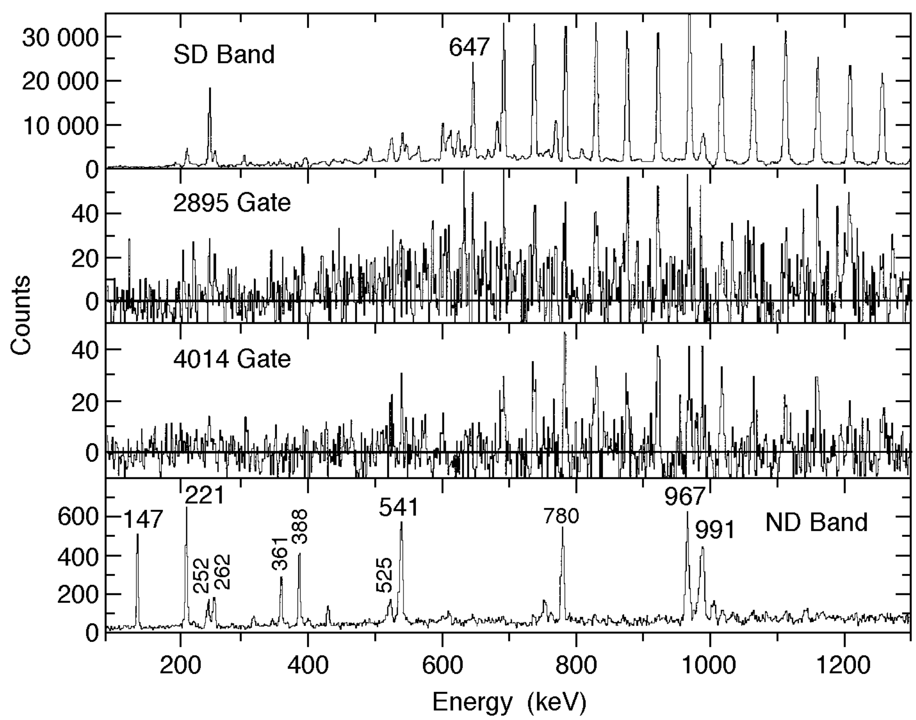

Fig. I-52. Spectra where gates have been placed on the two strongest one-step primary transitions, 4014 and 2895, and any combination of two SD lines. Also shown on top is a spectrum after gates have been placed on three SD lines and, on the bottom, the sum of spectra when gates are placed on ND lines above the 147 keV line in the normal level scheme of ^{152}Dy (i.e., selecting gamma cascades fed at high spins).

c.7. Phase Transitions Above the Yrast Line in ^{154}Dy

(T. L. Khoo, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, T. Lauritsen, D. Nisius, P. G. Varmette, W. C. Ma,* V. Martin,† J. L. Egido,‡ P. Bhattacharyya,§ P. J. Daly,§ Z. W. Grabowski,§ J. H. Hamilton,¶ A. V. Ramayya,¶ and C. T. Zhang§)

Mean-field theory suggests that nuclei can undergo phase transitions. An especially interesting example is the transitional nucleus ^{154}Dy, which is predicted[1] to change from a collective to an oblate aligned-particle structure with increasing spin and temperature. In a mesoscopic system, such as a nucleus, thermal shape fluctuations are expected to smear the phase transition and a question is whether remnant signatures of the phase transition persist at high excitation energies. A sudden change from collective to aligned-particle configurations at spin 34 $\hbar$ has indeed been confirmed along the zero-temperature yrast line in ^{154}Dy[2]. However, in excited states, where thermal fluctuations are dominant even at moderate temperature, it remains a challenge to obtain unambiguous signatures for a phase transition.

Calculations[3] based on results of mean-field theory and incorporating fluctuations have suggested that the quasicontinuum (QC) collective E2 spectrum can provide such a signature. Specifically, an E2 spectrum consisting of a unique two-peak feature was predicted[3] for ^{154}Dy, when the gamma cascade straddles the two regions on either side of the phase-transition boundary. In contrast, only one broad QC peak is detected in the vast majority of nuclei. This two-peak feature in the QC E2 spectrum has been, in fact, previously observed[4]. The calculations of Ref. 3 suggest that, while fluctuations indeed smear out the phase transition, they also play a critical role in providing an observable signature via the E2 spectrum. That is because no collective E2 spectrum would normally be expected in the oblate phase; it arises only because thermal fluctuations cause admixtures of collective (prolate and triaxial) shapes. This has been amply demonstrated in Ref. 3, where the calculated E2 spectra reproduce the different features observed[4,5] in ^{152,154,156}Dy. A stringent test of the calculations consists of proving that the different E2 peaks indeed arise from the two phase regions, as will be done in this work.

The hot excited states in nuclei remain a little explored frontier since there are only few experimental investigations of excited nuclear states above the yrast line, compared to studies of cold yrast states. This is partly because there has been no clear-cut way to specify the spin-excitation energy being studied. We propose a new, but simple, way to provide this specification. By demanding that cascades feed the yrast line at a particular spin, the precursor QC spectrum then arises from states of higher spins. This can be simply accomplished by setting coincidence gates on specific yrast transitions. For example, cascades which feed into a low-spin region of the yrast line can be selected; in this case we predict two E2 peaks, one from each phase region. On the other hand, cascades selected by demanding entry into the yrast line at high spin traverse only the nominally oblate region; only the upper E2 peak is then expected. Furthermore, the average initial point of the cascade is also deduced from the resulting QC spectrum. It is this knowledge of *both the initial and final points* that allows the decay pathways to be constrained.

The experiment was performed at the Lawrence Berkeley 88" Cyclotron. Excited states in ^{154}Dy were populated via the ^{36}S(^{122}Sn,4n) reaction with a 165-MeV beam. The γ rays were detected with the early-implementation phase of the Gammasphere spectrometer, which consisted of 36 Compton-suppressed Ge detectors at that time.

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[1]V. Martin and J. L. Egido, Phys. Rev. C **51**, 3084 (1995).
[2]W. C. Ma *et al.*, Phys. Rev. Lett. **61**, 46 (1988).
[3]V. Martin *et al.*, Phys. Rev. C **51**, 3096 (1995).
[4]R. Holzmann *et al.*, Phys. Rev. Lett. **62**, 520 (1989).
[5]R. Holzmann *et al.*, Phys. Lett. **B195**, 321 (1987).
[6]K. Kumar and M. Baranger, Nucl. Phys. **A110**, 529 (1968).

Spectra were obtained for ^{154}Dy at three detector angles (forward, 90º, backward), coincident with selected pairs of yrast transitions. Each spectrum was analyzed with corrections for neutron interaction, coincidence summing, detector response (unfolding) and photopeak efficiency. Discrete peaks (originating from the yrast region) were removed to obtain the QC portion of the γ-ray spectra (from excited states above the yrast region). The E2, dipole and statistical components of the spectra were extracted. From the multiplicity and average energy of each component, the total spins and energies removed by all γ rays entering each selected spin region could be deduced. The average entry point for the total ^{154}Dy channel was thus found to be 56.1 and 31 MeV.

The spectra feeding the different regions of the yrast line are given in Fig. I-53, where they are compared to equivalent theoretical spectra. A distinct and unusual feature is the occurrence of two broad peaks. The spectrum of E2 transitions from excited states of a nucleus of approximately fixed deformation normally consists of a single broad peak since the transition energy, E_γ = (2I-1) $\hbar^2/$, grows monotonically with spin I. (is the moment of inertia.) Hence, the two-peak spectra provide a clear signal of a deviation from constant deformation

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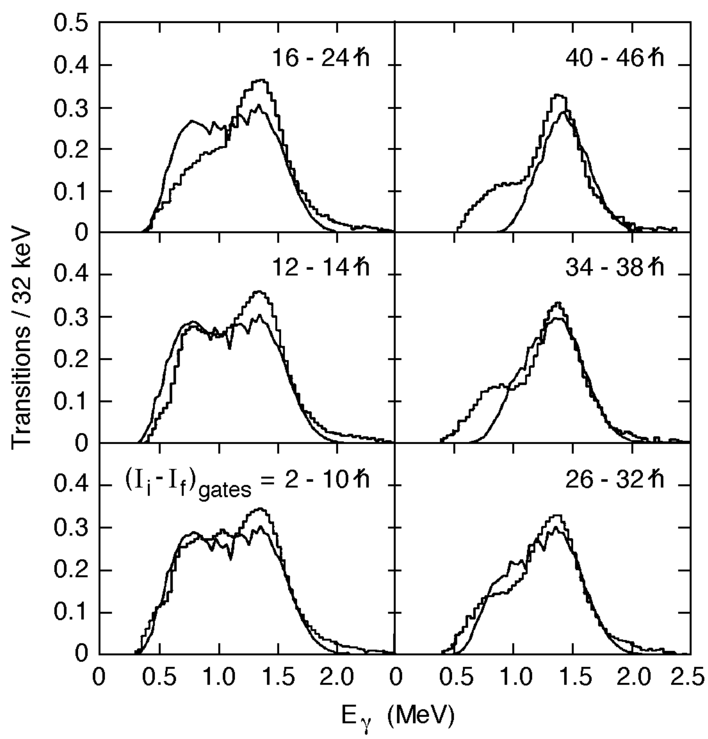

Fig. I-53. Integral spectra of the quasicontinuum E2 transitions feeding into and above the indicated spin intervals. Histograms represent experimental results, solid lines the theoretical calculations. The labels I_i-$I_{f\ gates}$ denote the spin interval of the transitions used for coincidence gates.

To quantitatively understand the origin of the two peaks, we have performed theoretical calculations to simulate the QC decay of this nucleus by using a Monte Carlo method[3]. The collective E2 strengths, which carry information about the structure and phase transition, are microscopically calculated as a function of spin I and excitation energy E from finite-temperature Hartree-Fock (FTHF) theory, with the standard set of Pairing-Plus-Quadrupole force parameters and configuration space[6]. In order to reproduce the features of a finite system, we have to go beyond mean field theory by including fluctuations in the shape degrees of freedom[1]. The average entry spin and energy for the reaction are obtained directly from the experiment. The procedure produces spectra that are equivalent to the experimental ones, where the discrete lines are removed.

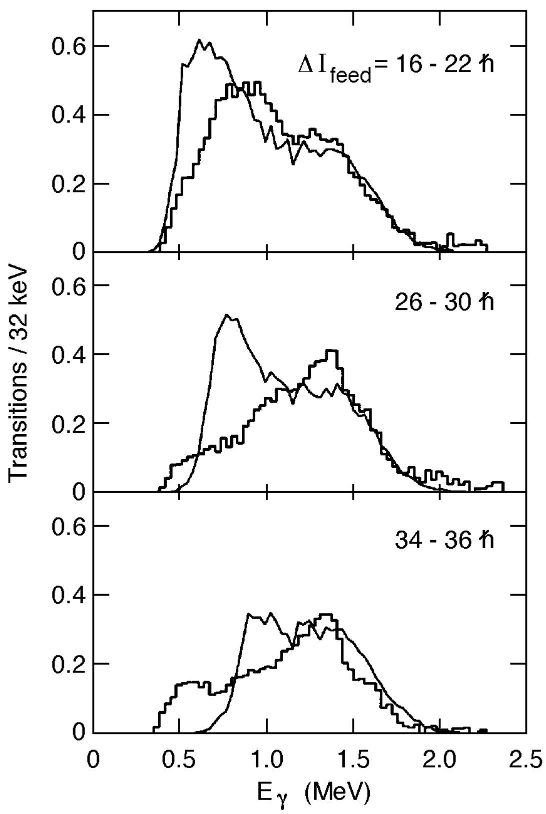

Fig. I-54. Differential E2 spectra feeding into the yrast line only in the indicated spin region ΔI_{feed}. Histograms and solid lines correspond to experiment and theory.

Figure I-53 shows the experimental and theoretical QC E2 spectra from coincidence gates from different spin regions. The spectra are normalized such that the area under each spectrum gives the total multiplicity of the associated γ rays. Two peaks, centered around 0.8 and 1.4 MeV, are prominent in the spectra from low-spin gates ¾ as found in a previous study[4] at Argonne.

The two-peak feature indicates a redistribution of γ-ray energies along the deexcitation pathways. In the later decay stages, when the cascades approach the yrast line at medium and low spins, the moment of inertia increases and transition energies shift downwards, causing the clustering around 800 keV and the dip around 1.1 MeV. In the spectra gated at higher spins, contributions of cascades traversing the low-spin prolate region of the I-E plane are eliminated, thus reducing the strength of the low-energy component. This demonstrates that the low-energy component originates mainly from regions of lower spins. The high-energy peak begins to dominate over the low-energy one for cascades feeding regions as low as 16-24 ħ and, in the theoretical spectra, becomes almost the only component for feeding above 32 ħ. This clearly identifies the region I > 32 ħ as the one with the smaller average moment of inertia.

The spectra in Fig. I-53 might be termed integral spectra. Each spectrum, which is obtained from coincidence gates on yrast transitions of specific spin, selects all QC cascades that feed into the yrast line above that spin. As the spin threshold increases, the QC pathways become more narrowly defined in spin, thus better specifying the I-E region being studied. However, as the threshold spin is lowered, the selectivity of such integral spectra decreases since all contributions from higher spins persist. It is possible to emphasize the particular QC cascades from a lower-spin region, by using differential spectra that feed *only* a narrow spin interval. For example, the QC spectrum feeding into the yrast states with only I = 16-22 ħ can be extracted by subtracting the spectra gated on the transitions depopulating the 16^+ and 24^+ levels (after correct normalization) ¾ see Fig. I-54. The low-energy E2 component is now significantly stronger than in the integral I = 16-24 ħ spectrum (Fig. I-53). Again this emphasizes that this component must arise from the low-spin region. In contrast, in the differential spectrum feeding the spin interval 26-30 ħ, this low-energy component is markedly smaller, indicating that the γ cascade crosses the phase-transition boundary around spin 32 ħ. Although the trend of a low-energy component that diminishes with yrast entry spin is reproduced by theory, discrepancies in details indicate that, in the calculation, the γ cascade crosses the phase boundary at higher spin, I > 36 ħ.

In conclusion, two broad peaks are observed in both experimental and theoretical quasicontinuum spectra. The pronounced change in relative strengths of the two peaks, when going from low-spin gates to high-spin gates, provides an incisive probe of the change in nuclear structure in the two zones of the I-E plane. The low-energy E2 component originates from the lower spin region, with prolate deformation. The high-energy component is largely from the nominally oblate region of the phase diagram, where strong fluctuations give rise to E2 transitions. Despite the fluctuations present in a finite system, signatures of a phase transition are seen to clearly persist in both the experimental and theoretical spectra. A paper has been submitted to Physical Review Letters.

c.8. Lifetimes of Triaxial Superdeformed Bands in ^{168,169}Hf (T. Lauritsen, M. P. Carpenter, T. L. Khoo, C. J. Lister, R. V. F. Janssens, S. Siem, P. G. Varmette,* H. Amro,* M. Bergstrom,* A. Bracco,** J. Domsheit,‡ G. B. Hagemann,* B. Herskind,* G. Sletten,* K. A. Smith,* S. Odegaard,* W. C. Ma,§ D. Hartley,† L. L. Riedinger,† H. Hubel,‡ S. Frattini,** and B. Million**)

Superdeformed (SD) shapes, coexisting with normal prolate shapes, have been predicted in N ~ 94 and Z ~ 71 nuclei[1,2]. These shapes are unusual and interesting in that they are predicted to be triaxial -- as opposed to all other SD bands which have identical minor axes. Such triaxial bands were first observed in the odd proton Lu isotopes[3]. Last year, in a Gammasphere experiment at ANL, two triaxial superdeformed band candidates were found in the even proton ^{168,169}Hf isotopes. The spectrum from ^{168}Hf is shown in Fig. I-55. The ultra cold semi-symmetric reaction, ^{76}Ge + ^{96}Zr at 310 MeV from the ATLAS accelerator, was used to populate these bands at very high spins.

In order to verify that these bands indeed are i) superdeformed and ii) triaxial a new experiment was performed - this time with a thick target - in order to measure the lifetime of the states using the DSAM technique. The same reaction as mentioned above with a beam intensity of 5 pnA over 6 days was used. For the fragile target to sustain this intense beam, the beams from ATLAS were wobbled in both the x and y direction. Thus the beam was distributed over a 5 × 5 mm area. The data analysis is in progress.

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[1] I. Ragnarsson, Phys. Rev. Lett. **62**, 2084 (1989).
[2] S. Aaberg, Nucl. Phys. **A520**, 35c (1990).
[3] W. Schmitz, Phys. Lett. **B303**, 230 (1993).

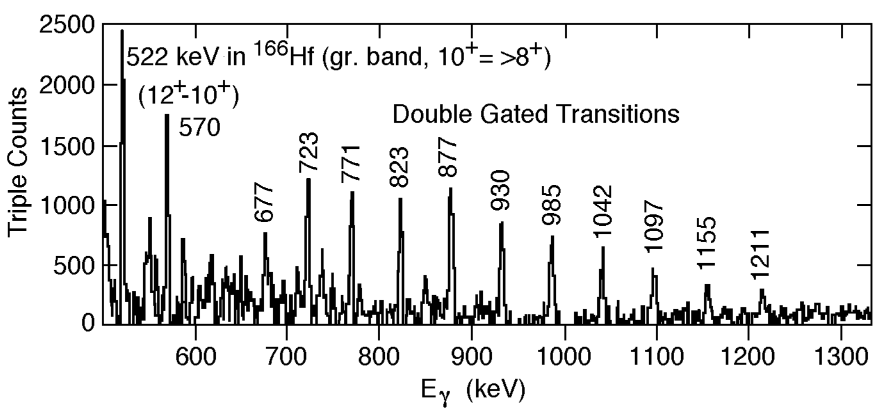

Fig. I-55. Spectrum where double gates have been placed on the transitions in the triaxial SD band in ^{168}Hf.

c.9. Spins and Excitation Energy of the Yrast Superdeformed Band in ^{191}Hg

(S. Siem,* P. Reiter, T. L. Khoo, M. P. Carpenter, T. Lauritsen, D. Gassmann, I. Ahmad, I. Calderin, S. M. Fischer, G. Hackman, R. V. F. Janssens, D. Nisius, H. Amro,‡ T. Døssing,† U. Garg,§ F. Hannachi,¶ B. Kharraja,§ A. Korichi,¶ A. Lopez-Martens,¶ E. F. Moore,‡ and C. Schuck¶)

The total gamma-spectrum following the decay out of the yrast SD band in ^{191}Hg has been extracted using the methods described in[1]. The gamma-rays following the ^{174}Yb(^{22}Ne,5n)^{191}Hg reaction were collected with Gammasphere and the beam was provided by the 88" Cyclotron at LBNL. From the total gamma-spectrum the excitation energies and spins of the yrast SD band members have been determined. The level fed by the 351 keV transition (the decay-out level) has an excitation energy of 5.73 ± 1.0 MeV and spin 17.0 ± 0.7 $\hbar$, leading to two possible spins: 33/2 $\hbar$ or 35/2 $\hbar$.

The result from the quasicontinuum analysis is in good agreement with the previous result from a one-step linking transition[2]. A second one-step transition of 3310 keV, with 3 σ statistical significance, has been tentatively assigned to feed a $33/2^-$ known normal-deformed level. There are now two one-step transitions; both place the decay-out level at 6000 keV. The angular distribution of the stronger one-step line (2778 keV) shows a big positive value for the A2 coefficient (0.57 ± 0.48), which is consistent with ΔI = 0, suggesting a 35/2 $\hbar$ spin assignment for the decay-out level. We rule out the possibility of it being an E2 transition, because that would make the other one-step transition a M3 transition competing with a M1 transition that is not observed. The spin is consistent with a $j_{15/2}$ particle configuration assignment[3]. However, the experimental data do not allow for a parity assignment. For the parity of the SD band to be consistent with a $j_{15/2}$ particle configuration assignment, the one-step lines must be M1 transitions. From neutron capture experiments it is known that the ~8 MeV E1 transitions are about 5 times more likely than M1 transitions. However, in ^{191}Hg the 1-step lines have significantly lower energy (~ 3 MeV). In fact, M1 transitions around this energy are observed both in neutron capture and also from the decay of the SD band in ^{194}Pb.

In conclusion, the excitation energy and spin of the yrast SD band in ^{191}Hg has been determined to be 6000 keV and 35/2 $\hbar$ for the decay-out level. The energy above yrast of the SD band at the point of decay out is 2.778 MeV. The excitation energy of the yrast SD band extrapolated to 13/2 $\hbar$, the spin of the ground state, is 4.74 MeV. It is important to obtain these quantities in an odd-even nucleus since that gives information on the relative pair correlation energies in ND and SD states, thereby providing a stringent test for theory. Information on pair quenching in excited states will be obtained by comparing the quasicontinuum spectra following the decay of the SD bands in ^{191,192,194}Hg. In addition, these spectra will be compared with theoretical statistical decay spectra[4] from excited states in even-even and odd-even nuclei.

A paper on this work is being written.

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[1]R. G. Henry *et al*., Phys. Rev. Lett. **73**, 777 (1994); T. Lauritsen et al., Heavy Ion Physics **6**, 229 (1997), Proc. Symp. on Nucl. Structure at the Limits, ANL (1996).
[2]P. Reiter *et al*., Physics Division Annual Report for 1997, ANL-98/24, p. 38.
[3]M. P. Carpenter *et al*., Phys. Rev. C (1995).
[4]T. Døssing *et al*., Phys. Rev. Lett. 75 (1995) 1276.

c.10. Determination of Spin and Excitation Energy of Superdeformed Bands in ^{192,194}Hg from the Quasicontinuum Gamma Rays

(T. Lauritsen, T. L. Khoo, I. Ahmad, M. P. Carpenter, R. V. F. Janssens, A. Lopez-Martens,* H. Amro,† S. Berger, L. Calderin, T. Døssing,¶ S. M. Fischer,§ G. Hackman, D. T. Nisius, F. Hannachi,* A. Korichi,* and E. F. Moore†)

Superdeformed (SD) bands in the mass 190 region decay suddenly, over a few states, at relatively low spin and high excitation energy. The decay path is very fragmented and only in a few cases have one-step or two-step decays been seen. Presently, in this mass region, only three superdeformed bands have been linked to the normal states they decay to via discrete one step links[1,2,3]. Most of the gamma rays from the decay of the SD bands form a quasicontinuum. Thus, for most SD bands in this mass region, the excitation energy and spins of the bands are not known experimentally.

However, by extracting and analyzing the decay quasicontinuum spectrum in coincidence with the SD bands it is also possible to determine the excitation energy and spin of the bands. This “quasicontinuum analysis method” (QC) was tested in ^{194}Hg, which is one of the few cases where the excitation energy and spin of the first superdeformed band is known, and was then applied to the first superdeformed band in ^{192}Hg, where no one-step decays been seen.

The derived excitation energy and spin in ^{194}Hg, using the quasicontinuum analysis method, were found to be in excellent agreement with the exact result determined from one-step and two-step decay lines in the nucleus. The extracted spin and energy of the 10^+ SD state in the yrast SD band was determined to be 10.8(1.0) $\hbar$ and 6.6(5) MeV, respectively, using the QC method. This should be compared to the exact result: 10 $\hbar$ and 6.6 MeV of reference[1,4]. For ^{192}Hg, extrapolated to zero angular momentum, the excitation energy of the SD band was found to be 5.3(5) MeV using the QC method. Figure I-56 shows a composite plot of the continuum spectra in coincidence with the SD band in ^{192}Hg. The statisticals, quadrupole and M1/E2 dipoles are from the feeding of the SD band. The remainder, after the latter quasicontinuum components have been subtracted from the total continuum, are the quasicontinuum gamma rays from the decay of the SD band.

A paper with these results has been submitted to Phys. Rev. C.

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[1]T. L. Khoo, Phys. Rev. Lett. **76**, 1583 (1996).
[2]A. Lopez-Martens, Phys. Lett. **B380**, 18 (1996).
[3]D. P. McNabb, Phys. Rev. C **56**, 2474 (1997).
[4]G. Hackman, Phys. Rev. Lett. **79**, 4100 (1997).

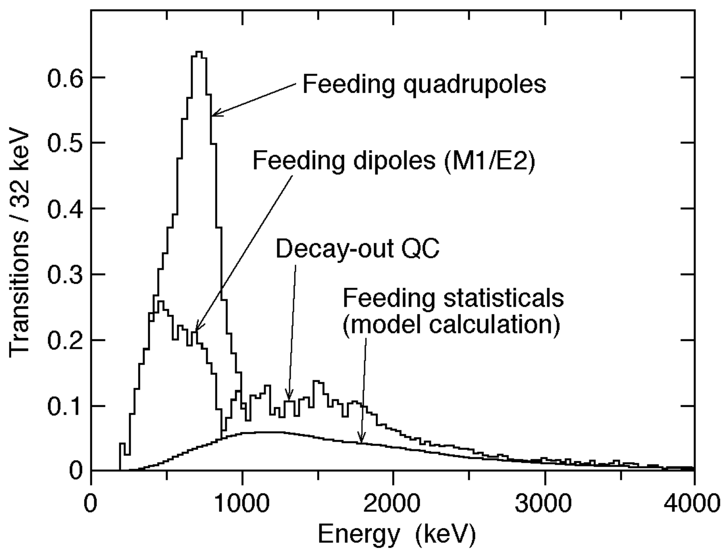

Fig. I-56. Composite plot of the continuum spectra in coincidence with the SD band in ^{192}Hg. The feeding components are: the statisticals, quadrupole and M1/E2 dipoles. The decay-out QC are the quasicontinuum gamma rays from the decay of the SD band.

c.11. Fluctuations in the Strengths of Primary Transitions from Decay Out of a Superdeformed Band (T. L. Khoo, T. Lauritsen, I. Calderin, M. P. Carpenter, G. Hackman, I. Ahmad, S. Fischer, R. V. F. Janssens, D. Nisius, A. Lopez-Martens,† T. Døssing,* A. Korichi,† F. Hannachi,† and E. F. Moore§)

The decay from SD states is precipitated by sufficient mixing with one or two of the nearest normal-deformed (ND) states among which they are embedded. The decay spectrum is then governed by the admixed highly-excited ND state. In analogy with neutron-capture gamma rays, we call the transitions that directly deexcite the state primary gamma rays. In the decay spectrum of ^{194}Hg (band 1), 34 primary transitions above 2.6 MeV have been detected above a 3σ level. These transitions have a distribution in strength.

The fluctuations in the strength distribution can provide an indicator of the chaoticity of excited ND states around 4.3 MeV. In the fully chaotic limit, where the wavefunction is complex, the distribution is expected to be a χ^2 distribution, with the number of degrees of freedom ν equal to 1, giving the so-called Porter-Thomas distribution.

A technique based on the maximum likelihood method has been developed for analyzing the distribution of the transition strengths. The analysis shows that the observed distribution is consistent with a χ^2 distribution with $\nu = 1$ (Porter−Thomas distribution). However, the uncertainties in ν and in the average strength θ are very large because the observed primary transitions represent the high-intensity tail of the maximum-likelihood distribution. In fact, some of the 1-step lines exhibit strengths up to 9 times the average strength, raising the possibility that there may be some perseverance of selection rules for decay from states at ~ 4.3 MeV. Since it is difficult to explain why this happens in only ^{194}Hg, a more likely explanation is that chance (and fortune) is responsible for the large 1-step strengths. (In ^{194}Pb, where the excitation energy of the SD band is significantly lower, the primary transitions are expected to be stronger.) In summary, the distribution of the strength of primary decay lines in ^{194}Hg is consistent with decay from a chaotic state.

This work has been published in Nuclear Physics A.

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c.12. Superdeformation in ^{193}Pb: Observation of Three Additional Excited Bands

(M. P. Carpenter, R. V. F. Janssens, D. Roβbach,* A. N. Wilson,† C. Barton,† D. M. Cullen,‡ H. Hubel,* S. L. King,‡ A. Korichi,§ and A. T. Reed‡)

The occurrence of superdeformation in nuclei with mass numbers around A ~ 190 results from large gaps in the single-particle spectra (N = 112 and Z = 80) at large deformation (β_2 ~ 0.5). The nucleus ^{193}Pb, with 82 protons and 111 neutrons, lies just below the neutron shell closure, and thus, provides an ideal system for studying neutron excitations around the N = 112 shell gap. The properties of excited superdeformed (SD) bands allow the identification and characterization of orbitals lying close to the neutron Fermi surface and provides information on the excitations across the shell gap.

Previous work[1,2] identified six SD bands in ^{193}Pb. Bands 1 and 2 are assigned to $j_{15/2}$ intruder orbital. Bands 3 and 4 show a small signature splitting at high rotational frequency and have been assigned to the [642]3/2 quasineutron configuration. Cross-talk was observed between the weakest pair of bands (bands 5 and 6), allowing an estimate of the g-factor to be made. The result suggests that the [624]9/2 was the favorable assignment.

We have recently performed a new measurement on ^{193}Pb using the Gammasphere spectrometer array at Lawrence Berkeley National Laboratory. In addition to the previously known six SD bands, three new bands have been observed. Two of them are a pair of signature partner bands which show similar transition energies to bands 5 and 6. These two new bands have been assigned the [512]5/2 quasineutron configuration. The third new band has been assigned to the favored signature of the [752]5/2 Nilsson orbital. In addition, a more reliable gyromagnetic factor, g_k has been obtained for bands 5 and 6 which is in good agreement with calculations for the [624]9/2 state.

A paper reporting results from this study has recently been published in Nuclear Physics A[3].

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1J. R. Hughes *et al*., Phys. Rev. C **51**, R447 (1995).
2L. Ducroux *et al*., Phys. Rev. C **53**, 2701 (1996).
3D. Roβbach *et al*., Nucl. Phys. **A660**, 393 (1999).

c.13. Quasicontinuum Spectrum of Gamma Rays Which Depopulate SD States in ^{194}Pb

(T. L. Khoo, T. Lauritsen, D. P. McNabb,* J. A. Cizewski,* K.-Y. Ding,* W. Younes,* D. Archer,† R. W. Bauer,† J. A. Becker,† L. A. Bernstein,† K. Hauschild,† R. M. Clark,‡ M. A. Deleplanque,‡ R. M. Diamond,‡ P. Fallon,‡ I. Y. Lee,‡ A. O. Macchiavelli,‡ F. S. Stephens,‡ and W. H. Kelley§)

Primary gamma rays from the decay out of the SD band in ^{194}Pb have been identified and the spins, likely parity and excitation energies of the band have been determined[1] from experiments performed with both Eurogam and Gammasphere. The focus of this work is the analysis of Gammasphere data for the total decay spectrum. As for ^{192,194}Hg, this spectrum consists of both sharp primary transitions and an unresolved quasicontinuum component. In ^{194}Pb, however, the primary lines have a significantly larger fraction of the total decay yield, due largely to the smaller excitation energy of the SD band, which reduces the phase space for the unresolved component. The total decay spectrum out of SD states has been extracted. The energy of the decaying SD states that is derived from

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1A. Lopez-Martens *et al*., Phys. Lett. **B380**, 18 (1996); K. Hauschild *et al*., Phys. Rev. C **55**, 2819 (1997).
2T. Døssing *et al*., Phys. Rev. Lett. **75**, 1276 (1995).

the total decay spectrum agrees with that determined from the discrete lines. About 0.9 MeV below the end point, the spectrum rises rapidly. This feature, which has been predicted by Døssing et al.,[2] reflects a region of low level density located immediately above the normal-deformed yrast line, to which decay is naturally reduced. This work, which constituted part of the Ph. D. thesis of D. McNabb from Rutgers, has been accepted as a Rapid Communication in Physical Review C.

c.14. Actinide Signature Measurements for Spent-Fuel Characterization

(R. V. F. Janssens, I. Wiedenhöver, J. D. Cole,* M. W. Drigert,* R. Aryeinejad,* E. L. Reber,*and J. K. Jewell*)

Experiments to study the radiation emitted from neutron-induced fission on selected actinide targets have continued at the ANL Intense Pulsed Neutron Source. Following the irradiation of ^{235}U samples performed in 1998, a new set of data with a 5 gram ^{239}Pu target was collected in 1999. The measurements are performed with 8 Compton-suppressed spectrometers of the Argonne-Notre Dame BGO gamma-ray facility. The results will be applied to the problem of determining fissile isotopic ratios for arms control issues and are also forming the basis for techniques addressing concerns about the disposal and storage of spent nuclear fuel. Of particular importance is the study of gamma rays above 1 MeV in prompt fission fragments as it offers the possibility of relatively straightforward isotopic assignments. A preliminary report of this work has been published[1]. Another campaign of measurements is scheduled for 2000.

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*Idaho National Engineering Laboratory

[1]J. D. Cole *et al*., Proceedings of International Conference on Perspectives in Nuclear Physics, J. H. Hamilton, H. K. Carter and R. B. Piercey editors, World Scientific, p. 35 (1999).