D. OTHER TESTS OF NUCLEAR STRUCTURE UNDER EXTREME CONDITIONS

A broad-based program of nuclear structure studies continued during the last year. Radiative capture was one interesting theme with studies in both light ($^{12}C+^{12}C$) and heavy ($^{90}Zr + ^{89}Y$) nuclei. The dynamics of the radiative capture process is interesting in itself, and these ultra-cold reactions seem to be rich in potential for populating unusual non-yrast structures. New high spin results continue, including observation of the long-predicted deformed multi-particle, multi-hole states in ^{40}Ca, the observation of extremely large deformation in cadmium nuclei, and finally, the observation of the direct decay between superdeformed bands in ^{152}Dy and lower-lying normally deformed configurations. This latter experiment was one of the prime motivations for building Gammasphere. The experiment which led to successful observation of this decay mode, and in addition, the decay of a more highly excited superdeformed band, arose from a close collaboration between groups from ANL and LBNL and data collected from Gammasphere at ATLAS and the 88" cyclotron.

d.1. Radiative Fusion of $^{12}C + ^{12}C$, $^{12}C + ^{16}O$ and $^{16}O + ^{16}O$ (C. J. Lister, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, A. Wuosmaa, D. Jenkins,* B. Truett,† B. R. Fulton,‡ J. Pearson,‡ M. Freer,§ P. Fallon,¶ A. Gorgen,¶ and A. O. Macchiavelli¶)

Radiative Capture of heavy ions, the process of complete fusion without particle evaporation, is never favored because the high Coulomb barrier in the entrance channel always leads to highly excited residues that dominantly decay by particle emission. However, studying the nuclei which do cool by gamma-emission can tell us a great deal about the fusion process, and appear to selectively populate states in the final nuclei which are very hard to reach by any other means.

The fusion of "light" heavy ions, like carbon and oxygen, is particularly interesting. The overall fusion-evaporation cross-section is known to vary rapidly in energy with resonance-like structures. The nature of these resonances has never been unambiguously determined. Clearly, radiative capture can help understand this puzzle, as gamma-spectroscopy might allow the widths and spins of the resonances to be determined. The seminal work of Sandorfi and Nathan[1,2] showed that direct capture could be measured, and the resonant structure investigated. Their technique, using large NaI(Tl) detectors to measure high energy gamma rays, only allowed investigation of "direct" single GQR gamma decays, although they did find tantalizing evidence for "multi-step" decay.

The development of large arrays, like Gammasphere, has opened the possibility of observing the entire decay flux and investigating the fusion and decay processes more directly, especially investigating higher spin resonances which do not decay to the groundstate in a single step. Our measurements show that multi-step pathways are the dominant decay mechanism. Gamma-gamma correlations can accurately allow reconstruction of the parent state and the intermediate steps which the decay proceeds through. With sufficient data, the widths of the reconstructed resonances can be measured, to a level which is not possible by other means.

We have performed a series of experiments at ANL and at LBNL to investigate radiative capture. Using Gammasphere as a total energy calorimeter, the radiative capture events can be clearly seen, as they have the highest "total sum energy". Selecting these events by total energy, one can then investigate them in more detail and look at the cooling paths. For the

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[1]A. M. Sandorfi, *Treatise on Heavy Ion Science*, Vol. 2., Sec. 3, ed. D. Allan Bromley.

[2]A. Nathan, A. M. Sandorfi and T. J. Bowles, Phys. Rev. C **24**, 932 (1981).

^{12}C + ^{12}C system we have conducted a thin target excitation function. The absolute yield of radiative capture can be seen to resonate, and the decay path changes character between "on" and "off" resonance. The "on resonance" pattern is confined to passing through rather few intermediate energy states. These states then preferentially seem to decay to the known low-lying K = 2 band, and not to yrast states, despite phase-space favoring the yrast decays. Recently, we also found multi-step radiative capture in ^{12}C + ^{16}O and ^{16}O + ^{16}O reactions.

The data analysis is still in progress. Qualitatively, it appears clear that the "one-step" decays observed by Sandorfi and Nathan constitutes only a small part of the total radiative capture cross-section. The key challenge is extract quantitative cross-sections. This is difficult, as the calorimetric "event trigger" efficiency is very difficult to estimate, as it is a convoluted function of germanium and BGO responses, and is energy and multiplicity dependent. This needs careful simulation, and probably more detailed measurements. It is clear that the trigger efficiency falls rapidly with multiplicity, so the potential for investigating high spin (J > 4) resonances is very difficult through a calorimetric trigger. However, if the fused residues are independently detected and counted, and became the trigger, then much more efficient and quantitative studies should be possible. This approach was proven to be possible by Sandorfi[1] and appears appropriate for the "upgraded" FMA and Gammasphere when it returns to ATLAS. A proposal for a test experiment to detect the fused products is being developed.

d.2. Superdeformation in the Doubly Magic Nucleus ^{40}Ca (R. V. F. Janssens, M. P. Carpenter, T. Lauritsen, D. Seweryniak, C. J. Lister, E. Ideguchi,* D. G. Sarantites,* W. Reviol,* A. V. Afanasjev,† M. Devlin,* C. Baktash,‡ D. Rudolf,§ A. Axelsson,¶ A. Galindo-Uribarri,‡ D. R. LaFosse,|| F. Lerma,* M. Weiszflog,¶ and J. N. Wilson*)

The coexistence of spherical and highly deformed configurations in doubly magic ^{40}Ca has been predicted for many years, originally by Gerace and Green, and some candidates for the first members of the bands known since the 1970's. Hartree Fock calculations by Zamick and Zheng have consistently indicated that a variety of multi-particle, multi-hole states should polarize the core and lead to deformation. It is an interesting issue to study the balance between the energy gained in deformation and the cost in promotion of particles into the $f_{7/2}$ shell. The predictions indicated that 8p-8h (i.e. two alpha particle) excitations would be energetically very favored and have a deformation close to $\beta = 0.6$, that is a "superdeformed" shape. However, only with the development of highly efficient 4π gamma arrays like Gammasphere, triggered by channel selection devices such as microball, has the experimental possibility of extending these highly deformed collective structures to high spin, and measuring their shapes, through lifetime determinations, became feasible. The experimental challenges are considerable, as it is difficult to create light nuclei at very high spin, charged particle evaporation carries away much of the flux, the gamma-ray multiplicities are relatively low and the key gamma rays are of high energy so are difficult to detect.

In a recent experiment these challenges were overcome. The $^{28}Si(^{20}Ne,2\alpha)^{40}Ca$ reaction was used with an 84-MeV neon beam from the ATLAS accelerator. Gammasphere and microball provided a sensitive and efficient setup. The known high spin level scheme of ^{40}Ca was greatly extended.[1] Several bands were developed, two of them to $J^{\pi} = 16^{+}$. The residual Doppler Shift Method was used to extract the mean quadrupole moments of the bands. The band based on the known third $J^{\pi} = 0^{+}$ has the properties expected from the 8p-8h band with a mean quadruple moment of Q = 1.80 eb, consistent with a uniformly charged axial shape of $\beta = 0.59$. This observation confirms the predictions of highly deformed shapes co-exiting with spherical configurations which were made more than 30 years ago.

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[1]E. Ideguchi, D. G. Sarantites *et al.*, Phys. Rev. Letts. **87**, 222501 (2001).

d.3. Large Angle Alpha Scattering on ^{44}Ti (K. E. Rehm, C. L. Jiang, I. Ahmad, J. Caggiano, P. Collon, J. P. Greene, D. Henderson, A. Heinz, R. V. F. Janssens, R. C. Pardo, T. Pennington, J. P. Schiffer, R. H. Siemssen, A. Wuosmaa, M. Paul,* and P. Mohr†)

The analysis of large angle α scattering on ^{44}Ti, the first α-type N = Z nucleus above ^{40}Ca, is complete. For lighter sd-shell nuclei enhanced cross sections for elastic α scattering were observed at angles beyond 90°.[1] Because this effect is especially pronounced for scattering on α-particle nuclei (e.g. ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca) it was argued[2] that α cluster and exchange effects in the target nucleus might also play a role. Since no stable N = Z α-particle nuclei exist beyond ^{40}Ca the question whether anomalous large angle scattering ends at A = 40 could not be studied in the past.

Technical details for this experiment were presented in last year's annual report. We since performed optical model and Distorted Wave Born Approximation (DWBA) calculations to describe the measured angular distributions.

The angular distributions for elastic scattering of alphas from ^{40}Ca (E_{lab} = 240 MeV, E_{cm} = 21.8 MeV) and ^{44}Ti (E_{lab} = 261.5 MeV, E_{cm} = 21.8 MeV) obtained in this experiment are shown in Fig. I-33 by the open and solid points, respectively. While for ^{40}Ca at backward angles elastic cross sections in the vicinity of the Rutherford values are observed, the corresponding yields for ^{44}Ti are about a factor of 20 smaller and, thus, are comparable to the yields obtained for non-alpha-particle nuclei such as ^{42,44,48}Ca or heavier nuclei. The solid lines are the result of an optical model fits which follow closely the analysis[3] which was successfully used for a description of elastic alpha scattering on a few nuclei between ^{40}Ca and ^{208}Pb.[3] The real part of the potential is calculated by the double folding model using the density of ^{44}Ti.[4] For the imaginary part a pure Woods-Saxon parameterization was chosen, and the parameters were adjusted to the new experimental data. The smaller cross sections at backward angles for ^{44}Ti require a stronger absorptive potential roughly twice as strong as for ^{40}Ca, but comparable to the results obtained for heavier nuclei such as ^{58,60}Ni.

The strong B(E2) value of the first excited state in ^{44}Ti (B(E2) = 0.061 e^2b^2) allowed also for a measurement of the 2^+ E_x = 1.083 MeV angular distribution which is shown in Fig. I-34 together with the cross section of the elastic channel. The yields for inelastic scattering at backward angles are comparable to the elastic cross sections. The angular distribution from a DWBA calculation performed with the finite-range code PTOLEMY using the optical potential from Fig. I-33, a B(E2) = 0.061 e^2b^2 and a nuclear deformation parameter β = 0.2 is shown by the solid line in Fig. I-34. Similar to the results observed for the 2^+ excitation in the system α + ^{44}Ca the ^{44}Ti data are found to be in good agreement with the calculations.

These first measurement of elastic and inelastic α scattering with an N = Z nucleus heavier than ^{40}Ca showed that the anomalous large angle scattering (ALAS) seems to end at ^{40,41}Ca. An optical-model analysis of the α + ^{44}Ti data gave parameters which are in good agreement for the scattering of α's on heavier nuclei.

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[1]R. Planeta, H. Dabrowski, L. Freindl and K. Grotowski, Nucl. Phys. **A326**, 97 (1979).
[2]D. Agassi and N. S. Wall, Phys. Rev. **C7**, 1368 (1973).
[3]U. Atzrott, P. Mohr, H. Abele, C. Hillenmayer and G. Staudt, Phys. Rev. **C53**, 1336 (1996).
[4]R. Ejnisman, D. Goldman, K. S. Krane, P. Mohr, Y. Nakazawa, E. B. Norman, T. Rauscher and J. Reel, Phys. Rev. C **58**, 2531 (1998).

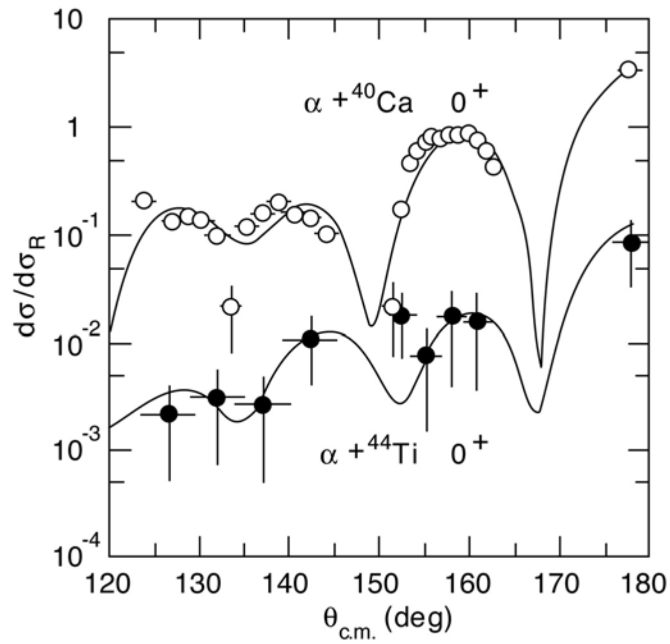

Fig. I-33. Ratio between the differential cross sections for elastic scattering and the corresponding Rutherford values measured for the systems α + ^{40}Ca and ^{44}Ti at a center-of-mass energy of 21.8 MeV. The cross sections for the ^{44}Ti target are smaller than the ones for ^{40}Ca by 1 - 2 orders of magnitude. The solid lines are optical model calculations using a double-folding potential for the real part and a Woods-Saxon parameterization for the imaginary part. See text for details.

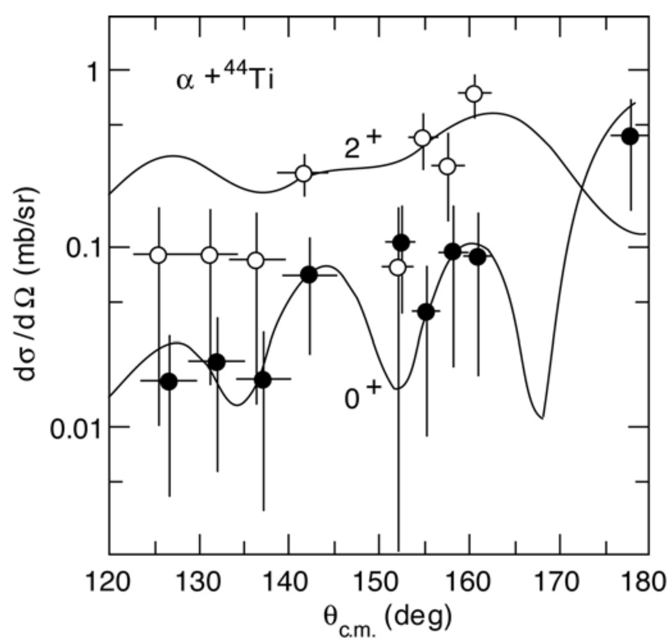

Fig. I- 34. Differential cross sections for elastic scattering (solid points) and inelastic excitation of the first 2$^+$ state (open points) in ^{44}Ti. The solid lines are the result of optical model (elastic) and DWBA (inelastic) calculations, described in the text.

d.4. Very Extended Shapes in the A ~ 110 Region (M. P. Carpenter, R. V. F. Janssens, R. M. Clark,* P. Fallon,* M. Cromaz,* M. A. Deleplanque,* R. M. Diamond,* A. Goergen,* G. J. Lane,* I. Y. Lee,* A. O. Macchiavelli,* R. G. Ramos,* F. S. Stephens,* C. E. Svensson,* K Vetter,* D. Ward,* and R. Wadsworth†)

Over the last fifteen years, great strides were made in the study of superdeformed nuclei. Much of the initial effort was directed at identifying regions of superdeformation which weren predicted by theoretical models using a standard parameterization of the nuclear shape. Until recently, in all regions for which superdeformed nuclei have been found, the major to minor axis ratios do not exceed 2:1. It was pointed out by Chasman that one must use a modified parameterization of the nuclear shape which explicitly treats necking degrees of freedom when the major to minor axis ratio exceeds 2:1.[1] Recently, calculations by Chasman,[2] using the cranked Strutinsky method with a four-dimensional shape representing quadrupole, octupole, hexadecapole, and necking degrees of freedom, predict that a region of "extended" shapes with axis ratios 2:1 and greater exist at high angular momentum in nuclei with A ~ 110.

In order to test these calculations, high-angular momentum states in ^{108}Cd were populated via the ^{64}Ni(^{48}Ca,4n) reaction at a beam energy of 207 MeV. The beam was provided by the ATLAS accelerator at Argonne National Laboratory. Gamma rays were detected with the Gammasphere spectrometer outfitted with 101 Compton-suppressed Ge detectors. From an analysis of the data, a rotational sequence of quadrupole transitions were identified in ^{108}Cd, and it is estimated that the states in the band lie between I = 40(2) - 60(2) $\hbar$. The moments of inertia and the deduced lower limit of the transition quadrupole moment suggest a very extended prolate shape for the nucleus, with a axis ratio >1.8:1. This is among the most deformed nuclear structures ever observed, and it is possible that the band may have an axis ratio greater than 2:1 as predicted by Chasman.[2]

A paper reporting the results of this work was recently published in Physical Review Letters.[3]

*Lawrence Berkeley National Laboratory, †University of York, United Kingdom
[1]R. R. Chasman, Phys. Lett. **B302**, 134 (1993).
[2]R. R. Chasman, Phys. Rev. C **64**, 024311 (2001).
[3]R. M. Clark et al., Phys. Rev. Lett. **87**, 202502 (2001).

d.5. Investigation of Anti-Magnetic Rotation in ^{100}Pd (R. V. F. Janssens, M. P. Carpenter, F. G. Kondev, T. Lauritsen, A. V. Afanasjev,*† S. Zhu,† U. Garg,† S. Frauendorf,† B. Kharraja,† S. S. Ghugre,‡ and S. N. Chintalapudi‡)

"Magnetic rotation" is a topic of great interest and activity in nuclear structure over the past few years. Strong M1 bands were observed in the nuclei of the Pb and Sn regions. These bands, while as regularly spaced as the bands observed in well deformed and even superdeformed nuclei, show very weak E2 transitions, implying a small deformation. The interpretation of this apparent contradiction was given in terms of the "shears mechanism".[1] In case of the Pb nuclei, a pair of $h_{9/2}i_{13/2}$ protons and between one and three $i_{13/2}$ neutron holes generate the angular momentum. The particles are in stretched coupling and so are the holes. Their angular momenta form the two "blades" of a pair of shears, which gradually close when the total angular momentum increases along the band. The particles and holes move in circular orbitals in the planes perpendicular to their angular momenta. These loops of nucleonic currents are crossed when the shears are open. This anisotropic arrangement breaks the rotational symmetry. "Magnetic rotation" alludes to these currents and the magnetic moment they create, generating the strong M1 radiation.

Associated with, and complementary to, magnetic rotation is the concept of "anti-magnetic rotation". In this scenario, the coupling for the A ~ 110 case is such that two pairs of stretched proton $g_{9/2}$ holes point in opposite directions and gradually align along the direction of the stretched $h_{11/2}$ neutrons creating a "fork", with the neutrons forming the middle prong and the proton holes forming two symmetric side prongs. Angular momentum, then, is generated mainly by "bending" the side prongs. In contrast to the M1 bands, this arrangement is symmetric with respect to a rotation about the total angular momentum vector by an angle of π. Consequently, the signature, α, is a good quantum number and the resulting "fork bands" have a regular ΔI = 2 structure, in contrast with the ΔI = 1 sequences associated with the "shears bands". The magnetic moment disappears in the symmetric arrangement of the current loops, which nevertheless specify the orientation. (The term "anti-magnetic" rotation alludes to the analogy with ferro and anti-ferromagnetism).

High spin states were studied in the nucleus ^{100}Pd with the aim of investigating this novel phenomenon of "anti-magnetic rotation". The reaction ^{72}Ge(^{35}Cl, αp2n)^{100}Pd was used at a bombarding energy of 135 MeV. The experiment was carried out at the ATLAS facility and the Gammasphere detector array was employed in its "stand alone" mode. A cascade of four "rotational-band-like" transitions is proposed as corresponding to anti-magnetic rotation, based on the observed spectroscopic properties and a comparison with calculations in the configuration-dependent cranking Nilsson-Strutinsky formalism.

A paper describing these results was recently published.[2]

*Argonne National Laboratory and the University of Notre Dame, †University of Notre Dame, ‡IUCDAEF-Calcutta Centre, Calcutta, India

[1]S. Frauendorf, Nucl. Phys. A **557**, 259c (1993).

[2]S. Zhu *et al*., Phys. Rec. C **6**4, 041302(R) (2001).

d.6. Direct Decay-Out from the Superdeformed Band to the Yrast Line in $^{152}_{66}$Dy$_{86}$

(T. Lauritsen, M. P. Carpenter, R. V. F. Janssens, D. G. Jenkins, T. L. Khoo, K. S. Abu Saleem, I. Ahmad, J. P. Greene, A. M. Heinz, C. J. Lister, D. Seweryniak, S. Siem, R. C. Vondrasek, F. G. Kondev,* T. Døssing,† P. Fallon,‡ B. Herskind,† A. Lopez-Martens,§ A. O. Macchiavelli,‡ D. Ward,‡ R. Clark,‡ M. Cromaz,‡ F. Hannachi,§ A. Korichi,§ G. Lane,‡ P. Reiter,¶ and I. Wiedenhöver||)

The excitation energy, spin and parity of the yrast superdeformed band in ^{152}Dy[1] have been firmly established. The evidence comes mainly from the measured properties of a 4011 keV single-step transition connecting the yrast superdeformed level fed by the 693 keV transition to the 27$^-$ yrast state. Four additional, weaker, linking γ rays were placed as well. The excitation energy of the lowest superdeformed band member is 10,644 keV and its spin and parity was determined to be $J^\pi = 24^+$.

The first experimental evidence for a 4011 keV linking transition in ^{152}Dy, as well as hints of others, was found in a Gammasphere experiment performed at Argonne National Laboratory. Due to the low intensities of the observed linking transitions, another much longer experiment (12 days) was performed with Gammasphere at Lawrence Berkeley National Laboratory. The band was populated with the reaction ^{108}Pd(^{48}Ca,4n)^{152}Dy with a 191 MeV (mid-target) ^{48}Ca beam.

Figure I-35a shows the spectrum obtained by placing pairwise coincidence gates on transitions in the yrast SD band in ^{152}Dy. At higher γ-ray energies, shown in Fig. I-36a, several candidates for decay-out transitions are clearly seen. In particular, γ rays at 2713 and 4011 keV are prominent while a number of other, weaker, candidates are visible as well.

The coincidence spectrum obtained by placing pairwise gates on SD lines and on the 4011-keV transition is presented in Fig. I-35b. It is clearly seen that the 647 and 602 SD lines (see Fig. I-37) are not in coincidence with the 4011-keV γ~ray, whereas the 693 keV and higher SD lines are. This unambiguously establishes that the 4011 keV transition originates from the SD level fed by the 693 keV line. Of the normal yrast transitions in the spectrum, the 221 and 541 keV γ rays have the full intensity of the SD band (0.8(3) and 0.9(2), respectively), whereas there is no indication of the normal 967 keV transition (the intensity is 0.3(3)), which should be detectable despite the proximity of the 970 keV SD γ-ray. A comparison with the spectrum in Fig. I-35a shows no new peaks with an area larger than 3 standard deviations. This strongly suggests that the 4011-keV γ ray feeds directly into the 27$^-$ yrast state in a single step. This establishes the excitation energy of the SD level fed by the 693 SD line as 11,893 keV -- as shown in the partial level scheme of Fig. I-37. To determine the spin of the 11,893-keV SD level an angular distribution analysis of the 4011-keV transition was performed. The intensity of this γ ray, as a function of polar angle, is presented in Fig. I-36b. Using the functional form $\theta = A_0 (1 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta))$, the angular distribution coefficients were determined to be: $A_2 = -0.35(12)$ and $A_4 = -0.02(16)$ – consistent only with a stretched or anti-stretched dipole character. Thus, based on the 4011-keV transition, the feeding SD level must have a spin of either 26 or 28 $\hbar$.

With the energy of the SD band determined by the 4011-keV line, four additional γ rays in the 3-MeV region of Fig. I-36 can be placed in the level scheme as direct links between the SD band and the normal states. They are included in Fig. I-37. All four of these additional links are very weak and, thus, it is difficult to place coincidence gates on them. However, in a spectrum of pairwise gates placed on the 693-keV line and on clean SD transitions above it, the 2895-, 3044-, 3364- and 3585-keV γ rays are clearly present, whereas a similar spectrum with a gate on the 647-keV line only shows the two transitions with the highest energy, i.e., the 2895- and 3044-keV γ rays are absent. Thus, the latter two transitions emanate from the 11893-keV SD level, and the two others are associated with the deexcitation of the SD state directly below it at 11,246-keV. These weaker one-step linking transitions also resolve any remaining ambiguity concerning the spins of the SD band members. Only when 28^+ is assigned to the 11893 SD level are the multipolarities of the 2895 and 3364 keV lines reasonable: M1 and E1, respectively. A 26^+ assignment would result in respective M3 and E3 multipolarities which are improbable, be it only because of the competition with the in-band, highly collective 602 keV γ ray.

These results were published.[2]

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[1]P. J. Twin *et al*., Phys. Rev. Lett. **57**, 811 (1986).

[2]T. Lauritsen et al., Phys. Rev. Lett. **88**, 042501 (2002).

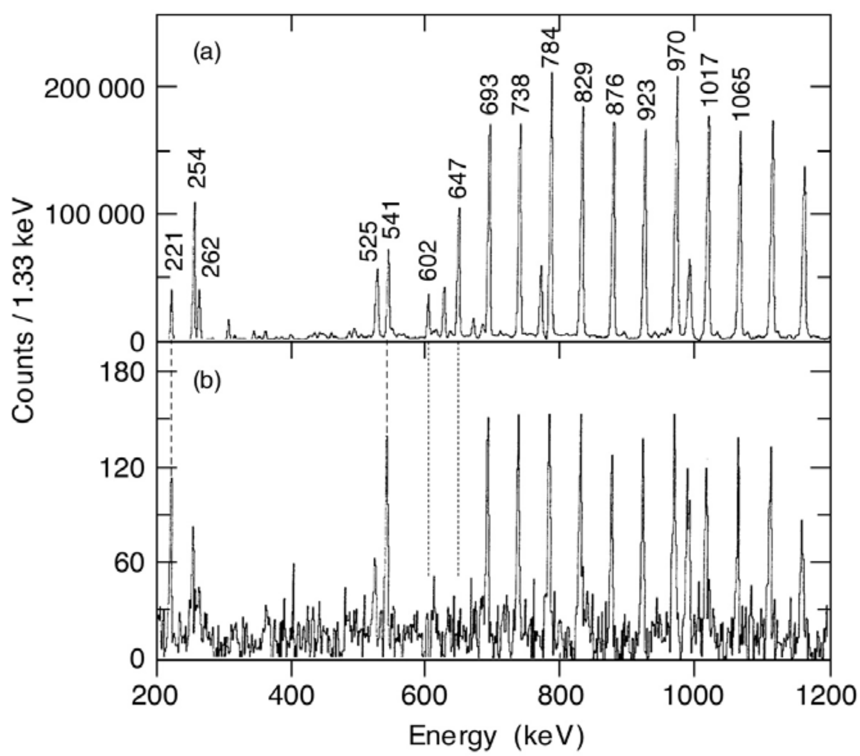

Fig. I-35. (a) Spectrum from pairwise coincidence gates in the yrast SD band of ^{152}Dy. The 94 cleanest combinations of the following SD transitions were used: 647, 693, 738, 784, 829, 876, 923, 1017, 1065, 1161, 1209, 1257, 1305, 1353, 1402 and 1449 keV. (b) Spectrum obtained from setting pairwise gates on a SD line and the 4011-keV transition. All SD transitions listed above (except that of 647 keV) were used as gates.

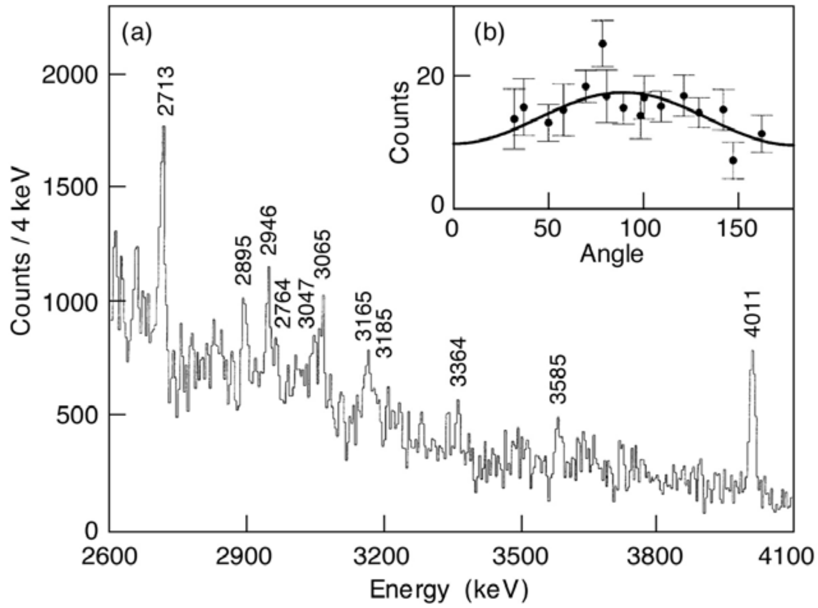

Fig. I-36. (a) High-energy portion of the spectrum in coincidence with ^{152}Dy SD transitions. (b) Angular distribution of the 4011 keV transition.

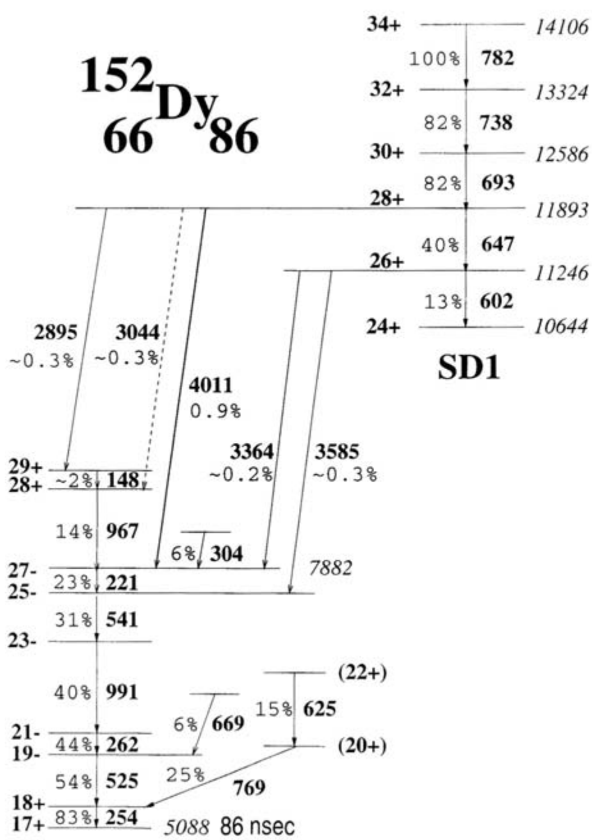

Fig. I-37. Partial level scheme of ^{152}Dy showing the lowest part of the yrast SD band and normal states to which the SD band mainly decays.

d.7. Octupole Excitation in Superdeformed $^{152}_{66}Dy_{86}$
(T. Lauritsen, R. V. F. Janssens, M. P. Carpenter, D. G. Jenkins, T. L. Khoo, K. S. Abu Saleem, I. Ahmad, J. P. Greene, A. M. Heinz, C. J. Lister, D. Seweryniak, S. Siem, R. C. Vondrasek, F. G. Kondev,* T. Døssing,† P. Fallon,‡ B. Herskind,† A. Lopez-Martens,§ A. O. Macchiavelli,‡ D. Ward,‡ R. Clark,‡ M. Cromaz,‡ F. Hannachi,§ A, Korichi,§ G. Lane,‡ P. Reiter,¶ and I. Wiedenhöver||)

Three transitions of dipole character were identified linking an excited superdeformed (SD) band in ^{152}Dy to the yrast SD band. As a result, the excitation energy of the lowest level in the excited SD band has been measured to be 14239 keV. The states in this band were determined to be of negative parity and odd spin. The measured properties are consistent with an interpretation in terms of a rotational band built on a collective octupole vibration.

In a number of nuclei, strong shell effects are responsible for an excited minimum associated with a large, prolate deformation (major to minor axis ratio of about 2:1). The physical properties of the excitations occurring in this superdeformed (SD) minimum continue to be the subject of much current interest.

The large data set that was used to link the ^{152}Dy yrast SD band to the normal deformed levels,[1] was also exploited to obtain the best possible spectrum of the very weakly populated (~5% of the yrast SD band[2]) SD band 6. The band was populated with the reaction $^{108}_{64}$Pb (^{48}Ca,4n)^{152}Dy with a 191 MeV (at mid-target) ^{48}Ca beam delivered by the 88-inch cyclotron facility at the Lawrence Berkeley National Laboratory. The target consisted of a stack of two 0.4-mg/cm^2 self-supporting ^{108}Pd foils. The Gammasphere array, with 100 Compton suppressed germanium detectors, was used to measure the γ rays of interest.

Band 6 has been proposed to decay into band 1[2] and Fig. I-38 clearly shows that, indeed, that is the case. A search was conducted for linking transitions between bands 6 and 1. Due to small differences in the moments of inertia of SD bands 1 and 6, any set of linking transitions between them will be characterized by specific energy spacings which depend on which levels are actually linked. Figure I-39a presents the high energy part of the coincidence spectrum of Fig. I-38a. Three weak transitions can be seen at 1675, 1697 and 1716 keV separated by one of the possible energy spacings (~20 keV). Coincidence gates were placed on these transitions together with relevant lines in SD band 6, while also requiring the isomer tag: the resulting spectra are given in Fig. I-40. The spectrum with a gate on the 1697 keV line (panel B) clearly shows only transitions in SD band 6 with energies $E_\gamma \leq 849$ keV, i.e. the 804 keV and 760 keV γ rays of the sequence are clearly missing. Under the same coincidence conditions, only transitions of the yrast SD band with $E_\gamma \geq 783$ keV are observed. This unambiguously establishes the ordering in the level scheme proposed in Fig. I-41. The spectrum with a gate on the 1675-keV line (panel C), which connects the two SD bands just below the 1697-keV linking transition, exhibits the same expected coincidence relationships, i.e., only the band 6 SD lines with $E_\gamma \leq 804$ keV are seen together with band 1 SD transitions with $E_\gamma \geq 738$ keV. The appearance of a ~784 keV line in the latter gate is spurious since its intensity was found to change *dramatically* with the background subtraction when compared to the intensities of band 1 and 6 γ rays. Thus, the 784-keV line in this gate is an artifact of a difficult background subtraction. The coincidence spectrum gated on band 6 lines together with the 1716 keV linking transition (not shown) has less statistics, but corroborates the proposed level scheme. Thus, an excited SD band in the mass 150 region has for the first time been linked to an yrast SD band, which in turn is linked to the normal states it decays into.[1]

An angular distribution analysis of the three linking transitions at 1675, 1697 and 1717 keV finds negative A_2 coefficients in every case (-0.4(3), -0.5(4) and -0.9(5), respectively). If the areas of the three lines are added up and analyzed together, the combined A_2 coefficient is determined to be -0.3(2), see Fig. I-39b. This value is consistent with those expected

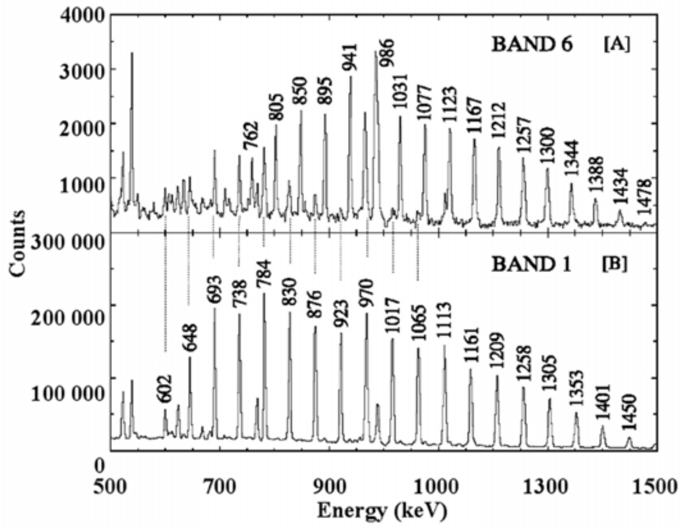

Fig. I-38. (a) Spectrum from triple coincidence gates on lines in SD band 6 of ^{152}Dy. Clean combinations of the following SD transitions were used in the analysis: 760, 804, 849, 894, 940, 1031, 1076, 1122, 1167, 1211, 1256, 1300, 1344 and 1389 keV. (b) Spectrum obtained from setting pairwise gates on clean SD lines in band 1 of ^{152}Dy.[1]

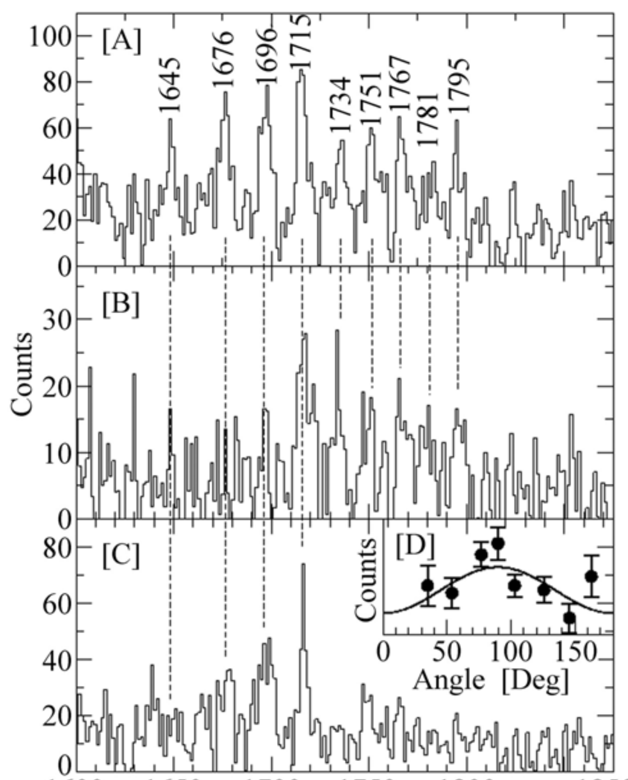

Fig. I-39. (a) Summed coincidence spectrum obtained by placing gates on clean SD-band 6 high-energy transitions and SD-band 1 low-energy transitions. The nine transitions linking SD band 6 to band 1 are marked with their energies. (b) As (a), but requiring the 830-keV transition in band 1. (c) As A, but requiring the 895-keV transition in band 6 and any SD-band 1 transitions below 876 keV. (d) Angular distribution of the sum of the intensities in the 1676-, 1696- and 17l5-keV linking transitions vs. the polar angle of the Gammasphere detectors.)

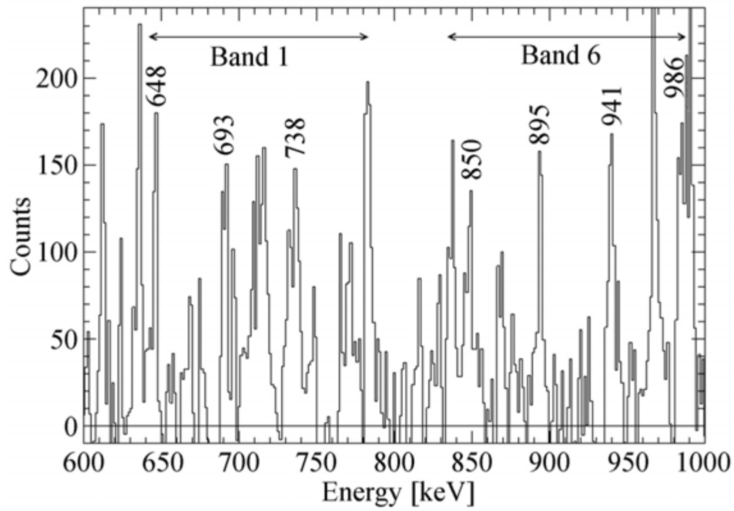

Fig. I-40. Summed coincidence spectrum obtained by placing gates on the 1696-keV linking transition and clean lines in SD band-6.

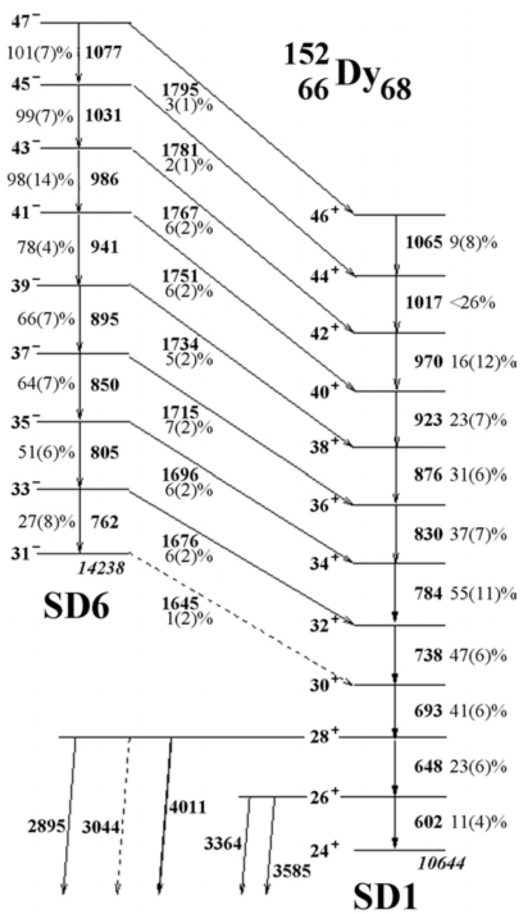

Fig. I-41. Partial level scheme of ^{152}Dy showing the lowest part of SD band 6, the lowest part of the yrast SD band 1 and the transitions that link the yrast SD band 1 to the normal states.[1] The transition intensities, given in %, reflect the requirement of the isomer tag and are with respect to the strongest lines in SD band 6.

for stretched or anti-stretched E1 or M1 transitions (-0.24 - -0.21), but inconsistent with transitions of E2 character or with E1 transitions involving no spin change (where large positive A_2 values of +0.34 and +0.45 are expected, respectively).

RPA calculations by Nakatsukasa *et al.*[3] interpret SD band 6 as an octupole excitation with signature $\alpha = 1$. At zero frequency the band is characterized by K = 0, but K-mixing is significant at the frequencies of interest here because of the Coriolis force. Experiment and calculations are compared in Fig. I-42, where the Routhinan of band 6 with respect to the yrast SD band is given as a function of the rotational frequency. The figure presents the lowest octupole excitation (dashed line), and the first 1p - 1n configuration (solid line). The calculations reproduce the magnitude and evolution with frequency of the $J^{(2)}$ moment of inertia satisfactorily (see Fig. I-40 in Ref. 3), and the agreement is also reasonable for the energy of the octupole excitation: theory and experiment are only ~250 keV apart. Furthermore, the evolution of the Routhian with frequency is well reproduced when the interband transitions are considered to be of the J + 1 → J type. This agreement argues for the spin assignment given in Fig. I-41.

A publication of this result is in preparation..

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[1]T. Lauritsen *et al*., Phys. Rev. Lett. **88**, 042501 (2002).
[2]P. G. Dagnall *et al*., Phys. Lett. **B335**, 313 (1994).
[3]T. Nakatsukasa *et al*., Phys. Lett. **B343**, 19 (1995).

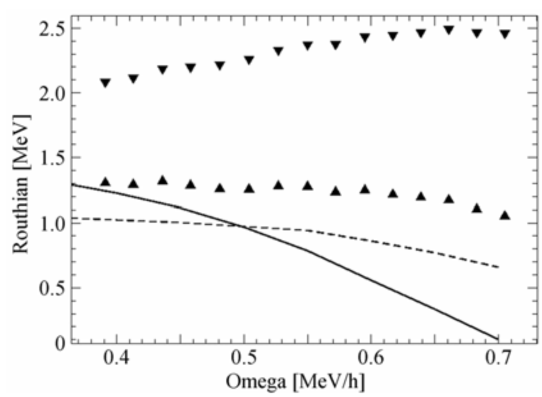

Fig. I-42. Routhians of band 6 with respect to band 1 as a function of rotational frequency. The up-triangles are the experimental data with the high spin assignment to band 6 and the down-triangles the experimental data with the low spin assignment. The dashed (solid) line is the result of the RPA calculation for negative-parity states with signature $\alpha = 1$.[3] The dashed line characterizes the lowest excitation mode in the SD well associated with a collective octupole vibration. The solid line likewise shows the lowest 1p - 1h excitation. This excitation is associated with SD band 2.[3]

d.8. Empirical Investigation of Extreme Single-Particle Behavior of Nuclear Quadrupole Moments in Highly Collective A ~ 150 Superdeformed Bands (R. V. F. Janssens, S. T. Clark,* G. Hackman,* S. N. Floor,* J. Norris,* S. J. Sanders,* R. M. Clark,† P. Fallon,† G. J. Lane,† A. O. Macchiavelli,† and C. E. Svensson†)

The intrinsic quadrupole moment Q_0 of superdeformed rotational bands in A ~ 150 nuclei depends on the associated single-particle configuration. We derived an empirical formula based on the additivity of effective quadrupole moments of single-particle orbitals that describes existing measurements from ^{142}Sm to ^{152}Dy. To further test the formula, the predicted Q_0 moments for two superdeformed bands in ^{146}Gd of 14.05 eb were confronted with a new measurement yielding 13.9 ± 0.4 eb and 13.9 ± 0.3 eb, respectively. The data were taken with Gammasphere at the 88 Inch cyclotron facility at LBNL. This excellent agreement provides empirical evidence of extreme single-particle behavior in highly deformed, collective systems. A paper reporting these results was recently published.[1]

*University of Kansas, †Lawrence Berkeley National Laboratory
[1]S. T. Clark *et al*., Phys. Rev. Lett. 87, 172503 (2001).

d.9. Competition Between Terminating and Collective Structures Above Spin 40 in ^{154}Dy

(R. V. F. Janssens, T. L. Khoo, M. P. Carpenter, I. Ahmad, S. M. Fischer, T. Lauritsen, D. T. Nisius, W. C. Ma,* I. Ragnarsson,† M. A. Riley,‡ J. R. Terry,* J. P. Zhang,* P. Bhattacharyya,§ P. J. Daly,§ J. H. Hamilton,¶ A. V. Ramayya, ¶ R. K. Vadapalli, P. G. Varmette,* J. W. Watson,* C. T. Zhang,§ and S. J. Zhu*)

High-spin states in ^{154}Dy were studied with the Gammasphere spectrometer using the ^{36}S(^{122}Sn,4n) reaction. Band terminating states were identified in the spin range I = (36 - 48), and were found to compete with collective rotational cascades up to the highest observed spins. Several "sidebands" feeding the terminating structures were identified as well. A band dominated by M1 transitions was observed to terminate at I = 42^-. The data are interpreted within the framework of configuration-dependent cranked Nilsson-Strutinsky calculations without pairing. The calculations give good reproduction of the observed bands and terminating structures (see Fig. I-43). The results reveal the “anatomy” of a phase transition from collective to single-particle motion and show how terminating states descend below collective structures as the angular momentum increases. This work was published in Physical Review C.

*Mississippi State University, †Lund Institute of Technology, Lund, Sweden, ‡Florida State University, §Purdue University, ¶Vanderbilt University

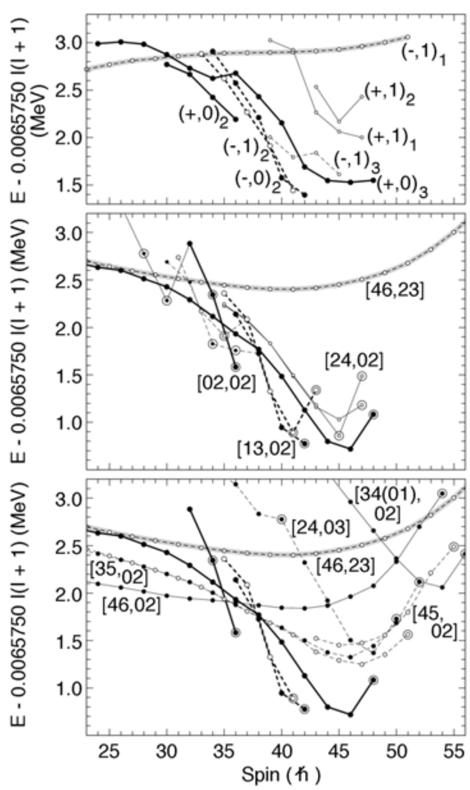

Fig. I-43. Observed terminating bands of ^{154}Dy in the upper panel with their calculated counterparts in the middle panel. Note that the [13,02] label refers to the two bands terminating at 41^- (43^-) and 42^-, and [24,02] refers to the three bands terminating at 47^+ and 48^+. In the lower panel, some configurations predicted to terminate in the I = (50 - 55) ħ range are added. Collective configurations are indicated by thick shaded lines.

d.10. First Evidence for Triaxial Superdeformation in ^{168}Hf

(R. V. F. Janssens, M. P. Carpenter, F. G. Kondev, T. L. Khoo, T. Lauritsen, C. J. Lister, S. Siem, I. Wiedenhöver, H. Amro,* P. G. Varmette,* W. C. Ma,* B. Herskind,† G. B. Hagemann,† G. Sletten,† A. Bracco,‡ M. Bergstrom,† J. Domscheit,§ S. Frattini,‡ D. Hartley,¶ H. Hubel,§ B. Million,‡ S. W. Odegard,* R. B. Piercey,* L. L. Riedinger,¶ K. A. Schimdt,† J. N. Wilson,† and J. A. Winger*)

Potential energy surface calculations predicted that nuclei with Z ~ 72 and N ~ 94 constitute a region of exotic shapes coexisting with the normally deformed prolate states. At high spins, these exotic shapes are predicted to lie lowest in energy and assume a stable triaxial superdeformed shape with a quadrupole deformation parameter $\beta_2 \sim 0.4$. Experimentally, rotational bands associated with this shape were reported in $^{163\text{-}165}$Lu. The association of these bands with the superdeformed triaxial minimum was inferred through a comparison of measured spectroscopic information with theoretical calculations. The most significant experimental observables include the quadrupole moments and the dynamic moments of inertia, which are strongly influenced by triaxiality.

In order to further extend this new region of superdeformation as well as test the predictive powers of model calculations, two separate measurements were undertaken to study high angular momentum states in ^{168}Hf. In both experiments, the ^{96}Zr(^{76}Ge,4n) was used to populate high spin states in ^{168}Hf. The 310-MeV germanium beam was provided by the ATLAS accelerator at Argonne National Laboratory. Gamma rays were detected with the Gammasphere spectrometer consisting of 101 Compton-suppressed Ge detectors. In the first experiment, a self-supporting thin foil (0.67 mg/cm^2) of ^{96}Zr was used as a target. From an analysis of the data, three rotational bands with characteristics consistent with those of the triaxial superdeformed structures identified in the Lu isotopes were identified and assigned to ^{168}Hf. Relative to the ground state transition in ^{168}Hf these bands are populated at 0.25, 0.15 and 0.12%. In the second experiment, the target consisted of a thin layer (0.67 mg/cm^2) of ^{96}Zr backed by 21 mg/cm^2 evaporated Au, which slowed down and stopped the recoiling nuclei. Due to the fact that the bands are weakly populated, an average quadrupole moment using the DSAM technique could only be established for band 1. The value of 11.4 eb established for the band provides a direct measure of the large deformation associated with the band and is consistent with theoretical calculations which predict a high-spin SD minima ($\beta_2 \sim 0.4$) with a stable triaxial deformation of $\gamma \sim 20°$. This result constitutes the first evidence for triaxial superdeformation in an even proton system of this region.

A paper reporting the results of this work was recently published in Physics Letters B.[1]

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*Mississippi State University, †Niels Bohr Institute, Copenhagen, Denmark, ‡University of Milan, Italy, §University of Bonn, Germany, ¶University of Tennessee

[1]H. Amro *et al.*, Phys. Lett. **B506**, 39 (2001).

d.11. Study of ^{169}Hf at High Rotational Frequency

(M. P. Carpenter, R. V. F. Janssens, F. G. Kondev, T. L. Khoo, T. Lauritsen, C. J. Lister, S. Siem, I. Wiedenhöver, K. A. Schmidt,* M. Bergstrom,* G. B. Hagemann,* B. Herskind,* G. Sletten,* P. G. Varmette,* J. Domscheit,† H. Hubel,† S. W. Odegard,‡ S. Frattini,§ A. Bracco,§ B. Million,§ W. C. Ma,¶ R. Terry,¶ D. J. Hartley,‖ L. L. Riedinger,‖ and A. Maj**)

High-spin properties of the nucleus ^{169}Hf were studied through the fusion evaporation reaction ^{96}Zr(^{76}Ge,3n)^{169}Hf at a beam energy of 310 MeV. The 310-MeV germanium beam was provided by the ATLAS accelerator at Argonne National Laboratory. Gamma rays were detected with the Gammasphere spectrometer consisting of 101 Compton-suppressed Ge detectors. The main focus of this investigation was to identify triaxial superdeformed bands in the Hf isotopes. Such structures were found in ^{168}Hf,[1] but no evidence for these types of bands could be found in ^{169}Hf. Nevertheless, a thorough analysis of the data has yielded considerable new information on the level structure of ^{169}Hf. The previously known rotational bands were extended considerably, and 6 new bands were established. Quasiparticle assignments are suggested for the new band structures, and it appears that coupling to vibrational degrees of freedom play a role.

Of the six new bands, four form coupled pairs of strong M1 transitions. Both coupled pairs of bands are believed to contain two quasiprotons in their three quasiparticle configuration. Four bands were extended to such high spin that a second clear upbend was observed. It has been suggested that these bands are associated with a five quasiparticle configuration at the highest spins and, furthermore, that the aligning orbitals are a proton pair. Based on a comparison of the data to model predictions, the alignment of a mixture of $h_{9/2}$ and $h_{11/2}$ proton orbitals is the most likely explanation for the observed upbend.

A paper reporting the results of this work was recently published in the European Physical Journal A.[2]

*Niels Bohr Institute, Copenhagen, Denmark, †University of Bonn, Germany, ‡University of Oslo, Norway, §University of Milan, Italy, ¶Mississippi State University, ||University of Tennessee, **Niewodniczanski Institute of Physics, Krakow, Poland.

[1]H. Amro *et al.*, Phys. Lett. **B506**, 39 (2001).
[2]K. A. Schmidt *et al.*, Eur. Phys. J. **A** 12, 15 (2001).

d.12. K-Hindered Decay of a 6-qp Isomer in ^{176}Hf

(G. Mukherjee,* F. Kondev, K. Abu Saleem, I. Ahmad, M. P. Carpenter, A. Heinz, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, C. J. Lister, D. Seweryniak, I. Wiedenhöver, P. Chowdhury,† R. D'Alarcao,† I. Shestakova,† H. El-Masri,‡ P. M. Walker,‡ D. M. Cullen,§ C. Wheldon,‡¶ D. L. Balabanski,|| M. Danchev,|| T. M. Goon,|| D. J. Hartley,|| L. L. Riedinger,|| O. Zeidan,|| M. A. Riley,** R. Kaye,†† G. Sletten,‡‡ and G. D. Dracoulis§§)

High-K isomers in the Hf region provide an opportunity to test the conservation of the K quantum number at high spin. In this work, a known 6 quasiparticle isomer in ^{176}Hf was studied. The fusion evaporation reaction ^{130}Te(^{48}Ca, 2n)^{176}Hf with a pulsed 194 MeV beam from ATLAS was used to investigate the K-hindered decays from high-K states in ^{176}Hf using the Gammasphere array. The beam was pulsed in two different time windows: a 1 ns "ON" and 820 ns "OFF" and an "on-demand" beam switching in which the beam was switched off for 100 μs following a triple coincidence. Gamma-rays of the $K^\pi = 14^-$ band are observed in the gated spectra from out-of-beam a γ–γ matrix and a γ–γ–γ cube with no extra line above 20^-. This gives an indication that the $K^\pi = 14^-$ band is fed from the $K^\pi = 22^-$ six-quasiparticle isomeric ($t_{1/2}$ = 43 μs) state. Since no γ-ray transition was observed to account for this, we propose a K-hindered decay of the $K^\pi = 22^-$ isomer to the 20^- state of $K^\pi = 14^-$ band through an unobserved, highly converted 37 keV E2 transition. The reduced hindrance factor for this ΔK = 8 decay was estimated to be very low (f_ν = 2.5) suggesting K-mixing and a mixed configuration of a nearby $K^\pi = 20^-$ state.

*Argonne National Laboratory and the University of Massachusetts, †University of Massachusetts, ‡University of Surrey, United Kingdom, §University of Manchester, United Kingdom, ¶University of Liverpool, United Kingdom, ||University of Tennessee, **Florida State University, ††Purdue University, Calumet, ‡‡Niels Bohr Institute, Denmark, §§Australian National University, Australia

d.13. Narrow Spreading Widths of Excited Bands in a Superdeformed Well

(T. L. Khoo, T. Lauritsen, D. Ackermann, I. Ahmad, H. Amro, D. J. Blumenthal, I. Calderin, S. M. Fischer, G. Hackman, R. V. F. Janssens, D. Nisius, M. P. Carpenter, A. Lopez-Martens,* T. Døssing,† B. Herskind,† M. Matsuo,‡ K. Yoshida,§ S. Asztalos,¶ R. M. Clark,¶ M. A. Deleplanque,¶ R. M. Diamond,¶ P. Fallon,¶ F. Hannachi,* A. Korichi,* R. Krücken,¶ I. Y. Lee,¶ A. O. Macchiavelli,¶ R. W. MacLeod,¶ G. J. Schmid,¶ F. S. Stephens,¶ and K. Vetter¶)

Excited states within a superdeformed (SD) well provide opportunities to investigate: (i) the excited states of a false vacuum; (ii) a transition from ordered motion along the yrast line to chaotic motion above, where quantum numbers and symmetries break down, perhaps through an ergodic regime; (iii) the robustness of collectivity with increasing excitation energy; (iv) the evolution with energy and spin of moments of inertia, collective spreading widths, in-band probabilities, quadrupole moments; and (v) the largely-unexplored feeding mechanism of SD bands.

Data for the present work came from a Gammasphere experiment[1] conducted at LBNL with the $^{150}Nd(^{48}Ca,4n)^{194}Hg$ reaction. E_γ - E_γ matrices were constructed from pair wise gates on (a) SD and (b) normal-deformed (ND) transitions in ^{194}Hg; (a) selects only transitions feeding SD band 1, while (b) includes other SD transitions, which do not necessarily feed into the SD yrast line, but continue to lower spin. In the SD-gated matrix (see Fig. I-44), 3 ridges (parallel to the diagonal) with $E_\gamma > 450$ keV could be seen and, in the other matrix, 5-6 ridges, which persist down to ~340 keV. The former matrix represents the first instance where ridges are detected with gates on SD transitions. The persistence of ridges to lower energy in the ND-gated matrix occurs because the γ cascades are not forced into the SD yrast line and implies small tunneling to ND states - even ~2 MeV above the SD minimum. The ridges reveal the following properties: (1) narrow spreading widths (~ 5 - 10 keV), which increase with spin; (2) ridge spacings and, hence, $J^{(2)}$ identical to that of SD band 1; (3) N_{path} ~ 100 - 150, from fluctuation properties; (4) in-band probability ~1, for $E_\gamma > 790$ keV; and (5) ratio of ridge intensity/total E2 strength ~1 for $E_\gamma < 770$ keV. The large number of unresolved bands suggests that they are excited, probably from an interval 1.5 - 2 MeV above the SD yrast line. Yet, unexpectedly, the moments of inertia are nearly identical to that of the yrast SD band.

Features (1 - 3) were anticipated by theory;[2] further analyses indicate that there are 2 - 8 components in the wave functions, which are, hence, quite complex. Despite this large mixing among many bands, which should broaden the rotational strength, the ridge spreading widths are narrow. This implies surprisingly small changes in the amplitudes and phases of the wave function with repeated spin increments of 2 ħ, suggesting rotational coherence. Perhaps the excited unresolved SD bands in ^{194}Hg are candidates for ergodic bands.[3]

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*C.S.N.S.M, IN2P3-CRNS, Orsay, France, †The Niels Bohr Institute, Denmark, ‡Graduate School of Science and Technology, Niigata University, Niigata, Japan, §Institute of Natural Science, Nara University, Nara, Japan, ¶Lawrence Berkeley National Laboratory

[1]R. Krücken *et al.*, Phys. Rev. C 54, R2109 (1996).
[2]K. Yoshida and M. Matsuo, Nucl. Phys. A 636, 169 (1998).
[3]B. R. Mottelson, Nucl. Phys. A 557, 717c (1993).

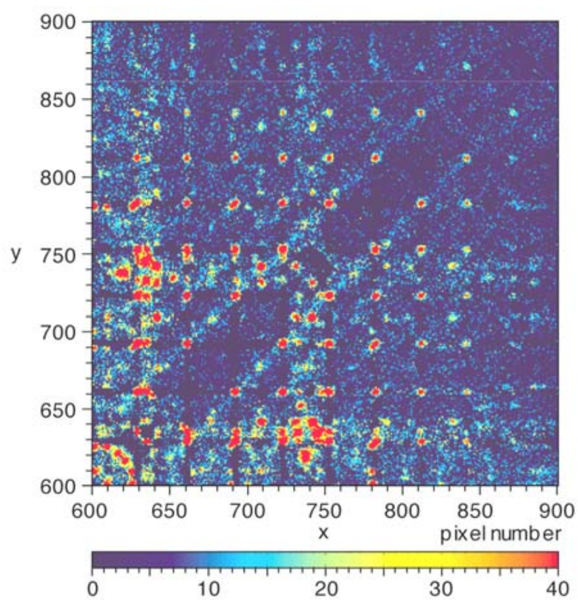

Fig. I-44. E_γ - E_γ matrix obtained with pair wise gates on lines of the yrast superdeformed (SD) band I in ^{194}Hg. Note that the 3 ridges, which are parallel to the diagonal, are narrow and have the same spacings as the regular grid points from SD band I.

d.14. Limits of the Energy-Spin Phase Space Beyond the Proton Drip Line: Entry Distributions of Pt and Au Isobars (M. P. Carpenter, F. G. Kondev, T. L. Khoo, T. Lauritsen, R. V. F. Janssens, K. Abu Saleem, I. Ahmad, C. N. Davids, A. Heinz, C. J. Lister, G. L. Poli, J. J. Ressler, D. Seweryniak, I. Wiedenhöver, M. B. Smith,* J. A. Cizewski,* H. Amro,† M. Danchev,‡ D. J. Hartley,‡ W. C. Ma,† W. Reviol,§ and L. L. Riedinger‡)

Nuclei lying beyond the proton drip line provide an ideal laboratory for the study of the amount of energy and angular momentum which a weakly-bound system can sustain. These limits of existence can be determined by measuring the entry distribution[1] populated in a fusion-evaporation reaction. The entry distribution is the initial population as a function of excitation energy *E* and spin *I*, after particle evaporation from the compound system, from which γ emission to the ground state originates. It was suggested[2] that the entry distribution should be limited beyond the drip line, since only a small region of the energy-spin phase space, just above the yrast line, does not decay by proton emission.

Entry distributions were measured for $^{173-177}$Au nuclei, all of which lie beyond the drip line, and compared with those of the more stable Pt isobars. These systems were populated following the bombardment of ^{92,94,96}Mo targets by beams of ^{84}Sr, provided by the ATLAS accelerator. Fusion-evaporation products were selected using the Argonne Fragment Mass Analyzer, and the recoil-decay tagging method was used to select the α-decaying states of interest. Prompt γ rays were detected using the 106-module Gammasphere array as a calorimeter. Total modular energy *H* and multiplicity *K* were measured. The response functions of the array enable the conversion of modular (*H, K*) to energy and multiplicity, which can be related to spin by realistic assumptions[1] of the angular momenta carried by the components of the γ-ray cascade. Comparisons have been made between the entry distributions associated with odd-*A* Au and Pt isobars. In ^{173}Au the entry distribution (Fig. I-45) is colder than that at ^{173}Pt, which provides the first evidence for the limits of excitation energy and angular momentum which a nucleus beyond the proton drip line can sustain. The observed results cannot be explained by simple calculations based on *Q*-values or by statistical model calculations, both of which predict similar distributions for isobars.

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[1]P. Reiter *et al.*, Phys. Rev. Lett. **84**, 3542 (2000).

[2]T. L. Khoo, in *Tunneling in Complex Systems*, Proceedings from the Institute for Nuclear Theory, v. 5, p. 229, ed. Steven Tomsovic (World Scientific 1998).

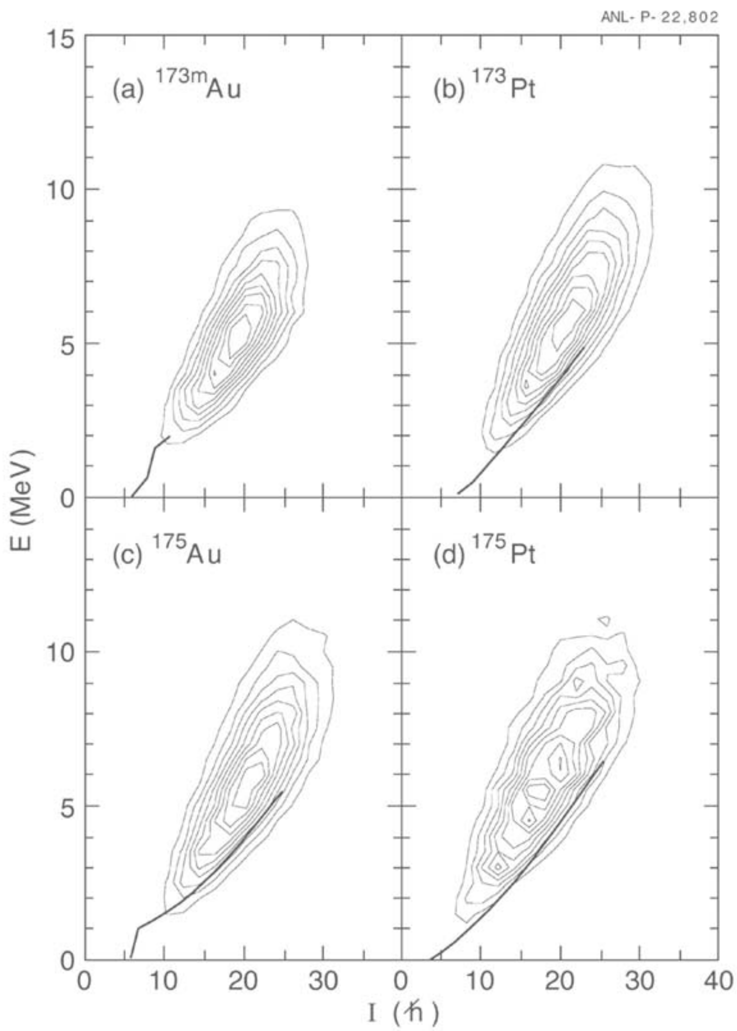

Fig. I-45. Two-dimensional (I,E) entry distributions for (a) ^{173m}Au, (b) ^{173}Pt, (c) ^{175}Au and (d) ^{175}Pt. Each contour line represents a change of 10% of the maximum value. The yrast line for each isotope is presented as a thick line.

d.15. Investigation of the Decay Out of Superdeformed Bands in ^{194}Hg by Lifetime Measurements (T. L. Khoo, P. Reiter, A. Dewald,* R. Kühn,* R. Peusquens,* P. von Brentano,* R. Krücken,† M. A. Deleplanque,† I. Y. Lee,† R. M. Clark,† P. Fallon,† A. O. Macchiavelli,† R. W. MacLeod, † and F. S. Stephens,† and K. Hauschild‡)

The lifetimes of low-lying states in the superdeformed (SD) bands of ^{194}Hg were measured by means of the recoil distance method using Gammasphere and the Cologne plunger device. The deduced transitional quadrupole moments in all three bands were found to be constant within the experimental uncertainties and equal those extracted from Doppler-shift attenuation method measurements for the higher-lying states, confirming that the decay out does not strongly affect the structure of the SD bands. The experimental findings are used to discuss the different mechanisms proposed for the decay out of SD bands. This work was published in Physical Review C.[1]

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[1]A. Dewald et al., Phys. Rev. **C64**, 054 309 (2001).

d.16. Effective Charge of the $\pi h_{11/2}$ Orbital and the Electric Field Gradient of Hg from the Yrast Structure of ^{206}Hg (R. V. F. Janssens, M. P. Carpenter, I. Wiedenhöver, B. Fornal,* R. Broda,* K. H. Maier,* J. Wrzesinski,* G. J. Lane,† M. Cromaz,† A. O. Macchiavelli,† R. M. Clark,† K. Vetter,† A. P. Byrne,‡ G. D. Dracoulis,‡ M. Rejmund,¶ and J. Blomqvist‖)

The γ-ray decay of excited states of the two-proton hole nucleus, ^{206}Hg, was identified using Gammasphere and ^{208}Pb + ^{238}U collisions. The yrast states found include a $T_{1/2}$ = 92 (8) ns 10^+ isomer located above the known 5^- isomer. The B(E 2; $10^+ \rightarrow 8^+$) strength is used to derive the quadrupole polarization charge induced by the $h_{11/2}$ proton hole. Also, the implied quadrupole moment was used to provide an absolute scale for the electric field gradient of Hg in Hg metal. These results were published.[1]

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[1]B. Fornal *et al.*, Phys. Rev. Lett. **87**, 212501 (2001).

d.17. Unexpected Behavior of Heavy-Ion Fusion Cross Sections at Extreme Sub-Barrier Energies (C. L. Jiang, H. Esbensen, K. E. Rehm, B. B. Back, R. V. F. Janssens, J. A. Caggiano, P. Collon, J. Greene, A. M. Heinz, D. J. Henderson, I. Nishinaka, T. O. Pennington, and D. Seweryniak)

In an earlier report it was found[1] that the behavior of excitation functions of some heavy-ion fusion reactions exhibits an abrupt decrease of the cross section at extreme sub-barrier energies. This behavior cannot be reproduced with present models, including those based on a coupled-channels approach. In order to study this phenomenon in more detail excitation functions for fusion-evaporation in the systems ^{58}Ni + ^{89}Y and ^{60}Ni + ^{89}Y were measured at low cross sections.

The excitation function for evaporation residue production in the system ^{60}Ni + ^{89}Y, covering cross sections from about 100 mb to less than 100 nb, is presented in Fig. I-46a by open circles, while the results for ^{58}Ni + ^{89}Y are shown by solid circles. It should be noted that precise measurements of very small fusion cross sections are experimentally challenging. Reactions on small amounts of heavier isotopic target contaminants can dominate the low-energy yields due to their higher center-of-mass energies. Since yttrium has only one stable isotope, it was chosen as the target. In addition, even low-intensity isobaric contaminants in the beam, e.g., a ^{58}Fe contamination in a ^{58}Ni beam can also affect the fusion cross sections at the lowest energies because of the strong dependence of these cross sections on the respective Coulomb barriers, as seen in our experimental results of ^{58}Ni + ^{89}Y. The excitation function decreases first exponentially followed by a slower decrease caused by the contamination of a weak ^{58}Fe beam. Estimates show that a ^{58}Fe/^{58}Ni ratio of 10^{-5} - 10^{-4} can produce this result. In the following, only data for ^{60}Ni + ^{89}Y will be discussed.

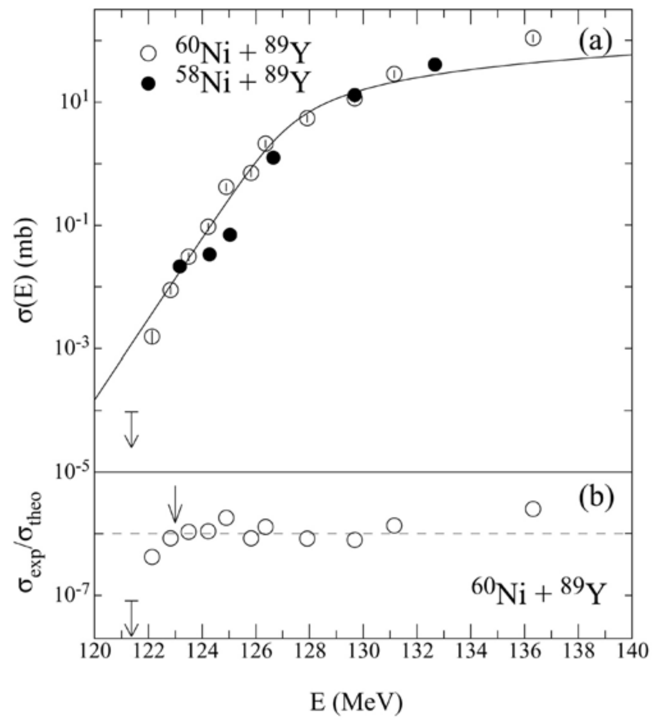

Fig. I-46. Experimental evaporation residue cross sections σ(E), (a) and $\sigma_{exp}/\sigma_{theo}$, (b) ($\sigma_{theo}$ calculated from the Wong formula), plotted as function of the center-of-mass energy for systems ^{60}Ni + ^{89}Y and ^{58}Ni + ^{89}Y. The incident energies have been corrected for the finite target thickness (including the influence of drastic change in the cross section with energy).

The solid line in Fig. I-46a is the result of a calculation using the Wong parameterization[2] for ^{60}Ni + ^{89}Y with the parameters $\hbar\omega_0$ = 4.16 MeV and Vw = 126.6 MeV. At the lowest energies the experimental cross sections fall below the calculated values, as is best seen from the ratio $\sigma_{exp}/\sigma_{theo}$ given in Fig. I-46b. From these data an energy E_0 (defined as the energy at which the drop-off occurs, see arrow in Fig. I-46b) can be derived. Remarkably, the values E_0 for ^{60}Ni + ^{89}Y and four other systems (^{58}Ni +^{58}Ni,[4] and ^{90}Zr + ^{89}Y,^{90}Zr,^{92}Zr[5]) indicate that the onset of the steeper than expected decrease in the fusion cross section occurs at an energy E_0 ~ 0.91 V_b, where V_b is the Coulomb barrier calculated from the systematics of Ref. 3. This observation suggests that this reduction in cross section is an entrance channel effect. The systems mentioned above all involve closed-shell ("stiff") nuclei in the entrance channel. For reactions involving open-shell ("soft") nuclei in the entrance channel, firm E_0 values are not yet available, and the upper limits obtained suggest that there is a nuclear structure dependence to this phenomenon. It is likely that larger channel-coupling effects for these softer participants are pushing the appearance of the phenomenon towards lower E_0/V_b values.

To better illustrate the steep fall-off in the product σE, the exponential slopes defined as $L(E) = d(ln(\sigma E))/dE$ are plotted as a function of E/E_0 for three systems in Fig. I-47. In addition to the straightforward determinations from consecutive data points, slopes were also derived from least-squares fits to three data points in an attempt to avoid

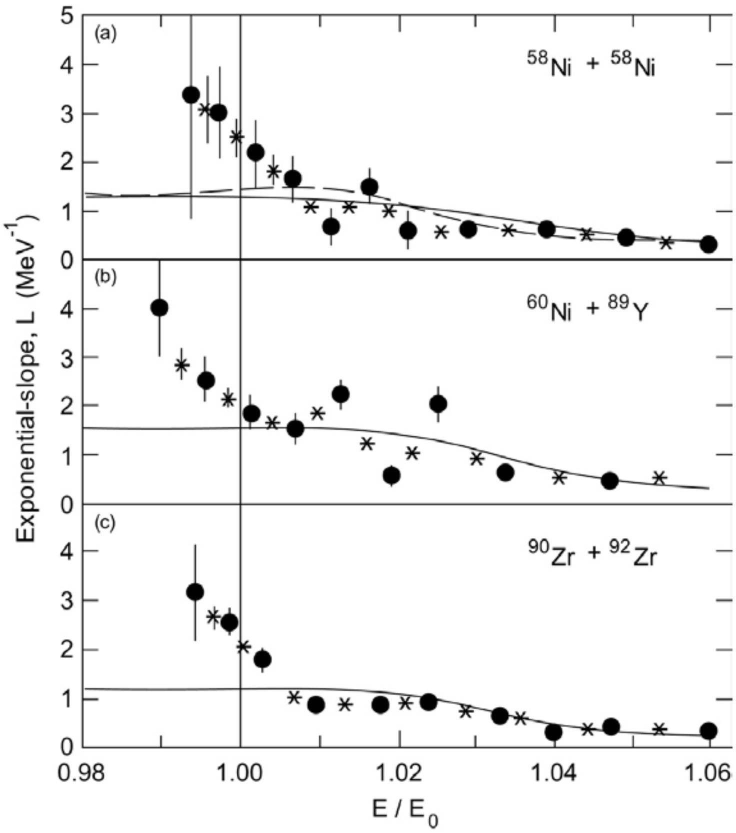

Fig. I-47. Exponential slopes L(E), d(ln(σE))/dE, plotted as function of E/E_0 for the systems $^{58}Ni + ^{58}Ni$, $^{60}Ni + ^{89}Y$ and $^{90}Zr + ^{92}Zr$. Solid circles and stars correspond to slope determinations from consecutive data points and from least-squares fits to three data points, respectively. Solid and dashed lines are the results of theoretical calculations with the Wong formula and the coupled-channel formalism, respectively.

fluctuations, which may arise as a result of large errors for small cross sections or of uncertainties in the determination of the beam energy. In Fig. I-47, the slopes determined from two or three consecutive points are given as solid circles and stars, respectively, at the corresponding average energies. The dashed and solid lines in the figure represent the results of coupled-channels calculations and of the Wong formula, respectively. While all calculated slopes approach a constant value of ~1.5 MeV^{-1}, the experimental data exhibit a continuous increase with decreasing energies. It would clearly be of great interest to investigate whether the behavior observed here persists at even lower energies for systems involving soft nuclei in the entrance channels.

Some aspects of the cross sections at low energies can be understood on the basis of the underlying *Q*-values, while others remain unexplained. In fusion reactions between two heavy ions, the reaction *Q*-values are always negative. As a result, once the excitation energy in the compound system E_{ex} reaches zero, which occurs at a finite bombarding energy, the cross section must be zero, and thus the exponential slope of σE should approach infinity. Hence, for a heavy-ion system, the slope $L(E)$ should increase towards infinity with decreasing energy. Any theoretical model attempting to describe the fusion behavior at extreme sub-barrier energies should include the properties of the fused system as expressed through the *Q*-value. The *Q*-value alone is, however, not sufficient to explain the phenomenon explored in this study. Present fusion models assume that the fused system can be populated at an excitation energy and spin corresponding to the entrance channel kinetic energy and angular momentum. This assumption is valid only as long as the total width of the compound state remains larger than the level spacing. When this condition is not satisfied a reduction of the fusion probability ensues, as is well known from capture reactions with thermal neutrons. For most of the systems under study here, however, the fall-off of the cross sections occurs at excitation energies E_{ex} ~ 20 - 30 MeV where the level densities are still very high. These observations argue for another physical reason for the reduced penetration or another hindrance implied by the negative *Q*-value; the most likely being an entrance channel phenomenon. More low-energy cross section measurements for both fusion-evaporation and fusion-fission are needed to fully understand this interesting behavior, in particular for soft systems.

[1]C. L. Jiang, H. Esbensen, K. E. Rehm, Physics Division Annual Report 2000, Argonne National Laboratory, page 72.
[2]C. Y. Wong, Phys. Rev. Lett. **31**, 766 (1973).
[3]L. C. Vaz and J. M. Alexander, Phy. Rep. **69**, 373 (1981).
[4]M. Beckerman *et al*., Phy. Rev. C **25**, 837 (1982).
[5]J. G. Keller *et al*., Nucl. Phys. **A452**, 173 (1987).

d.18. High Energy Photons from Very Symmetric Reactions: The Giant Dipole Resonance in the Highly Rotating ^{179}Au Nucleus

(M. P. Carpenter, V. Nanal, B. B. Back, F. G. Kondev, T. L. Khoo, C. J. Lister, A. M. Heinz, R. V. F. Janssens, D. Jenkins, T. Lauritsen, E. F. Moore, D. Seweryniak, F. Camera,* A. Bracco,* F. Della Vedova,* S. Leoni,* S. Mantovani,* B. Million,* M. Pignanelli,* O. Wieland,* M. Thoenessen,† R. Varner,‡ I. Dioszegi,§ A. Lopez-Marten¶, and D. Hofman‖)

The high energy gamma-rays emitted by the symmetric reaction ^{90}Zr + ^{89}Y at a beam energy of 352 MeV were measured with an experimental set up consisting of four clusters of $^{37}BaF_2$ detectors, the Fragment Mass Analyzer (FMA) and a BGO multiplicity filter. Such symmetric fusion of two nearly closed shell medium heavy nuclei has the special feature of leading to radiative fusion, where a warm compound nucleus can deexcite to its ground state without the evaporation of nucleons. There are two possible mechanisms leading to "radiative fusion: (a) a direct reaction in which the emission of a single γ-ray populates "directly" the states below the nucleon separation energy or (b) a two-step process, namely the formation of the compound nucleus ^{179}Au and the 0 nucleon channel is one of several decay modes in a statistical decay process.

The first attempt to measure γ-rays from the symmetric reactions of medium mass nuclei was performed at GSI over a decade ago. It was found that the relative population of the 0, 1 and 2 nucleon evaporation channels strongly depends on the E1 strength (measured with reasonable statistics only up to 4-5 MeV) but it was not possible to draw conclusions on the properties of the giant dipole resonance and on nuclear shapes involved in the reaction. In the present experiment the high-energy γ-ray spectra associated with the evaporation of 0, 1 and 2 nucleons were measured up to 13 MeV with an increase of statistics of more of two orders of magnitude. Our analysis (see Fig. I-50) indicates that the radiative-fusion process is a statistical one, namely the zero particle emission channel can be described as statistical decay from the compound nucleus with a shape and deformation similar to that deduced from the yrast line. The GDR spectra for the 1n and 1p channels also imply similar deformations. This suggests that shell effects are also important when the nucleus is excited at a moderate temperature. This conclusion is supported by the fact that the width of the GDR has a value that is close to that predicted by a thermal fluctuation model including shell effects.

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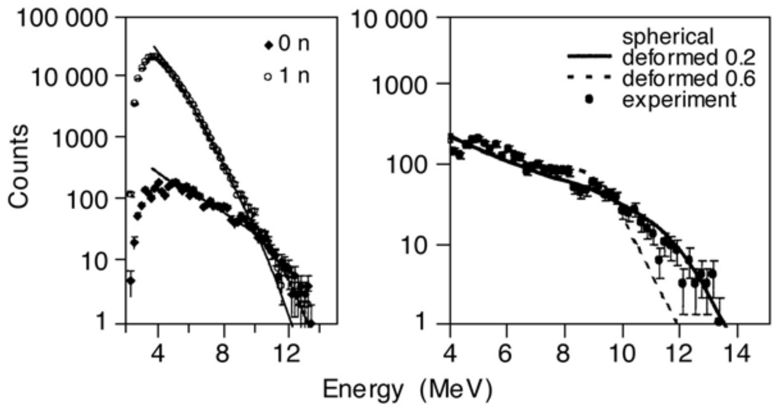

Fig. I-50. Left panel: The high-energy γ-ray spectra associated with the 0- and 1-nucleon emission channels are shown in comparison with statistical model calculations. Right panel: The high-energy γ-ray spectra associated with the 0-particle emission channel in comparison with different statistical model calculations corresponding to different nuclear deformations.

d.19. Hot GDR in ^{118}Sn (B. B. Back, M. Carpenter, T. L. Khoo, T. Pennington, P. Heckman,* J. P. Seitz,* E. Tryggestad,* T. Baumann,* M. Thoennessen,* R. L. Varner,† D. J. Hofman,‡ and V. Nanal§)

In December of 2000, an experiment was performed at Argonne National Laboratory (Exp. 889) to study the giant dipole resonance (GDR) in ^{118}Sn. The experiment employed two fusion-evaporation reactions, namely ^{18}O + ^{100}Mo and ^{17}O + ^{100}Mo. The beams of ^{18}O and ^{17}O were accelerated to energies of 95 and 78.8 MeV, respectively.

The typical way to study the GDR is to excite the nucleus of interest, and measure the γ-decay spectrum. This spectrum is then compared to statistical model calculations to extract the parameters of the GDR. The spectrum contains information from the initial excited nucleus, as well as all daughter nuclei populated along its decay. Consequently, to extract the GDR parameters from the γ-ray spectrum, it is necessary to average over many decay steps.

In this experiment, the γ-decay spectrum for both ^{118}Sn and ^{117}Sn were measured. This was done with the intention of subtracting out all daughter contributions from the ^{118}Sn decay spectrum. By exciting ^{117}Sn to the energy of the ^{118}Sn nucleus after it evaporates one neutron, the contributions of daughter nuclei can be measured and subtracted. The subtracted spectrum will only contain information from the initial excited nucleus. As a result, the parameters of the GDR can be extracted without having to average over many decay steps. This will allow for the first direct comparison of the GDR built on excited states with the ground state measurement. It will also be possible to investigate the effects of averaging over many decay steps on the extracted GDR parameters.

The γ rays were measured with the BaF_2 array, while the FMA detected evaporation residues. A coincidence condition between the two detector systems was required to ensure that detected γ rays originated from the initial compound nucleus. The array of BGO detectors was used as a multiplicity filter, and allowed for the initial spin of the excited nucleus to be determined.

Preliminary results are shown in Fig. I-51. In this figure, the γ-ray spectra are shown for the two reactions studied in this experiment. These spectra were extracted from data in the following way: first, gates were placed on Sn

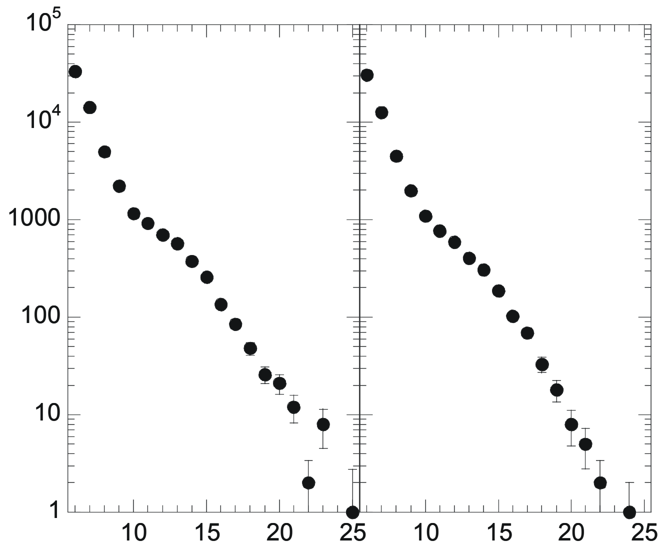

Fig. I-51. Gamma-ray spectra from experiment 889. The left panel shows the result from ^{118}Sn formed in the reaction ^{18}O + ^{100}Mo, while the right panel shows the result from ^{117}Sn formed in the reaction ^{17}O + ^{100}Mo.

evaporation residues. The residues were detected with a PPAC located in the focal plane of the FMA. Next, all events detected with the BaF_2 array in coincidence with the gated residues were analyzed. The γ rays were isolated using time of flight techniques. The final energy of a γ ray was determined by using a reconstruction routine. This routine adds the energy of neighboring detectors together to reconstruct the true energy. Finally, if the multiplicity of the BGO array was between three and five, the energy of the γ ray was put into a histogram.

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d.20. BaF_2 GDR Measurement Collaboration (B. B. Back, M. Carpenter, P. Collon, A. Heinz, D. Henderson, D. Jenkins, J. Joswick, M. Kelly, T. L. Khoo, F. Kondev, C. J. Lister, T. Pennington, J. Rohrer, R. Siemssen, D. Seweryniak, P. Wilt, V. Nanal,* D. J. Hofman,† S. Mitsuoka,‡ I. Dioszegi,§ A. Bracco,¶ F. Camera,¶ M. Halbert,‖ R. Varner,‖ K. Eisenman,** P. Heckman,** J. Seitz,** M. Thoennessen,** U. Garg,†† B. McClintock,‡‡ and R. J. van Swol‡‡)

A set of experiments to study the properties of hot nuclei with, for the first time, well-defined specification of spin and excitation energy has been completed. This work is a collaboration of Argonne, Oak Ridge, Michigan State University, Texas A&M University, Tata Institute for Fundamental Research, Stony Brook, Notre Dame University, and INFN Milano. The BaF_2 detectors were supplied by Oak Ridge, Michigan State and Texas A&M. A total of 148 BaF_2 were mounted in four packs of 37 crystals each centered at angles of ±90 and ±121 degrees with respect to the beam axis in front of the Fragment Mass Analyzer. The advantage of this arrangement is that it is possible to uniquely identify the mass of the γ-emitting nuclei as they are detected in the focal plane of the FMA. In addition, a BGO array, consisting of 48 crystals from the Argonne-Notre Dame array and from Yale, was mounted at the target position to provide information on the total γ-ray energy and multiplicity of the final γ-ray cascade to further define the entry distribution in angular momentum and excitation energy of the fusion product. For a given decay channel at different bombarding energies, it is thus possible to map out a wide range of angular momentum while keeping the excitation energy above yrast line similar.

The physics topics were chosen to study the emission of high-energy γ-rays in different areas of the nuclear chart and of different ground state shapes In one study, we chose three nuclei, namely Sn, Er and Dy to represent different mass regions likely to be sensitive to different mechanisms responsible for the broadening of GDR width. We selected spherical nuclei, stiff deformed nuclei and transitional nuclei. These efforts constitute the most comprehensive systematic investigation of the GDR spectra from hot nuclei in exclusive measurements. Subsequently, nuclei ranging in mass from ^{118}Sn to ^{224}Th were studied. A pair of experiments focused on high-energy γ rays from radiative-capture reactions, which represents a unique case with emission of only γ rays and no particles. Data analysis is still in progress. It is almost complete in the radiative capture work led by the Milan group (see section d.18).

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d.21. Yield and Activity Calculations for Facilities for Short-Lived Nuclear Beams

(C. L. Jiang, B. B. Back, I. Gomes, A. M. Heinz, J. Nolen, K. E. Rehm, G. Savard, and J. P. Schiffer)

As mentioned in the last annual report[1] detailed yield calculations were carried out in response to the recommendations of the ISOL Task Force Report to NSAC for a 100-kW, 400-MeV/u accelerator,[2] for beams re-accelerated to precise low energies as well as for fast fragmentation beams. These yield calculations were extended to rates of 10^{-4} particles/sec, which are adequate for certain experiments. The results were submitted for publication and are available on the web.[3]

For medical and material science applications, radioisotopes play an important role. Large intensities of relatively short lived isotopes, that are not easily obtained at other facilities, can be produced at the coming advanced RIA. Very large activities could be produced in dedicated primary production targets, but the detailed extraction procedures of the isotopes depend on the chemistry of the element and have to be applied case by case. In the following we therefore used only the data from the yield calculations to estimate the activities for longer lived isotopes that can be readily collected in a stopping foil after the mass separator for reaccelerated beams. The collection time should depend on the half lives of the nuclei to be used. Some activity results are shown in Fig. I-48

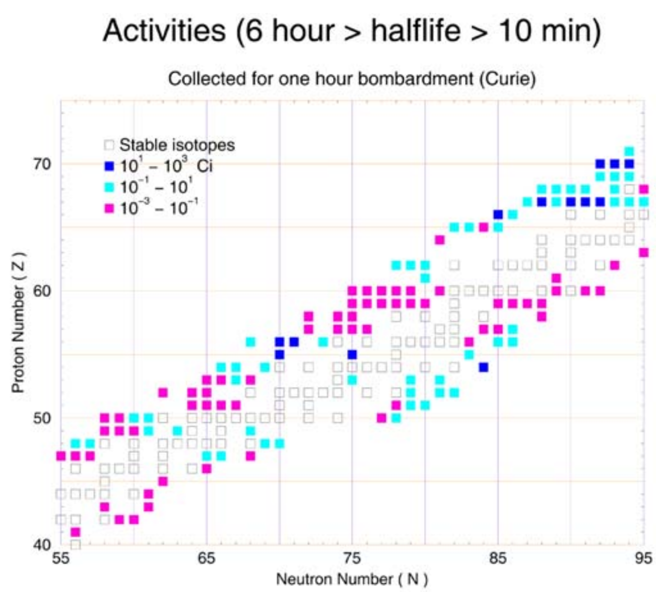

Fig. I-48. Contour map of calculated activities for isotopes collected with a 100-kW, 400-MeV/u RIA facility in a one-hour bombardment after the mass separator. The map includes only isotopes whose half lives are longer than 10 minutes and shorter than 6 hours.

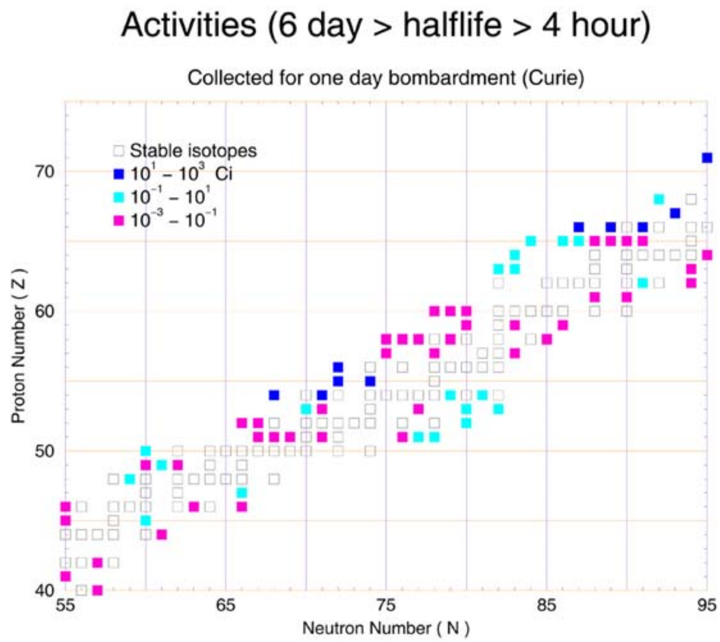

Fig. I-49. Same as in Fig. I-49 for a one-day bombardment and half lives are longer than 4 hours and shorter than 6 days.

and Fig. I-49 for nuclei in the mass range A = 100 - 150. The results for radioisotopes covering the whole mass range can be found at the same web address. The bombarding time was taken as one hour and activities produced for half lives between 10 minutes and 6 hours are shown in Fig. I-48, while in Fig. I-49 the bombarding time was taken as one day and half lives are between 4 hours and 6 days. This probably covers the range of lifetimes that are most likely to be of interest in applications. There are many blanks in the figures, corresponding to nuclei whose lifetimes are out of their range of the specific calculations. For a number of elements and isotopes much higher (in some cases up to 4 - 5 orders of magnitude) intensities might be feasible with specially designed primary target and fast chemical processing.

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[1]C. L. Jiang, B. Back, I. Gomes, A. M. Heinz, J. Nolen, K. E. Rehm, G. Savard and J. P. Schiffer, Physics Division Annual Report 2000, Argonne National Laboratory, page 75.
[2]ISOL Task Force Report to NSAC, November 22, 1999. See **http://srfsrv.jlab.org/isol/**.
[3]See **http://www.phy.anl.gov/ria/index.html**.