E. OTHER NUCLEAR STRUCTURE RESEARCH

Gammasphere at ATLAS allows a full program of gamma-ray spectroscopy to be explored. “Two-beamline” operation has allowed both the FMA and Gammasphere projects to be productive. A wide variety of programs continue at Gammasphere, including studying hot nuclei and studying nuclei at the very highest angular momenta.

e.1. Investigation of $^{12}C(^{12}C,\gamma)^{24}Mg$ Radiative Capture (C. J. Lister, N. Hammond, D. Jenkins,† P. Chowdhury,‡ and D. Hutcheon§)

The $^{12}C + ^{12}C$ reaction has a historic role in heavy ion physics, as the strongly resonant scattering and fusion cross-sections offered the promise of exotic new phenomena like “nuclear molecules” and elongated cluster configurations. A great deal of effort was put into measuring and understanding the resonances. One line of investigation, through the energy dependence of radiative capture (the complete fusion of the ions without emission of particles) clearly indicated a direct connection between some of the resonances and states in the fused compound system, ^{24}Mg.[1,2]

The original radiative capture experiments measured “one-step” decays, emission of ~20 MeV photons which cooled the nucleus from the compound nuclear state to the ground (or low-lying) states. The cross-sections were small, <<1 μb, and attributed to enhanced radiation from part of the giant quadrupole resonance. For twenty years it has remained an open question as to whether this mechanism is the dominant process in radiative capture, and if more information can be learned either about the fusion reaction mechanism or about the structure and shapes of states involved in the fusion and cooling process.

We have conducted a series of experiments using Gammasphere, using the Argonne Fragment Mass Analyzer (FMA) and using the DRAGON separator at the ISAC facility at TRIUMF in Canada. Considerable progress has been made, and a paper published[3] on some of our findings. In short, for the resonances populated near 16 MeV in beam energy, thought to have angular momentum J ~ 4.

- The fusion cross-section, inferred from measuring ^{24}Mg residues, is considerably larger than the “1-step” channel observed by Nathan and Sandorfi.[2] The enhancement is energy dependent, but is usually >5 times stronger.
- The major radiative capture flux passes through a few doorway states at ~11 MeV in excitation in ^{24}Mg. These states are only a few of the many that could be populated at this energy. Gamma ray calorimetry confirmed the finding of large radiative capture cross-section, and allowed to doorway states to be identified.
- The arrival at low spin is also selective, with population of the K = 2 excited band much stronger than the ground-state band.

The experiment at the DRAGON facility concentrated on studying near barrier resonances at energies of 12.0, 13.4 and 15.8 MeV. An array of BGO counters triggered by identified A = 24 residues was used to study the gamma-decay. The findings were similar to the higher energy experiment: that the main radiative capture mechanism was dominated by multi-step decays. Online analysis suggested the same doorway states were involved at all beam energies, but this effect is still being studied. These data are undergoing analysis.

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†University of York, United Kingdom, ‡University of Massachusetts-Lowell, §TRIUMF, Vancouver, British Columbia.

[1]A. M. Sandorfi and A. M. Nathan, Phys. Rev. Lett. **40**, 1252 (1978).
[2]A. M. Sandorfi in *Treatise on Heavy Ion Science*, Vol. 2, Sect. 2, ed. D. A. Bromley (Plenum Press, New York 1984).
[3]D. G. Jenkins *et al*., Phys. Rev. C **71**, 041301(R)/1-5 (2005).

e.2. Variation with Mass of B(E3; $0^+ \rightarrow 3^-$) Transition Rates in A = 124-134 Even-Mass Xenon Nuclei (M. P. Carpenter, D. T. Henderson, R. V. F. Janssens, C. J. Lister, E. F. Moore, T. O. Pennington, W. F. Mueller,* J. A. Church,* D. C. Dinca,* A. Gade,* T. Glasmacher,* Z. Hu,* A. F. Lisetskiy,* H. Olliver,* B. C. Perry,* I. Wiedenhöver,‡ and K. L. Yurkewicz*)

Three years ago, an experiment at ATLAS measured transition matrix elements for even-mass $^{124-134}$Xe nuclei using sub-barrier Coulomb excitation in inverse kinematics. These xenon isotopes are located in a transitional region where the dominant structure evolves from a weakly-deformed, gamma-soft rotor to a vibrator. The description of these nuclei represents a stringent test of theoretical models.

Thus far, the analysis has focused on the excitation of the 3^- state. For the determination of the electromagnetic transition matrix elements, the angle-dependent gamma-ray yields were analyzed using the Coulomb excitation code GOSIA, which combines the semi-classical theory of multiple Coulomb excitation and the measured gamma-ray deexcitation patterns with a numerical least-squares analysis to determine the electromagnetic matrix elements from the experimental gamma-ray yields. In addition to the gamma-ray yields determined in the present experiments, gamma-ray branching ratios and multipole mixing ratios found in the literature for relevant transitions were used when ever possible as additional information to constrain the determination of the matrix elements further. The measured B(E2; $0^+ \rightarrow 2^+$) and B(E3; $0^+ \rightarrow 3^-$) transition rates are presented as a function of mass in Fig. I-32 and a number of features are readily visible. First, the B(E2) values decrease steadily from the lighter to the heavier Xe isotopes, illustrating a drop in collectivity as the N = 82 shell closure is approached. In contrast, the B(E3) rates remain relatively constant for ^{124,126,128}Xe, but exhibit a marked drop in strength for the next three isotopes $^{130-134}$Xe, while a large return in collective octupole strength occurs for ^{136}Xe.

Calculations with the Quasiparticle Phonon Model (QPM)[1] have been carried out in an attempt to understand the data. As can be seen in Fig. I-32, the generally decreasing trend in B(E2) values toward heavier xenon isotopes is reproduced, but the overall strength is overpredicted in the heaviest nuclei. Likewise, the calculated B(E3) values for ^{124,126,128}Xe isotopes are in reasonable agreement with the data, but the dramatic drop in E3 strength for $^{130-134}$Xe is not accounted for. The model suggests that, as the mass increases, the contributions to the E3 strength come increasingly from higher-energy 2-qp configurations, as well as from admixtures of 4-qp configurations, and/or multi-phonon excitations for which the model is rather schematic.

A paper reporting these results has been submitted for publication.[2]

*Michigan State University, †Florida State University.

[1] V. G. Soloviev, The Theory of Atomic Nuclei: Quasiparticles and Phonons, Inst. of Phys. Publ., Bristol, 1992.

[2] W. F. Mueller *et al.*, submitted to Phys. Rev. C.

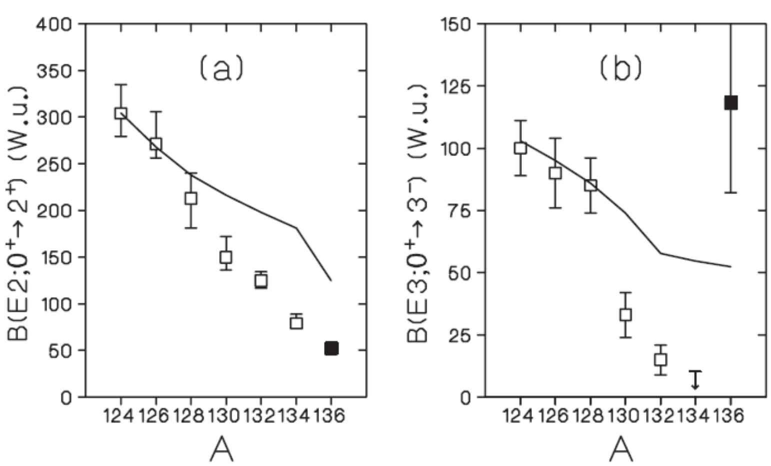

Fig. I-32. Comparison between measured reduced transition probabilities and calculations with the QPM model.

e.3. Rotational Damping, Ridges and the Quasicontinuum of γ Rays in ^{152}Dy

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

The effort to [i] understand the feeding and decay of superdeformed band 1 in ^{152}Dy, [ii] measure the ridges and quasicontinuum of gamma rays when gates are placed on discrete normal and superdeformed transitions and [iii] extract the rotational damping in the superdeformed and normal wells of the nucleus has progressed significantly.

We have now measured the entry distribution for the reaction ^{108}Pd(^{48}Ca,4n)^{152}Dy at ^{194}MeV. The measured entry distribution was subsequently the starting point for gamma cascades that are followed in Monte Carlo calculations which will attempt to simultaneously reproduce the ND and SD QC and ridge spectra. The calculation of the QC and ridge spectra allows for the extraction the rotational damping widths in the SD and ND wells of ^{152}Dy and will elucidate the feeding and decay of SD bands in the A 150 mass region. The measured total entry distribution is shown in Fig. I-33.

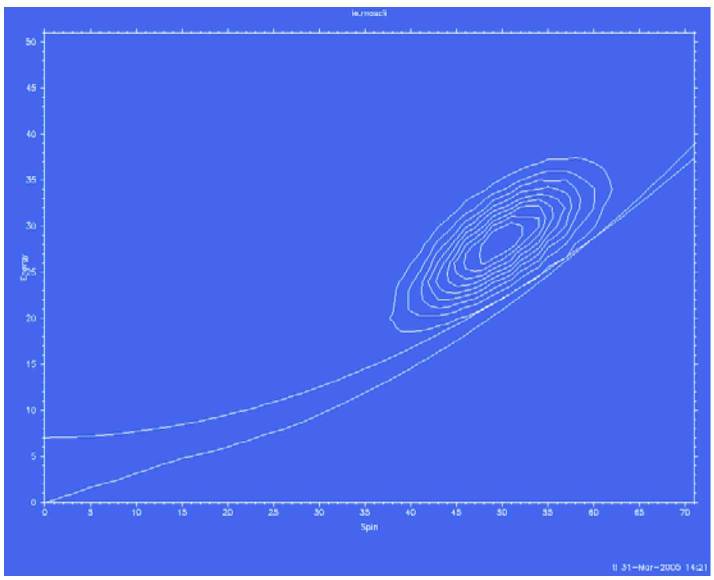

Fig. I-33. Measured (I,E) entry distribution for the gamma cascades that feed ND states above the 17^+ isomer in ^{152}Dy. The two lines are the ND and SD yrast lines used in the MC calculations. The yrast lines have been extrapolated where data was not available.

The Monte Carlo calculations have also been expanded to use more realistic (scaled) functions of the rotational damping parameters Γ_{rot}, Γ_{μ} and the fraction of narrow to wide component, I_{nar}, taken from theoretical models.[1] These distributions are now functions of spin and excitation energy over the yrast lines. Using these functions add known effects such as motional narrowing to the calculations as well as a spin dependence, especially of Γ_{rot}, and the strong dependence on excitation energy for all the rotational damping parameters.

The ridges and quasicontinuum of gamma rays gated on discrete normal and superdeformed transitions can be reproduces as well as when average values were used in the Monte Carlo calculations (see previous annual report). However, it was fund that the theoretical functions had to be scaled as show in Table I-2 in order to reproduce the measured ridge and quasicontinuum spectra. The rotational damping parameter values that are probed by the cooling gamma cascades are shown in Figs. I-34, I-35 and I-36.

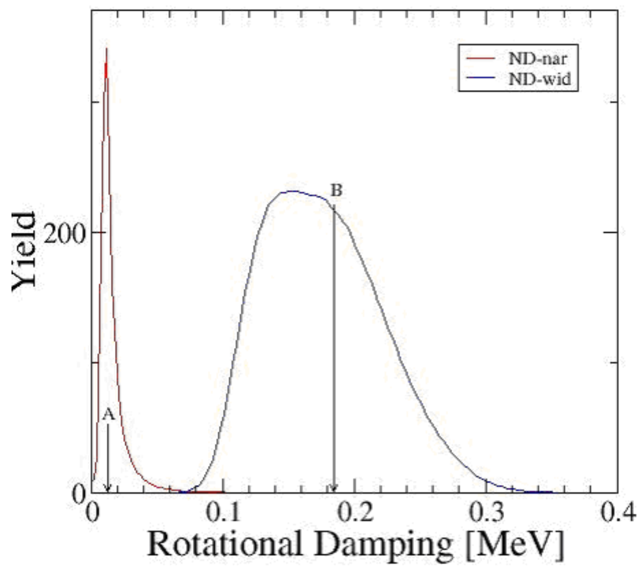

Fig. I-34. Distributions of narrow and wide rotational damping widths, Γ_{μ} and Γ_{rot} that are sampled by the gamma cascades in the ND well when gates are placed on clean combination of discrete ND lines. "A" and "B" marks the associated mean values that were obtained in the first MC1 calculations with average rotational damping parameters.

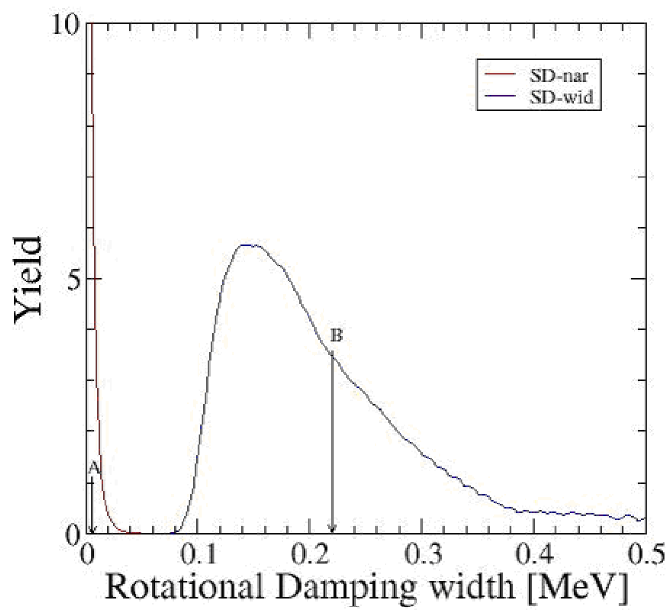

Fig. I-35. Distributions of narrow and wide rotational damping widths, Γ_{μ} and Γ_{rot} that are sampled by the gamma cascades in the SD well when gates are placed on clean combinations of discrete SD lines. The narrow fraction has been down scaled by a factor of 5 with respect to the wide components distribution. "A" and "B" marks the associated mean values that were obtained in the MC1 calculations with average rotational damping parameters.

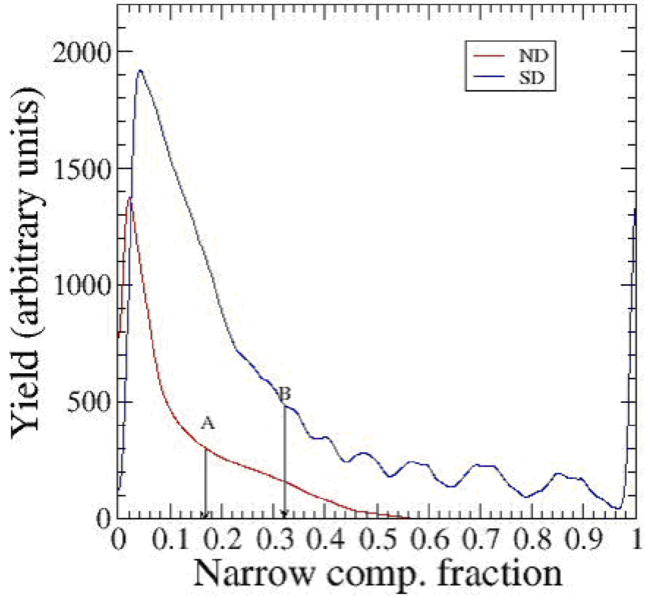

Fig. I-36. Distributions of narrow to wide rotational damping width fractions in the ND and SD wells. "A" and "B" marks the mean values that were obtained in the first MC calculations with average rotational damping parameters.

The SD entry distribution was also measured and is shown in Fig. I-37. Compared to the ND (I,E) entry distribution in Fig. I-33, the SD entry distribution is clearly moved towards higher spins and relative lower excitation energies. To show this effect more clearly a difference spectrum was generated by normalizing the SD and ND 2D spectra in Figs. I-37 and I-33, respectively, to have the same number of counts and subtracting the ND distribution from the SD distribution. The resulting 2D distribution is shown in Fig. I-38 in a contour plot. Positive channels (solid lines) shows enhanced entry point selection and negative channels (dashed lines) shows areas of the total entry distribution in the (I,E) plane where gamma cascades that feed SD band ~1 are unlikely to start from. Obviously, the part of the entry distribution below the lowest of the two yrast lines in Fig. I-37 is unphysical and is attributed to uncertainties in the measurement of the entry distribution. The analysis is nearly complete and a first draft of a Phys. Rev. C article is almost ready.

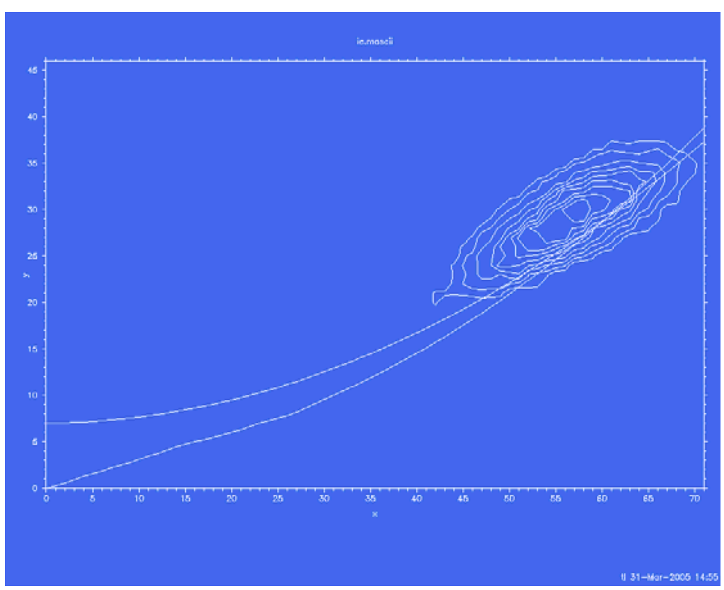

Fig. I-37. Measured (I,E) entry distribution for the gamma cascades that feed SD band 1 in ^{152}Dy. The mean entry spin and energy is 56.3 ħ and 30.2 MeV.

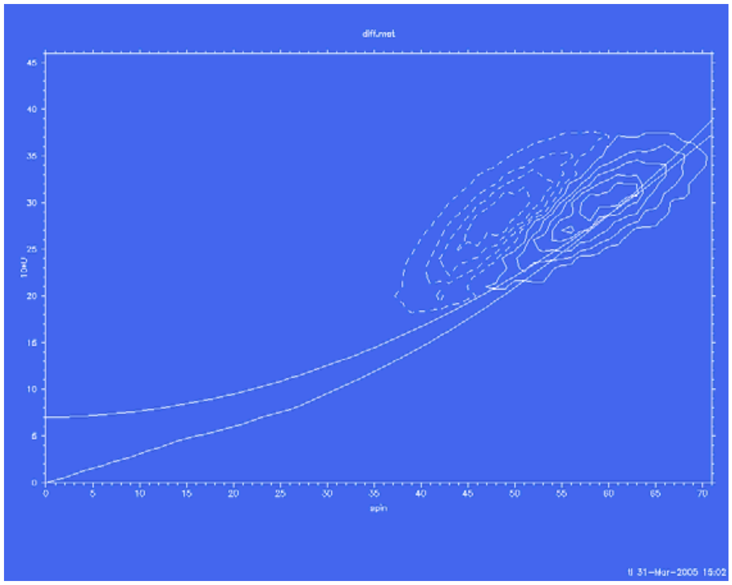

Fig. I-38. Normalized difference between the SD and ND entry distributions in ^{152}Dy.

Table I-2. In order to reproduce the ND and SD QC spectra and ridges in the MC calculation, it was necessary to multiply the theoretical rotational damping widths and narrow fractions with the factors shown in this table. Also shown are the resulting mean values of the distributions of Γ_μ, Γ_{rot} and I_{nar}. These are preliminary results, the analysis is still in progress.

Quantity	ND factor	ND mean val	SD factor	SD mean val
Γ_μ	0.08	16.8 keV	0.034	5 keV
Γ_{rot}	0.50	176 keV	5.5	220 keV
I_{nar}	40	12%	120	32%

*Lawrence Berkeley National Laboratory, †Niels Bohr Institute, Copenhagen, Denmark, ‡C.S.N.S.M., IN2P3-CNRS, Orsay Campus, France.
[1]B. Lauritzen *et al*., Nucl. Phys. **A457**, 61 (1986).

e.4. Study of Multi-Quasiparticle Isomers in the A ~ 180 Region Using Deep-Inelastic and Multi-Nucleon Transfer Reactions

(I. Ahmad, M. P. Carpenter, S. J. Freeman, N. J. Hammond, R. V. F. Janssens, T. Lauritsen, C. J. Lister, G. Mukherjee, D. Seweryniak, F. G. Kondev,* G. D. Dracoulis,† G. J. Lane,† A. P. Byrne,† T. Kibedi,† P. Nieminen,† H. Watanabe,† P. Chowdhury,‡ and S. K. Tandel‡)

A characteristic feature of many axially symmetric, deformed nuclei near A ~ 180 is the dominance of high-Ω orbitals in the vicinity of both the neutron and proton Fermi surfaces. This gives rise to the presence of multi-quasiparticle K-isomers with half-lives ranging from a few nanoseconds to hundreds of years. Most of the studies so far have focused on neutron deficient structures that are accessible by heavy-ion fusion evaporation reactions. The information for nuclei near the valley of stability or on the neutron-rich side of it is rather scarce, despite the fact that this is the region where the longest lived isomers are known (and predicted) to reside, and hence, there is interest for various applications. The most notable examples include the K^{π} = 16^+, 31-y isomer in ^{178}Hf and the K^{π} = $23/2^-$, 160-d isomer in ^{177}Lu. Spectroscopic studies in this region provide important nuclear structure information on the limits of existence of high-K isomeric states at the extremes of proton and neutron numbers, and on the seniority dependence of the major residual interactions in deformed nuclei.

We have pursued studies using Gammasphere and 820 MeV pulsed ^{136}Xe beams on natural Lu and enriched ^{176}Lu, and ^{174,176}Yb targets aimed at identifying multi-quasiparticle states in nuclei near ^{176}Lu, and neighboring ytterbium, hafnium, and tantalum isotopes. The targets were approximately 6 mg/cm^2 in thickness backed by 25 mg/cm^2 Au foils. The choice of the beam energy (~20% above the Coulomb barrier) resulted in the population of a variety of structures near and beyond the line of stability in these nuclei via so-called multi-nucleon transfer and deep-inelastic reactions. Complementary experiments aimed at measuring the lifetimes of long-lived isomers were also carried out.

Many new high-seniority isomers have been identified and the results on the predicted 5-quasiparticle K^{π}= $39/2^-$ isomer in ^{177}Lu,[1] the 7-quasiparticle K^{π}= $49/2^+$ isomer in ^{179}Ta that exhibits an unusually fast decay[2] (shown in Fig. I-39) and a suite of multi-quasiparticle isomers in ^{174}Yb[3] have already been published. A number of isomers and corresponding excited structures were also observed in nuclei near ^{176}Lu and ^{176}Yb. For these the data analysis is still in progress.

*Nuclear Engineering Division, Argonne National Laboratory, †Australian National University, Canberra, Australia, ‡University of Massachusetts-Lowell.

[1]G. D. Dracoulis *et al.*, Phys. Lett. **B584**, 22 (2004).

[2]F. G. Kondev *et al.*, Eur. Phys. J. A **22**, 23 (2004).

[3]G. D. Dracoulis *et al.*, Phys. Rev. C **71**, 044326 (2005).

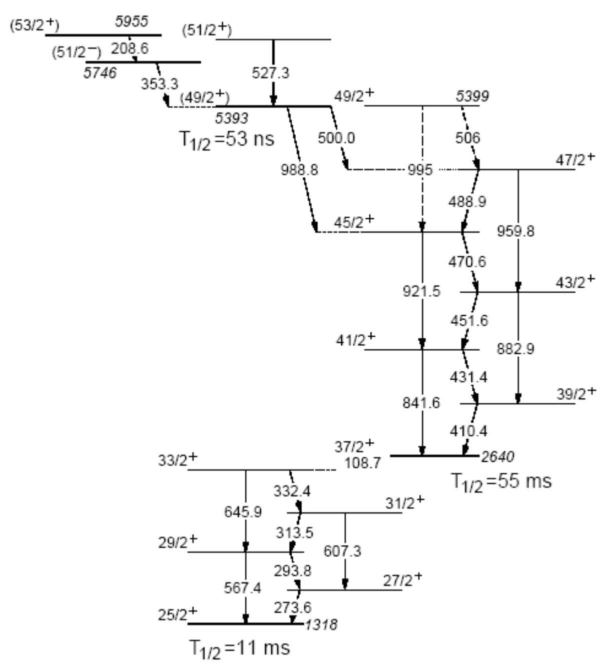

Fig. I-39. Partial level scheme of ^{179}Ta showing the decay of the K^{π} = $49/2^-$ and previously known $37/2^+$ isomers.[2]

e.5. Pair Gaps in the Normal- and Super-Deformed Wells of ^{191}Hg (T. L. Khoo, T. Lauritsen, M. P. Carpenter, I. Ahmad, I. Calderin, T. Duguet, S. M. Fischer, D. Gassmann, G. Hackman, R. V. F. Janssens, E. F. Moore, D. Nisius, S. Siem,* P. Reiter,†† P.-H. Heenen,† H. Amro,‡ I. T. Døssing,§ U. Garg,¶ F. Hannachi,|| B. Kharraja,¶ A. Korichi,|| I-Y. Lee,** A. Lopez-Martens,|| A. O. Machiavelli,** and C. Schück||)

Although about 250 superdeformed (SD) bands have been found in the A = 150 and 190 regions, the energies and quantum numbers have been determined for only a handful of SD bands. The excitation energies and spins of the yrast superdeformed band in ^{191}Hg have been found from two single-step γ transitions and the quasi-continuum spectrum connecting the superdeformed and normal-deformed states. This is the first case where the energies and spins of a SD band have been determined in an odd-A nucleus. The results are compared with those from self-consistent mean-field calculations with different Skyrme interactions. The SLy4 interaction gives better agreement with experiment than other interactions, such as SkP and SkM*.

By comparing the energies of normal-deformed (ND) and SD states in adjacent even-even and odd-A nuclei, we can extract information of the pair correlations in the respective wells. The neutron separation energy contains information about the Fermi energy λ_N, the neutron pairing gap $\Delta^{pairing}$, as well as a so-called polarization energy E^{pol} arising from occupying a single-particle level: $\Delta^{(2)} = (-1)^N S_n \sim \Delta^{pairing} + E^{pol} + (-1)^{N+1}\lambda_N$ where N is the number of valence neutrons. The masses of the normal- and super-deformed "ground-states" at zero rotational frequency in ^{191,192}Hg give S_n = 9.5 and 8.6-8.9 MeV, for the ND and SD wells, respectively. In other words, it is easier to remove a neutron from the SD well. With λ_N taken from Hartree-Fock-Boglyubov theory with the Skyrme SLy4 interaction, we obtain $\Delta^{pairing} + E^{pol}$ = 1.1 and 0.7-1.0 MeV for ND and SD states. (E^{pol} is expected to be around ±100 keV.) The latter value establishes that a pair gap exists for SD states, but the uncertainties are too large to determine that its value is smaller than that for ND states.

A paper on this work has been published.[1]

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*Argonne National Laboratory and University of Oslo, Norway, †Service de Physique Nucleaire Theorique, Brussels and Oak Ridge National Laboratory, ‡Argonne National Laboratory and North Carolina State University, §The Niels Bohr Institute, Copenhagen, Denmark, ¶University of Notre Dame, ||C.S.N.S.M., Orsay, France, **Lawrence Berkeley National Laboratory, ††University of Cologne, Germany.

[1]S. Siem *et al*., Phys. Rev. C **70**, 014303 (2004).

e.6. Temperature and Spin Dependence of the Giant Dipole Resonance Width in ^{117,118}Sn (B. B. Back, M. P. Carpenter, T. L. Khoo, T. Pennington, D. J. Hofman,* P. Heckman,† T. Baumann,† I. Diószegi,† S. Mitsuoka,† V. Nanal,‡ J. P. Seitz,† M. Thoennessen,† E. Tryggestad,† and R. L. Varner§)

The dependence of the GDR width on temperature and spin was investigated in Sn nuclei, by using the reactions ^{17}O + ^{100}Mo and ^{18}O + ^{100}Mo to form ^{117}Sn and ^{118}Sn, respectively. Widths of $\Gamma = 6.9 \pm 0.5$ MeV and $\Gamma = 8.2 \pm 0.5$ MeV were extracted for temperatures of 1.74 and 1.84 MeV, respectively. The large increase of the width over this relatively small temperature range is inconsistent with the thermal shape fluctuation model. However, the spin dependence of the width is well reproduced by the model. The experiment was performed with the LEPPEX BaF_2 array (from ORNL, MSU and TAMU) at ATLAS. Coincidences with evaporation residues detected in the Fragment Mass Analyzer selected exclusively γ rays following the decay of the compound nuclei ^{117,118}Sn – see Fig. I-40. This work constituted part of the thesis of P. Heckman at MSU.[1]

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*University of Illinois at Chicago, †Michigan State University, ‡Tata Institute of Fundamental Research, Mumbai, India, §Oak Ridge National Laboratory.

[1]P. Heckman *et al*., Nucl. Phys. **A750**, 175 (2005).

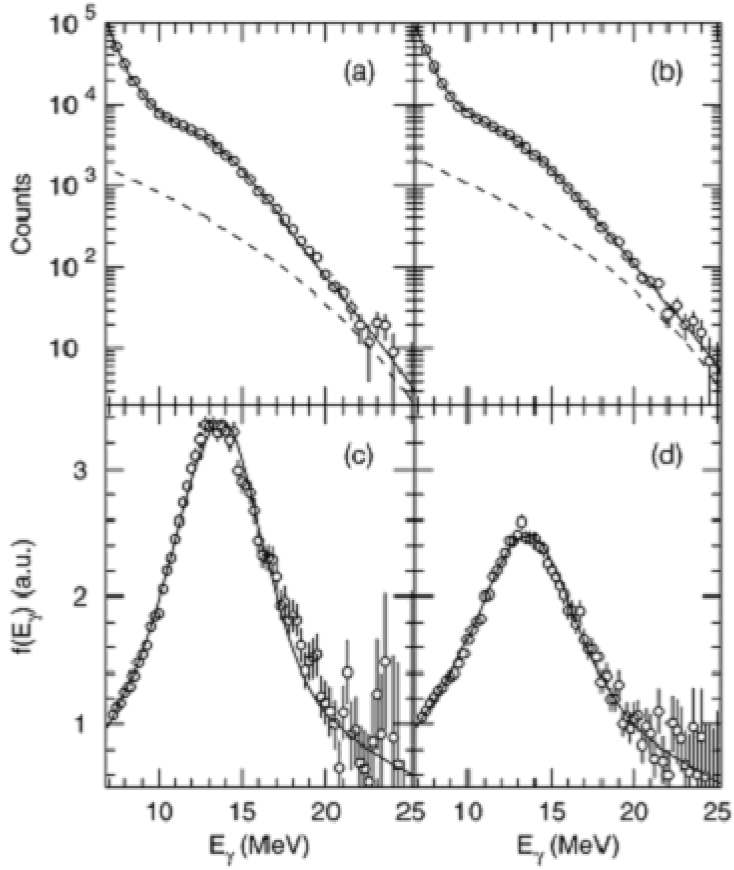

Fig. I-40. The open circles in panels (a) and (b) show the γ-ray decay spectra for the compound nuclei ^{117}Sn and ^{118}Sn, respectively. The open circles in panels (c) and (d) show the divided plots of f(E$_\gamma$) for ^{117}Sn and ^{118}Sn, respectively. The solid curve in all panels shows the overall fit, while the dashed curve in panels (a) and (b) corresponds to the bremsstrahlung contribution.

e.7. Observation of the Hot GDR in Neutron-Deficient Thorium Evaporation Residues

(B. B. Back, M. P. Carpenter, M. P. Kelly, T. L. Khoo, R. H. Siemssen, T. Pennington, J. P. Seitz,* I. Diószegi,† K. Eisenman,* P. Heckman,* D. J. Hofman,‡ S. Mitsuoka,* V. Nanal,§ M. Thoennessen,* and R. L. Varner¶)

The giant dipole resonance built on excited states was observed in very fissile nuclei in coincidence with evaporation residues - see Fig. I-41. The reaction ^{48}Ca + ^{176}Yb populated evaporation residues of mass *A* = 213 - 220 with a cross section of ~200 μb at 259 MeV. The experiment was performed at ATLAS with the LEPPEX BaF_2 array (from ORNL, MSU and TAMU). Coincidences with evaporation residues detected in the Fragment Mass Analyzer ensured exclusive selection of only γ rays following the decay of the compound nucleus ^{224}Th. In addition, coincidences with the Argonne-Notre Dame BGO array were recorded to provide multiplicity and sum-energy data. This work constituted part of the thesis of J. Seitz at MSU. The extracted giant dipole resonance parameters are in agreement with theoretical predictions for this mass region.[1]

*Michigan State University, †State University of New York-Stony Brook, ‡University of Illinois at Chicago, §Tata Institute of Fundamental Research, Mumbai, India, ¶Oak Ridge National Laboratory.

[1]J. P. Seitz *et al*., Nucl. Phys. **A750**, 245 (2005).

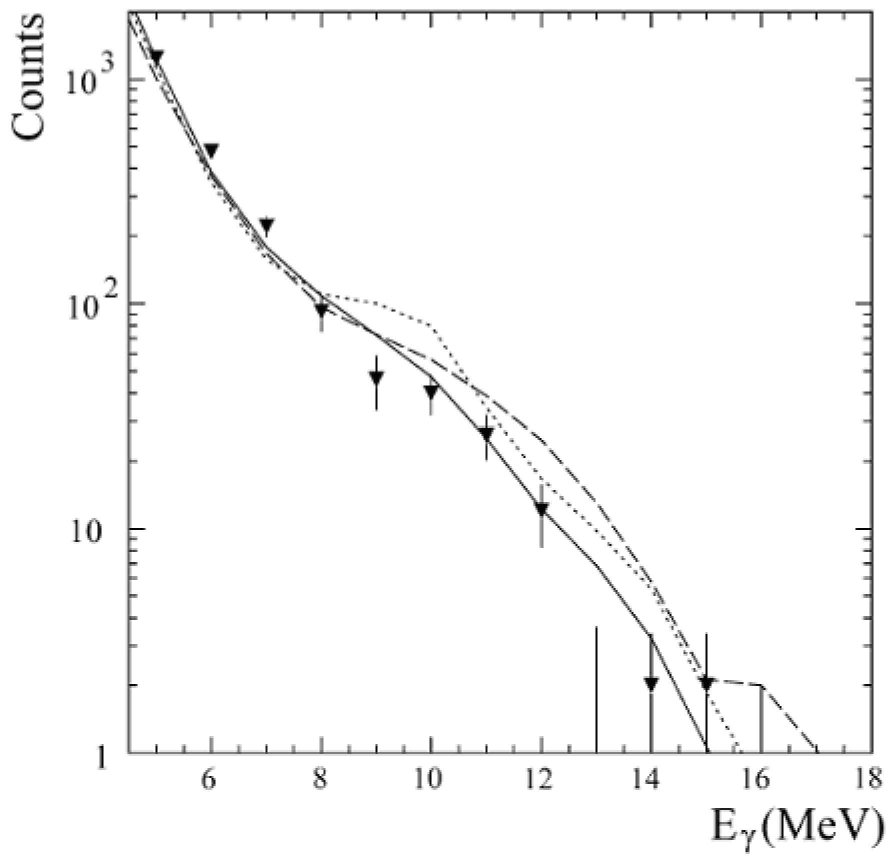

Fig. I-41. High-energy γ-ray spectra in coincidence with evaporation residues compared to results from statistical model calculations assuming different deformations: β = -0.1 (solid), β = 0.3 (dashed) and β = 0.56 (dotted).