B. STRUCTURE OF NUCLEI VERY FAR FROM THE VALLEY OF STABILITY

The program to explore the structure and stability of nuclei along the proton dripline continues to be a forefront theme in our nuclear structure research. It has many interesting facets, both for astrophysical processes (especially the rp-process) and for developing our understanding of the structure and stability of poorly-bound nuclei. It provides a natural bridge that connects contemporary research with future projects which exploit radioactive beams. Modifications that will allow a higher level of sensitivity for Gammasphere experiments at the dripline are being executed and will be in place for operation in 2003. The techniques of proton decay spectroscopy also continue to be refined, allowing studies of shorter lived, and more weakly produced species further from stability. In both cases, upgrades to the FMA have significantly increased the sensitivity of future experiments.

The possibility of studying the structure of very neutron-rich nuclei in the future seems very good, including some nuclei close to the predicted r-process nucleosynthesis trajectory. In this domain conventional heavy-ion fusion-evaporation is not useful, due to the curvature of the valley of stability, but by investigating the prompt gamma-ray spectroscopy of fission fragments, and by studying gamma rays following multi-nucleon transfer reactions, very considerable progress is possible. Many of these studies provide a natural compliment to the data recently obtained from fast-fragmentation facilities. The fast fragmentation allows the identification of low-lying states in these nuclei, which can be developed in many cases with detailed spectroscopy using Gammasphere. The precise determination of the masses of dozens of very neutron-rich fission fragments has started, using a fission source, the gas-cooler and the CPT. Many of these masses have not been measured before, and of the nuclides that have been measured, most are being improved in precision from hundreds of kilo-electron volts to tens of kilo-electron volts.

B.1. Proton-Rich Nuclear Spectroscopy

b.1.1. The ^{56}Ni(^{3}He,p) Reaction and the Question of T = 0, T = 1 Pairing in N = Z Nuclei

(K. E. Rehm, C. N. Davids, J. P. Greene, A. Heinz, R. V. F. Janssens, C. L. Jiang, E. F. Moore, G. Mukherjee, R. Pardo, D. Seweryniak, J. P. Schiffer, A. O. Macchiavelli,* A. Görgen,* P. Fallon,* M. Cromaz,* J. Cizewski,† J. Thomas,† and M. Paul‡)

A wealth of experimental evidence has accumulated over the years in support of the existence of *nn* and *pp* pairs, but there is little or no evidence for *np* pairing mainly because of the experimental difficulties in studying intermediate mass N = Z nuclei. Nevertheless, following recent advances in the experimental techniques and considering the new possibilities that are becoming available with radioactive beams, there has been a revival of nuclear structure studies along the N = Z line. Our analysis of experimental binding energies of nuclei along the N = Z line indicates that the odd-odd T = 1 states are as bound as the ground-state in their even-even neighbors, and this can be interpreted as a consequence of full isovector pairing.[1] The odd-odd T = 0 states were found to be less bound than the even-even neighbors by an energy $2\Delta \sim 2(12/A^{1/2})$ MeV which amounts to the blocking of the T = 1 correlations. This result not only suggests that the T = 0 states behave like any other odd-odd nucleus ground state in the nuclear chart, but also leaves no room to support the existence of an isoscalar pair condensate. Near closed shells, the strength of the pairing force relative to the single-particle level-spacing is expected to be less than the critical value needed to obtain a superconducting solution, and the pairing field then gives rise to a collective phonon.[2] It then seems natural to ask whether T = 0 collective effects may show as a vibrational phonon.

Based on a re-analysis of the pairing vibrational spectra near ^{56}Ni[3] one can infer a rather collective behavior in the T = 1 particle-particle channel and a single-particle character for the T = 0, consistent with the results from the binding energy differences. We know however, that a more sensitive probe of pairing correlations is provided by two nucleon transfer reactions and submitted a proposal to study the reaction ^{56}Ni(^{3}He,p) to confirm the conclusions implied by the analysis above. We argued that the (^{3}He,p) reactions in even-even N = Z nuclei will give a unique fingerprint of *np* pairing correlations.

The work proceeded in two steps. First, we carried out a series of runs to study the (^{3}He,p) reaction in inverse kinematics, using the stable beams of ^{28}Si, ^{32}S, ^{36}Ar, and ^{40}Ca. The setup, similar to that previously used in Refs. 4 and 5, consisted of an annular Si strip detector (16 rings × 16 sectors) covering the angular range from 167° to 154°, a ^{3}He gas target cell (50 μg/cm^2) and the FMA. Although the (^{3}He,p) reaction is extremely clean in the backward angles, the singles spectrum is dominated by charged particles emitted by compound reactions in the Ti windows of the gas cell. Therefore, coincidences with the FMA are very important, even for the stable beam reactions, to sufficiently clean up the spectrum.

We note that the angular range covered by the Si detector in the CM system is 8° - 16°, where the $\Delta l = 0$ transfer cross sections are favored. A summary of the energy matched proton spectra for the systems studied is shown in Fig. I-15. The different number of counts reflects the different running times. In each case, the beam current was kept at a level of about 200 epA. The 0^+ and 1^+ states of interest are indicated. A strong proton group with energy ~3 MeV is observed in all cases, and requires further analysis.

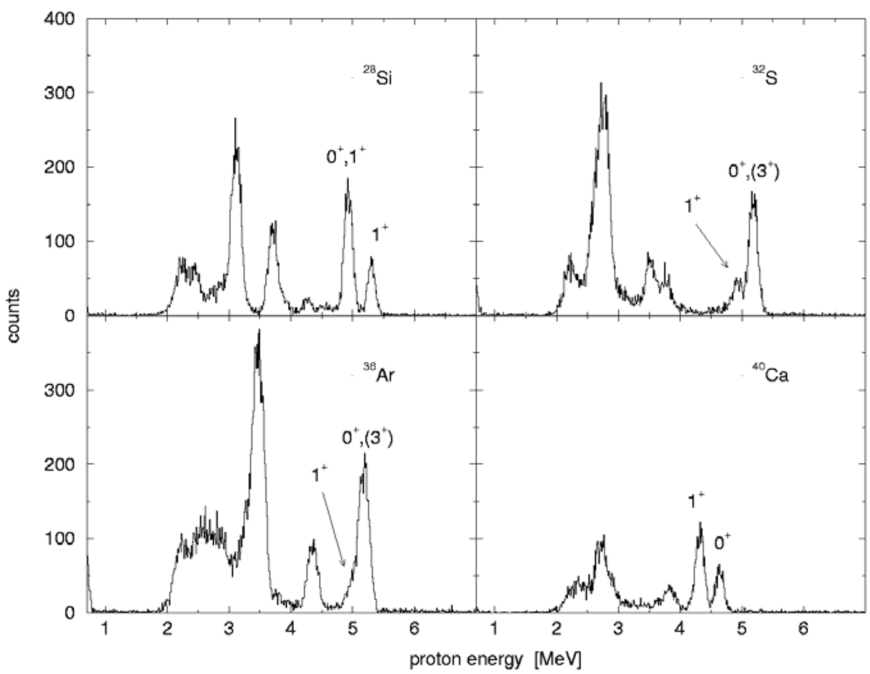

Fig. I-15. Summary of the proton spectra in coincidence with the FMA, obtained for several (d,p) reactions using stable beams. The protons are measured at backward angles in the laboratory and the beam-like reaction products are detected near 0° in the FMA.

*Lawrence Berkeley National Laboratory, †Rutgers University, ‡Hebrew University, Jerusalem, Israel.

[1]A. O. Macchiavelli *et al*., Phys. Rev. **61**, 041303R (2000).

[2]D. R. Bes and R. A. Broglia, Nucl. Phys. **80**, 289 (1966).

[3]A. O. Macchiavelli *et al*., Phys. Lett. **B480**, 1 (2000).

[4]K. E. Rehm *et al*., Phys. Rev. Lett. **80**, 259 (1996).

[5]C. L. Jiang *et al*., to be published.

After the successful completion of this part, we proceeded with the ^{56}Ni experiment. In September 2002, a ^{56}Ni cone was produced at the IPNS that was then transferred to the ATLAS tandem source. Unfortunately, the beam intensity on target turned out to be at least a factor of 10 less than our original estimate of 3×10^5 /s, which was insufficient to accumulate enough statistics for the (^{3}He,p) reaction. Possible improvements in the Tandem injection and transmission are presently being considered for a second attempt.

b.1.2. Unravelling the Backbends in ^{68}Se and ^{72}Kr: The Quest for np-Pairing (C. J. Lister, S. M. Fischer,* and D. P. Balamuth†)

It has been widely speculated that short range neutron-proton correlations, either with $T = 0$ or $T = 1$ would influence the high-spin behavior of nuclei, particularly in modifying the rotational frequencies at which correlated pairs break apart. It was suggested that evidence for an effect of this kind would be found in studying the cascades of gamma rays following heavy-ion reactions, as the pair breaking is associated with changes in moment of inertia. The effect is widely expected to be most clear-cut in $N = Z$ nuclei, as those nuclei have the biggest overlap of neutrons and protons near the Fermi surface, so are most susceptible to np-pairing correlations. Thus, comparison of $N = Z$ and $N = Z + 2$ nuclei in middle mass (A ~ 70) nuclei, seems to offer the optimum situation for studying these correlations. Of particular interest is the $T = 0$, $J \neq 0$ deuteron-like isoscalar mode that could lead to a recondensation of particles at the Fermi Surface.

We conducted several investigations of the key $N = Z$ nuclei ^{68}Se and ^{72}Kr. It is clear that these nuclei behave unusually. However, our new data, when combined with other recent studies of $N = Z + 2$ ^{70}Se and ^{74}Kr, reveal a complicated situation of shape-coexistence, and the naïve expectations that np-pairing strengths can be extracted seem very optimistic. All the nuclei show evidence for two shapes, both triaxial, one with lower collectivity (triaxiality parameter, γ, positive) and one of high collectivity (γ negative). Each shape has its own alignment scheme. One also can observe that the bands in each minima have very different quadrupole moments, and irregularities in the moments of inertia arise when bands of very different structure cross. Figure I-16 shows the experimental routhians (the relative energy of states in the rotating frame). Even spin, positive parity bands are shown. Clearly, several common features can be seen, with one set of states which evolve smoothly with rotational frequency, and a further set that shows very strong irregularities.

In all, when like bands are compared, there seems very little room for "alignment delay" the fingerprint expected for enhanced pairing. It must be said, however, that it is very difficult to reproduce the very high crossing frequencies in the more collective sequences in krypton isotopes without invoking some new physics.

A paper has been accepted for publication in Physical Review C.[1]

*DePaul University, †University of Pennsylvania.

[1]S. M. Fischer, C. J. Lister, and D. P. Balamuth, Phys. Rev. C**67**, 064318/1-13 (2003).

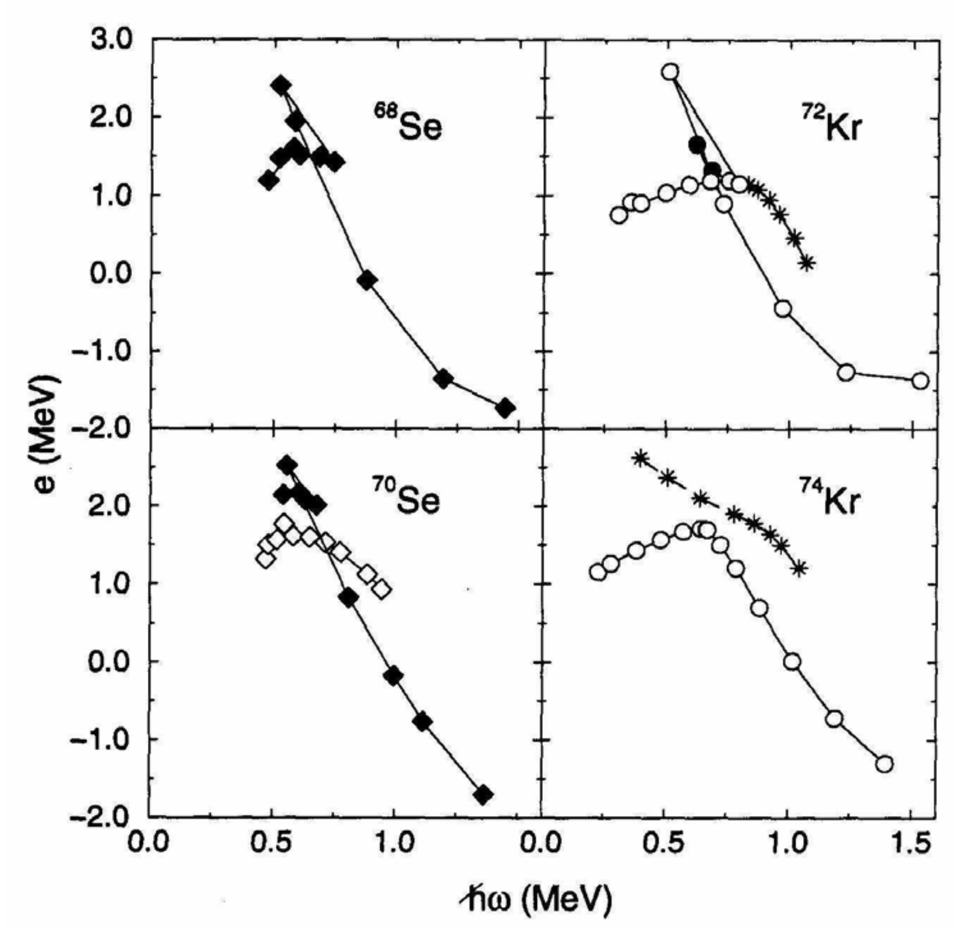

Fig. I-16. The experimental routhians for even spin, positive parity bands in ^{68,70}Se and ^{72,74}Kr, revealing evidence for shape coexistence in all spin ranges, but little evidence for "alignment delay" that might be associated explicitly with np-pairing correlations.

b.1.3. Structure and Significance of Isomers in Intermediate Mass N = Z Even-Even Nuclei (C. J. Lister, N. Hammond, S. Sinha, G. Mukherjee, S. M. Fischer,* D. Balamuth,† B. Blank,‡ A. Aprahamian,§ and A. Woehr§)

Isomers in intermediate mass N = Z nuclei are interesting for structural and astrophysical reasons. In structure, the interest in the isomers arises from investigating and understanding their shape co-existence. In ^{72}Kr, a low-lying shape-isomeric first excited state was found[1] which can only decay through conversion electrons, so that it will have a very long lifetime in hot, highly ionized nucleosynthesis sites. In astrophysics, these isomers can have a strong influence on "waiting points" in the rp-process; suitable isomers can drastically enhance the destruction rates of the parent nuclei through (p,γ) reactions.

A key waiting point nucleus of interest is ^{68}Se. It was shown[2] to exhibit extremely clear-cut shape co-existence, with an oblate groundstate and prolate excited states. The low-lying prolate bandhead was expected to be isomeric in analogy with the recent ^{72}Kr discovery. However, both isomer searches following fragmentation[3] at GANIL and prompt spectroscopy with Gammasphere[2] failed to find the prolate bandhead. These studies constrain the possible location of this state rather tightly. A recoil-shadow experiment to find this shortlived (~10 ns) bandhead and understand its decay properties is being designed and will be constructed at the University of Notre Dame.

A further experiment was approved to run at ATLAS using Gammasphere and the FMA. The goal is to seek "linking" transitions between oblate and prolate shapes in ^{72}Kr. The intensity of these γ-decays will provide information about mixing of wavefunctions in the two minima.

*DePaul University, †University of Pennsylvania, ‡Sabbatical visitor from the University of Bordeaux, France, §University of Notre Dame.
[1]E. Bouchez *et al*., Phys. Rev. Lett. **90**, 082502 (2003).[2]S. M. Fischer *et al*., Phys. Rev. Lett. **84**, 4064 (2000).
[3]A. Goergen, University of Saclay, private communication (2003).

b.1.4. Gamma Vibration and Quasiparticle Excitations in ^{80}Sr (C. J. Lister, T. Sienko, and R. A. Kaye*)

^{80}Sr lies towards the middle of the deformed A ~ 80 region. It was studied extensively and detailed papers[1-4] were published on its properties, which now include several superdeformed bands. Surprisingly, despite its large production cross section and the numerous investigations, there remains considerable disagreement about spin assignments and band structure, even at the lowest spins.

In this study, ^{80}Sr was copiously produced following the ^{24}Mg(^{58}Ni,2p)^{80}Sr reaction at 200 MeV. The investigation of the prompt decay γ-rays used Gammasphere, triggered by both Mass and Charge selection. Mass identification was achieved using the Fragment Mass Analyzer (FMA) selecting only A/q = 80/25 ions, and charge selection was obtained using an ion chamber. After suitable data manipulation, a γ–γ coincidence matrix was produced which consisted of >95% ^{80}Sr correlations. A coincidence window on the 386 keV first excited state had >10^6 correlated counts.

Many new excited states were found. The unusually clean data set allowed identification of weakly populated non-yrast structures. Several features were clarified. The even- and odd- spin members of the gamma vibrational band were found and extended to high spin. The band starts at low excitation, well below other quasi-particle excitation, as might be expected for a collective excitation. The odd- even-energy staggering of spins was found to be intermediate between the "rigid" and "gamma-soft" limits. The new assignments now fit well with systematic trends of gamma-vibrational structures in the region (see Fig. I-17). The J = 7 states identified by Davie *et al*.[1] are now assigned to have negative parity, again in better agreement with neighboring nuclei. Finally, at the highest spins, the yrastline stops being a smooth rotational sequence, and considerable "forking" is found as quasi-particle excitations with larger moments of inertia approach and then cross the rotational ground state band. The highest spins may well correspond to the low-collectivity, near-oblate motion predicted by Nazarewicz *et al*.[5] many years ago.[6]

A paper was written and accepted for publication in Physical Review C.

*Purdue University-Calumet.
[1]R. F. Davie *et al*., Nucl. Phys. **A463**, 683 (1987).
[2]D. Winchell *et al*., Phys. Rev. C **61**, 044322 (2000).
[3]J. Döring *et al*., Phys. Rev. C **59**, 59 (1999).
[4]M. Devlin, F. Lerma, D. Sarantites, *et al.*, Phys. Lett. **B415**, 328 (1997); Phys. Rev. Lett. **83**, 5447 (1999).
[5]W. Nazarewicz, J. Dudek, R. Bengtsson, T. Bengtsson, and I. Ragnarsson, Nucl. Phys. **A435**, 397 (1985).
[6]T. Sienko, C. J. Lister, and R. A. Kaye, Phys. Rev. C**67**, 964311/1-8 (2003).

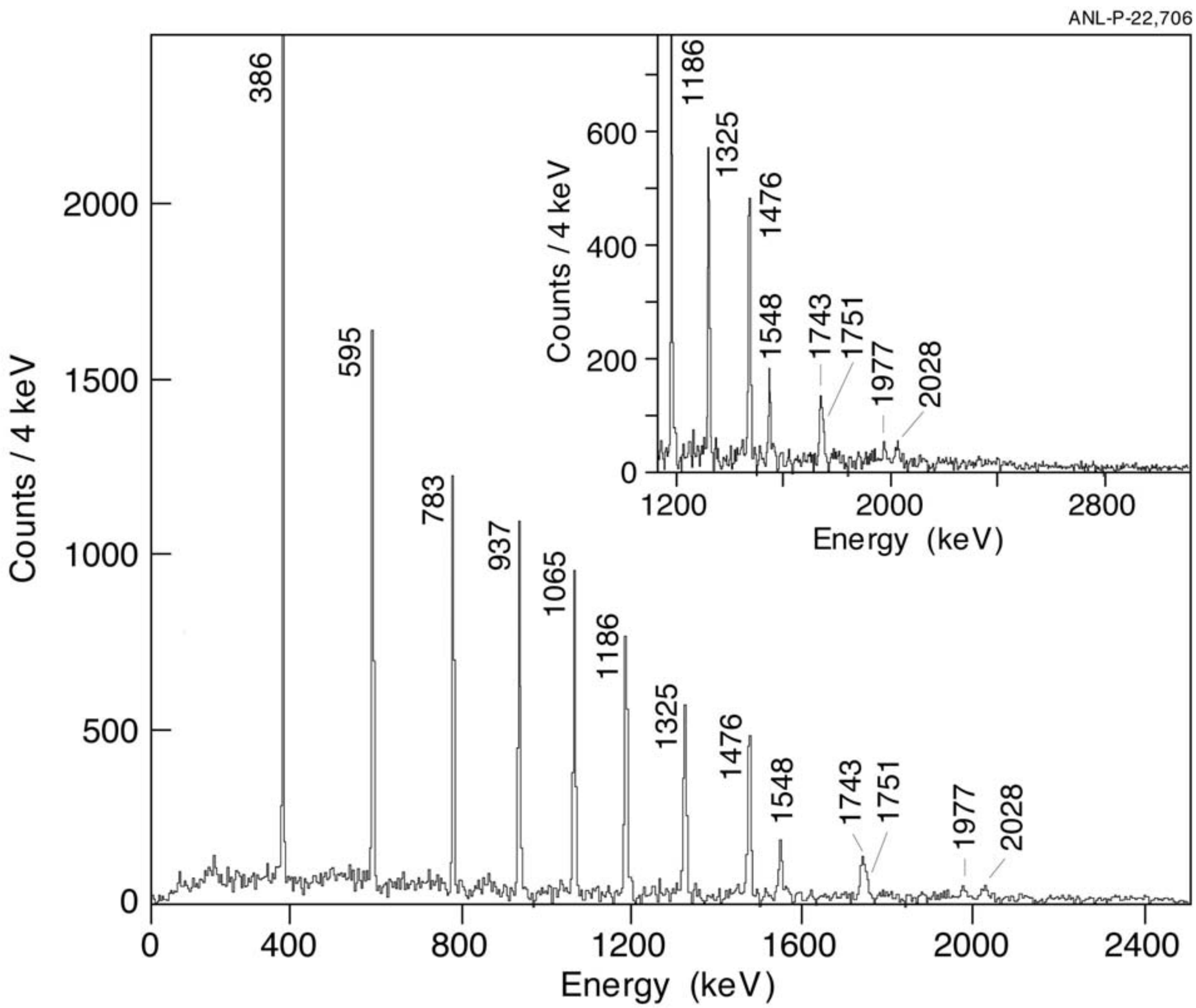

Fig. I-17. A sample of the high quality γ–γ data from this experiment, showing a single gate set on the 1579 keV J = 18 →16 decay in the yrast line. Above this point "forking" of the band occurs; the yrast sequence has a backbend which has been predicted to correspond to a change from a collective near-prolate to non-collective near-oblate shape.

b.1.5. The Spectroscopy of T = 0 and T = 1 Low-Lying States in Odd-Odd N = Z Nuclei

(C. J. Lister, G Mukherjee, N. Hammond, S. Sinha, S. M. Fischer,* D. P. Balamuth,† and S. Freeman‡)

The study of N = Z odd-odd nuclei beyond ^{58}Cu is topical for many reasons. The nuclei are structurally interesting as the low-lying multiplets contain information about both long- and short-range neutron-proton correlations and coupling with both isospin T = 0 and T = 1. They lie along the rp-nucleosynthesis path, so low lying isomers can influence rp-reaction rates. Finally, the ground states have superallowed Fermi decays, so understanding the wavefunctions of low-lying states help improve the calculation of small structure-dependent corrections needed to test the Standard Model.

We completed a study of ^{70}Br.[1] In it we investigated methods to optimize the population of the important low spin, non-yrast states. This was difficult; the nuclei lie far from stability, so reactions to populate the isotopes of interest are limited and fusion of very heavy ions appears to be essential for detailed spectroscopy. The states of greatest interest have

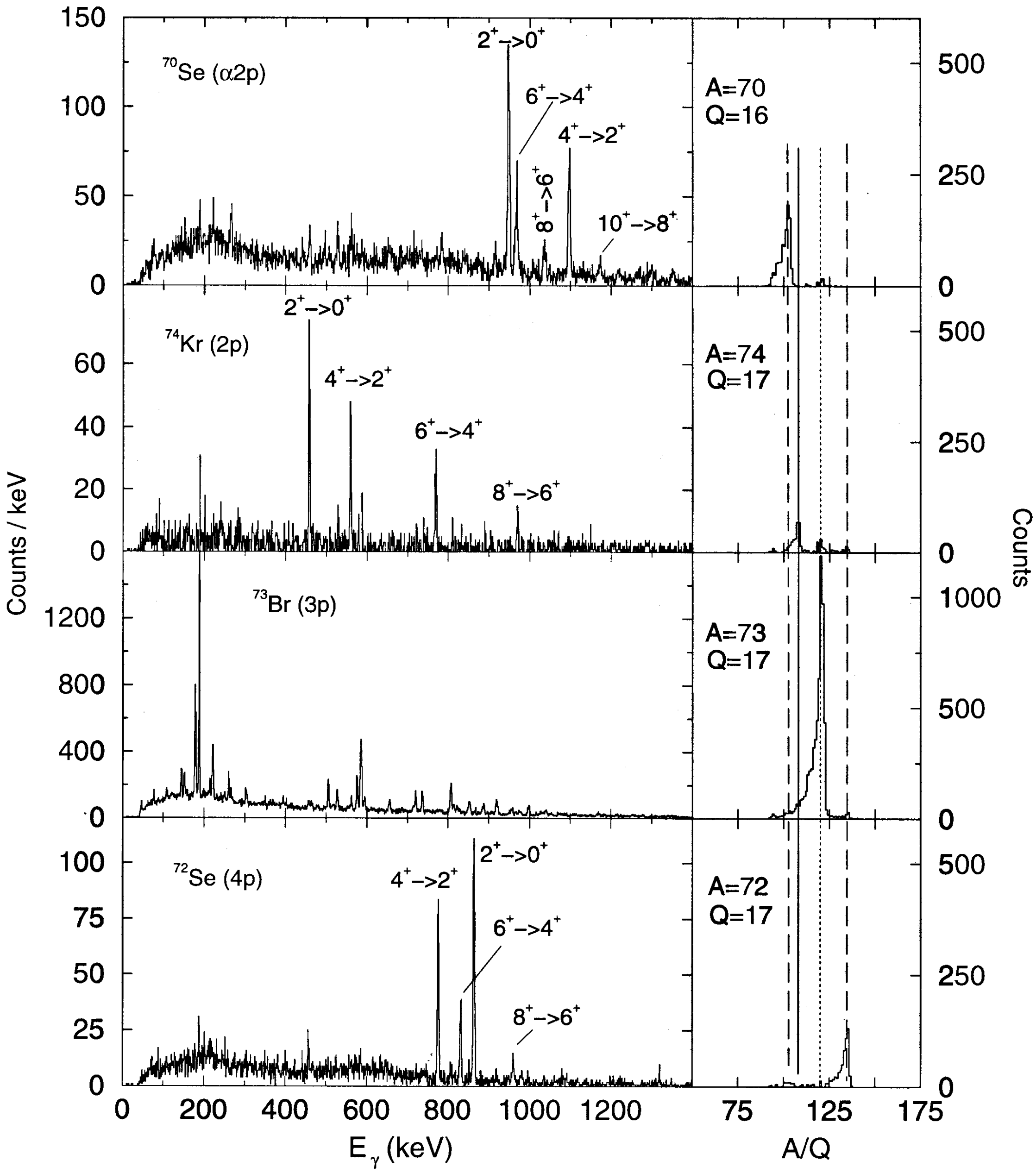

Fig. I-18. The panels on the left show recoil and mass gated γ-ray spectra from a single, unsuppressed 70% HPGe detector from the reaction ^{36}Ar + ^{40}Ca at 104 MeV. The panels on the right show the PGAC "X" spectra with a recoil requirement and a gate on a strong γ-ray transition in the corresponding nucleus of interest. The mass peaks are identified by mass number and charge state. These data were collected over a period of ~14.5 hours.

low spin, and so are not normally well populated in heavy ion reactions. They are best reached by cold, near-barrier (even sub-barrier) fusion. These cold reactions at very low energy have small production-cross sections, typically ~100's μb. Consequently, even with the largest current detector arrays, this type of study is difficult and lies at the edge of feasibility.

With the anticipation of a new Gammasphere campaign at ANL we performed a test experiment to find the optimum conditions for studying ^{74}Rb and ^{78}Y

identified using the FMA. These odd-odd N = Z nuclei lie near the center of the A ~ 80 region. They are expected to have quite stable deformation, so provide the best base for investigating neutron-proton correlations. We are interested in the energy dependence of populating the important states in these nuclei through the ^{40}Ca(^{36}Ar,pn)^{74}Rb and ^{40}Ca(^{40}Ca,pn)^{78}Y reactions. In practice, these channels are too weak for a test experiment using a single germanium detector, but the stronger (~50 mb) surrogate ^{40}Ca(^{36}Ar,2p)^{74}Kr and ^{40}Ca(^{40}Ca,2p)^{78}Sr reactions allow the partial wave distributions to be extracted by measuring the yields of known states. We studied Fragment Mass Analyzer (FMA) gated gamma spectra, and neutron-gated spectra in order to optimize settings for clean, high beam current investigations. Figure I-18 shows some mass-gated spectrum which clearly reveals the excellent channel selection. We measured excitation functions for both systems, and studied the spin distributions in the residues. At the peak of the yield, the mean entry spin appears to be ~8 h, ideal for low spin, non-yrast studies.

The cross sections appear to be similar to the ^{70}Br project, and clearly FMA gating is ideal for these weak channels. With Gammasphere and the neutron shell, mass and neutron gated gamma-spectra should be very clean and ideal for the investigations planned in 2003.

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*DePaul University, †University of Pennsylvania, ‡Sabbatical Visitor from University of Manchester, United Kingdom.
[1]D. G. Jenkins *et al*., Phys. Rev. C **65**, 064302 (2002).

b.1.6. Single Particle States in ^{111,113,115}Sb Populated via β-Decay (D. Seweryniak, C. N. Davids, G. Mukherjee, S. Sinha, J. Shergur,* W. B. Walters,* A. Woehr,* P. Boutachkov,† I. Dillmann,‡ A. Teymurazyan,† and I. Zartova†)

The structure of the odd-A Sb nuclides attracted interest over the years mainly because their low-energy, low-spin states involve the coupling of the single Sb proton with the adjacent Sn core.[1] Specifically, the neutron deficient odd-A Sb isotopes provide an important testing ground for shell model calculations based on the heaviest self-conjugate double magic nucleus, ^{100}Sn. Difficulties with the shell model arise as A increases because the higher density of states and more complex configurations. One complication arises from the monopole shift that lowers the $g_{7/2}$ single-proton level to ~800 keV in the light Sb nuclides. As a result, the lowered $g_{7/2}$ core coupled states mix with the core-coupled states associated with the $d_{5/2}$ proton ground state. In addition, more states are added because of the presence of a $9/2^+$ intruder orbital that also mixes with the other configurations to form complicated level structures. Some of these collective states in the A ≥ 115 region have been described well by particle-phonon coupling using the Interacting Boson-Fermion Model (IBFM).[2,3] The nuclei in the region of A ~ 110-115 then provide an ideal place to map the model spaces of both approaches and to compare their predictive power.

The low-energy states in ^{109}Sb were identified by J. J. Ressler *et al*. in a study of the β^+/EC decay of ^{109}Te. At the time of these measurements, the significantly lowered positions of the $1/2^+$ and $3/2^+$ states were a surprise, as the $1/2^+$ level is well below the minimum for ^{121}Sb. However, the positions of the lowest $1/2^+$ and $3/2^+$ states were well reproduced in two recent shell-model calculations.[5,6] It was noted that with present day capabilities, this is as far from ^{100}Sn as the shell model could be properly used. Given the success of the calculations on ^{115,117}Sb with the IBFM, an attempt was made by J. J. Ressler at Yale, in collaboration with V. Zamfir to extend such IBFM calculations to fit the levels observed for ^{109}Sb. The results were not encouraging and, with only poor or no data for the low-spin levels in the intervening nuclides, there was little guidance as to how to evolve the IBFM parameters away from the N = 64 partial shell closure. The goal of the calculations is more ambitious than just a few low-energy levels, but also to account for the rather extensive level structure which arises from the mixing of the two sets of core-coupled states up to the pairing energy that is rather well fit for ^{117}Sb as reported by Lobach and Bucurescu.[2] Thus, the goal of these experiments was the determination of the energy levels in ^{111,113}Sb with low spins (≤ $9/2^+$) up to the 2 MeV pairing energy that can be populated in the β-decay of the respective ^{111,113}Te parents. These new data would be used to bridge the gap between the shell-model region for nuclides with A ≤ 109 and the mid-shell nuclides with N = 64 and 66 to determine how the IBFM and the shell model overlap in this region.

Our experiment was performed at the Argonne Tandem Linear Accelerator System (ATLAS). The parent ^{111,113,115}Te nuclides were produced using a fusion-evaporation reaction of a beam of 225 MeV ^{56}Fe ions on targets of $^{60,62,64}Ni$. All of the Te recoils were produced through the 2pn reaction channel. Reaction products were separated on the basis of their mass to charge ratio M/Q at charge state 24. Following mass separation, the recoils were implanted in the tape of a moving tape collector (MTC). The tape was moved periodically to a Pb-shielded counting station. Count and collect times were varied from ~1 half life for the nuclide of interest to maximize coincidence events, to as long as 3 half-lives in order to permit identification of parent and daughter gamma rays on the basis of half-life. We used two large HPGe detectors (45% and 65%) and two small Ge detectors (~25%) to detect the γ-rays coming from the deposited radioactive source on the tape. In addition to the Ge detectors, two β-scintillators were used to veto zero-degree β–γ coincidences in the same detector, and gate 180º β–γ coincidences. We collected γ-singles, γ–γ coincidences, and γ-t data to isolate transitions in the corresponding $^{111,113,115}Sb$ daughters. Towards the end of the experiment, the collection and counting periods were shortened to permit observation of the decay of the short-lived $^{111,113,115}I$ nuclides into their corresponding Te daughters.

Analysis of γ–γ matrices and γ-t spectra confirmed the previously reported low-spin structure for ^{115}Sb. Similar analysis resulted in the identification of at least 20 new gamma transitions and eight new levels in ^{113}Sb. Six of the new levels are above 2 MeV, and are probably 3-quasi-particle levels formed from the coupling of a $d_{5/2}$ proton, the odd $g_{7/2}$ neutron, and a $d_{3/2}$ neutron formed from the spin-flip Gamow-Teller decay of the formerly paired $d_{5/2}$ proton. Recent results also suggest that the previously reported 1018-keV level has a spin of $5/2^+$. Previous experiments had suggested either $3/2^+$ or $5/2^+$, but feeding from the $9/2^+$ 1550 keV level, and feeding to the $7/2^+$ 815-keV level lends support for our $5/2^+$ assignment. As for ^{111}Sb, at least 6 coincidences are seen with the previously observed 851-keV transition, most which come from levels ~2 MeV (Fig. I-19). Once level structures in $^{111,113}Sb$ are identified, calculations will be performed to test the applicability of various models to this light Sb region.

*University of Maryland, †University of Notre Dame, ‡University of Mainz, Germany.

[1] G. Van den Berghe and K. Heyde, Nucl. Phys. **A163**, 478 (1971).

[2] Yu N. Lobach and D. Bucurescu, Phys. Rev. C **58**, 1515 (1998).

[3] Yu N. Lobach and D. Bucurescu, Phys. Rev. C **57**, 2880 (1998).

[4] J. J. Ressler *et al*., Phys. Rev. C **66**, 024308 (2002).

[5] D. Dean, Oak Ridge National Laboratory, private communication (2002).

[6] E. Dikman *et al*., Phys. Rev. C **64**, 067305 (2001).

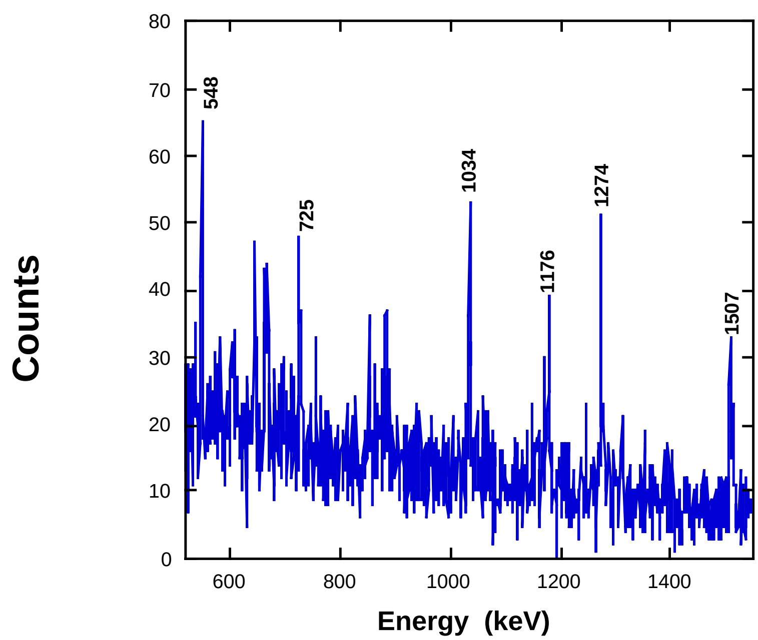

Fig. I-19. γ–γ coincidences with the 851-keV transition in ^{111}Sb. Transitions associated with ^{111}Te decay are labeled.

b.1.7. Identification of Excited States in ^{140}Dy (M. P. Carpenter, C. N. Davids, R. V. F. Janssens, C. J. Lister, D. Seweryniak, I. Ahmad, A. Heinz, T. L. Khoo, E. F. Moore, D. M. Cullen,* A. M. Fletcher,* S. J. Freeman,* L. K. Pattison,* J. F. Smith,* F. G. Kondev,† A. M. Bruce,‡ K. Abu Saleem,§ G. Mukherjee,¶ C. Wheldon,|| and A. Woehr**)

Recently, a new region of deformed proton emitters was established ranging from La to Tm. The first cases found were in ^{131}Eu and ^{141}Ho.[1] Initially, the deformation and single-particle parentage of the proton-emitting states were deduced from calculations employing the multiparticle theory of Bugarov and Kadmensky.[2] In the case of ^{141}Ho, the deformation of the proton emitting states were confirmed by in-beam γ-ray spectroscopy utilizing the Recoil Decay Tagging (RDT) technique which established rotational bands on top of the these states.[3] While the deformation of the ^{141}Ho rotational bands deduced from the in-beam work is consistent with those inferred from the proton decay measurements, critical information about the ^{140}Dy daughter nucleus is still missing. In fact, one of the important assumptions in the calculations of the decay rates from deformed proton emitters is that the parent and daughter have the same deformation. Proton emission to the 2^+ level in ^{140}Dy was not observed, however, an upper limit for the branching ratio between the 2^+ and 0^+ feedings into ^{140}Dy was placed at 1% for decays from the assigned $7/2^-$ ^{141}Ho, ground state.[3] Due to the fact that ^{140}Dy decays by β emission, in-beam γ spectroscopy using the RDT technique is not possible.

Recently, Cullen et al.[4] suggested that the yrast band of ^{140}Dy could be identified at least up to the 8^+ level by measuring γ rays emitted following the decay of a predicted $K = 8^-$ isomer. Studies to identify this isomer in ^{140}Dy and its subsequent γ decay were performed recently at the ATLAS facility by looking for delayed γ rays after implantation of mass selected recoils at the focal plane of the Fragment Mass Analyzer. From an analysis of the data, the 8^- isomer in ^{140}Dy was established at 2.16 MeV, and its subsequent decay by γ emission was followed to the ground state. The half-life of the isomer was measured to be 7.3(15) μs, and the excitation energy of the 2^+ state is 202 keV. Figure I-20 shows both the time spectrum associated with the decay of the isomer and the proposed level structure deduced from the isomer's decay. Using the Grodzins formula, the deformation of the ground state in ^{140}Dy is deduced to be $\beta_2 = 0.24(3)$ which agrees well with the value of 0.25(3) deduced for the rotational bands in ^{141}Ho. The new information obtained here supports the role of deformation in proton emission and the previous assignments of single-particle configurations to the two proton emitting states in ^{141}Ho. In addition, the reduced hindrance factor measured for the isomer is consistent with the trend observed for 8^- isomers observed in the lighter even-even N = 74 isotones.

A paper reporting the results of this work was recently been published in Physics Letters B.[5] A similar study at Oak Ridge National Laboratory[6] has also been published.

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*University of Manchester, United Kingdom, †Technology Division, Argonne National Laboratory, ‡University of Brighton, United Kingdom, §Illinois Institute of Technology, ¶University of Massachusetts-Lowell, ||University of Surrey, Guildford, United Kingdom, **University of Maryland.
[1]C. N. Davids *et al*., Phys. Rev. Lett. **80**, 1849 (1998).
[2]V. P. Bugrov and S. G. Kadmensky, Sov. J. Nucl. Phys. **49**, 967 (1989).
[3]D. Seweryniak *et al*., Phys. Rev. Lett. **86**, 1458 (2001).
[4]D. M. Cullen *et al*., Nucl. Phys. **A682**, 264c (2001).
[5]D. M. Cullen *et al*., Phys. Lett. **B529**, 45 (2002).
[6]W. Krolas et al., Phys. Rev. C**65**, 031303 (2002).

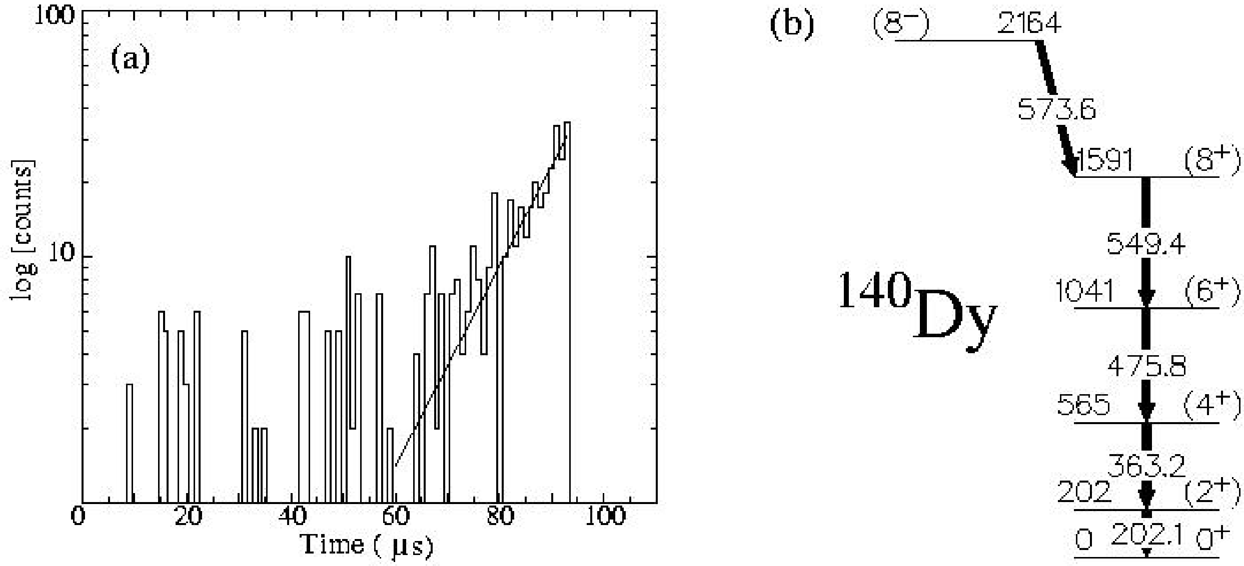

Fig. I-20. (a) Time delay between the implant of a residue and the detection in prompt coincidence of any two of the five γ transitions associated with the decay of the isomer. The solid line represents a fit to the data which yields a half-life of 7.3 μsec. (b) Proposed level sequence following the decay of the 8^- isomer in ^{140}Dy.

b.1.8. In-Beam Spectroscopy of the Proton Unbound Nucleus ^{143}Ho (D. Seweryniak, M. P. Carpenter, C. N. Davids, N. Hammond, R. V. F. Janssens, T. L. Khoo, F. G. Kondev, T. Lauritsen, C. J. Lister, G. Mukherjee, P. J. Woods,* S. J. Freeman,† D. Cullen,† C. J. Chiara,‡ W. Reviol,‡ D. G. Sarantites,‡ R. Clark,§ P. Fallon,§ A. Gorgen,§ A. O. Macchiavelli,§ and D. Ward§)

The proton-rich nuclei ^{145,146,147}Tm and ^{141}Ho are known proton emitters.[1-4] They are situated in the transitional region where the nuclear shape changes from spherical, close to the N = 82 shell, to oblate, and than rapidly to prolate. Properties of the ground-state rotational band in ^{141}Ho indicate possible triaxiality. The ^{145}Tm proton decay rate and the branching to the 2^+ state was reproduced using the particle-vibrator picture. The ^{143}Ho nucleus is the nearest isotone of ^{145}Tm and has only two neutrons more than ^{141}Ho. Information on its excited states will allow connections to be made with the more complete information on more neutron-rich nuclei.

A ^{54}Fe beam from the 88-inch Cyclotron at LBNL impinging on a thin ^{92}Mo target was used to populate nuclei around ^{141}Ho. Prompt γ rays were detected in Gammasphere. To select reaction channels evaporated protons and α particles were detected using MICROBALL, and evaporated neutrons were measured in the Neutron Wall. The ^{143}Ho nuclei were produced as the p2n evaporation channel with the calculated cross section of about 50 μb. Figure I-21 shows γ-ray spectra measured in coincidence with different numbers of detected protons, α particles and neutrons. Three γ-ray lines can be seen in Fig. I-21d corresponding to the p2n channel. These transitions are coincident and form a band. Based on the γ-ray energies this band is most likely the decoupled $h_{11/2}$ proton band. Further data analysis is in progress.

*University of Edinburgh, United Kingdom, †University of Manchester, United Kingdom, ‡Washington University, §Lawrence Berkeley National Laboratory.

[1]M. Karny *et al.*, Phys. Rev. Lett. **90**, 012502 (2003).
[2]P. J. Woods *et al.*, Nucl. Phys. **A553**, 485c (1993).
[3]O. Klepper *et al.*, Z. Phys. **A305**, 125 (1982).
[4]C. N. Davids *et al.*, Phys. Rev. Lett. **80**, 1849 (1998).

Figure I-22 shows the energies of the $15/2^- \rightarrow 11/2^-$ transitions in the decoupled proton $h_{11/2}$ bands and the energies of 2^+ states in the even-even nuclei around ^{141}Ho. The energy of the first transition in ^{143}Ho agrees very well with the 2^+ energy in the daughter nucleus ^{142}Dy. The $15/2^- \rightarrow 11/2^-$ energies observed in the lighter N = 76 isotones are similar to ^{143}Ho which indicates that deformation does not change when more protons are added to the core. It is consistent with the calculated deformations. Thus the structure of the proton emitter ^{145}Tm could indeed be similar to ^{143}Ho.

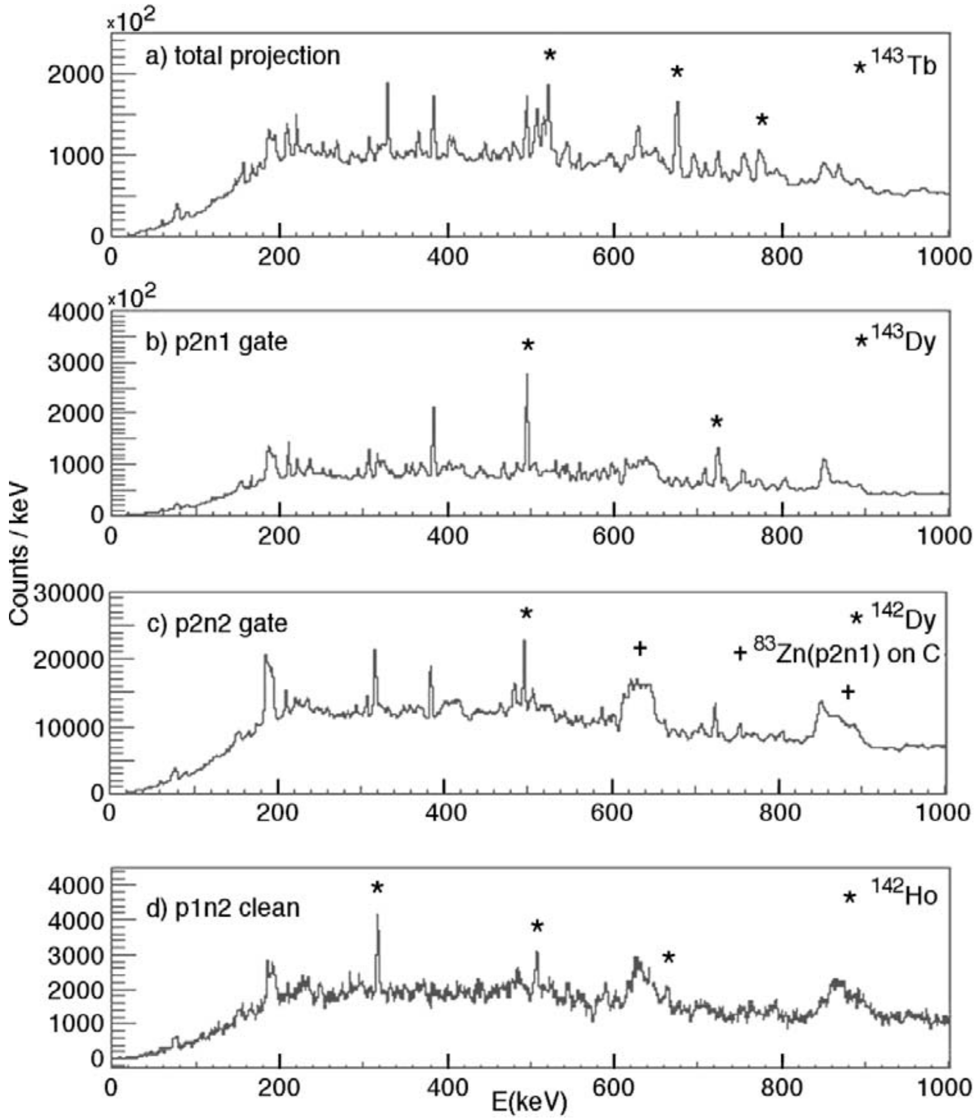

Fig. I-21. Gamma-ray spectra measured in coincidence with different number of detected evaporated particles: a) total γ-ray spectrum, b) 2 protons and 1 neutron, c) 2 protons and 2 neutrons, d) 1 proton and 2 neutrons. In spectrum d) contribution from higher proton multiplicity and 1 neutron channels were subtracted out.

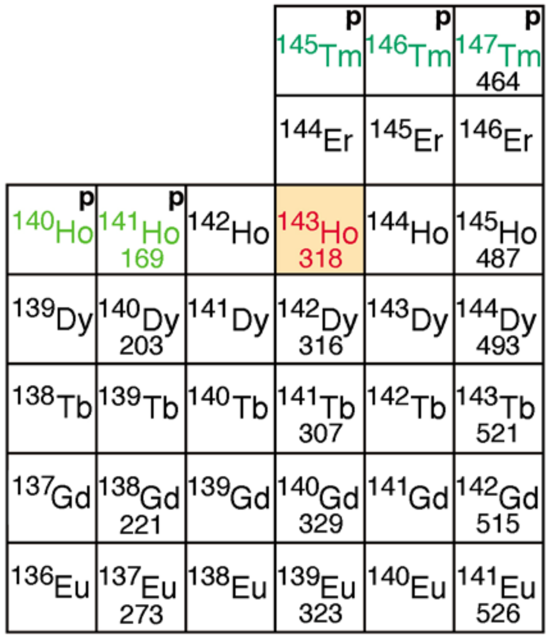

Fig. I-22. Systematics of the E(15/2$^-$)-E(11/2$^-$) energies in odd-Z nuclei and the E(2$^+$) energies in even-even nuclei around ^{141}Ho.

b.1.9. New Results in Proton Radioactivity (C. N. Davids, D. Seweryniak, A. Heinz, G. Mukherjee, P. J. Woods,* J. Shergur,† P. Munro,* A. Robinson,* T. Davinson,* A. A. Sonzogni,‡ and W. B. Walters†)

Analysis of data on the new proton emitter ^{135}Tb was completed. It was produced with an estimated cross-section of 1 nb via the ^{92}Mo(^{50}Cr,p6n) reaction. This proton emitter is expected to be highly deformed, with a predicted β_2 value of 0.32. We observed a single proton peak at 1.18(15) MeV, with a half-life of 1.00(28) ms. No fine structure was observed. The predicted branching ratio to a 2$^+$ state at an excitation energy of 127 keV is about 8%, which is just below our sensitivity. The candidate proton single-particle states for this nucleus are 3/2$^+$, 5/2$^+$, and 7/2$^-$. Figure I-23 shows a comparison between experimental and calculated half-lives for decay from these three states, using a spectroscopic factor S_j of 0.5. It is clear that only a spin-parity of 7/2$^-$ agrees with the observed half-life for this nuclide.

A search for the predicted deformed proton emitter ^{125}Pm (Z = 61) proved to be unsuccessful. We used the ^{92}Mo(^{40}Ca,p6n) fusion-evaporation channel, but were unable to see any proton events after several days of running with about 20 pnA of beam.

*University of Edinburgh, United Kingdom, †University of Maryland, ‡Brookhaven National Laboratory.

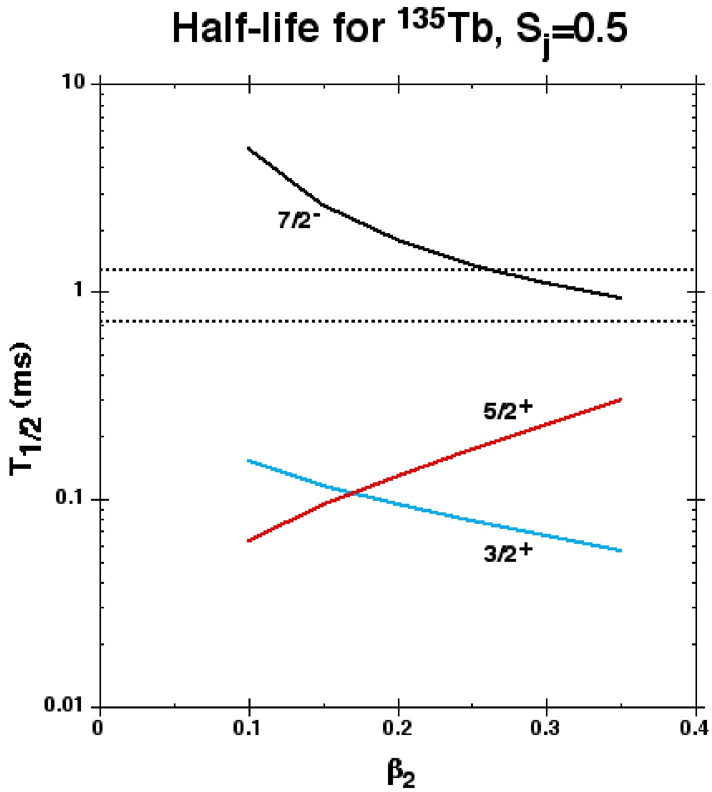

Fig. I-23. Calculated half-lives vs. quadrupole deformation parameter β_2 for ^{135}Tb. The dashed lines indicate the experimental results.

b.1.10. Proton Decay of Non Axially-Symmetric Deformed Nuclei (C. N. Davids and H. Esbensen)

Current calculations of decay rates and fine structure branching ratios for deformed proton emitters assume that both the parent emitter and daughter nucleus are axially symmetric. We calculated, in the adiabatic limit, the decay rate of a deformed nucleus where this symmetry requirement is relaxed. One obtains a set of coupled equations for the radial wave functions of the system consisting of an unbound proton coupled to a deformed even-even core. In the adiabatic limit these equations are diagonal in K, which is the projection of the total angular momentum on the long or 3-axis. However, the wave functions also contain components with different Ω, which is the projection of the proton angular momentum j on the 3-axis. Only Ω-values differing from K by ±2, ±4, etc. are allowed, subject to the restriction $|\Omega| \leq j$.

This formalism was applied to the ground state decay of the proton emitter ^{141}Ho, with K = 7/2$^-$. The wave function is expanded in spherical components with j = 7/2$^-$, 9/2$^-$, 11/2$^-$, 13/2$^-$, and 15/2$^-$, resulting in a total of 30 coupled equations. This is to be compared with the axially-symmetric case, where there are only 5 equations. Figure I-24 shows the calculated total decay rate and 2$^+$ branching ratio, as a function of $a_{22} = 0.707\ \beta_2 \sin\gamma$. For $a_{22} = 0$, the calculated total width has a value that agrees with experiment, with a spectroscopic factor of 0.73,[1] and the calculated branching ratio for decay to the 2$^+$ state of 0.007 also agrees with the experimental value of 0.0070(15).[2] As a_{22} is increased the total decay rate decreases slowly and the 2$^+$ branching ratio increases rapidly.

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[1]C. N. Davids *et al.*, Phys. Rev. Lett. **80**, 1849 (1998).
[2]K. Rykaczewski *et al.*, Proceedings of the International Conference on Nuclear Structure "Mapping the Triangle", Grand Teton National Park, WY, May 22-25, 2002, AIP Proceedings **638**, 149 (2002).

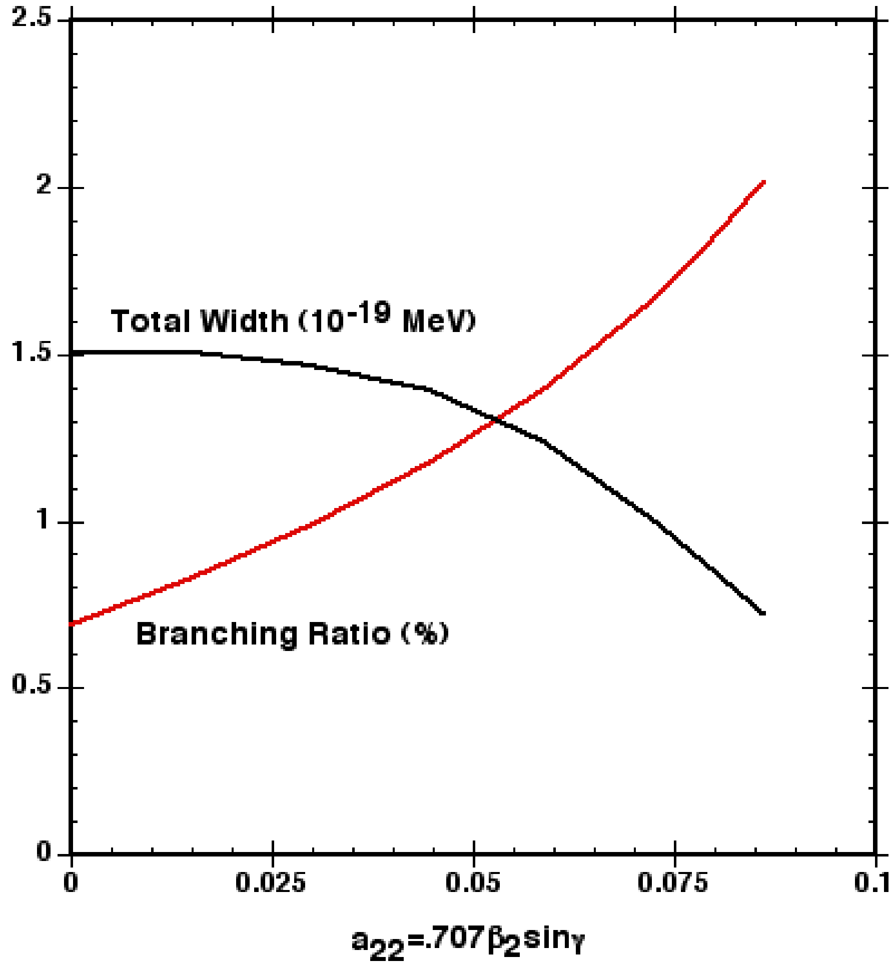

Fig. I-24. Calculated total decay width and 2^+ branching ratio for ^{141}Ho, plotted as a function of a_{22}.

b.1.11. 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 were made between the entry distributions associated with odd-A Au and Pt isobars. In ^{173}Au the entry distribution 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.

A paper reporting these results was recently published in Physics Letters B.[3]

*Rutgers University, †Mississippi State University, ‡University of Tennessee, §Washington University.
[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, ed. Steven Tomsovic (World Scientific 1998) v. 5, p. 229.
[3]M. B. Smith *et al*., Phys. Lett. **B551**, 262 (2003).

b.1.12. In-Beam γ-Ray Spectroscopy of ^{172}Pt (M. P. Carpenter, R. V. F. Janssens, K. Abu Saleem, I. Ahmad, C. N. Davids, A. Heinz, T. L. Khoo, T. Lauritsen, C. J. Lister, G. L. Poli, J. Ressler, D. Seweryniak, I. Wiedenhöver, M. Danchev,* D. J. Hartley,* F. G. Kondev,† L. L. Riedinger,* H. Amro,‡ D. L. Balabanski,* J. A. Cizewski,§ W. C. Ma,‡ W. Reviol,¶ and M. B. Smith§)

Collective structures in ^{172}Pt were investigated by measuring in-beam γ rays with mass selection and the recoil-decay tagging technique. The experiment was performed with the ATLAS superconducting linear accelerator at the Argonne National Laboratory. The main emphasis of this experiment was to study high-spin states in the proton unbound systems ^{173,175,177}Au, and a paper reporting the results on these nuclei was published recently.[1] High-spin states in ^{172}Pt were weakly populated in the 2*p*2*n* channel of the ^{84}Sr + ^{92}Mo reaction. Two energies, 390 and 395 MeV, were used to bombard the self-supporting, isotopically enriched, ^{92}Mo target. Prompt γ rays were detected with 101 Ge detectors in the Gammasphere array. Mass and alpha decay information was obtained at the focal plane of the Fragment Mass Analyzer using the PGAC and DSSD setups. The discrepancy in the ground-state band from previous studies was resolved, and a new collective structure that is likely based on an octupole vibration was identified. The level scheme for ^{172}Pt deduced from this work is shown in Fig. I-25. A paper reporting the results of this work was recently published in Phys. Rev. C.[2]

*University of Tennessee-Knoxville, †Technology Division, Argonne National Laboratory, ‡Mississippi State University, §Rutgers University, ¶Washington University.
[1]F. G. Kondev *et al*., Phys. Lett. **B512**, 268 (2001).
[2]M. Danchev *et al*., Phys. Rev. C **67**, 014312 (2003).

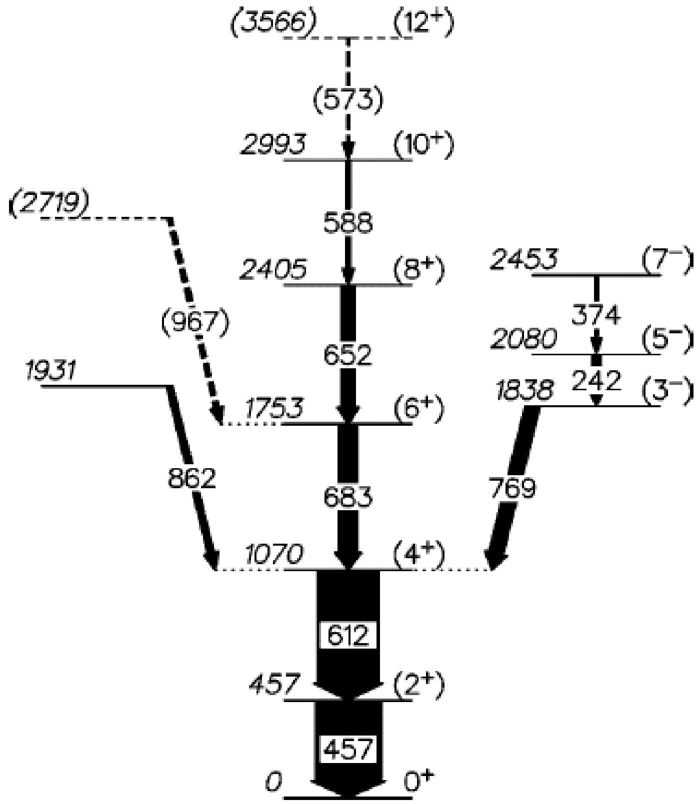

Fig. I-25. Level scheme for ^{172}Pt deduced from this work.

b.1.13. Triple Shape-Coexistence in ^{179}Hg (M. P. Carpenter, F. G. Kondev, D. Jenkins,* R. V. F. Janssens, I. Ahmad, J. Caggiano, C. N. Davids, A. Heinz, T. L. Khoo, T. Lauritsen, C. J. Lister, D. Seweryniak, A. A. Sonzogni, I. Wiedenhöver, K. Abu Saleem,† H. Amro,‡ A. N. Andreyev,* T. Enqvist,§ P. T. Greenlees,§ B. Herskind,¶ P. M. Jones,§ D. T. Joss,|| R. Julin,§ S. Juutinen,§ H. Kettunen,§ P. Kuusiniemi,§ M. Leino,§ A.-P. Leppännen,§ W. C. Ma,‡ P. Nieminen,§ R. D. Page,* J. Pakarinen,§ C. D. O'Leary,** P. Raddon,§ P. Rahkila,§ J. Ressler,†† W. Reviol,‡‡ L. L. Riedinger,¶¶ D. G. Sarantites,‡‡ S. Siem,§§ A. Simons,** J. Uusitalo,§ P. G. Varmette,‡ and R. Wadsworth**)

Neutron-deficient, even-even Hg (Z = 80) isotopes between N = 96 and 110 exhibit a coexistence at low spin between two shapes: a weakly deformed oblate ground state and a more deformed, excited, prolate band. The energy difference between the two minima exhibits a parabolic trend as a function of neutron number and minimizes around mid-shell (N ~ 102) where the prolate 0^+ state lies ~260 keV above the 0^+ ground state. In contrast, the ground states of the odd-mass, ^{181,183,185}Hg (N = 101,103,105) isotopes are associated with a prolate shape. In addition, a weakly-deformed, oblate high-spin ($J^\pi = 13/2^+$) isomer was identified in each of the three odd-mass Hg isotopes, albeit the excitation energies were not established. The mechanism responsible for this preferred prolate shape at low spin in the odd-mass isotopes is still not understood

Based on the experimental results available at present, it is hard to predict which type of structures will be observed in the neutron-deficient odd-A Hg isotopes (N < 100). In particular, it is of interest to map out the evolution of the single-particle states for both the prolate and oblate shapes in the lightest odd-A isotopes and to compare these with trends observed in the even-even Hg neighbors. We started such investigations by performing several measurements on

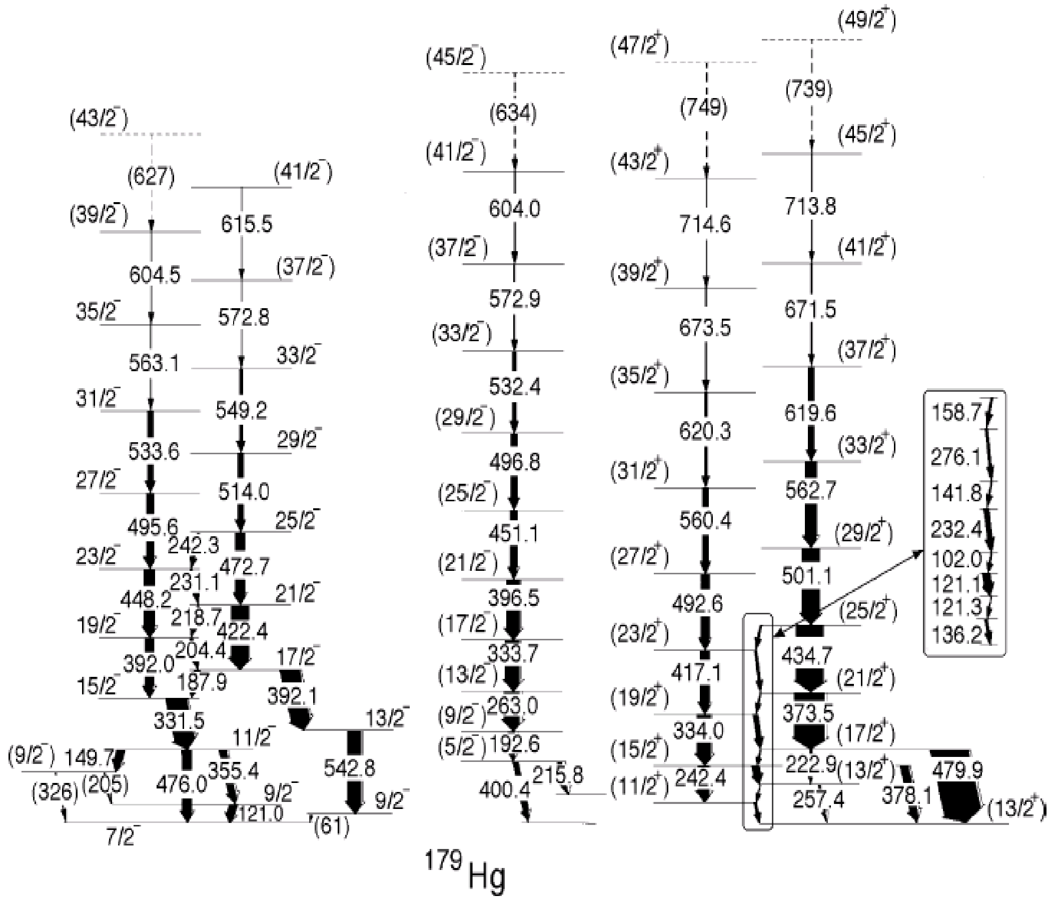

Fig. I-26. Level scheme for ^{179}Hg deduced from γ-ray coincidence data measured with Gammasphere. High-spin states in ^{179}Hg were populated in the reaction ^{90}Zr(^{90}Zr,n) reaction. The beam was supplied by the ATLAS accelerator at Argonne National Laboratory.

^{179}Hg (N = 99). The first was an in-beam experiment using Gammasphere coupled to the FMA. The second measurement was performed at RITU and studied in detail the α decay of ^{183}Pb into ^{179}Hg.

For the in-beam study, excited states in ^{179}Hg were populated with the ^{90}Zr(^{90}Zr,n) reaction using beams delivered by ATLAS. Gamma rays associated with ^{179}Hg were identified by the RDT technique using Gammasphere coupled to the FMA. The level structure deduced from this work is shown in Fig. I-26. In the heavier odd-A Hg isotopes, the ground state spin/parity is ½$^-$ and associated with a deformed configuration. For ^{179}Hg, the ground state is established to be 7/2$^-$ and is associated with a near-spherical shape. Three rotational bands are evident in the level scheme and have a deduced prolate deformation of β_2 ~ 0.2. The oblate shape is associated with the 13/2$^+$ isomer into which rotational band 3 decays into.

For the decay experiment, a 200-MeV ^{42}Ca beam from the cyclotron at the University of Jyväskylä was incident on a target consisting of two stacked 500-μg/cm^2 self supporting ^{144}Sm foils, producing ^{183}Pb via the ^{144}Sm(^{42}Ca,3n) reaction. Gamma rays at the target position were detected by the JUROSPHERE II. Fusion-evaporation residues were separated from scattered beam and fission products using the RITU gas-filled separator. Five 25-35% HPGe surrounded the focal plane detector affording a total efficiency of about 1% at 1.3 MeV.

Before the current study was performed, four distinct α−decay lines were identified in the decay of ^{183}Pb. While a detailed level scheme had not been established, it was assumed that the four α decays represent branches from a single state in the parent.[1] Our data confirms the existence of these four previously known α decays, however, the lifetimes associated with the four α lines allows them to be divided into two pairs of decays from two different states (see Fig. I-27); one with a half- life of 415(20) ms and one with a half-life of 535(30) ms. By observing coincidences with γ rays at the focal plane, we find that the 6698(5) keV and 6570(10) keV α decays feed excited states in ^{179}Hg which decay by γ emission. The 6698 keV α decay is correlated with two γ rays with energies of 110.8 and 60.6 keV which are in prompt coincidence with each other, but in delayed coincidence with the emission of the α particle. The half-life of the isomeric state at 172 keV from which these transitions decay is determined to be 6.4(9) μs. The 60.6 keV transition was also observed in the in-beam work and corresponds to a decay of a $9/2^-$ state into the $7/2^-$ ground state. Based on intensity balances and the half life, we deduce that the 110.8 keV transition has M2 multiploarity and thus comes from a $13/2^+$ state. The deduced hindrance factor of 1.3 for the 6698 keV α decay is essentially unhindered and establishes a $13/2^+$ isomer in ^{183}Pb. This $13/2^+$ to $13/2^+$ decay is also observed in both ^{185}Pb and ^{187}Pb and is interpreted as the decay from a spherical single-particle state in the parent to a weakly deformed oblate state in the daughter. This is also our interpretation as well, allowing us to assign excitation energies to all levels measured above the isomer in the in-beam work. The $13/2^+$ isomer in ^{183}Pb also decays to the ground state via a 6860(11) keV decay with a deduced hindrance factor of 67(18). This large hindrance factor for the α decay is not inconsistent with the structural change associated with a decay connecting a spherical state in ^{183}Pb with the ground state of ^{179}Hg which has been suggested to arise from the coupling of a $h_{9/2}$ or $f_{7/2}$ neutron to a weakly-deformed prolate core. In fact, the decay work fully confirms the conclusions we deduced on the shape of the ground and $13/2^+$ isomeric state from our in-beam work, and thus confirming the three-shape scenario.

A paper reporting the results from the in-beam work was recently been published in Physics Letters B.[2] A paper reporting the results from the decay work was recently published in Physical Review C.[3]

*University of Liverpool, United Kingdom, †Argonne National Laboratory and Illinois Institute of Technology, ‡Mississippi State University, §University of Jyväskylä, Finland, ¶Niels Bohr Institute, Copenhagen, Denmark, ||University of Keele, United Kingdom, **University of York, United Kingdom, ††Argonne National Laboratory and University of Maryland, ‡‡Washington University, §§Argonne National Laboratory and University of Oslo, Norway, ¶¶University of Tennessee-Knoxville.
[1]K. S. Toth *et al*., Phys. Rev. C **39,** 1150 (1989).
[2]F. G. Kondev *et al*., Phys. Lett. **B528**, 221 (1989).
[3]D. J. Jenkins *et al*., Phys. Rev. C **66**, 011301(R) (2002).

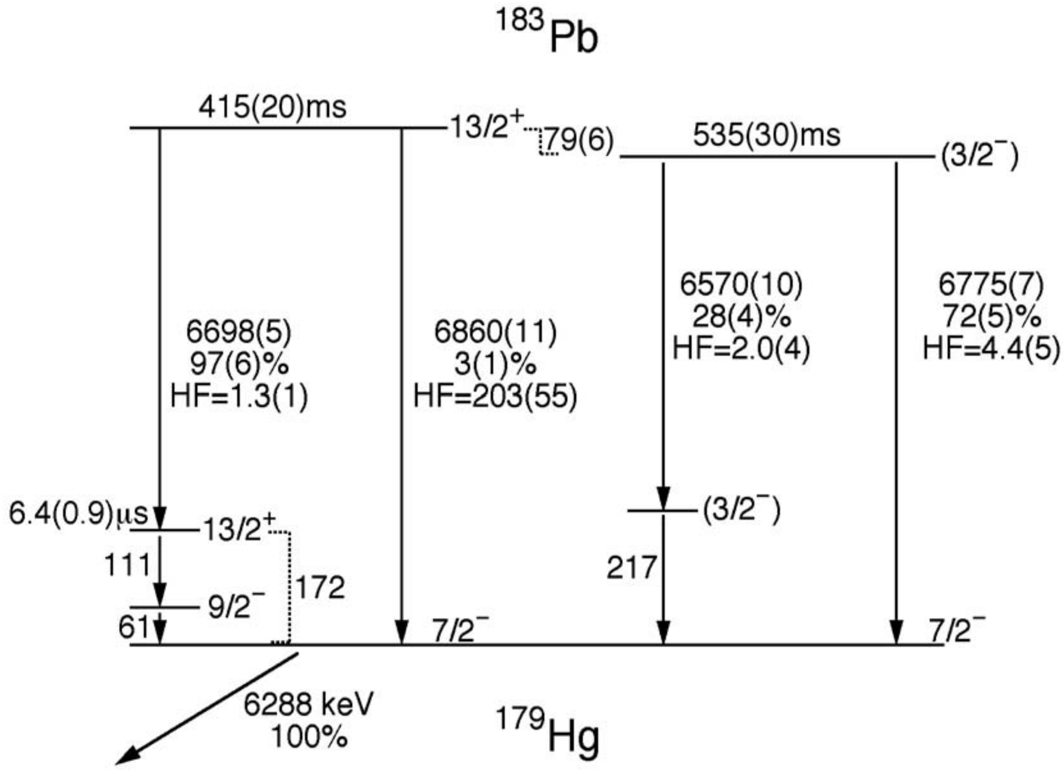

Fig. I-27. Decay scheme showing the α decay of two isomers in ^{183}Pb to low-lying states in ^{179}Hg.

b.1.14. Alpha Decay of ^{181}Pb (M. P. Carpenter, F. G. Kondev, S. Sinha, R. V. F. Janssens, I. Ahmad, C. N. Davids, S. Freeman, N. Hammond, T. L. Khoo, T. Lauritsen, C. J. Lister, G. Mukherjee, D. Seweryniak, A. Woehr,* and D. J. Jenkins†)

This past fall, we measured with the FMA and DSSD setup, the α decay of recoils produced in the ^{90}Zr + ^{92}Mo reaction. For one of these products, ^{181}Pb, we observe two α lines at 7035 and 7090 keV with nearly equal intensity. Both of these decays are correlated with the 6580-keV α decay of ^{177}Hg. This is in contrast to the previously reported α line at 7065 keV.[1] It is likely that this singly reported α decay is in fact the two that we observe. In the heavier odd-A Pb isotopes, two α-decaying states were identified and associated with a high-spin ($13/2^+$) and a low-spin ($3/2^-$) isomer. Presumably, the two α-decaying states that we observe correspond to similar states in ^{181}Pb. With respect to ^{181}Tl, our preliminary analysis confirms the 6180-keV α line reported in Ref. 1, and no other α decays associated with ^{181}Tl were identified. We do, however, observe a significant β-decay branch inferred from the observation of the 6005-keV α line of ^{181}Hg, a nuclide we cannot make via the 1-particle evaporation channel from the compound ^{182}Pb. Whether the β-decay competes directly with the state emitting the 6180-keV α line or comes from another state whose α decay is highly hindered cannot be determined from the present data. A complete analysis of this data set is currently underway.

∗ University of Maryland, †University of York, United Kingdom.

[1]K. S. Toth *et al*., Phys. Rev. C **53**, 2513 (1996).

B.2. Neutron-Rich Nuclear Spectroscopy

b.2.1. Structure of ^{52,54}Ti and Shell Closures in Neutron-Rich Nuclei Above ^{48}Ca

(R. V. F. Janssens, M. P. Carpenter, F. G. Kondev, T. Lauritsen, D. Seweryniak, B. Fornal,* P. F. Mantica,† B. A. Brown,† R. Broda,* P. Bhattacharyya,‡ M. Cinausero,§ P. J. Daly,‡ A. D. Davies,† T. Glasmacher,† Z. W. Grabowski,‡ D. E. Groh,† M. Honma,¶ W. Krolas,* S. N. Liddick,†, S. Lunardi,|| N. Marginean,§ T. Mizusaki,** D. J. Morrissey,† A. C. Morton,† W. F. Mueller,† T. Otsuka,†† T. Pawlat,* H. Schatz,† A. Stolz,† S. L. Tabor,‡‡ C. A. Ur,|| G. Viesti,|| I. Wiedenhover,‡‡ and J. Wrzesinski*)

The structure of neutron-rich nuclei recently became the focus of much theoretical and experimental effort. Central to the on-going investigations is the expectation that substantial modifications can occur to the intrinsic shell structure of nuclei with a sizable neutron excess. Alterations to the energy spacings of the orbitals and/or to their ordering can have a considerable impact on global nuclear properties such as the nuclear shape or the type of excitations characterizing the low-energy level spectra. The so-called "island of inversion" phenomenon discovered in neutron-rich exotic nuclei near N = 20 ^{30}Ne, ^{31}Na, $^{32-34}$Mg is perhaps one of the best examples so far of an unanticipated structural change.

Interactions between protons and neutrons were invoked to account for the presence of a subshell gap at N = 32 in neutron-rich nuclei located in the vicinity of the doubly-magic nucleus ^{48}Ca.[1] Specifically, it was proposed that a weakening of the $\pi 1f_{7/2}$ $\nu f_{5/2}$ proton-neutron monopole interaction as protons are removed from the $1f_{7/2}$ single-particle orbital (filled at Z = 28), combined with a significant $2p_{1/2}$-$2p_{3/2}$ spin-orbit splitting results in the emergence of the N = 32 subshell in nuclei such as ^{52}Ca and ^{56}Cr. This subshell manifests itself by the large excitation energy of the first 2^+ state. More recently, shell-model calculations introducing a new effective interaction for pf-shell nuclei were carried out.[2] They are able to account for the observations of Ref. 1. In particular, the energy of the first 2^+ states in Ca, Ti, Cr, Fe and Ni isotopes are well reproduced. Interestingly, these calculations also suggest the presence of an additional N = 34 shell gap in the Ca and Ti isotopic chains.

The purpose of the present work was two-fold. First, the observation that the N = 32 subshell gap survives in the presence of $f_{7/2}$ protons, which so far relies mostly on the Cr systematics of Ref. 1, was reinforced by presenting first data on the ^{54}Ti nucleus. Second, new tests of the effective interaction for pf-shell nuclei[2] were carried out by confronting the level structures of ^{52}Ti and ^{54}Ti up to medium spin with the results of shell-model calculations. These new data were obtained by combining two experimental techniques seldom used together to investigate exotic nuclei: beta-decay studies of products from a fragmentation reaction and in-beam gamma-ray spectroscopy following deep-inelastic reactions. This approach was necessary because the two Ti isotopes of interest are neutron-rich and cannot be readily investigated at high spin with the more commonly used (HI,xn) fusion-evaporation reactions.

Prior to the present studies, nothing was known about the excited states of ^{54}Ti. Information about low lying levels was obtained from an investigation of the beta decay of the parent, ^{54}Sc, produced via fragmentation of a 140 MeV/nucleon ^{86}Kr beam at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The MSU study identified the first two gamma-ray transitions in ^{54}Ti. Based on the MSU data, the high spin structure in this nucleus up to a spin $J^\pi = 10^+$ was then delineated from a Gammasphere experiment at ATLAS, where a 305 MeV ^{48}Ca beam was sent on a thick ^{208}Pb target. Data were obtained as well for the $^{50-52}$Ti isotopes. It should be pointed out that the identification of ^{54}Ti using a cross coincidence technique with transitions in reaction partners from the Gammasphere data was impossible. Thus, the beta-decay measurement described above was of crucial importance to validate the ^{54}Ti assignment. We believe that this approach of combining beta decay studies following fragmentation with prompt spectroscopy measurements following deep inelastic reactions represents a new, powerful tool to study nuclei on the neutron-rich side of the valley of stability. The new level schemes obtained for the neutron-rich even Ti isotopes are given in Fig. I-28. The first important result from the present measurements can be readily inferred from a close inspection of the figure: the $E(2^+)$ energy dips from 1554 to 1050 keV between ^{50}Ti and ^{52}Ti, before increasing significantly to 1495 keV in $^{54}Ti_{32}$. This behavior mirrors the one found in Ref. 1, and is consistent with the suggestion of a subshell closure at N = 32.

Another distinct feature of the level structures in Fig. I-28 is the presence of higher-energy transitions ($E_\gamma > 2$ MeV) at moderate spins. Large jumps in transitions energies of this type are often regarded as signatures for excitations involving the breaking of the core, e.g., the valence space was exhausted and higher angular momentum levels require excitations across a (sub)shell gap. In order to explore both of these observations further, a number of shell-model calculations were carried out with the Hamiltonian described in Ref. 2. The results of the calculations are compared with the data in Fig. I-28, where it can be seen that the data a reproduced satisfactorily. From this comparison, it is clear that the ^{54}Ti data strongly support the calculations with a high $f_{5/2}$ effective single-particle energy at N = 34 and are, thus, pointing towards a shell closure at N = 34.

These results were recently published.[3] Follow-up experiments to delineate the level structure of ^{56}Ti and to measure the degree of collectivity of the 2^+ state in the even Ti isotopes are being planned.

*Niewodniczanski Institute of Nuclear Physics, Kracow, Poland, †Michigan State University, ‡Purdue University, §INFN, Laboratori Nazionali di Legnaro, Italy, ¶University of Aizu, Fukushima, Japan, ||Dipartimento di Fisica dell'Università and INFN Sezione di Padova, Italy, **Senshu University, Kanagawa, Japan, ††University of Tokyo, Japan, ‡‡Florida State University.

[1]J. I. Prisciandaro *et al*., Phys. Lett. **B510**, 17 (2001).

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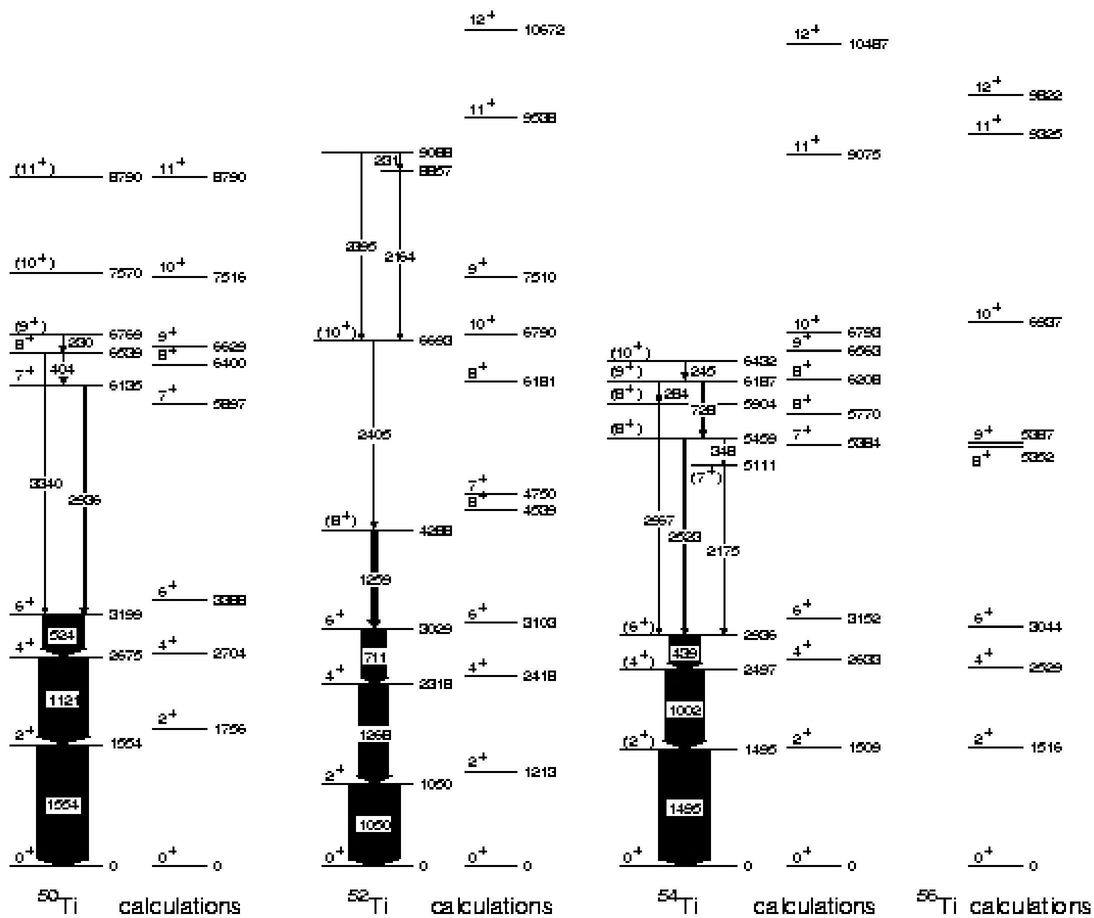

Fig. I-28. Comparisons between shell-model calculations and data for the even-even $^{50-54}$Ti isotopes.

b.2.2. First Observation of the ν9/2[404] Orbital in A ~ 100 Mass Region (I. Ahmad, W. Urban,* J. A. Pinston,† T. Rzaca-Urban,* A. Zlomaniec,* G. Simpson,‡ J. L. Durell,§ W. R. Phillips,§ A. G. Smith,§ B. J. Varley,§ and N. Schulz¶)

A new band was identified in ^{99}Zr from our investigation of ^{248}Cm fission fragment prompt gamma ray spectroscopy. The prompt γ-γ coincidence measurement was performed with the Eurogam2 array of Compton-suppressed Ge spectrometers using a ^{248}Cm fission source. The level scheme built on the basis of the coincidence relationships between gamma rays in ^{99}Zr and its complementary fragments is shown in Fig. I-29. Angular correlations establish spin-parity of $9/2^+$ to the 1038.8 keV level. The half-life of this level was measured to be 54(10) ns. We give a $9/2^+$[404] assignment to this level because this is the only $9/2^+$ Nilsson state available in this mass region. This is the first observation of the $9/2^+$[404] orbital in the mass 100 region. The results of this work were published.[1]

*Warsaw University, Krakow, Poland, †Institut des Sciences Nucleaires, Grenoble, France, ‡Institut Laue-Langevin, Grenoble, France, §University of Manchester, United Kingdom, ¶Institut de Recherches Subatomiques, Strasbourg, France.

[1]Eur. Phys. J. A **16**, 11 (2003).

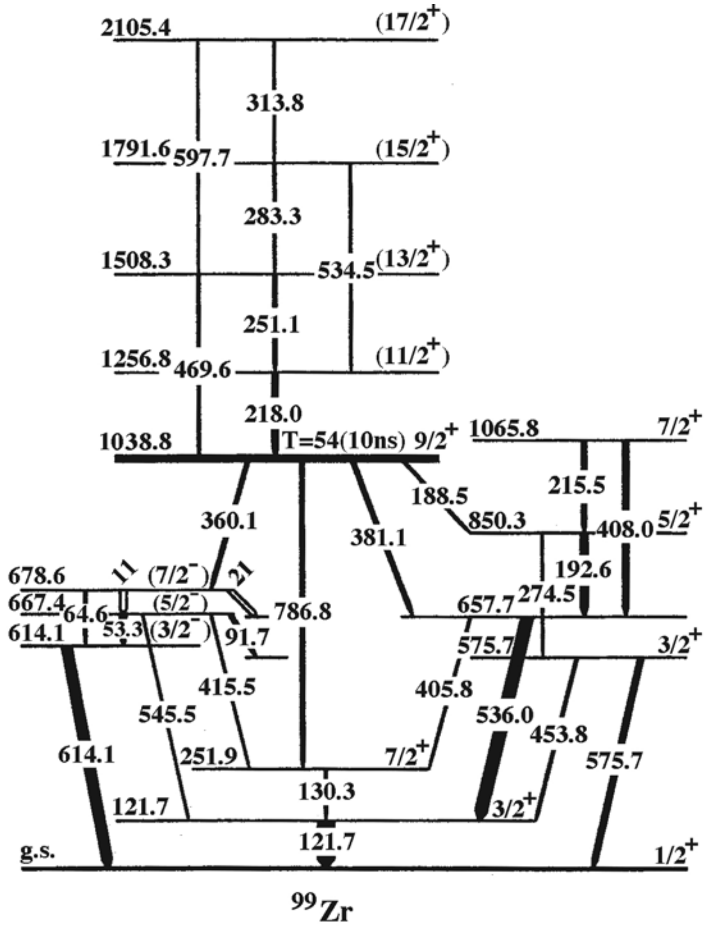

Fig. I-29. A partial level scheme of ^{99}Zr showing the new band at 1038.8 keV.

b.2.3. Precise Mass Measurement of Neutron-Rich Nuclei from Fission Fragments of ^{252}Cf

(G. Savard, J. P. Greene, A. Heinz, Z. Zhou, J. C. Wang,* J. Clark,* F. Buchinger,† J. E. Crawford,† S. Gulick,† J. K. P. Lee,† K. S. Sharma,‡ and J. Vaz‡)

Precise mass measurements for neutron-rich isotopes $^{141\text{-}145,147}$Ba, $^{143\text{-}149}$La, $^{145,147\text{-}149,151}$Ce, and ^{149,151}Pr were made at the Canadian Penning Trap (CPT) mass spectrometer. In these measurements, a ^{252}Cf fission source is mounted in front of the Havar window of the CPT gas catcher (see Fig. I-11 in section a.10.) filled with about 150 torr of helium gas. Fission fragments entering the gas catcher are thermalized in the helium gas and guided by electric fields to the nozzle of the gas catcher. The high-purity of the system allows a significant fraction of the ions to remain in the 2^+ charge state in the helium gas. The ions are extracted out of the gas catcher by the gas flow and injected into a RFQ cooler in which the ions are captured, cooled by buffer gas collisions and ejected as ion bunches. The ion bunches are then transported, mass selected through a deflector pulse and transferred to a linear RF trap where they are captured, further cooled by helium buffer gas and accumulated. The ions ejected from the linear RF trap are finally delivered into a precision Penning trap where their cyclotron frequency $\nu_c = qB/(2\pi m)$ is measured. The mass of a nuclei can then be obtained by comparing its ν_c and ν_c' of a reference ion whose mass is well known. In the Penning trap, a dipole radio frequency field is used to clean out contaminant ions or excite the wanted ions to a certain magnetron motion orbit before a quadrupole radio frequency field is applied to convert the magnetron motion into cyclotron motion with the same radius of orbit. The cyclotron frequency is determined by employing a time-of-flight technique.

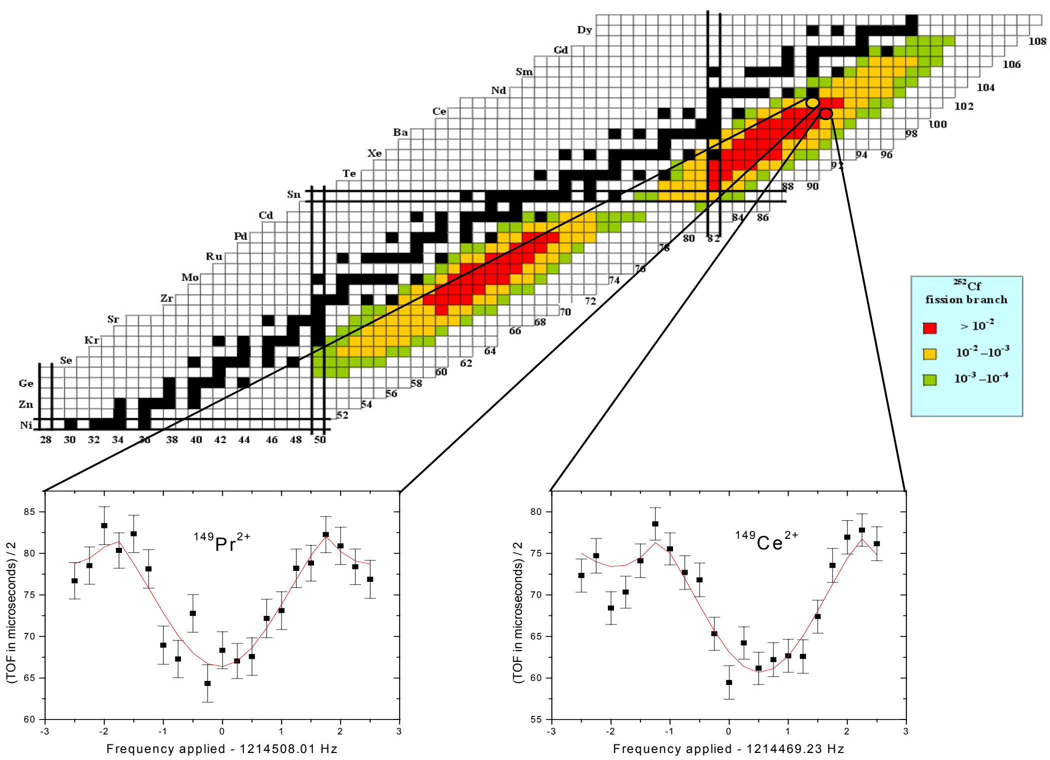

Fig. I-30. Distribution of fission fragments from ^{252}Cf and resonance curves for $^{149}Pr^{2+}$ and $^{149}Ce^{2+}$ obtained during the May 2002 run.

During March 2002, ν_c of $^{145}Ba^{2+}$, $^{145,147}La^{2+}$, $^{147,149}Ce^{2+}$, and $^{149}Pr^{2+}$ were measured with a quadrupole field excitation time of 200 ms. During each measurement, a molecule, C_5H_9, was used as a reference to calibrate the magnetic field. The masses of the C_xH_y (or $C_xH_yO_z$) molecules are known to better than 10^{-9} accuracy and this uncertainty is negligible for these measurements. ν_c of $^{145}Ba^{2+}$ was also measured with 500 ms excitation time. This longer excitation time yields a resolution of 600000 and a typical accuracy of about 5×10^{-8} (or about 7 keV) for the statistics accumulated in these measurements. In the May 2002 run, a 500 ms excitation time for the quadrupole field was employed for all of the measurements of $^{145}Ba^{2+}$, $^{145,147}La^{2+}$, $^{147,149}Ce^{2+}$, and $^{149}Pr^{2+}$. Four other isotopes ^{147}Ba, $^{145,151}Ce$ and ^{151}Pr were measured with 200 ms excitation time. In the June and July 2002 run, $^{141-144}Ba^{2+}$, $^{143,144,146,148}La^{2+}$ and $^{148}Ce^{2+}$ were measured with either 500 ms excitation or 200 ms excitation. Before and after each measurement, molecules C_5H_{11}, C_4H_9O and $C_3H_6O_2$ were used to calibrate the magnetic field. The masses of ^{145}Ba, $^{145,147}La$, $^{147,149}Ce$, and ^{149}Pr obtained from the above first two runs are consistent within the uncertainty. ν_c of C_5H_9, C_5H_{11}, C_4H_9O and $C_3H_6O_2$ during the whole measurement period are consistent to a few part 10^{-8}. A later test showed the frequency shift caused by contaminant ions to be less than a part 10^{-8} per ion if only a few ions are stored in the Penning trap. Since in all of the above measurements only a few ions were stored in the Penning trap for each cycle, frequency shifts caused by contaminant ions are not a problem. Fig. I-30 shows the distribution of fission fragments from ^{252}Cf and the resonances of $^{149}Pr^{2+}$and $^{149}Ce^{2+}$ obtained during the May 2002 run.

The masses measured at the CPT are compared with the Audi & Wapstra tabulated/extrapolated mass tables in Fig. I-31. For $^{141-144}Ba$, $^{143-145}La$, $^{145,148}Ce$ and ^{149}Pr, the measured masses are in excellent agreement with tabulated values. The masses of four of these isotopes (the less exotic barium isotopes $^{141-144}Ba$) were measured to high precision with the ISOLTRAP system at CERN and we agree with these measurements. For the other isotopes, we find larger deviations with the largest deviations occurring at ^{145}Ba and ^{147}La where the differences between our measured masses and the tabulated values are more than 500 keV. These masses were previously obtained by beta-endpoint measurements which are more prone to systematic errors than the present technique. We performed a series of systematic checks which confirm that no unexpected systematic shifts are present at this level in our measurements and must conclude that previous measurements in this region were in error. The effects these new measurements will have on masses in the region are being investigated.

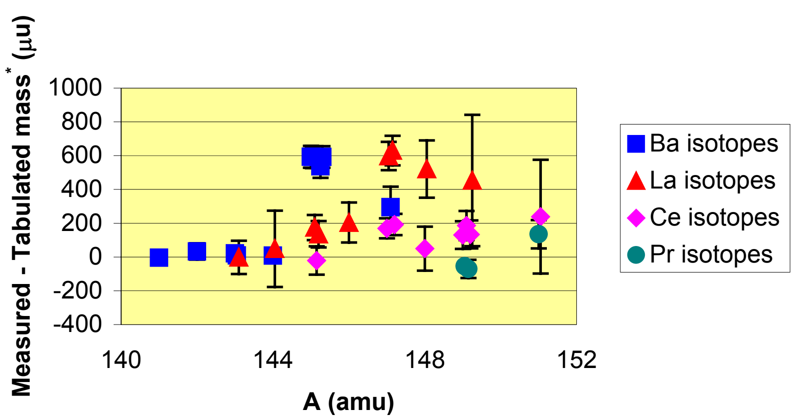

Fig. I-31. Comparison between masses measured at the CPT and tabulated values.

*Argonne National Laboratory and University of Manitoba, Winnipeg, Manitoba, †McGill University, Montreal, Quebec, ‡University of Manitoba, Winnipeg, Manitoba.

b.2.4. Beta-Decay Studies of r-Process Nuclides in the ^{132}Sn Region (A. Wöhr,* D. Seweryniak, B. Truett, W. B. Walters†, K.-L. Kratz,‡ O. Arndt,‡ B. A. Brown,§ I. Dillman,‡ D. Fedorov,¶ V. Fedoseyev,|| L. Fraile,|| P. Hoff,** U. Köster,|| A. N. Ostrowski,‡ B. Pfeiffer,‡ H. L. Ravn,|| M. D. Selliverstov,†† J. Shergur,* and the ISOLDE Collaboration)

Very neutron rich Ag, Cd, In and Sn isotopes lying in or near the r-process path were studied at CERN/ISOLDE using the highest achievable isotopic selectivity. These methods include the use of a resonance-ionization-laser-ion-source (RILIS) and a two step neutron-converter target in combination with a high-resolution mass separator.

Recently, it was possible to use the Cd-RILIS to study the β and γ-decay of ^{130}Cd to levels of ^{130}In.[1-3] This particular nuclide is of considerable importance to r-process nucleosynthesis as its half-life of 162 ms provides the ultimate barrier to the matter flow in the A ≅ 130 region. Moreover, a full understanding of the structure and decay of ^{130}Cd is essential to the calculation of the lower-Z N = 82 nuclides that also play a role in the buildup of the rising wing of the solar r-abundance A ≅ 130 peak. In order to observe γ-rays from ^{130}Cd decay in a region where large backgrounds of surface-ionized Cs and In isobars are present, many improvements have been incorporated. Hence, the ^{130}Cd was produced via neutron induced fission, but not by spallation. The use of the neutron converter target thus resulted in a considerable lowering of the ^{130}In contaminant and an almost complete suppression of spallation produced ^{130}Cs. For ^{130}Cd, it was possible to determine the 2120 keV energy for the 1^+ level to which the Gamow-Teller β-decay goes. Using βγ-coincidences, we measured the end-point for β-population of this level which allowed us to determine the Q_β value for ^{130}Cd decay. That Q value appears to be considerably higher than predicted by the mass formulae of Möller *et al.*,[4] Aboussir *et al.*[5] or Duo and Zuker,[6] but rather lies in the high-energy range of recent ***"quenched"*** mass models (HFB/SKP, HFB-2)[7,8] and the value listed in the Atomic Mass Evaluation of Audi and Wapstra.[9] The 8 major gamma rays found to follow the β-decay of ^{130}Cd include a γ–ray at 388 keV, reported by Hellström *et al.*,[10] to stem from a microsecond isomer. Since it seems that this level is populated in the decay of the 1^+ level at 2120 keV by the 1732 keV -ray, we can assume that it is likely to have spin and parity of 3^+. The relatively (and unanticipatedly) high energy of the 2120 keV 1^+ level is a consequence of two unexpectedly large position shifts in going from ^{128}In via ^{130}In. These levels are shown in Fig. I-32 where the evolution of the positions

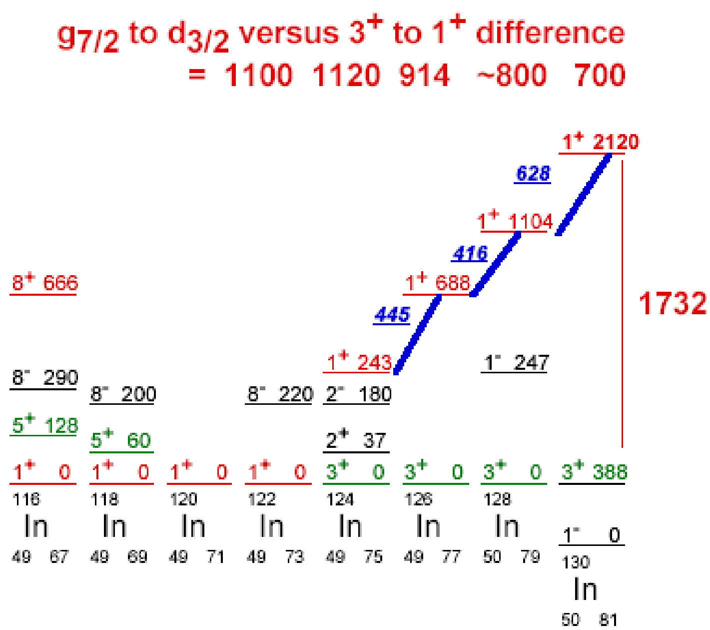

Fig. I-32. Evolution of nuclear structure upon approaching the N = 82 closed shell for the odd-mass Sn nuclides and the odd-odd In nuclides. The structure of ^{130}In is shown graphically relative to the 3^+ levels in the adjacent lighter In nuclides which are the ground states.

of the 1^+ levels in the odd-odd In nuclides are shown as N increases toward the closed shell at N = 82. The position of the 1^+ level is seen to increase by 445 and 416 keV in going from ^{124}In via ^{126}In to ^{128}In, but then jumps by 628 keV to ^{130}In. Added to that larger than expected shift is the dramatic inversion of the 3^+ and 1^- levels which lifts the 1^+ level to a position 2120 keV above the ground state. Earlier shell-model calculations showed a position for the 1^+ level at about 1500 keV and near degeneracy for the 1^- and 3^+ levels.

As a consequence of the renormalization of the $\nu\pi$ monopole interaction for ^{130}Cd decay, the half-lives of the so far unknown N = 82 “waiting-point" nuclei ^{128}Pd to ^{122}Zr will become longer than those predicted by recent shell models (see, e.g. Ref. 11). This leads to a better insight into the buildup of the solar r-process abundance peak at A ≅ 130.

Presently, we are approaching or have already reached the technical limits of studying very neutron-rich nuclei around N = 82 with the currently available ISOL techniques. However, there are still improvements that can be sought. In the near future the remaining r-process “waiting points" may be easier reached with fragmentation processes and their cocktail beams at fragment separators such as the A1900 at MSU. For further improvements and the accessibility of the N = 126 waiting-point nuclei, devices like the rare isotope accelerator RIA are needed.

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*Argonne National Laboratory and University of Maryland, †University of Maryland, ‡Universität Mainz, Germany, §Michigan State University, ¶CERN, Geneva, Switzerland, ||Petersburg Nuclear Physics Institute, Gatchina, Russia, **University of Oslo, Norway, ††Russian Academy of Science, Troitzk, Russia.

[1]I. Dillmann *et al.*, Proceedings of the International Conference on Capture Gamma Rays and Related Topics CGS11, Pruhonice, (World Scientific Press 2003) in print.
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b.2.5. The Strength of Octupole Correlations in Neutron-Rich Xe Isotopes (I. Ahmad, W. Urban,* T. Rzaca-Urban,* J. L. Durell,† W. R. Phillips,† A. G. Smith,† B. J. Varley,† and N. Schulz‡)

Excited states in ^{140}Xe and ^{142}Xe were studied using prompt gamma coincidences measured with the Eurogam2 array of Compton-suppressed Ge spectrometers and a ^{248}Cm fission source. Level schemes of the two nuclei were constructed on the basis of coincidence relationships between gamma rays in ^{140}Xe and ^{142}Xe, and their respective complementary fission fragments. Angular correlations and linear polarization measurements were used to deduce spins and parities of levels. On the basis of these results we report the first observation of an octupole band in ^{142}Xe which is shown in Fig. I-33. The octupole band in ^{140}Xe was extended to higher spins. Properties of octupole bands in Xe isotopes indicate that octupole correlations in these nuclei are weaker than the values in the corresponding Ba nuclei, contrary to theoretical predictions. This may be due to the role of the N = 88 neutron number. The results of this study were published.[1]

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*Warsaw University, Krakow, Poland, †University of Manchester, United Kingdom, ‡Institut de Recherches Subatomiques, Strasbourg, France.

[1]Eur. Phys. J. A **16**, 303 (2003).

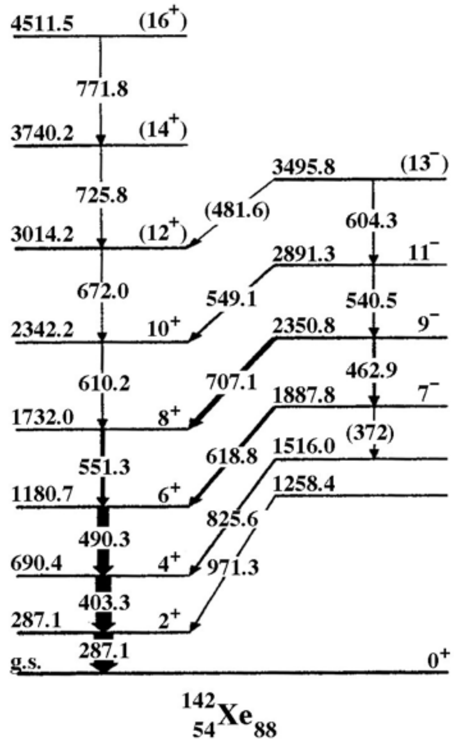

Fig. I-33. A partial level scheme of ^{142}Xe showing the octupole band identified in the present work.

b.2.6. New Low-Spin States in ^{134}Sb Observed in the Decay of ^{134}Sn and Estimate of the Energy of the 7$^-$ Isomer (I. Ahmad, L. R. Morss,* A. Korgul,† H. Mach,‡ B. Fogelberg,‡ W. Urban,† W. Kurcewicz,† T. Rzaca-Urban,† P. Hoff,§ H. Gausemel,§ J. Galy,‡ J. L. Durell,¶ W. R. Phillips,¶ A. G. Smith,¶ B. J. Varley,¶ N. Schulz,|| M. Gorska,** V. I. Isakov,†† K. I. Erokhina,‡‡ J. Blomquist,§§ F. Andreozzi,¶¶ F. Coraggio,¶¶ A. Covello,¶¶ and A. Gargano¶¶)

Excited states in ^{134}Sb ($t_{1/2}$ = 0.75 s), populated in the β^- decay of ^{134}Sn ($t_{1/2}$ = 1.2 s), were studied at the mass separator OSIRIS. Mass separated ^{134}Sn atoms were provided by the OSIRIS facility at Studvik where ^{134}Sn decay was first studied using thermal neutron fission of ^{235}U. In the present work, the ^{134}Sn activity was produced by the fast neutron fission of ^{238}U to improve the experimental sensitivity. The mass separated ^{134}Sn atoms were deposited on aluminized mylar tape. Gamma singles and γ-γ coincidence spectra were measured with a LEPS and a Ge spectrometers, in coincidence with β^- particles detected with a thin plastic scintillator. From these studies a level scheme, shown in Fig. I-34, was constructed. One of the important results of this investigation is the identification of a 13-keV level, which led to a revision of the ^{134}Sb level scheme. The new results are compared with different theoretical calculations and with the known data for the analogous neutron and proton two-particle nucleus ^{210}Bi. On the basis of this comparison, the energy of the $(\pi g_{7/2} \nu f_{7/2})7^-$ isomer is estimated to be about 250 keV, ~100 keV lower than previously reported. The results of this work were published.[1]

*Chemistry Division, Argonne National Laboratory, †Warsaw University, Poland, ‡Uppsala University, Sweden, §University of Oslo, Norway, ¶University of Manchester, United Kingdom, ||IReS, Strasbourg, France, **Katholieke University, Leuven, Belgium, ††Russian Academy of Sciences, Gatchina, Russia, ‡‡Russian Academy of Sciences, St. Petersberg, Russia, §§Royal Institute of Technology, Stockholm, Sweden, ¶¶Universita di Napoli Federico II and Instituto Nazionale di Fisica Nucleare, Italy.

[1]Eur. Phys. J. A **15**, 181 (2002).

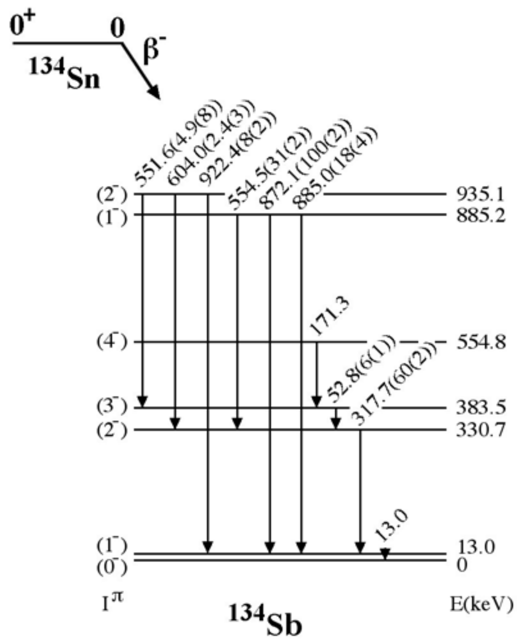

Fig. I-34. A partial level scheme of ^{134}Sb deduced from the results of the present investigation.