C. STRUCTURE OF NUCLEI FAR FROM STABILITY

It has emerged that the key issue of our time in nuclear structure concerns the evolution of nuclear behavior as one moves away from stability by varying the neutron-to-proton ratio. Traditional shell gaps are shown to disappear and new gaps arise. The exact origins of these phenomena still have to be understood, though modification of the spin-orbit effect and other residual interactions appears likely. We continue to probe nuclei along the proton dripline from light masses to heavy. In addition, our efforts to reach neutron-rich nuclei have grown, through fragmentation experiments, traditional fusion of very neutron-rich species, and using multi-nucleon transfer.

c.1. Proton-Rich Nuclei

c.1.1. Beta Decay Measurement of ^{68}Se (R. V. F. Janssens, C. N. Davids, S. M. Fischer, A. M. Heinz, D. Seweryniak, A. Woehr,*'† A. Aprahamian,* P. Boutachkov,* J. L. Galache,* J. Gorres,* M. Shawcross,* A. Teymurazyan,* M. C. Wiescher,* and D. S. Brenner‡)

Precise mass measurements of nuclei along the N = Z line are important input parameters for simulations of the rp-process. Of particular interest is the mass of the ^{68}Se rp-process waiting-point nucleus for determining the possibility of a two-proton capture branch bypassing its slow beta decay. The mass of ^{68}Se was measured via the beta-decay endpoint technique. ^{68}Se was produced at ATLAS by the ^{12}C(^{58}Ni,2n) reaction and, subsequently, implanted onto a moving tape system using the Fragment Mass Analyzer. A mass excess value of (-54189 ± 240) keV was determined from the beta-endpoint measurement of Q_{EC} = 4710(200) keV. The properties of the beta decay process were also studied in detail through the measurement of all characteristic gamma rays.

A paper reporting these results was accepted for publication.

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*University of Notre Dame, †University of Maryland, ‡Clark University.

c.1.2. Shape Co-existence in ^{71}Br and the Question of the Groundstate Spin of ^{71}Kr (C. J. Lister, D. Seweryniak, M. P. Carpenter, S. M. Fischer,* T. Anderson,† P. Kerns,† G. Mesoloras,† D. Svelnys,† D. P. Balamuth,‡ P Hausladen,‡ J Durell,§ B. J. Varley,§ and S. Freeman§)

When the N = Z line approaches the proton dripline above ^{56}Ni, a Coulomb-driven distortion of mirror symmetry is expected as the more proton rich partners become very weakly bound. Urkdal and Hamamoto[1] studied the case of ^{71}Kr and suggest it has a different groundstate spin to its mirror partner ^{71}Br, based on their reinterpretation of β-decay measurements. If so, this would be the first case known of such a change of groundstate spin. We performed a new "inbeam" spectroscopic measurement of ^{71}Br, following the ^{40}Ca(^{40}Ca,2αp) reaction at 145 MeV and using Gammasphere. Many new bands were found, with candidates for at least seven Nilsson bandheads below 1 MeV. Cross-linking decays tightly constrain most of the angular momentum assignments. The bandheads in ^{71}Br have properties consistent with two well defined shapes, prolate and oblate, that are found in the even-A neighbors and appear to be nearly degenerate in energy. The ^{71}Kr β-decay data, seen in the light of this new information on ^{71}Br, rigorously limit the groundstate of ^{71}Kr to $J^{\pi} = 5/2^-$ as originally suggested, and as would be normally expected for the mirror partner of $J^{\pi} = 5/2^-$ ^{71}Br, and in contradiction to the suggestion of Urkdal and Hamamoto.

A second interesting spectroscopic line of investigation for this N = Z+1 nucleus arises from the model of Chasman.[2] His interpretation for the low level density of odd-odd N = Z nuclei, which appears completely valid in this region, implies that the low-lying bandheads in even-Z, N = Z+1 nuclei should all be pure particle states with hole states lying >1 MeV, while the low-lying odd-Z nuclei should all be hole configurations. ^{71}Br appears to provide a good testing ground for this hypothesis, provided a set of rigorous spin and shape assignments can be made.

This very complicated decay scheme is in its final stage of analysis, extracting information on the quadrupole moments of each band from angular distribution data. This is a difficult and painstaking task, but crucial to interpretation in this case of shape co-existence. The work will be published in Physical Review this year.

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*Argonne National Laboratory and DePaul University, †DePaul University, ‡University of Pennsylvania, §University of Manchester, United Kingdom.

[1] P. Urkedal and I. Hamamoto, Phys. Rev. C **58**, 98 (1998).

[2] R. R. Chasman, Phys. Letts. **B577**, 47 (2003).

c.1.3. A Study of ^{72}Kr Shape Co-Exisitence (S. M. Fischer, C. J. Lister, N. J. Hammond, R. V. F. Janssens, M. P. Carpenter, T. Lauritsen, and E. F. Moore)

The N = Z = 36 nucleus ^{72}Kr attracted considerable attention as it appears to be the heaviest N = Z nucleus that can be studied to high spin, so is an ideal candidate for studying angular momentum driven shape changes and the changing role of neutron proton correlations.[1,2,3] Recent Coulomb excitation[4] of a radioactive ^{72}Kr beam dramatically demonstrated low-lying oblate-prolate coexistence, and the presence of a low-lying isomer that decays only by E0 electrons.

We ran a low spin experiment to further elucidate the shape co-existence by finding the non-yrast members of the oblate and prolate bands, and their interband crossing decays. To keep the population of the residues at low spin, the "light" heavy-ion reaction ^{16}O(^{58}Ni,2n)^{72}Kr at 200 MeV was used. The much stronger "2p" reaction channel was monitored to determine the spin distribution in the compound nucleus. Online monitoring suggested the mean entry spin was ~8 h. To compensate for the low cross-section (~50 μb) an intense beam was used, and a target rotating at 300 rpm. Several oxide targets were tested, the best being of SiO_2 of thickness 200 micrograms/cm^2. These targets were quite robust and could withstand ~20 pnA of beam for 24 hrs. During this time the oxygen content declined monotonically, falling to 50% of its stoichemetric value after a day of irradiation. The experiment involved detecting mass A = 72 residues at the FMA focal plane and determining the nuclear charge through energy loss in an ion-chamber. The highly-inverse reaction gave excellent Z-separation. Gammasphere was used to detect gamma radiation in "gated singles" mode.

The data set is under analysis. The long-term target deterioration caused small changes in the mean recoil energy, so the signals in the ion-chamber need careful time-dependent gain modification to achieve optimum Z-resolution. However, the data quality is very high and the prospects for non-yrast spectroscopy is excellent.

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[1] S. M. Fisher, C. J. Lister and D. B. Balamuth, , Phys. Rev. **C67**, 064318 (2003).

[2] N. S. Kelsall et al., Eur. Phys. J. **A20**,(2004) 131.

[3] R. A. Wyss and W. Satula, Acta. Phys. Pol. **B32**, 2457 (2001).

[4] E. Bouchez et al., Phys. Rev. Lett. **90**, 082502 (2003).

c.1.4. A Search for ^{74}Rb Isobaric Analog States (S. M. Fischer, C. J. Lister, N. J. Hammond, R. V. F. Janssens, M. P. Carpenter, T. Lauritsen, and E. F. Moore)

A study of low-spin non-yrast states in ^{74}Rb, similar to the ^{72}Kr investigation (see Sec. c.1.3.), was performed using the ^{40}Ca(^{36}Ar,pn) reaction at 125 MeV which is very close to the Coulomb barrier. The study was aimed at the unknown T = 1 non-yrast states that are the analogs of the ^{74}Kr ground state band and was made in order to determine if Coulomb energy shifts are anomalously large for near-dripline nuclei. Another goal was to determine the separation of the J = 1,T = 0 and J = 0 T = 1 states; a measurement that is pivotal is ascertaining the relative importance of T = 0 and T = 1 residual interactions. Great care was used to populate low spin non-yrast structures. The residue energy was low, only ~1.5 MeV/u, too low for clean separation in an ion chamber, so neutron detectors were used to select the channel of interest, further gated by A = 74 residues from the FMA.

The experiment was conducted successfully. Analysis is in progress. Clear candidates for the analog T = 1 band to above J = 6 were found. A search is underway for other expected low spin structures. However, it is clear that using very heavy ions for low-spin non-yrast spectroscopy is very difficult, as the states of interest are very weakly populated.

c.1.5. Ground-State Bands in the Proton Emitters ^{145,147}Tm (D. Seweryniak, C. N. Davids, M. P. Carpenter, N. Hammond, R. V. F. Janssens, T.-L. Khoo, G. Mukherjee, S. Sinha, A. Robinson,* P. J. Woods,* B. Blank,† T. Davinson,* S. J. Freeman,‡ N. Hoteling,§ Z. Liu,* J. Shergur,§ A. A. Sonzogni,¶ W. B. Walters,§ and A. Woehr||)

The excited states in the moderately deformed proton emitters ^{145,147}Tm were studied using the Recoil-Decay Tagging method. Prompt γ rays were detected in the Gammasphere Ge array. The γ rays were tagged by proton decays observed in a Double-Sided Si Strip Detector placed at the focal plane of the Argonne Fragment Mass Analyzer. Excited states in ^{147}Tm were studied previously using a modest Ge array.[1] Thanks to a much larger γ detection efficiency the ^{147}Tm ground-state band was significantly extended and the unfavored signature sequence was found.

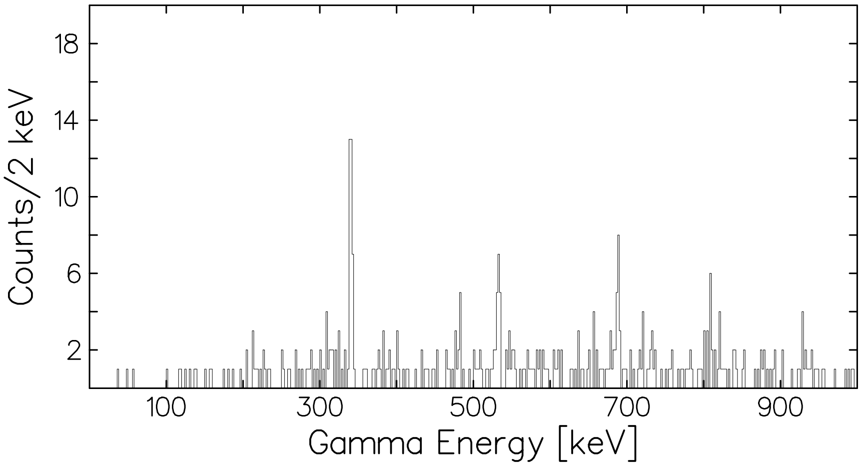

Fig. I-16. Gamma-ray spectrum tagged with ^{145}Tm protons.

The ^{145}Tm ground state decays primarily to the 0^+ ground state in the daughter ^{144}Er. A branch to the 2^+ state was observed recently.[2] The cross section for producing ^{145}Tm is only about 200 nb. The ^{145}Tm half-life is 3 μs. To avoid pileup of protons with implants fast delay-line amplifiers were developed. The performance of the delay-line amplifiers was similar to pulse digitizers used in Ref. 1. As a result, protons with decay times as short as 1 μs were observed. The ground-state band associated with ^{145}Tm is shown in Fig. I-16. In addition, coincidences between the proton fine structure line and the $2^+ \rightarrow 0^+$ γ-ray transition in ^{144}Er were detected at the focal plane of the FMA (see Fig. I-17). This is the first time that coincidences between proton decays and γ rays were seen.

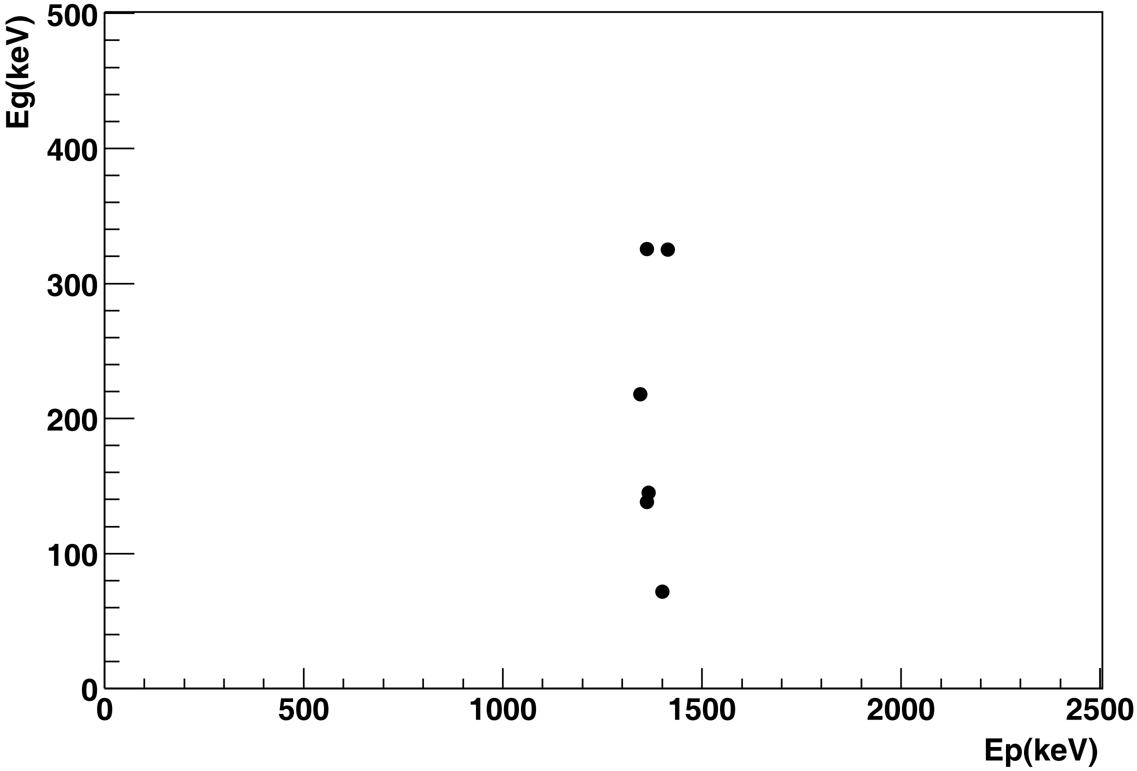

Fig. I-17. Coincidences between ^{145}Tm protons feeding the 2^+ state in the daughter nucleus and $2^+ \rightarrow 0^+$ γ rays.

The calculated deformation changes rapidly from oblate in ^{147}Tm (β_2 = -0.18) to prolate in ^{145}Tm (β_2 = 0.25).[3] On the other hand, the ^{145}Tm proton-decay rate and the branching ratio to the 2^+ state were reproduced using the particle-vibrator model.[4] The decay rates in ^{147}Tm are consistent with the assumption of spherical shape. The dominant γ-ray sequences feeding the ground states in ^{147}Tm and ^{145}Tm have properties of decoupled $\pi h_{11/2}$ bands. The energies of the bottom $15/2^- \rightarrow 11/2^-$ transitions indicate lower deformation than the calculated one in both ^{145}Tm and ^{147}Tm. The $E(19/2^-)/E(15/2^-)$ ratio, equivalent to $E(4^+)/E(2^+)$ for the even-even core, is about 2.5, which is characteristic of a γ-soft rotor, greater than 2.2 for a typical harmonic vibrator, and well below the rotor value of 3.33. This suggest an alternative way of viewing the proton decay in ^{145,147}Tm as emission of the $h_{11/2}$ proton aligned with the angular momentum of the γ-soft deformed core.

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[1] D. Seweryniak *et al.*, Phys. Rev. C 55, R2137 (1997).

[2] M. Karny *et al.*, Phys. Rev. Lett. 90, 012502 (2003).

[3] P. Moeller *et al.*, At. Data Nucl. Data Tables 59, 185 (1995).

[4] C. N. Davids and H. Esbensen, Phys. Rev. C 64, 034317 (2001).

c.1.6. Recoil-Decay Tagging Study of ^{146}Tm* (C. N. Davids, D. Seweryniak, B. Blank, M. P. Carpenter, N. Hammond, R. V. F. Janssens, G. Mukherjee, S. Sinha, A. Robinson,* P. J. Woods,* T. Davinson,* Z. Liu,* S. J. Freeman,† N. Hoteling,‡ J. Shergur, ‡ W. B. Walters,‡ A. Woehr,‡ and A. A. Sonzogni§)

^{146}Tm is an odd-odd proton emitter, lying in the transitional region between predicted deformed and near-spherical shapes. It is potentially a rich source of information regarding the role of the odd neutron in proton decay, since recent work[1] indicates that it emits at least 4 proton groups, with half-lives between 80 and 250 ms. In order to help shed light on the assignment of half-lives to the various groups, we performed an RDT experiment on ^{146}Tm, using Gammasphere to detect prompt γ-rays tagged by protons observed in a double-sided silicon strip detector located at the focal plane of the FMA recoil mass spectrometer. No previous work on the excited states of ^{146}Tm has been reported. The proton spectrum is shown in Fig. I-18. Gamma-ray spectra correlated with proton groups have been observed, and will be used to construct a decay scheme.

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[1] T. N. Ginter *et al.*, Phys. Rev. C **68**, 034330 (2003).

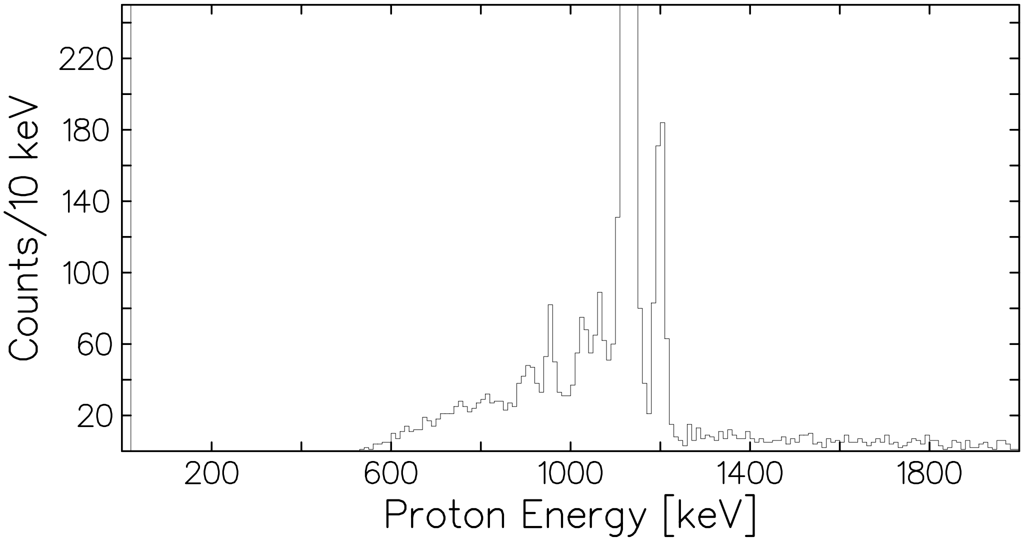

Fig. I-18. Protons from the decay of ^{146}Tm.

c.1.7. Proton Decay Study of ^{150}Lu and ^{150}Lu^{m} (C. N. Davids G. Mukherjee, D. Sewerniak, S. Sinha, P. Wilt, A. P. Robinson,* and P. J. Woods*)

^{150}Lu is an odd-odd nucleus with two proton-emitting states. The ground state emits a proton with energy 1261(4) keV[1]. Two measurements of the half-life yielded values of 35(10) ms[1] and 49(5) ms[2]. The short-lived isomeric state emits a proton with energy 1295(15) and half-life 30^{+95}_{-15} μs[2]. Since the large uncertainties in these quantities limits the precision with which the results can be compared with existing models for proton decay rates, the proton decay of ^{150}Lu was re-investigated. We produced ^{150}Lu by bombarding a ^{96}Ru target with a 297 MeV beam of ^{58}Ni from ATLAS. Our measurement of the half-life of the ground-state group yielded a value of 43(5) ms. Using the new delay-line shaping amplifiers, we made a more precise measurement of the energy and half-life for the isomeric state, obtaining Ep = 1286(6) keV and $T_{1/2}$ = $53^{+13}_{-8.7}$ μs. Using a particle-vibration coupling model to describe the decay of ^{150}Lu^{m}, a value of 12.8 μs was obtained, assuming the emitted proton to come from the $d_{3/2}$ orbital. This yields a spectroscopic factor of 0.24(6)[3], to be compared with the expected value of 0.67 from a low-seniority shell model calculation[4]. No information is available on the spin of either proton-emitting state in ^{150}Lu. Such a determination would help to resolve whether ^{150}Lu has a deformed or near-spherical shape.

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[1] P. J. Sellin *et al.*, Phys. Rev. C **47**, 1933 (1993).

[2] T. N. Ginter *et al.*, Phys. Rev. C **61**, 014308 (1999).

[3] C. N. Davids and H. Esbensen, Phys. Rev. C **64**, 034317(2001).

[4] C. N. Davids *et al.*, C **55**, 2255 (1997).

c.2. Neutron-Rich Nuclei

c.2.1. Is the Nuclear Spin-Orbit Interaction Changing with Neutron Excess?

(J. P. Schiffer, C.-L. Jiang, R. Lewis, K. E. Rehm, S. Sinha, S. J. Freeman,*
J. A. Caggiano†, C. Deibel†, A. Heinz†, A. Parikh† P. D .Parker†, and J. S. Thomas‡)

The single-particle character of nuclei underlies much of our understanding of nuclear structure. However, the sequence of single-particle states, especially the magnitude of the spin-orbit splitting, is largely empirical. The spin-orbit splitting in heavier nuclei is responsible for the "magic numbers" of closed shells, formed as the highest angular-momentum state is pushed down by the interaction to energies comparable to that of the next lower oscillator shell. There is not yet a quantitative understanding of the microscopic origins of the spin-orbit term.

Experimentally, data exist on spin-orbit doublets with low orbital angular momentum. Those with higher ℓ are experimentally inaccessible, since the splitting is so large that both members of the doublet cannot be observed simultaneously in the same nucleus. The spin-orbit splitting may be studied somewhat more indirectly by comparing the energies of the ℓ – 1/2 member of the highest ℓ-value in a particular oscillator shell that is pushed up in energy, (for example, $g_{7/2}$ or $h_{9/2}$ with those of the ℓ + 1/2 state from the next oscillator shell, which is pushed down (for example, $h_{11/2}$ or $i_{13/2}$).

A proton outside the closed shell of 50 protons provides the best opportunity for this investigation. Figure I-19 shows the binding energies of the 51-st proton in the first $7/2^+$ and $11/2^-$ states from data on the odd Sb isotopes. Since both these orbits are nodeless – their radial wave functions, and therefore sensitivity to changes in the potential are likely to be quite similar. However, their separation in energy changes by over 2 MeV. Taken at face value this could mean a reduction in the spin-orbit interaction by that amount. But, if there were strong mixing with more complicated states and subsequent fragmentation of single-particle strength, the observed change might perhaps be accounted for without requiring such a reduction.

The (α,t) reaction on all the stable, even Sn isotopes was studied. The angular momentum transfers with ℓ = 4 and 5 are well matched, and the cross sections are relatively large. The ESTU tandem Van de Graaf accelerator at Yale University delivered a beam of α particles at an energy of 40 MeV onto isotopically enriched Sn. The tritons were momentum analyzed in an Enge split-pole magnetic spectrograph.

A typical spectrum is shown in Fig. I-20(a), along with angular distributions in Fig. I-20(b) compared with distorted-wave Born approximation (DWBA) calculations using standard parameters. The spectroscopic factors are given in Table I-1 and they are consistent with being all equal at about 1.0, suggesting little fragmentation.

The DWBA calculations were carried out using both the codes DWUCK and PTOLEMY using a range of distorting potentials from the literature. The lowest $7/2^+$ and $11/2^-$ states in the Sb isotopes seem to have consistent spectroscopic factors, and within the usual constraints of transfer reactions exhibit near-single-particle-like $g_{7/2}$ and $h_{11/2}$ character.

The simplest explanation is that the observed energy systematics are a consequence of a decreasing overall spin-orbit splitting, with a suggestion that the effect is primarily in the energy of the intruder $h_{11/2}$ state.

A similar situation occurs in the N = 83 nuclei for the separation of the $h_{9/2}$ and $i_{13/2}$ neutron states. The available data on this energy difference are shown in the lower part of Fig. I-21, but the information on spectroscopic factors is not very quantitative, similar to the situation for the Z = 51 isotopes before the current work. When beams of radioactive nuclei become available with sufficient intensity these trends can be explored further. In particular, it is interesting to note that the data seem to suggest that the spin-orbit interaction for the unoccupied orbits has diminished to something on the order of half its normal value.

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*Argonne National Laboratory and University of Manchester, United Kingdom, †Yale University, ‡Rutgers University.

Table I-1 Spectroscopic factors for the $g_{7/2}$ and $h_{11/2}$ states.

Nucleus	$S_{7/2}$	$S_{11/2}$
^{113}Sb	0.99	0.84
^{115}Sb	1.10	0.93
^{117}Sb	0.95	0.97
^{119}Sb	0.88	0.99
^{121}Sb	1.13	1.12
^{123}Sb	0.98	1.00
^{125}Sb	1.10	1.12

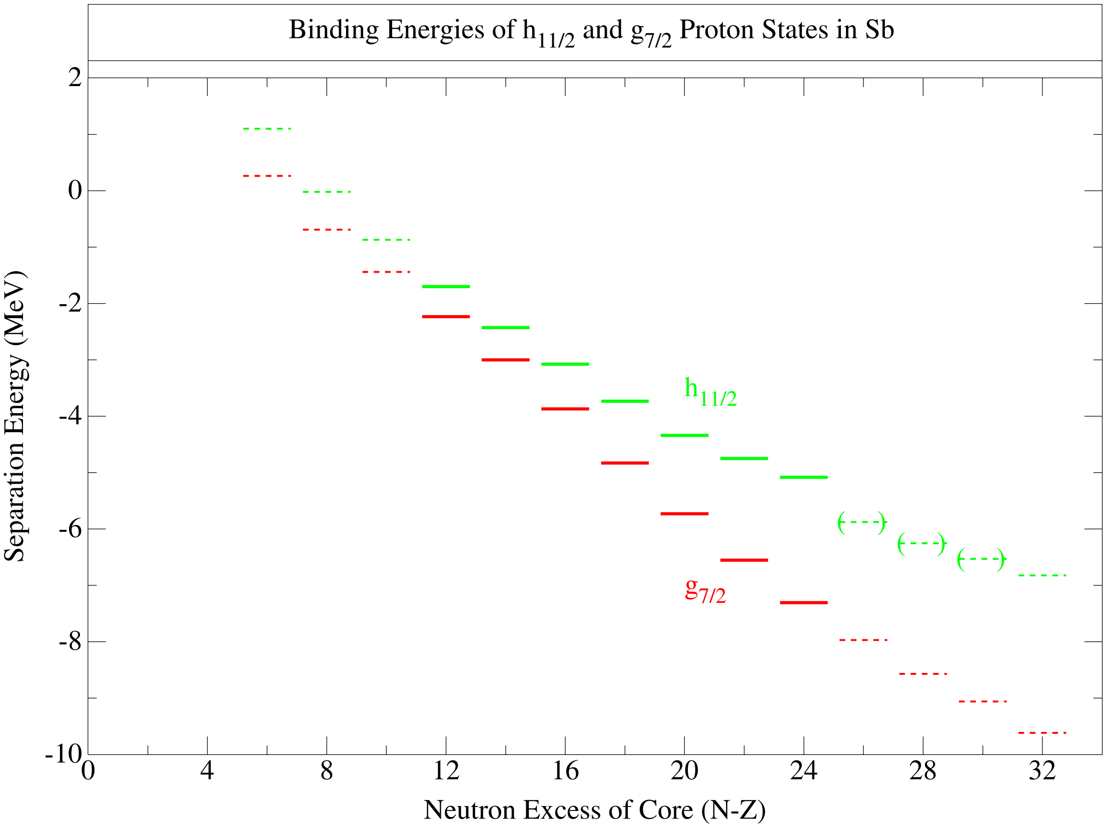

Fig. I-19. Present information on the lowest 7/2$^+$ and 11/2$^-$ states in odd-A Sb isotopes. The solid lines indicate the states that are accessible to proton-transfer reactions, the dashed lines are only known from gamma-ray spectroscopy, and the parentheses indicate tentative unpublished assignments.

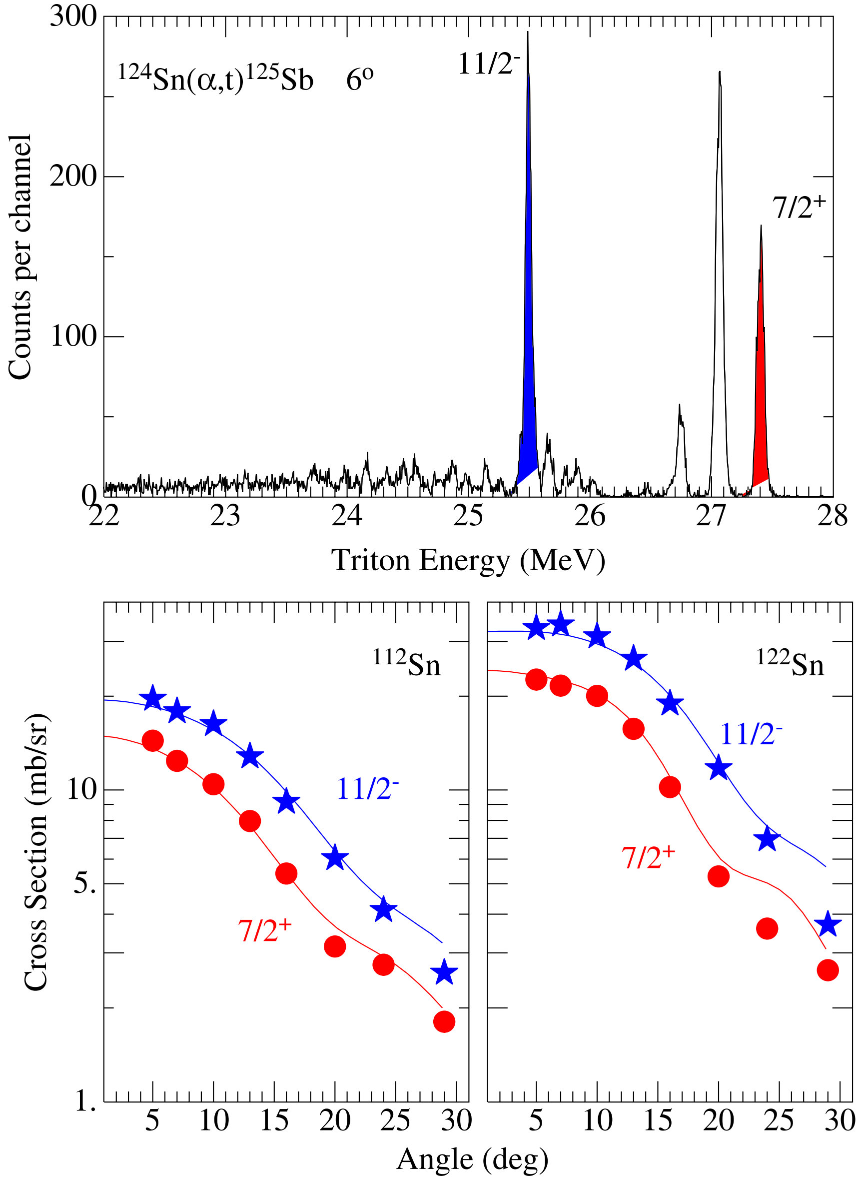

Fig. I-20. On top is a spectrum from the proton-adding (α,t) reaction on ^{124}Sn with the two relevant states shaded. The lower part of the figure shows angular distributions for corresponding states with two Sn isotopes. The lines are DWBA calculations with standard parameters.

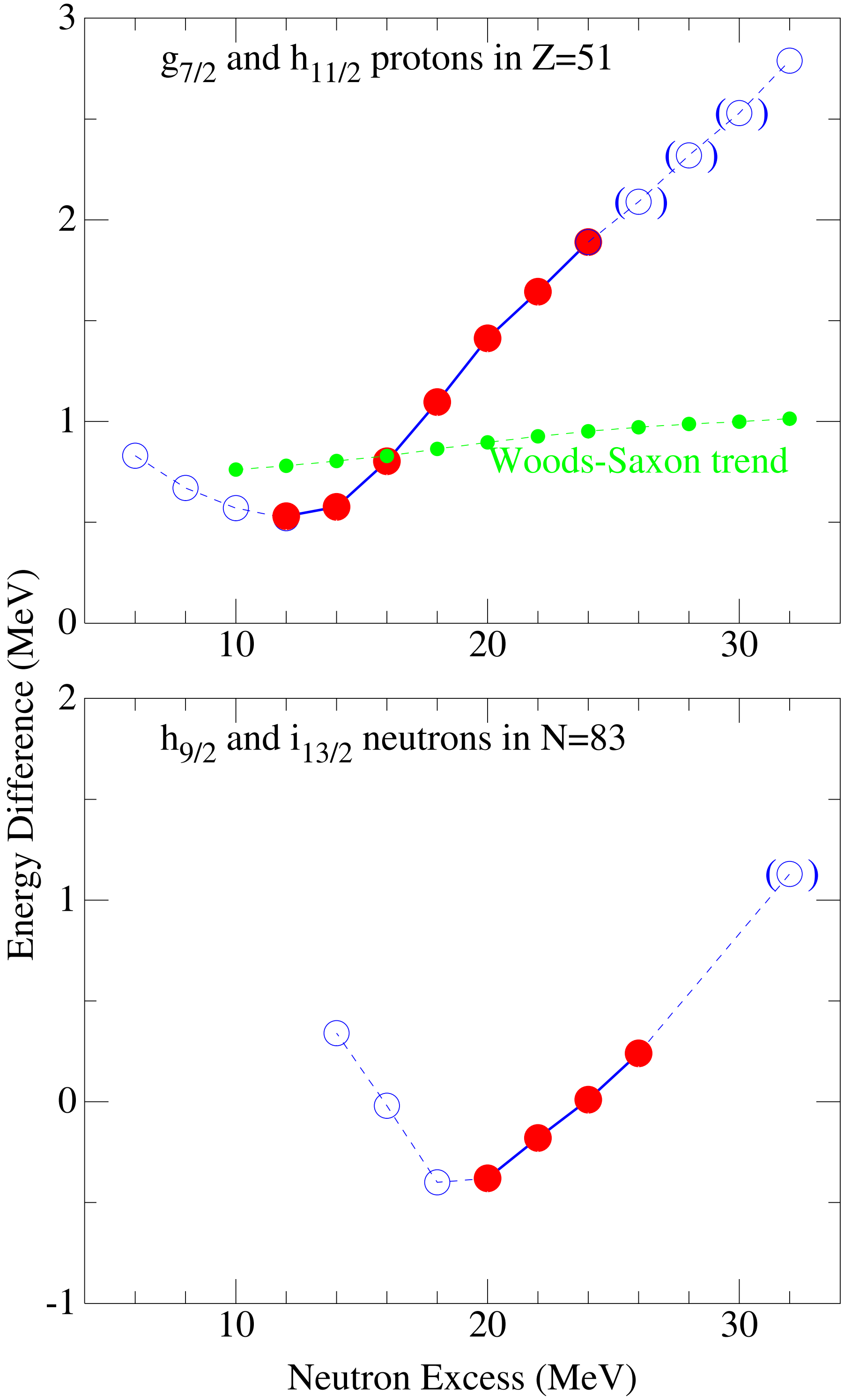

Fig. I-21. The top part of the figure shows the separation between the 7/2$^+$ and 11/2$^-$ states in the odd Sb isotopes. The solid points are for the cases that can be reached by proton transfer from stable Sn targets which are the subject of this work. The open symbols are from gamma-ray spectroscopy and those in parentheses are more tentative. The green points indicate the trend from a Woods-Saxon potential where the radii varied as $A^{1/3}$ and the depth was adjusted to fit the binding energy of the $g_{7/2}$ proton.

c.2.2. Structure of Neutron-Rich Cr Isotopes: Inadequacy of the fp Model Space and the Onset of Deformation (R. V. F. Janssens, M. P. Carpenter, N. J. Hammond, T. Lauritsen, C. J. Lister, T. L. Khoo, G. Mukherjee, D. Seweryniak, S. J. Freeman,* P. Chowdhury,§ S. M. Fischer,¶ S. Zhu,** A. N Deacon,* J. F. Smith,* S. L. Tabor,‡ B. J. Varley,* M. Whitehead,* I. V. Calderin,‡ S. L. Tabor,‡ B. A. Brown,† and M. Honma||)

The full $\pi f_{7/2}\nu fp$ model space is small enough for large-scale calculations to be performed and new effective interactions within it were developed recently.[1] These interactions have had some success in descriptions of low-lying excited states in neutron-rich fp-shell nuclei near N = 28, such as the weakening N = 32 subshell closure with increasing Z. However, predictions of an N = 34 subshell closure do not appear to be substantiated by the experiment.[2] Knowledge of excited states has, so far, been unavailable towards the mid-shell region, and the effective interaction and the extent of the applicability of the model space have not yet been tested extensively. The strength of the N = 40 gap and the influence of the $g_{9/2}$ orbital, with its potential to induce deformation, have therefore not been investigated fully.

The low-lying levels in ^{59,60}Cr were studied with the ^{13,14}C(^{48}Ca,2p) reactions at a beam energy of 130 MeV, using Gammasphere in combination with recoil measurements using the Fragment Mass Analyzer and a segmented-anode ion chamber. The residues of interest were selected and identified on the basis of *A/q*, energy-loss and time-of-flight measurements. This is the first time that multiple charged-particle channels were isolated in this region.

Data on ^{59}Mn, produced via the pn-evaporation channel from reactions on a ^{13}C target, set limits on the spin of the ground state in ^{59}Cr, enabling some spin-parity assignments of excited states to be made. The structure of ^{59}Cr (see Fig. I-22) obtained in this study is clearly inconsistent with results of shell-model calculations within the full fp shell and requires inclusion of the $\nu g_{9/2}$ orbital. The sequence of states is understood within Nilsson model calculations assuming a moderate oblate ground-state deformation. These results have recently been submitted for publication.

The experiment investigating the structure of ^{60}Cr produced in reactions on a radioactive ^{14}C target took place only recently and the data analysis is on-going. It is anticipated that the level scheme will provide further information on the development of deformation into the mid-shell region.

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*University of Manchester, United Kingdom, †Michigan State University, ‡Florida State University, §University of Massachusetts, ¶De Paul University, ||University of Aizu, Fukushima, Japan, **University of Notre Dame.

[1] M. Honma, T. Otsuka, B. A. Brown, and T. Mizusaki, Phys. Rev. C **65**, 061301 (2002).

[2] S. N. Liddick *et al.,* Phys. Rev. Lett. **92**, 072502 (2004).

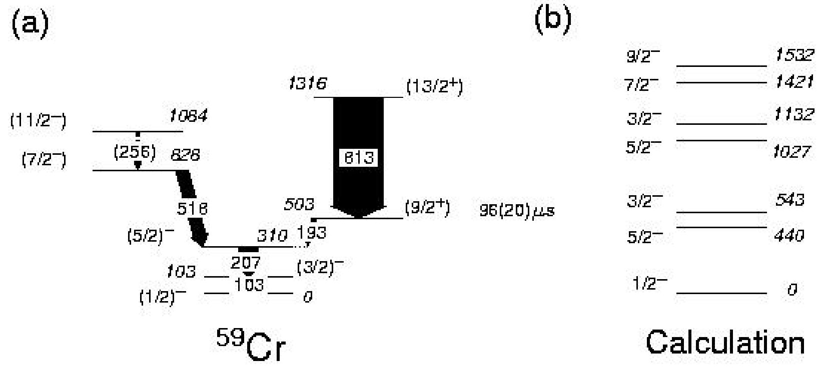

Fig. I-22. ^{59}Cr level scheme obtained from the present measurement compared with the result of a shell model calculation within the full fp shell basis using the GXPF1 interaction. The failure of the calculation to reproduce the data is indicative of the need to take the role of the shape driving $g_{9/2}$ orbital into account.

c.2.3. Lowest Excitations in ^{56}Ti and the Predicted $N = 34$ Shell Closure (R. V. F. Janssens, M. P. Carpenter, S. N. Liddick,* P. F. Mantica,* B. A. Brown,* A. C. Morton,* W. Fornal,‡ F. Mueller,* A. Stolz,* B. E. Tomlin,* J. Pavan,† S. L. Tabor,† M.Wiedeking,† R. Broda,‡ M. Honma,§ T. Mizusaki,¶ and T. Otsuka‖)

Recent experimental characterization of the subshell closure at $N = 32$ in the Ca, Ti, and Cr isotones[1,2] stimulated shell-model calculations that indicated the possibility that the $N = 34$ isotones of these same elements could exhibit characteristics of a shell closure, namely, a high energy for the first excited 2^+ level.[3] To that end, we studied the decay of ^{56}Sc produced in fragmentation reactions and identified new gamma rays in the daughter N = 34 isotone ^{56}Ti.

The parent nuclide ^{56}Sc, along with several other neutron-rich nuclei, was produced using the facilities at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. A primary beam of ^{86}Kr was accelerated to 140 MeV/u using the coupled K500 and K1200 cyclotrons and fragmented in a 343 mg/cm^2 ^{9}Be target placed at the object position of the A1900 fragment separator. The desired isotopes were separated in the A1900 and implanted into a 4-cm × 4-cm × 1500-μm double-sided Si strip detector (DSSD), segmented into 40 1-mm strips in the *x* and *y* dimensions. This detector is part of the dedicated beta-decay station at the NSCL.[4] β-delayed γ rays were monitored using 12 HPGe detectors from the MSU Segmented Germanium Array (SeGA). Five transitions were assigned to the decay of ^{56}Sc, with the most intense being a 1127-keV γ ray that is proposed as deexciting the first 2^+ state in ^{56}Ti.

The fact that the first 2^+ level is found at an energy of 1127 keV is quite surprising as it is located well below the expected position that would indicate the presence of an $N = 34$ shell closure in ^{56}Ti. This result cannot be explained with shell model calculations for the full *fp* shell using the GXFP1 interaction. It can possibly be explained if the $\nu f_{5/2}$ orbital is lower by roughly 0.8 MeV than previously thought. To preserve the calculated energies of the $\nu f_{5/2}$ level in higher-*Z* nuclei, a weaker monopole interaction between the $\pi f_{7/2}$ and $\nu f_{5/2}$ states would also be required. Further theoretical work is in progress.

A paper reporting these results was recently published.[4]

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[1] R. V. F. Janssens *et al.*, Phys. Lett. **B546**, 55 (2002).

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

[3] M. Honma *et al.*, Phys. Rev. C **65**, 061301 (2002).

[4] S.N. Liddick *et al.,* Phys. Rev. Lett. **92**, 072502 (2004).

c.2.4. Level Structure of ^{56}Ti and the Possible Shell Gap at $N = 34$ (R. V. F. Janssens, S. Zhu, M. P. Carpenter, N. Hammond, T. Lauritsen, C. J. Lister, E. F. Moore, D. Seweryniak, F. G. Kondev,§ S. Freeman,‡ B. Fornal,* R. Broda,* W. Krolas,* T. Pawlat,* J. Wrzesinski,* P. J. Daly,† Z. W. Grabowski,† S. Liddick,¶ P. Mantica,¶ and B. Tomlin¶)

A recent beta decay measurement[1] established the first excited state of ^{56}Ti to be located at 1127 keV; i.e., at a significantly lower energy than predicted by shell model calculations with the new full *fp* shell effective interaction GXFP1.[2] This result is somewhat of a surprise in view of the success of the calculations in accounting for the level structure of many neutron-rich nuclei just above ^{48}Ca.[2] In particular, the level

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[1] S. Liddick *et al.*, Phys. Rev. Lett. **92**, 072502 (2004).

[2] M. Homna *et al.*, Phys. Rev. C **65**, 061301 (2002).

[3] R. V. F. Janssens *et al.*, Phys. Lett. **B546**, 55 (2002).

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

sequences of the Ti and Cr isotopes, and the observed sub-shell closure at *N = 32* in ^{54}Ti[3] and ^{56}Cr[4] were reproduced satisfactorily.

Further information on the neutron-rich Ti isotopes was obtained at Gammasphere in a study of complex reactions of 330 MeV ^{48}Ca projectiles with a thick ^{238}U target. Coincidence cubes (γγγ) and hypercubes (γγγγ) were constructed and from the analysis new information was obtained on the level structures of neutron-rich nuclei around ^{48}Ca. In particular, the level scheme of ^{56}Ti has now been firmly delineated up to 6$^+$, tentatively up to 8$^+$, giving further insight into shell structure above ^{48}Ca. The new level scheme is compared with those of the other neutron-rich Ti isotopes in Fig. I-23. The sequences of states in ^{56}Ti and ^{52}Ti are strikingly similar, implying that the interactions at work on either side of the *N = 32* sub-shell closure are of approximately the same strength. Calculations to account for these results are in progress as is the detailed analysis of other reactions products.

A paper reporting the ^{56}Ti results is being prepared for publication.

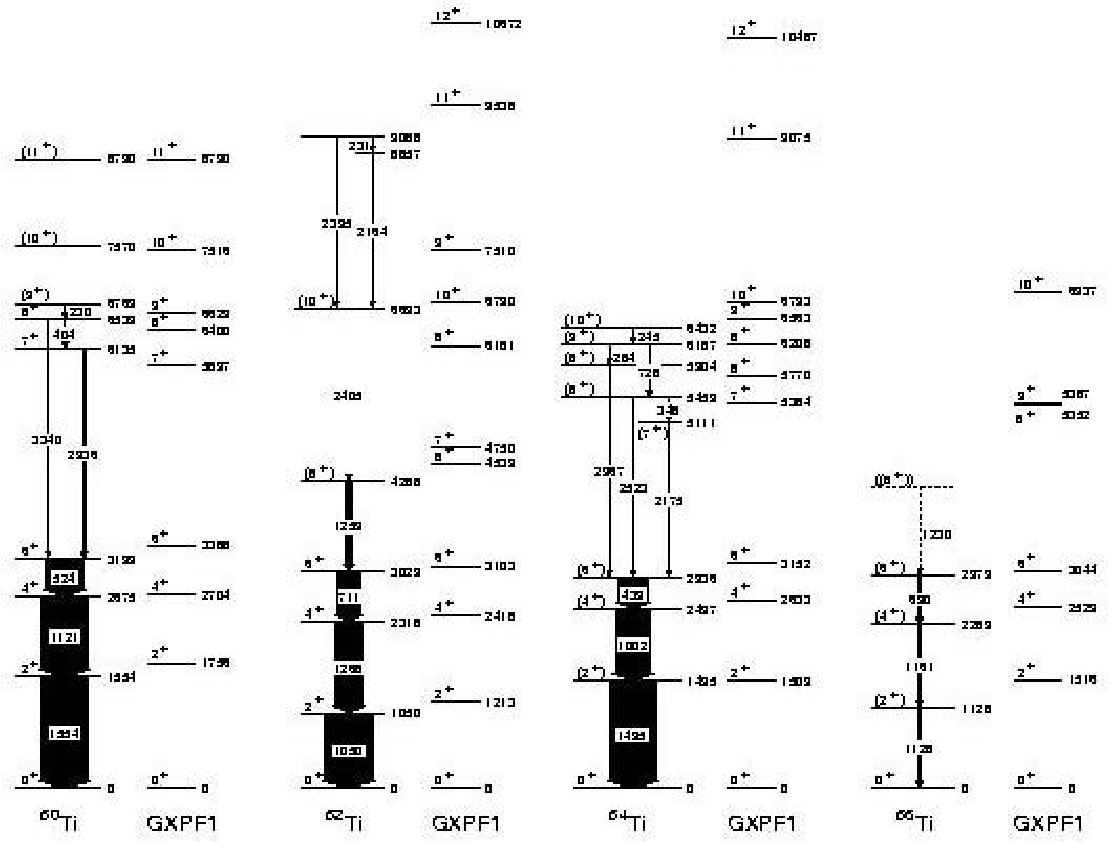

Fig.I-23. ^{56}Ti level scheme obtained from the present measurement compared with the corresponding level structure in other even-even Ti isotopes and with the results of shell model calculations with the GXPF1 interaction.

c.2.5. Reduced Transition Probabilities to the First 2^+ State in ^{52,54,56}Ti (R. V. F. Janssens, M. P. Carpenter, F. G. Kondev, P. Chowdhury,‡ D.-C. Dinca,* A. Gade,* D. Bazin,* C. M. Campbell,* J. M. Cook,* A. Deacon,§ T. Glasmacher,* J.-L. Lecouey,* S. N. Liddick,* P. F. Mantica,* W. F. Mueller,* H. Olliver,* K. Starosta,† J. R. Terry,* B. A. Tomlin,* K. Yoneda,* S. J. Freeman,§ R. Broda,† and B. Fornal†)

The neutron-rich Ti nuclei were the subject of much interest recently because of experimental evidence for a sub-shell closure at $N = 32$ in neutron-rich nuclei just above ^{48}Ca[1,2] and the development of a new effective interaction GXPF1[3] predicting a shell gap at N = 34. Interestingly, and perhaps surprisingly, the latter calculations do not appear to be substantiated by a recent beta-decay study of the level structure of ^{56}Ti.[4]

In order to gain further insight in these nuclei, an experiment was undertaken at the National Superconducting Cyclotron Laboratory where the titanium isotopes with A = 52, 54, and 56 were studied using intermediate-energy Coulomb excitation in inverse kinematics. ^{52,54,56}Ti fragments were produced via fragmentation of 130 MeV/u ^{76}Ge^{30+} primary beam at about 9 pnA average intensity on a ~300 mg/cm^2 ^{9}Be target. Following separation of the desired fragments in the A1900 separator[5], the beam was directed onto a ^{197}Au target. The Coulomb excitation process was tagged by requiring a coincidence between scattered Ti nuclei identified in the S800 magnetic spectrograph[6] and gamma rays detected with the Segmented Germanium Array (SeGA).[7]

The analysis is in progress. The measured B(E2; $0^+ \rightarrow 2^+$) rates will be compared with results of shell model calculations using a number of modern effective interactions.

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

[2] R. V. F. Janssens *et al*., Phys. Lett. **B546**, 55 (2002).

[3] M. Honma *et al*., Phys. Rev. C **65**, 061301 (2002).

[4] S. Liddick *et al*., Phys. Rev. Lett. **92**, 072502 (2004).

[5] D. J. Morrissey *et al*., Nucl. Instrum. Methods **B203**, 90 (2003).

[6] D. Bazin *et al*., Nucl. Instrum. Methods **B204**, 629 (2003).

[7] W. F. Mueller *et al*., Nucl. Instrum. Methods **A466**, 492 (2001).

c.2.6. New Bands and Spin Parity Assignments in ^{111}Ru (I. Ahmad, W. Urban,* T. Rzaca-Urban,* Ch. Droste,* S. G. Rohozinski,* J. L. Durell,† W. R. Phillips,† A. G. Smith,† B. J. Varley,† N. Schulz,‡ and J. A. Pinston§)

Levels in ^{111}Ru, populated in the spontaneous fission of ^{248}Cm, were studied by prompt gamma ray spectroscopy with the EUROGAM2 array. Spins and parities of levels were deduced from measurements of angular correlations, linear polarizations, and conversion coefficients. The gamma ray transitions, observed in the present work and those measured in previous studies, were used to construct a level scheme shown in Fig. I-24. The bands in Fig. I-24 are interpreted as neutron excitations into Nilsson orbitals originating from $h_{11/2}$, $g_{9/2}$ and $s_{1/2}$ spherical shell states. The deformed $\Omega = 1/2$ band, which contains large components of $d_{3/2}$, $d_{5/2}$ and $g_{7/2}$ shell states, was observed for the first time in this mass region. The results of this study were published.[1]

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[1] W. Urban *et al*., Eur. Phys. J.A **22**, 231 (2004).

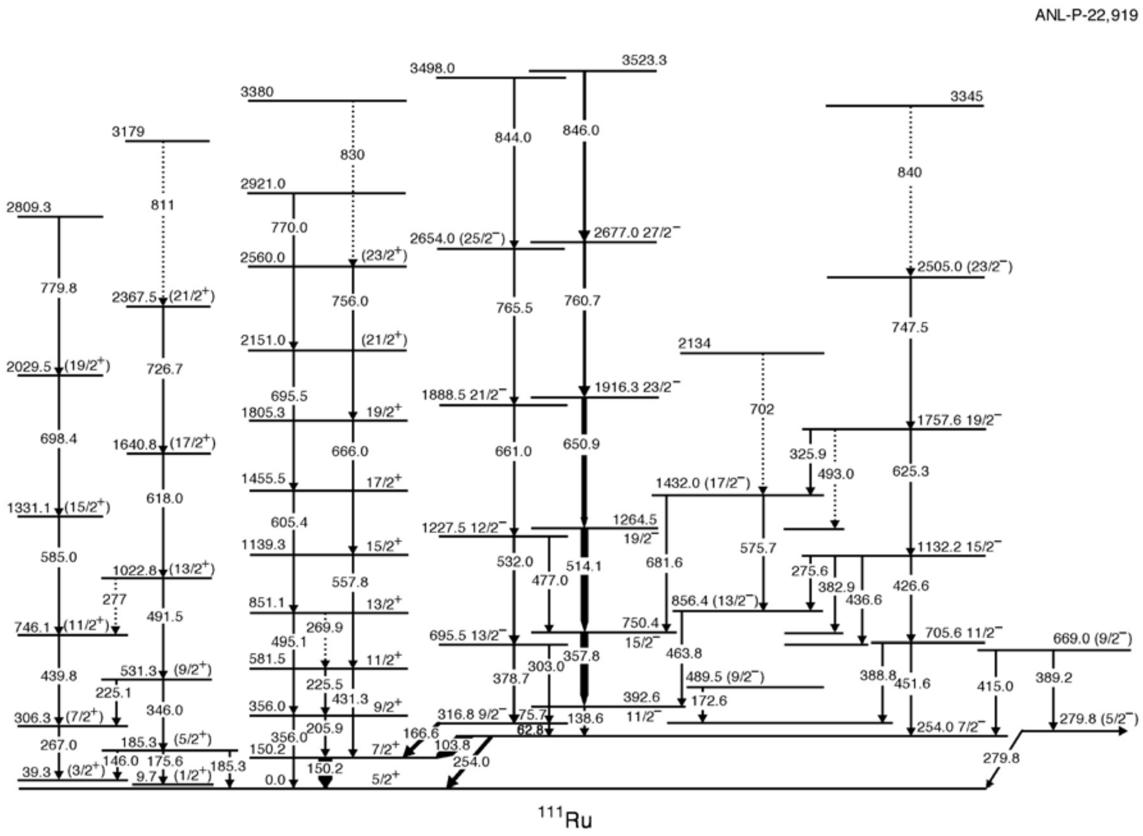

Fig. I-24. A partial level scheme of ^{111}Ru showing the new bands observed in the present work.

c.2.7. The Influence of $\nu h_{11/2}$ Occupancy on the Magnetic Moments of Collective 2^+ States in A ~ 100 Fission Fragments (I. Ahmad, J. P. Greene, M. P. Carpenter, T. Lauritsen, C. J. Lister, R. V. F. Janssens, D. Seweryniak, F. G. Kondev,* A. G. Smith,† D. Patel,† G. S. Simpson,† R. W. Wall,† J. F. Smith,† O. J. Onakanmi,† B. J. P. Gall,‡ O. Dorveaux,‡ and B. Roux‡)

The magnetic moments of 2^+ states in thirteen neutron-rich nuclei in the mass 100 regions were measured by time-integral perturbed angular correlations. The experiment was performed with the Gammasphere, located at Argonne. The neutron-rich nuclei were produced by the spontaneous fission of ^{252}Cf. Approximately 100 μCi of ^{252}Cf was electroplated on a 15-mg/cm^2 Fe foil. The activity was covered by a similar Fe foil on which In was evaporated and the sandwich was passed through a roller under high pressure. This source was placed in the center of the Gammasphere for gamma-gamma coincidence measurements. A pair of small permanent magnets provided 0.2 T field in the plane of the foil and the beam direction. The direction of the magnetic field was reversed every eight hours by rotating the magnet assembly through 180 degrees. Using the method outlined in our previous paper[1], the g factors for several nuclei were determined. These are shown in Fig. I-25 along with previous data. Also included in the figure are predictions of the IBA2 model using values of (g_π, g_ν) given in the legend. The agreement between the measurement and the IBA2 model suggests that the filling of the low-omega $h_{11/2}$ orbitals is responsible for the onset of collectivity in the mass 100 region. The results of this study were published.[2]

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[1] D. Patel *et al.*, J. Phys. G **28**, 649 (2002).

[2] A. G. Smith *et al.*, Phys. Lett. **B591**, 55 (2004).

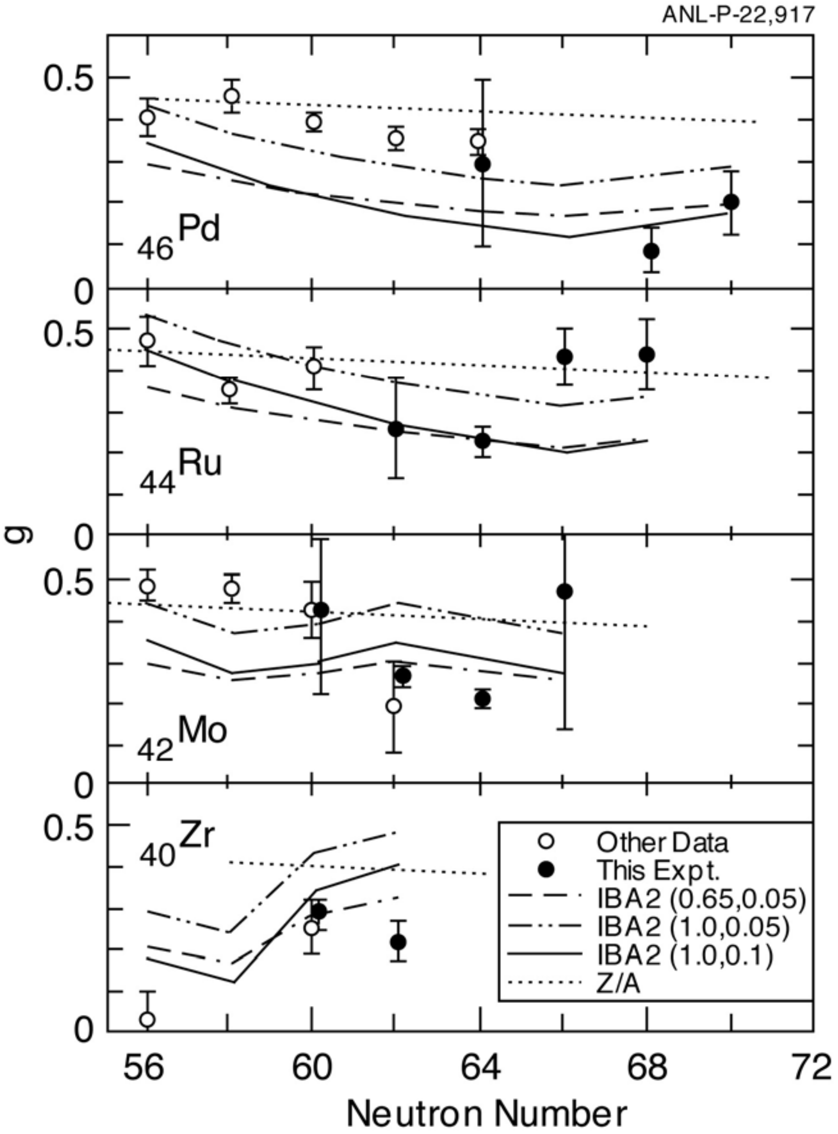

Fig. I-25. Values of g factor measured in the present work in the mass 100 region along with previous measurements. The experimental results are compared with the predications of IBA2 model using values of (g_π, g_ν) given in the legend.

c.2.8. Observation of Octupole Excitations in ^{141}Cs and ^{143}Cs Nuclei (I. Ahmad, W. Urban,* T. Rzaca-Urban,* J. L. Durell,† W. R. Phillips,† A. G. Smith,† B. J. Varley,† and N. Schulz‡)

Calculations indicate that the neutron-rich Cs isotopes are octupole deformed. We therefore investigated the level structure of ^{141}Cs and ^{143}Cs populated in the spontaneous fission of ^{248}Cm. The experiment was performed with the EUROGAM2 array of Compton-suppressed Ge detectors. In addition to gamma-gamma coincidence measurements, angular correlations and linear polarizations were also determined which helped in spin and parity assignments to ^{141}Cs and ^{143}Cs levels. Our data show that ^{141}Cs and ^{143}Cs are octupole deformed as predicted by theory. The level scheme of ^{143}Cs is shown in Fig. I-26 and the results of the present work are published.[1]

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[1] Phys. Rev. C **69**, 017305 (2004).

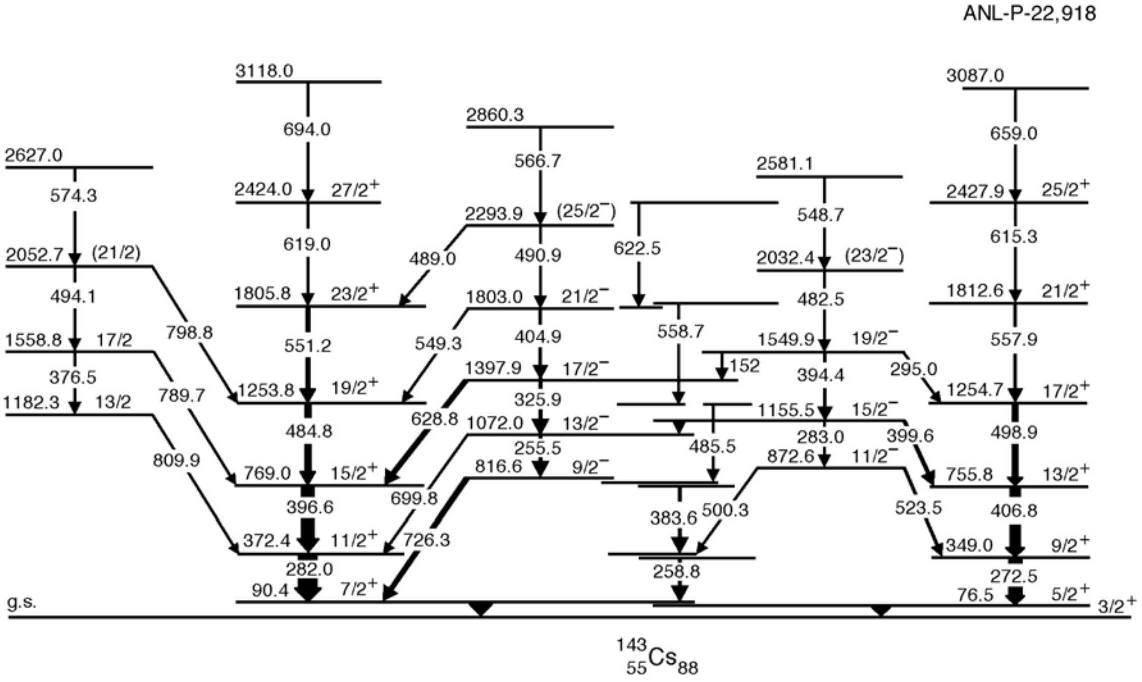

Fig. I-26. A partial level scheme of ^{143}Cs.