# C. SPECTROSCOPY OF TRANS-LEAD NUCLEI

The structure and stability of the very heaviest elements continues as a forefront area of research, both theoretically and experimentally, as it provides one of the ultimate tests of our understanding of nuclear binding. Progress in understanding the shapes of nuclei and the sequence of quantum states near the Fermi surface of the very heaviest nuclei continues on many fronts. This progress will lead to an improved vision of the location and stability of possible "superheavy" elements. In addition, investigations of the spin and excitation dependence of the fission barrier in these very heavy systems may help guide future synthesis experiments. The development of a new FMA chamber with a large target wheel and with the possibility of gas cooling, combined with the production of very intense heavy-ion beams has opened the way for synthesizing nuclei beyond Z = 104, $^{257}$Rf, the highest atomic number nucleus studied at ATLAS to date.

## c.1. Coulomb Excitation and Few Nucleon Transfer Reactions in $^{209}$Bi + $^{248}$Cm at 1450 MeV

(K. Abu Saleem,* R. V. F. Janssens, M. P. Carpenter, I. Ahmad, J. P. Greene, J. Caggiano, A. Heinz, T. L. Khoo, T. Lauritsen, C. J. Lister, D. Seweryniak, A. Sonzogni, F. G. Kondev,† I. Wiedenhöver,‡ G. Hackman,§ P. Chowdhury,¶ D. Cline,|| and A. O. Machiavelli**)

For the last few years, the behavior of the actinide nuclei at high spin has been investigated at ATLAS using the so-called "Unsafe" Coulex technique. In earlier reports we have described our work on the $^{232}$Th nucleus studied by bombarding the target with a 1400 MeV $^{209}$Bi beam from ATLAS. The Gammasphere array was used to detect the gamma rays of interest. In this pilot experiment 11 rotational bands were observed in the Coulomb excitation channel. In addition, several rotational bands associated with nucleon transfer/pick-up channels were identified as well.

The success of this experiment enticed us into continuing this project on other important actinide nuclei, and an experiment was performed using the $^{209}$Bi + $^{248}$Cm reaction at 1450 MeV (roughly 14% above the Coulomb barrier). Again, the Gammasphere array was used to collect the data. The analysis has revealed four rotational bands in the target nucleus. The yrast sequence (see Fig. I-26) has now been traced up to $32^+$, considerably higher than reported earlier.[1] The spin assignments (tentatively proposed in Ref. 1) for the octupole band have been firmly established, and new out-of-band transitions have been placed in a coherent level scheme. Two additional positive parity bands have been assigned to this nucleus as well. In addition to rotational bands in the Coulomb excitation channel, the yrast band of $^{246}$Cm, populated in the two-neutron pick-up channel, has also been observed. Several other rotational cascades are present in the data. They are still under investigation and have not yet been assigned to a specific nucleus.

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[1]G. Hackman *et al*., Phys. Rev. C **57**, R1506 (1998).

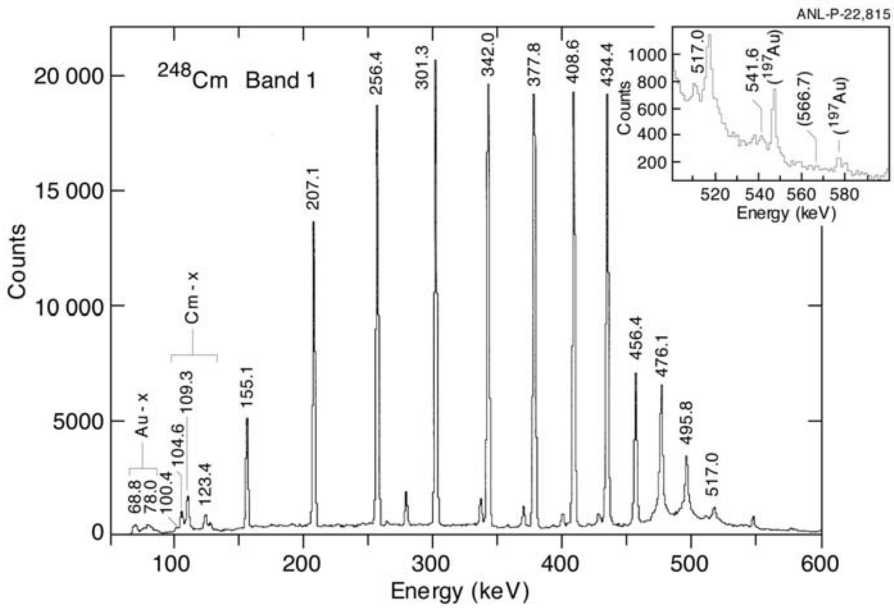


*Fig. I-26. Coincidence spectrum produced from double gates on transitions in the yrast band of $^{248}$Cm.*

## c.2. Coulomb Excitation and Few Nucleon Transfer Reactions with $^{209}$Bi Beams on $^{237}$Np and $^{241}$Am Targets (K. Abu Saleem,* R. V. F. Janssens, M. P. Carpenter, I. Ahmad, J. P. Greene, J. Caggiano, A. Heinz, T. L. Khoo, T. Lauritsen, C. J. Lister, D. Seweryniak, A. Sonzogni, F. G. Kondev,† I. Wiedenhöver,‡ G. Hackman,§ P. Chowdhury,¶ D. Cline,|| and A. O. Machiavelli**)

In order to understand the evolution of the moment of inertia of even-even systems as a function of rotational frequency, and in particular, in order to understand the origin of the alignments observed in the various bands of these nuclei, it is often important to also investigate the properties of rotational sequences in the odd neighbors. In the actinide region, some information is available on a number of odd neutron nuclei, but odd proton systems are poorly known. Yet, alignments such as those of $i_{13/2}$ protons are thought to play an important role. In order to remedy this situation, we have extended our so-called "Unsafe" Coulex studies to the nuclei $^{237}$Np and $^{241}$Am.

A $^{209}$Bi beam from ATLAS at 1450 MeV bombarded thin $^{237}$Np and $^{241}$Am radioactive targets evaporated on thick Au backings. The data from the two experiments were collected with the Gammasphere array. Four band structures have been delineated to high spin in $^{237}$Np; the representative level scheme is given in Fig. I-27. The ground state band is constituted of two signature partners (bands 1 and 2) and is assigned to the 5/2[642] state, which originates from the $i_{13/2}$ orbital. The two other sequences, bands 3 and 4, are also signature partners. They are assigned to the 5/2[523] state, and originate from the $h_{9/2}$ orbital. The absence of a backbending or a significant upbending in the $i_{13/2}$ band structures and the presence of such a phenomenon in the $h_{9/2}$ excitations argue strongly in favor of an interpretation of the rise of the moments of inertia in the even-even U isotopes in terms of an $i_{13/2}$ proton alignment.

In addition to the bands measured in the Coulomb excitation channel, rotational cascades have also been observed corresponding to more complex reactions (the beam energy was ~15% above the Coulomb Barrier): rotational sequences belonging to $^{238}$U and $^{236}$Pu, for example, have been delineated.

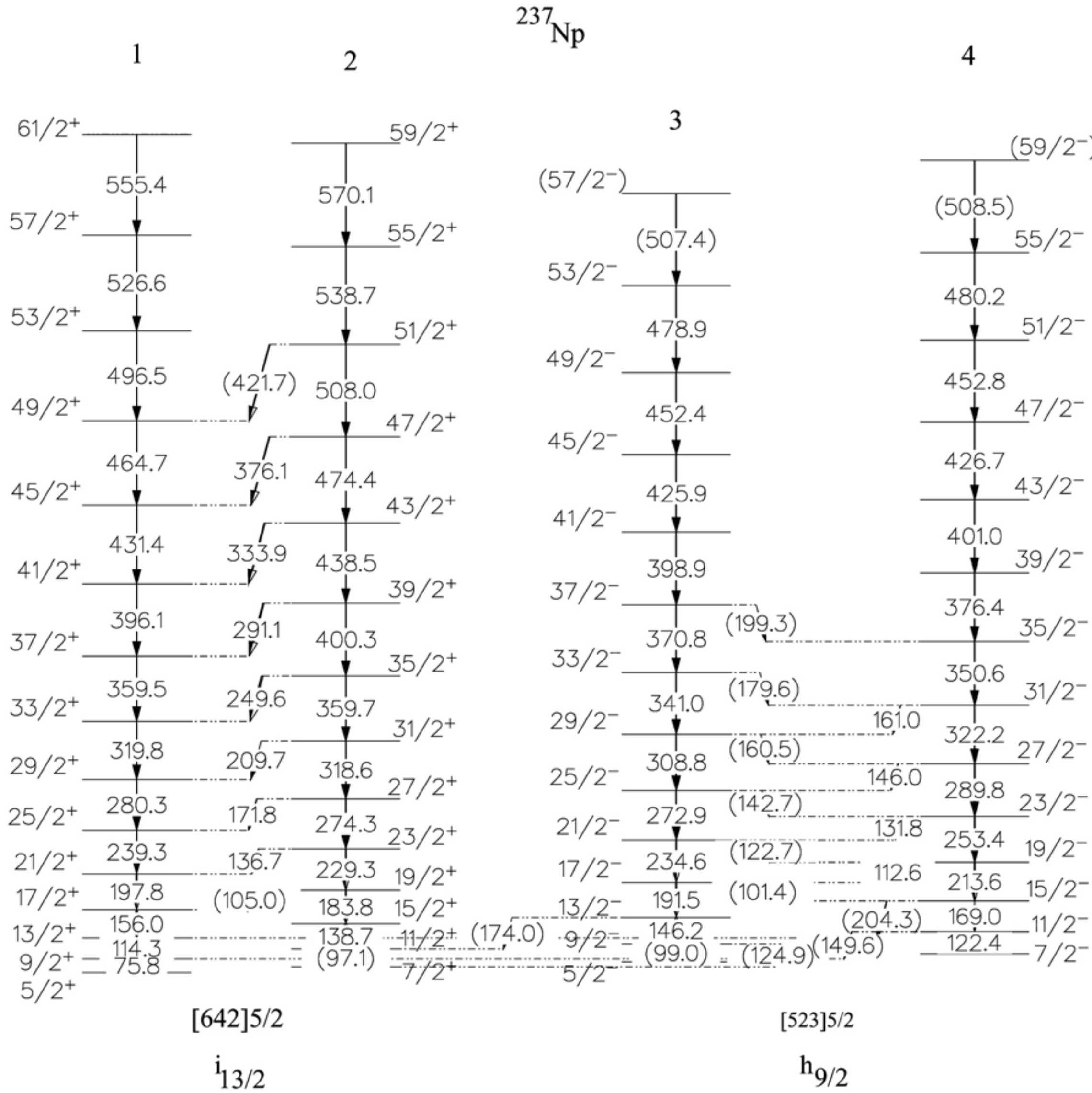


*Fig. I-27. Level scheme of the nucleus $^{237}$Np as obtained in the present experiment.*

Six band structures have been established in $^{241}$Am; they can again be grouped in pairs of signatures partners[1] based respectively on the 5/2[523] ($h_{9/2}$) configuration, the 5/2[642] ($i_{13/2}$) state, and the 3/2[521] ($2f_{7/2}$) level. As can be seen in Fig. I-28 where the experimental alignments of the various bands are presented as a function of the rotational frequency together with similar data for $^{242}$Pu,[2] a sharp upbending is seen in bands 1 and 2 at roughly the same frequency than in the yrast sequence of the even-even neighbor. In contrast, the $i_{13/2}$ rotational bands show a decrease in alignment over the same frequency range. This observation unambiguously assigns the strong backbending in $^{242}$Pu to the alignment of a pair of $i_{13/2}$ protons.

Cranked Shell Model calculations are underway in order to understand the band structures that are now known through out this actinide region.

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[1]R. B. Firestone *et al.*, Table of Isotopes, 8th edition, volume II, 1996.

[2]I. Wiendenhöver *et al.*, Phys. Rev. Lett. **83**, 2143 (1999).

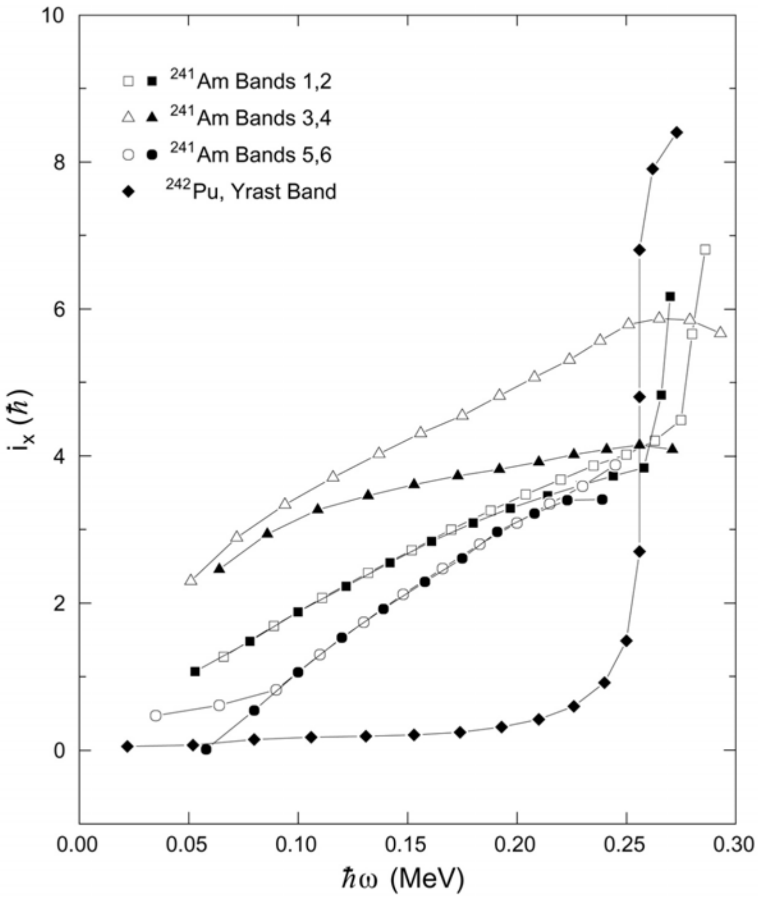


*Fig. I-28. Experimental alignments as a function of rotational frequency for the six bands discovered in $^{241}$Am. The data are being compared with those of $^{242}$Pu from Ref. 2.*

## c.3. Estimation of the N = 162 Gap (I. Ahmad, R. R. Chasman, and H. Esbensen)

Alpha-decaying isomers were discovered[1] at GSI in 1996 in the nucleus $^{273}$110. Two favored alpha transitions were identified with energy differences of 1.35 MeV and a half-life ratio of 1545. We performed calculations of level energies in $^{273}$110 and the daughter $^{269}$Hs using a Wood-Saxon potential and pairing force. On the basis of our calculations, we interpreted the lower energy transition of 9.73 MeV as a decay from the ground state of $^{273}$110 to the excited particle state in the daughter $^{269}$Hs with the same configuration. The high-energy transition of 11.08 MeV was interpreted as a decay from the excited low-spin hole state to the ground state of $^{269}$Hs, both states having the same single-particle configuration. Our calculations gave an energy difference of 1.69 MeV between the alpha transitions of the two isomers which was in good agreement with the measured energy of 1.35 MeV. Figure I-29 shows our interpretation of the decay of the two isomers.

We submitted a paper for publication in Phys. Rev. C in August 2001. While the paper was being processed we received a preprint from GSI[2] in which the results of all heavy element data measured at GSI since 1994 were reanalyzed. These authors found that the 9.73 MeV decay was wrong; it did not have the correct decay chain. Since the existence of one of the isomers is no longer substantiated, we withdrew our paper. Even so, our calculations still predict an isomer in $^{273}$110 with half-life of several ms and α decay energy of ~10 MeV.

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[1]S. Hofmann, *et al*., Z. Phys. **354**, 229 (1996).
[2]S. Hofmann, *et al*., submitted to Eur. Phys. J.

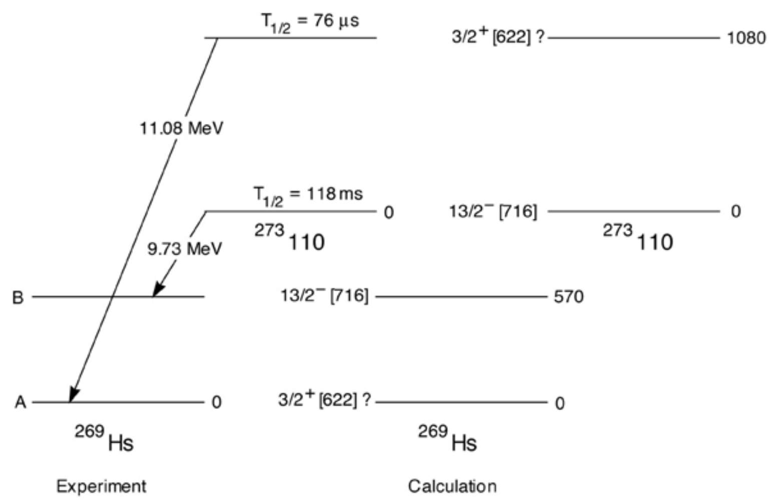


*Fig. I-29. The original experimental[1] and the calculated quasiparticle energies in $^{273}$110 and $^{269}$Hs.*

## c.4. Spectroscopy of Transfermium Nuclei: $^{252}$No (T. L. Khoo, C. J. Lister, R.-D. Herzberg,* N. Amzal,* F. Becker,† P. A. Butler,* A. J. C. Chewter,* J. F. C. Cocks,‡ O. Dorvaux,‡ K. Eskola,§ J. Gerl,¶ P. T. Greenlees,‡ N. J. Hammond,* K. Hauschild,† K. Helariutta,‡,¶ F. Heßberger,¶ M. Houry,† G. D. Jones,* P. M. Jones,‡ R. Julin,‡ S. Juutinen,‡ H. Kankaanpää,‡ H. Kettunen,‡ W. Korten,† P. Kuusiniemi,‡ Y. Le Coz,† M. Leino,‡ R. Lucas,† M. Muikku,‡ P. Nieminen,‡ R. D. Page,* P. Rahkila,‡ P. Reiter,|| Ch. Schlegel,¶ C. Scholey,* O. Stezowski,* Ch. Theisen,† W. H. Trzaska,‡ J. Uusitalo,‡ and H. J. Wollersheim¶)

An in-beam study of excited states in the transfermium nucleus $^{252}$No has been performed using the recoil separator RITU together with the JUROSPHERE II array at the University of Jyväskylä. This is the second transfermium nucleus studied in an in-beam experiment. Levels up to spin 20 were populated and compared to levels in $^{254}$No. An upbend in the moment of inertia is seen at a frequency of 200 keV, corresponding to spin 16. We also use an improved systematics to connect the energy of the lowest $2^+$ state with its half-life and find the deformation of $^{252,254}$No, $\beta_2$ = 0.28, 0.29. This work has been published in Physical Review C.[1]

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[1]R.-D. Herzberg et al. Phys. Rev. **C65**, 014303 (2002).

## c.5. Structure, Fission Barrier and Limits of Stability of $^{253}$No (T. L. Khoo, A. Heinz, T. Lauritsen, C. J. Lister, D. Seweryniak, I. Ahmad, M. P. Carpenter, C. N. Davids, W. F. Henning, F. Kondev, R. V. F. Janssens, A. A. Sonzogni, S. Siem, I. Wiedenhöver, P. Reiter,* N. Amzal,† P. A. Butler,† A. J. Chewter,† J. A. Cizewski,‡ P. T. Greenlees,¶ K. Helariuta,¶ R. D. Herzberg,† G. Jones,† R. Julin,¶ H. Kankaanpää,¶ H. Kettunen,¶ W. Korten,§ P. Kuusiniemi,¶ M. Leino,¶ J. Uusitalo,¶ and K. Vetter||)

The heaviest nuclei exist only because the shell-correction energy creates a fission barrier; otherwise they would fission instantaneously. An accurate calculation of the shell-correction energy of the heaviest nuclei depends on the single-particle energies, which are also essential for interpreting the α decay of the superheavy elements. The most direct information on the single-particle energies comes from the quasiparticle energies of an odd nucleus. Direct information on the fission barrier for comparison with theory may be obtained from the entry distribution, a method that we recently introduced.[1] With these motivations, we have studied the single-particle energies and fission barrier of $^{253}$No, by using the $^{207}$Pb($^{48}$Ca,2n) reaction. The production cross section of $^{253}$No was measured as ~0.5 μb in an experiment with the gas-filled separator RITU at Jyväskylä. This showed that a γ-ray experiment was feasible. In a subsequent experiment at Argonne, the γ rays were detected with Gammasphere, in coincidence with the FMA. The γ-ray spectrum for $^{253}$No is dominated by the K x-rays and the gamma transitions are much weaker due to huge conversion electron competition. Heavy odd nuclei, such as $^{253}$No, represent the limits of in-beam γ spectroscopy.

Fortunately, in $^{253}$No only one band, built on the 7/2$^+$[624] orbital, is expected to have sufficiently small M1 branching ratios to permit less converted E2 γ competition. All the other low-lying bands, which are expected[2] to have very small γ branching ratios due to overwhelming competition from M1 conversion electrons. The 7/2$^+$[624] band should have a correspondingly larger γ-ray multiplicity than the other bands and, indeed, it was enhanced by demanding that 4 or more Gammasphere modules fire. Coincidence spectra help to confirm the band assignments: despite the low statistics, with only a few coincidences are seen in individual gates (as expected from our model calculations), the sum spectrum from all the gates shows counts primarily at the expected energies. The enhancement by high multiplicity, the coincidence spectra and a comparison with the calculated spectrum for the 7/2$^+$[624] band are all used to deduce the level scheme for the band. This combination of methods is necessary since conventional spectroscopic methods cannot be used due to the low cross sections (~50 nb) of the γ rays. The band head energy is assigned at 355 keV on the basis of an increased γ yield around this energy from E1 interband decays to the yrast band, which is expected[2] to be built on the 9/2$^-$[734] configuration. This energy is substantially lower than that calculated with the relativistic mean-field model (see Sec. c.11 in Chapter V. Theoretical Physics, of this document).

The moment of inertia $J^{(1)}$ of the 7/2$^+$[624] band in $^{253}$No is ~13% larger than that of $^{254}$No. A plot of $J^{(1)}$ as a function of transition energy shows that $J^{(1)}$ is almost constant at the lowest energies (up to 335 keV) and then monotonically increases thereafter. These are characteristic features of the moment of inertia of an odd nucleus. The smooth behavior of $J^{(1)}$ also provides support for the assignment of the transitions to the band.

We have also measured the two-dimension entry distribution as a function of spin vs. sum energy. It shows that the fission barriers in $^{253}$No are similar to that in $^{254}$No,[1] in both cases they are larger than 5 MeV at high angular momentum, thereby giving direct indication of significant fission barriers created by shell structure.

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

[2]I. Ahmad *et al*., Phys. Rev. C **14**, 218 (1976).

## c.6. Search for A High-K Isomer in $^{254}$No by γ and Electron Spectroscopy

(G. Mukherjee,* T. L. Khoo, D. Seweryniak, I. Ahmad, M. P. Carpenter, C. N. Davids, A. Heinz, R. V. F. Janssens, F. G. Kondev, T. Lauritsen, C. J. Lister, A. Woehr,† A. Aprahamian,‡ P. Boutachkov,‡ P. A. Butler,§ P. Chowdhury,¶ J. A. Cizewski,|| R. Herzberg,§ G. Jones,§ R. Julin,** M. Leino,** E. Ngijoi-yogo,¶ P. Reiter,†† M. Shawcross,‡ M. B. Smith,|| A. Teymurazyan,‡ and J. Uusitalo**)

The heaviest nuclei are stabilized against fission by shell effects. Hence the accuracy of theoretical predictions of superheavy elements depends on the correct proton and neutron shell structures. 2-quasiparticle states provide information on the single particle energies and on the pair gap. The primary aim of the present work was to determine the properties of a reported[1] 2-qp isomer ($T_{1/2}$ = 0.28 sec) in $^{254}$No.

The experimental study of nuclei with Z ≥ 102 are difficult due to their low production cross sections. Even in the quiet environment at the focal plane of a recoil separator, such as the FMA at Argonne, the small number of nuclei yield a decay rate much smaller than the background rate. Therefore, new techniques have to be developed to study the isomeric decays of these nuclei through delayed $\gamma$ rays, alphas and electrons.

$^{254}$No was populated by the reaction $^{208}$Pb($^{48}$Ca,2n) with 220 MeV, 50-pnA beam from ATLAS. Evaporation residues were identified by (M/Q) in the FMA and by gating on a $\Delta$E-TF 2D matrix. $\Delta$E is the energy loss in the focal plane PPAC and TOF the time of flight between the PPAC and a mciro channel plate detector. After traversing these detectors, ~1000 $^{254}$No residues were implanted into a Si PIN diode, one of five detectors in a box array, which detected electrons and $\alpha$'s and also served as an electron calorimeter. The $\gamma$ rays were detected in two clover Ge detectors and two LEPS's, closely packed to maximize the solid angle.

Prompt $\gamma$ - $\gamma$ and e - $\gamma$ coincidences, which occurred within 0.6 sec. of $^{254}$No implantation, give tentative indication of an isomer, but further analysis is necessary. Data on e - e coincidences are also being analyzed for evidence of the isomer.

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[1]A. Ghiorso et al., Phys. Rev. C 7 2032 (1973).

[2]P. Reiter et al., Phys. Rev. Lett. 82 509 (1999).

## c.7. Transition Intensities in $^{220}$Th (A. Heinz, T. L. Khoo, I. Ahmad, M. P. Carpenter, C. N. Davids, J. P. Greene, W. F. Henning, R. V. F. Janssens, F. G. Kondev, T. Lauritsen, C. J. Lister, D. Seweryniak, A. A. Sonzogni, I. Wiedenhöver, P. Reiter,* P. Bhattacharyya,† J. A. Cizewski,‡ G. D. Jones,§ R. Julin,¶ J. Uusitalo,|| and S. Siem**)

The nuclear fission barrier of unstable nuclei is difficult to determine. The measurement of the entry distribution - the total excitation energy of a compound nucleus after particle evaporation as function of the angular momentum[1] - provides a new method for determining the barrier. In this work, the fusion of $^{220}$Th has been investigated using a $^{48}$Ca beam at 206 MeV and 219.5 MeV impinging on a 810-$\mu$g/cm$^2$ thick $^{176}$Yb target. The recoils were identified using the mass-to charge information of the PPAC at the FMA focal plane. Gammasphere measured gamma radiation of the selected nucleus. In addition to the measured entry distributions we are able compare the transition intensities measured in this work with data from an experiment using the $^{208}$Pb($^{16}$O,4n)$^{220}$Th reaction, as a complementary indicator of the angular momentum in the evaporation residues. The latter reaction is expected to introduce less angular momentum into the compound-nuclear system. Due to the level scheme of two alternating parity bands connected by E1 transitions, it was necessary to define the transition intensity T(I) as function of nuclear spin in the following way: $T(I) = T(I^+) + T((I+1)^-)$. Figure I-30 shows the experimental result. Note that due to limits in the statistics, transitions beyond $11^- \rightarrow 10^+$ could not be observed for the higher beam energy.

This figure demonstrates clearly that neither the change of the reaction nor the increase in beam energy leads to a significant increase in angular momentum. A model calculation[3] predicts that the initial compound nucleus will have on the average 20 $\hbar$ more angular momentum at the higher beam energy. The experimental result indicates that fission is indeed limiting the maximum angular momentum that the compound nucleus can sustain. This finding is also consistent with the measured entry distributions[4], which can be seen by comparing Fig. I-30 and Fig. I-31. For the entry distributions, as well as for the measured transition intensities, the maximum angular momentum is about 20 $\hbar$.

Final analysis is in progress.

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

[2]B. Schwarz, Ph.D. thesis, University of Heidelberg, 1998.

[3]K. Hagino, private communication.

[4]A. Heinz *et al*., Physics Division Annual Report 2000, ANL-01/19, p. 29 (2001).

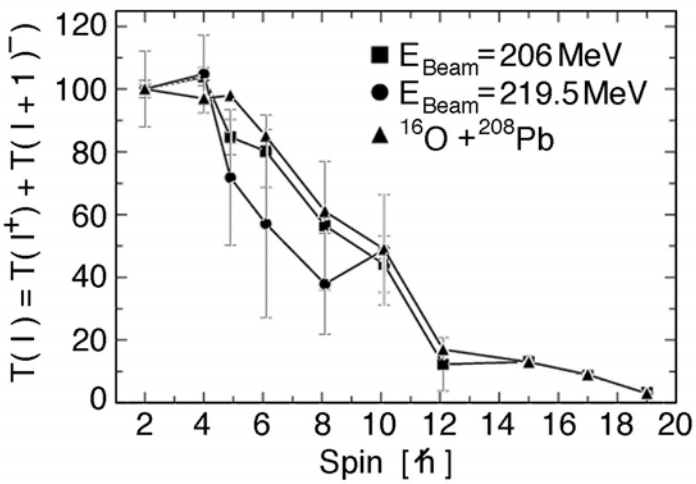


*Fig. I-30. Intensities of gamma-ray transitions of $^{220}Th$ at beam energies of 206 MeV (squares) and 219.5 MeV (circles) in comparison with data from Schwarz (triangles).[2] Preliminary result.*

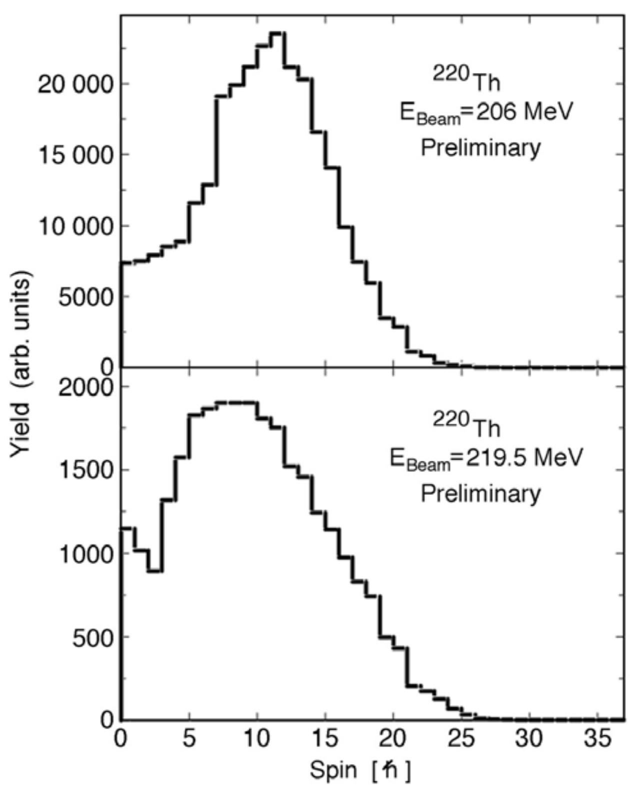


*Fig. I-31. Projections of the entry distribution of $^{220}Th$ on the spin axis at beam energies of 206 MeV and 219.5 MeV (see Ref. 4).*

## c.8. Production and Decay of $^{257}$Rf (A. Heinz, R. V. F. Janssens, D. Seweryniak, K. Abu Saleem, I. Ahmad, B. Back, M. P. Carpenter, C. N. Davids, J. P. Greene, D. J. Henderson, C.-L. Jiang, T. L. Khoo, F. G. Kondev, T. Lauritsen, C. J. Lister, E. F. Moore, R. C. Pardo, T. Pennington, G. Savard, J. P. Schiffer, R. H. Scott, R. C. Vondrasek, A. Woehr,* J. Shergur,* P. Collon,† and M. B. Smith‡)

As part of a program aiming at the study of the heaviest elements, the production and decay of $^{257}$Rf ($Z$ = 104) was investigated at ATLAS with the $^{50}$Ti + $^{208}$Pb reaction at 234 MeV. Beam intensities up to 73 pnA were obtained. The cross section for this reaction has been measured before to be about 5 nb.[1] Thus, this experiment presents a significant step towards lower cross sections in comparison with the experiments performed for the investigation of $^{254}$No where the production cross section is ≈ 3 $\mu$b.[2]

The $^{257}$Rf residues were passed through the Fragment Mass Analyzer, which provides a direct measurement of the mass-to-charge ratio, and were implanted in a double-sided Si strip detector with 40 × 40 strips, allowing for recoil-decay and decay-decay correlations. The mass information provides an additional tool in order to understand the rather complex decay spectrum.

In order to calibrate the measured alpha energies a $^{170}$Er target was used at the same beam energy to produce alpha emitters around $^{215}$Th.

First results confirm earlier measurements at GSI[1] which were made with higher beam intensities and show the feasibility of this kind of experiments with ATLAS.

A representative $\alpha$ energy spectrum and a position spectrum of the FMA focal plane are shown in Fig. I-32. Efficient α–γ spectroscopy will be needed to clarify the "fine structures" found in the α-spectrum.

*University of Maryland, †Columbia University, ‡Rutgers University

[1]F. Heßberger *et al*., Z. Phys, **A359**, (1997) 415.

[2]H. W. Gäggeler *et al*., Nuc. Phys. **A502**, 641c (1989); P. Reiter *et al*., Phys. Rev. Lett. **82**, 509 (1999)

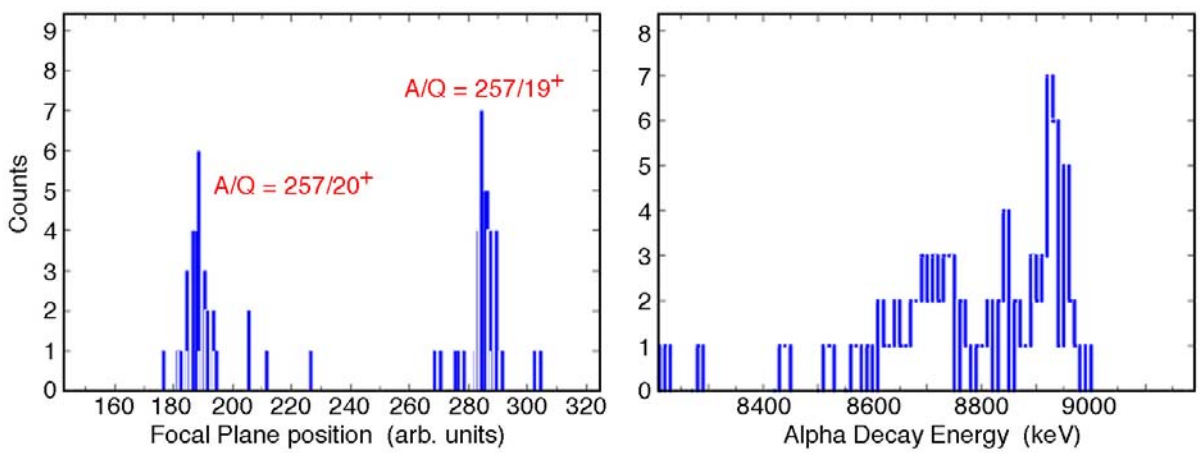


*Fig. I-32. Left panel: Position spectrum of $^{257}$Rf at the FMA focal plane. Right panel: Alpha energy spectrum of $^{257}$Rf. Both spectra are preliminary.*