C. SPECTROSCOPY OF TRANS-LEAD NUCLEI

The structure and stability of the very heaviest elements continues as a forefront area of our 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 continued. 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.

c.1. Structure of ^{208}Bi from Deep Inelastic Heavy Ion Reactions (M. P. Carpenter, R. V. F. Janssens, F. G. Kondev, T. Lauritsen, D. Seweryniak, I. Wiedenhöver, B. Fornal,* R. Broda,* W. Krolas,* T. Pawlat,* J. Wresinski,* K. H. Maier,† P. J. Daly,‡ P. Bhattacharyya,‡ Z. W. Grabowski,‡ S. Lunardi,§ C. A. Ur,§ G. Viesti,§ M. Cinausero,¶ N. Marginean,¶ and M. Rejmund||)

High-spin states in ^{208}Bi were studied at Gammasphere using deep inelastic reactions induced by a 305-MeV ^{48}Ca beam on a thick ^{208}Pb target. Much new information was obtained, in particular about states located above the known 10^- isomer in this nucleus. Specifically, yrast and near-yrast levels up to 5.6 MeV were delineated. The new findings include high spin members of $\pi\nu^{-1}$ multiplets (considering ^{208}Pb as the core) and states arising from two-particle two-hole couplings. Considerable overlap between these new data and earlier charged-particle spectroscopy studies turned out to be important for the interpretation of the results. Comparisons with shell-model calculations were carried out as well. Embedded among the 2p-2h states were three levels explained as octupole excitations built on specific 1p-1h states. Their energies were shown to be consistent with empirical predictions. A paper reporting these results qas recently submitted for publication.[1]

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[1]B. Fornal *et al.*, submitted to Phys. Rev. C.

c.2. First Identification of a μs Isomer in N = 127 ^{217}Th (G. Mukherjee,* T. L. Khoo, D. Seweryniak, I. Ahmad, M. P. Carpenter, C. N. Davids, A. Heinz, F. G. Kondev, T. Lauritsen, C. J. Lister, R. V. F. Janssens, A. Woehr,† A. Aprahamian,§ P. Boutachakov,§ 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**)

Superheavy nuclei are stabilized only due to the shell effects. Thus the predictions of the stable superheavies depend on the knowledge of the single particle energies. In the Pb region, the presence of $\Delta\ell = 3$ and $\Delta j = 3$ $f_{7/2}$ and $i_{13/2}$ proton orbitals give rise to ocutpole correlations which are, generally, not treated in the standard mean field calculations. In thorium isotopes, extra octupole correlation comes from the neutron $g_{9/2}$ and $j_{15/2}$ orbitals. The comparison of calculated single-particle energies to the experimental ones can be masked by the existence of this correlation. For example, calculations by K. Rutz et al.[1] recently predicted a substantial shell gap for Z = 92 between $\pi h_{9/2}$ and $\pi f_{7/2}$ orbitals and for N = 126. However, K. Hauschild et al. argued, from their experimental data, that the single particle orbitals near Z = 90 and N = 126 get modified due to a strong L = 3 correlation, as in ^{216}Th,[2] which contradicts the prediction.

Neighboring odd-A nuclei are the best laboratory to study the single-particle orbitals. A strong octupole core vibration in ^{217}Th is indicated from the systematics of low energy $15/2^-$ states in odd-A N = 127 nuclei. The level scheme of ^{217}Th is not known except for one excited state at 673 keV[3] which was assumed to be the $15/2^-$ state.

It is difficult to study these neutron deficient nuclei by prompt coincidence method because of the very low (~ few μb) production cross section and also since the fission channel cominates in this region. We studied the spectroscopy of ^{217}Th at the focal plane of the FMA at Argonne. The excited states in ^{217}Th were populated by the reaction ^{172}Yb(^{48}Ca,3n) with a 219 MeV of beam energy from the ATLAS at Argonne. The recoils were identified by (M/Q) in the FMA and by gating on a ΔE-TOF 2D matrix. ΔE is the energy loss in the focal plane PPAC and TOF the time-of-flight between the PPAC and a micro channel plate detector. After traversing these detectors, residues were implanted onto a catcher foil in front of a Si IN diode box. The γ rays were detected in two clover Ge detectors and two LEP's, surrounding the catcher foil. The flight time of the recoils through the FMA were ~1.4 μs, so we could only detect the γ rays decayed from a long-lived (more than a μs half life) isomer.

The mass gated γ-ray spectra are quite clean. Spectra gated by mass 216 and 217 are shown in Fig. I-35. The raw spectrum is shown in the upper panel for comparison. The x-rays are seen in both the gated spectra. The γ rays below the 128 μs isomer in ^{216}Th are observed in the spectrum gated by mass 216. In the spectrum gated by mass 217, two γ rays, 673 keV and 1270 keV, are seen clearly along with the Th x rays. Thus we assigned these γ rays to ^{217}Th.

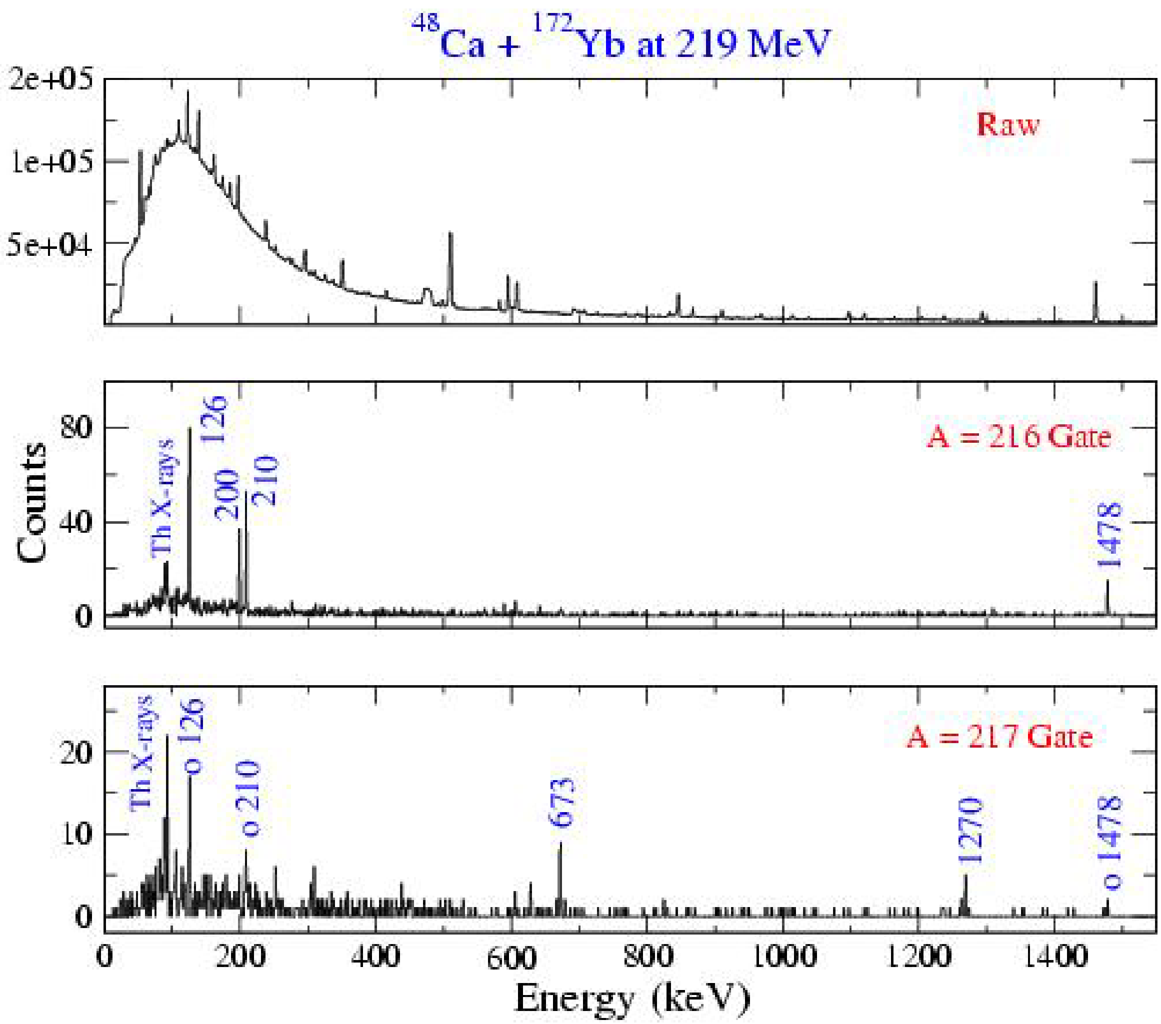

Fig. I-35. The γ-rays spectra from the present measurement. The raw spectrum (no mass gate) and the mass gated spectrum (gate on A = 216 and A = 217) are shown. The γ-rays accompanied by ``o" in the third panel correspond to the contamination from A = 216.

The half life corresponding to these two transitions are measured to be 20 ± 5 μs and is shown in Fig. I-36. Thus we could identify a long-lived isomer for the first time in this nucleus. The $25/2^+$ states in N = 127 isotones are isomeric with half lives of the order of a few μs. So, from the systematics of N = 127 we have assigned a spin-parity of $25/2^+$ to the isomer. In the γ-γ matrix gated by mass 217, we could identify a few other transitions and correlations among them. The statistics were low and have only a few founts in the peaks in the gated spectra due to the mass gating, but the spectra were very clean with almost zero background and the thorium x rays were observed in all the gated spectra. The proposed level scheme, based on the γ-γ correlation and the systematics, is shown in Fig. I-36.

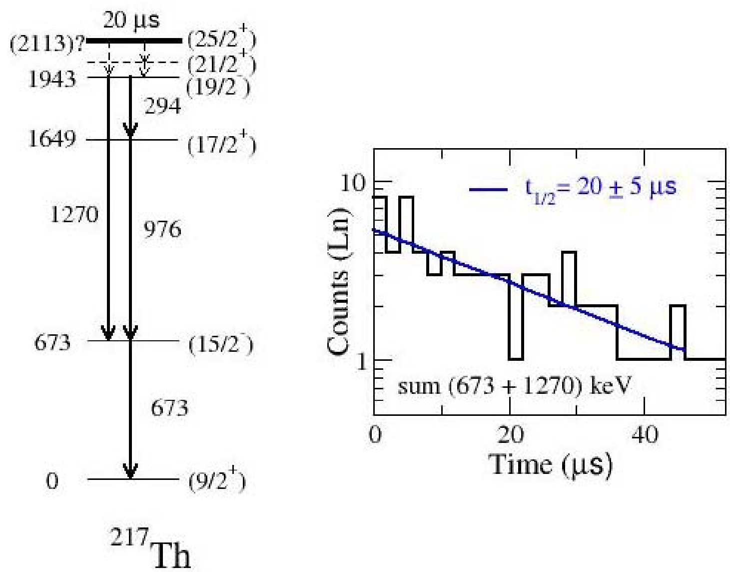

Fig. I-36. Tentative level scheme of ^{217}Th based on present measurement and systematics. These states are from the decay of a ~20 μs isomer. The half life fit of the isomer is also shown.

It can be seen from Fig. I-36 that the x-ray intensities in ^{217}Th are quite high ($K_{\alpha 1}$ = 74% of the 673 keV γ-ray intensity). The observed transitions in ^{217}T cannot account for this high yield of x rays, thereby indicating that there should be highly converted M2 and E3 transitions. A simple computation indicates the presence of at least 2 highly converted ($\alpha_\kappa \geq 10$) transitions. In the neighboring N = 127 isotones, the $25/2^+$ isomers decay by a low energy E2 transition (e.g. 57 keV in ^{215}Ra) to the $21/2^+$ state. The K electron binding energy in thorium is 109 keV, so the converted transitions should have energies more than 109 keV. A 115-keV E2 transition has a K electron conversion coefficient of aonly 0.24 which cannot account for the high yield of K x rays. Also, such an E2 transition fails to account for the half life of the isomer. The other possibility is that the isomer decays by a mixed E3/M2 transition to a $19/2^-$ state generated by the coupling of $j_{15/2}$ orbital with the 2^+ state in even-even ^{216}Th. Such a state was observed in the isotone ^{213}Rn,[4] about 400 keV above the $21/2^+$ state. The half life of the isomer and the yield of K x rays can be accounted for with a 170-KeV E3 transition between these two states. The $25/2^+$ state is generated by the coupling of the $g_{9/2}$ orbital with the octupole coupled 8^+ state observed in the neighboring even-even nucleus and so an enhanced E3 transition from this isomeric state can complete with an E2 transition (to the $21/2^+$ state). Thus the $19/2^+$ and $21/2^+$ states seem to lie close to each other in ^{217}Th. Though the $19/2^+$ state has been shown below $21/2^+$ state in Fig. I-36 but the ordering can be reversed as well and the 1270 keV γ ray to the $15/2^-$ state can either be an E12 or an E3 transition. The excitation of the isomer, shown in Fig. I-36, is, however, tentative since we do not know the energies of the missing converted transitions.

In conclusion, we observed a 20 ± 5μs isomer in ^{217}Th and proposed, for the first time, a level scheme beyond the first excited state from its decay. The spin-parity assignments are from the systematics and are tentative. The level scheme around the long lived isomeric state at 25/2$^+$ seems different than its isotone ^{215}Ra. There appears to be a 19/2$^-$ state similar to that in ^{213}Rn. But unlike in ^{213}Rn, this state lies close in energy to the 21/2$^+$ state. This is apparently due to the low energy of the 15/2$^-$ state in ^{217}Th because of the larger octupole correlation. Though the present data indicate a larger ocupole correlation in this nucleus but more data are required to extend the level scheme above this isomer. This is important to look for the second 25/2$^+$ state and for the measurement of the E3 transition strength of the 21/2$^-$ to 25/2$^+$ decay which would shed light on the possibility of the vanishing of Z = 92 shell gap.

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[1]K. Rutz et al.,. Nucl, Phys. **A634**, 67 (1998).
[2]K. Hauschild et al., Phys. Rev. Lett **87**, 072501 (2001).
[3]G. D. Dracoulis et al., Nucl. Phys. **A493**, 145 (1989).
[4]A.E. Stuchbery et al., Nucl. Phys. **A482**, 692 (1988).
[5]A. E. Stuchbery et al., Nucl. Phys. **A641**, 401 (1998).
[6]A. E. Stuchbery et al., Nucl. Phys. **A555**, 355 (1993).

c.3. **Coulomb Excitation and Few Nucleon Transfer Reactions in ^{209}Bi + ^{232}Th at 1400 MeV and ^{209}Bi + ^{248}Cm at 1450 MeV** (K. Abu Saleem,* R. V. F. Janssens, M. P. Carpenter, F. G. Kondev, I. Ahmad, J. Caggiano, J. P. Greene, A. Heinz, T. L. Khoo, T. Lauritsen, C. J. Lister, D. Seweryniak, I. Wiedenhöver, G. Hackman,† P. Chowdhury,‡ D. Cline,§ M. Devlin,¶ N. Fotiades,¶ A. O. Macchiavelli,|| E. H. Seabury,¶ and C. Wu§)

For the last few years, the actinide nuclei were extensively investigated at ATLAS. The so-called "Unsafe" Coulex technique was used with ^{232}Th, ^{237}Np, ^{241}Am, and ^{248}Cm targets and ^{209}Bi beams from ATLAS with energies ~15% above the respective Coulomb barriers. The data of interest were collected with the Gammasphere array. Partial results on some of the nuclei were presented in earlier annual reports.

Here, some of the new results on the even-even ^{232}Th and ^{248}Cm nuclei are presented. These nuclei offer the possibility to investigate in detail alignment phenomena as a function of angular momentum up to fairly high spin. In addition, low-lying rotational bands built on beta, gamma and octupole vibrations are also present in the level structures of these nuclei. Thus, there are ample possibilities to confront the data with theoretical calculations.

The level scheme of ^{248}Cm is given in Fig. I-37. The yrast band was traced to the 32$^+$ state. The observed alignment was attributed to a pair of $i_{13/2}$ protons, as is the case in other even-even nuclei in the region. These results can be understood in the framework of the cranked shell model, although the latter also predicts a $j_{15/2}$ neutron alignment that was not seen experimentally. In addition, three excited bands based on octupole (band 2), beta (band 3) and gamma (band 4) vibrations were delineated. The latter offer an opportunity to test the applicability of recent RPA calculations by Nakatsukasa *et al*.[1] Satisfactory agreement between calculated and observed alignments was observed. Similar conclusions were reached in the case of ^{232}Th, where a total of eleven band structures were found.

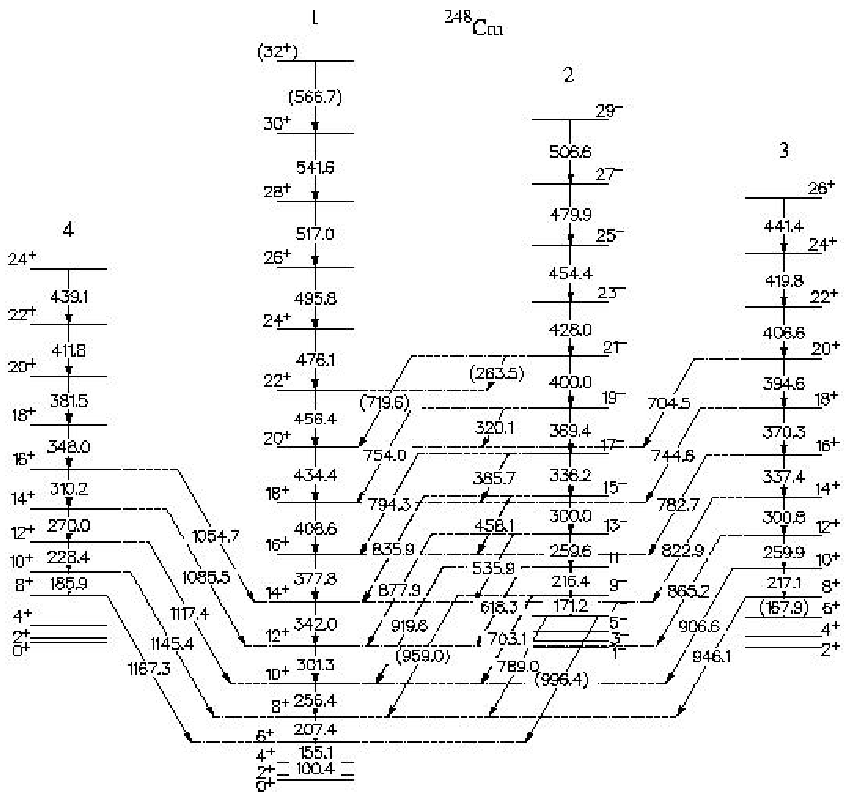

Fig. I-37. Level scheme obtained for ^{248}Cm in the present work.

The RPA calculations can be tested further by taking advantage of the so-called generalized intensity relations such as:

$$\sqrt{B(E\lambda; i \rightarrow f)} = Q_T < J_i, K_i, \lambda, (K_f - K_i) \mid J_f, K_f > (1 + q(E\lambda)[J_f (J_f + 1) - J_i (J_i + 1)])$$

As illustrated in Fig. I-38 for the case of an octupole band in ^{232}Th, the Coriolis mixing parameter q(E1) can be extracted from the measured relative γ-ray intensities between various decay pathways out of the levels of a vibrational band. In the same way the Q_T moment can be obtained. These two quantities then offer additional tests of the RPA predictions. Table I-2 compares theory and experiment for all even-even actinide nuclei where data are currently available, including the two cases studied in the present work.

The agreement between theory and experiment is rather satisfactory. In particular, theoretical general trends of q(E1) and Q_T with K and A are well reproduced.

These data are part of the thesis of K. Abu Saleem, which was submitted recently.[2]

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[1]T. Nakatsukasa *et al*., J. Phys. G **25**, 795 (1999) and references therein.

[2]K. Abu Saleem, PhD Thesis, Illinois Institute of Technology, December 2002.

Table I-2. Measured and calculated q(E1) (in units of $\hbar^{-1}$) Coriolis mixing parameter and Q_T moments (in units of e.fm) for the even-even actinide nuclei where data are presently available.

^{232}Th		$K = 0^-$	$K = 1^-$	$K = 1^-$
q(E1)	calc.	0.22	-0.11	-0.11
	exp.	0.0513(3)	-0.03(2)	-0.01(10)
Q_T	calc.	0.16	0.066	0.066
	exp.	0.0097(4)	0.0031(5)	0.0031(5)
^{238}U		$K = 0^-$	$K = 1^-$	$K = 1^-$
q(E1)	calc.	-0.017	0.12	0.12
	exp.	-0.002	0.044	-
Q_T	calc.	0.12	0.067	0.067
	exp.	0.016	0.0058	-
^{240}Pu		$K = 0^-$	$K = 1^-$	$K = 1^-$
q(E1)	calc.	0.006	-	-
	exp.	0.001(6)	-	-
^{248}Cm		$K = 0^-$	$K = 1^-$	$K = 1^-$
q(E1)	calc.	-	0.019	-
	exp.	-	0.0513(5)	-
Q_T	calc.	-	0.08	-
	exp.	-	0.0099(18)	-

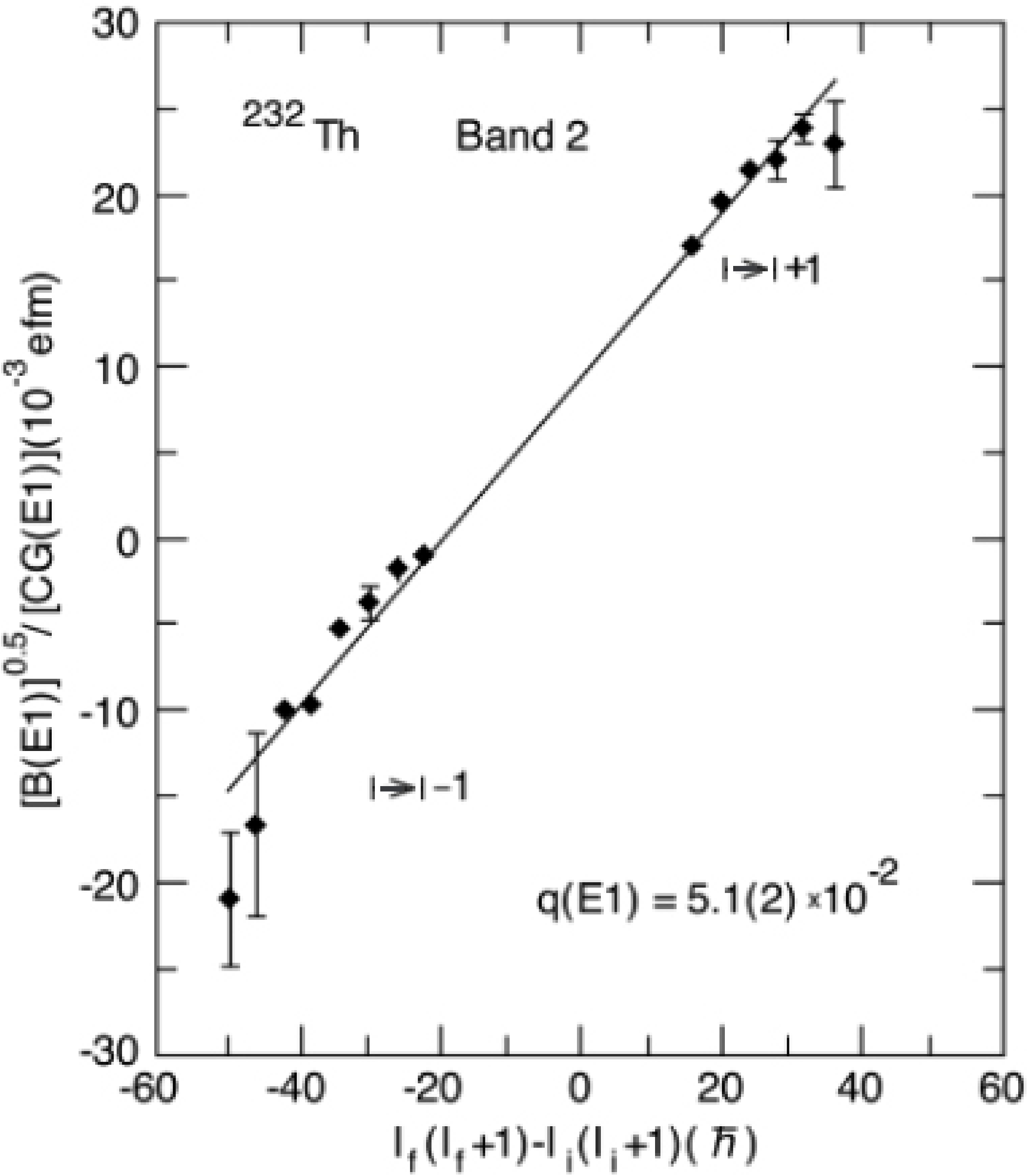

Fig. I-38. Reduced transition probabilities B(E1) as a function of the final and initial spins for the E1 transitions in the main octupole band in ^{232}*Th. The line represents a fit with the generalized intensity relation given in the text.*

c.4. Quantitative Determination of ^{252}Cf Source Strength from Fission γ-Rays

(I. Ahmad, E. F. Moore, J. P. Greene, C. E. Porter,* and L. K. Felker*)

The nuclide ^{252}Cf ($t_{1/2}$ = 2.645 yr) is routinely used in industry and research as a neutron source and also as a source of neutron-rich fission fragments. The main mode of decay is by α-particle emission (alpha branch 96.91%). More than 99% of the decay occurs to the ground state and the 43.4-keV, 2^+ state of ^{248}Cm. Thus there is no γ ray with sufficient intensity which can be used for ^{252}Cf assay. However, in the fission of ^{252}Cf (3.09%), many fragments are produced which decay by emission of high energy γ rays. We measured the absolute intensities of two γ rays which can be used for qualitative and quantitative analysis of ^{252}Cf samples.

We prepared thin sources of ^{252}Cf by molecular plating. Alpha pulse height analysis was used to determine the fraction of α particles from the ^{252}Cf decay. The source strength was obtained by measuring the alpha spectrum with a Si detector of known geometry. The gamma singles spectrum of ^{252}Cf source of known alpha decay rate was measured with a 25% Ge spectrometer whose absolute efficiency was determined with a calibrated source. We found two γ rays with large peak areas and determined their intensities. A high-energy portion of the γ-ray spectrum showing the γ rays of interest is displayed in Fig. I-39. The intensities of the 1435.8 and 1596.5 keV γ rays were determined to be (0.134 ± 0.006)% per ^{252}Cf decay and (0.19 ± 0.01)% per ^{252}Cf decay, respectively. The 1435.8 keV γ ray is produced in the decay of the fission fragment ^{138}Cs ($t_{1/2}$ = 32.2 min) and 1596.5 keV γ ray is associated with the decay of ^{140}Ba-La ($t_{1/2}$ = 12.746 d). The results of this investigation were submitted for publication.[1]

*Oak Ridge National Laboratory.

[1]Nucl. Instrum. Methods, in press.

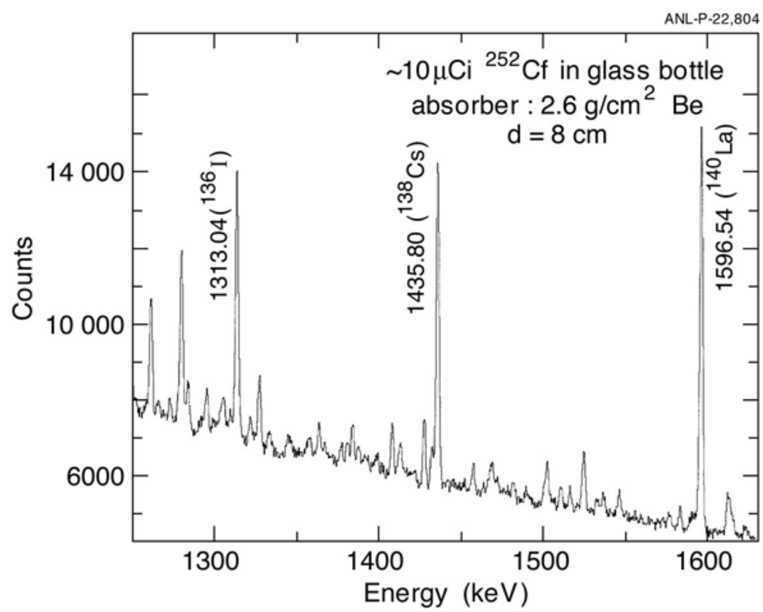

Fig. I-39. A portion of the γ-ray spectrum showing the γ rays of interest. The spectrum was measured with a 25% Ge spectrometer. The source was 10 μCi ^{252}Cf in a glass bottle.

c.5. Structure 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 are stabilized by a shell-correction energy, which lowers the ground-state, thereby creating a barrier against fission. The shell-correction energy originates from the clustering of single-particle orbitals. Hence, the single-particle eigenstates form the basis of the shell stabilization. The most direct data on the orbital energies come from odd-A nuclei, providing our motivation to investigate the odd-N nucleus ^{253}No. The single-particle energies also provide a direct test of nuclear models that predict the properties of superheavy nuclei. Thus, by testing model predictions[1] against data on the heaviest nuclei that are accessible for spectroscopy, one may judge their reliability for predicting the properties of superheavy elements, e.g. the next spherical shell closures beyond ^{208}Pb.

The production cross section of ^{207}Pb(^{48}Ca,2n)^{253}No reaction was measured as ~0.5 μb at Jyväskylä. In a subsequent experiment at Argonne, the γ rays were detected with Gammasphere, in coincidence with ^{253}No residues detected in the FMA. The γ-ray spectrum for ^{253}No has many weak lines, but is dominated by the K x-rays. Heavy odd-A nuclei, such as ^{253}No, represent the limits of in-beam γ spectroscopy due to overwhelming conversion electron competition in M1 transitions. Of the expected low-lying configurations in ^{253}No, only the 7/2+[624] orbital is expected to have sufficiently small M1 branching ratios to permit detection of intraband E2 γ rays. However, due to the low γ-ray cross sections of 25-50 nb, it was necessary to develop new methods based on (a) quantitative comparisons of results from experiment and from model predictions and (b) enhancement of transitions with high γ multiplicity. Similar methods will be required for in-beam γ spectroscopy of nuclei far from stability, which have diminishing cross sections.

The kinematic and dynamic moments of inertia, $J^{(1)}$ and $J^{(2)}$, of the 7/2+[624] band are shown in Fig. I-40, where they are compared with values from those of the neighboring nuclei ^{252,254}No. In the lower panel, the moments of inertia predicted[1,2] by Skyrme Hartree-Fock Bogolyubov theory (SHFB, with the Sly4 force) are given. The general trends are reproduced by theory, but details are not.

A bandhead energy of 355 keV is deduced from the data for the 7/2+[624] configuration. This energy compares with theoretical predictions of 222, 400 and 1200 keV, which are given by, respectively, a Nilsson model based on the Wood-Saxon potential and by self-consistent mean-field theories using the cranked relativistic Hartree Bogoliubov methods.[1,2] Of course, a systematic test of theory should encompass a set of quasiparticle states, and was recently performed for self-consistent mean-field theories.[1,2] For example, Ref. 3 points out that the relativistic mean-field method is able to describe many single-particle energies, but that several (including the 7/2+[624] orbital) that originate from specific spherical orbitals deviate by more than 1 MeV from experimental energies.

A Letter on the results is being prepared.

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[1]T. Bender *et al*., Nucl. Phys. A (2003), in press.
[2]Th. Duguet *et al*., Nucl. Phys. **A679**, 427 (2001).
[3]A. Afanasjev *et al*., Phys. Rev. C **67**, 024309 (2003); see report in theory section.

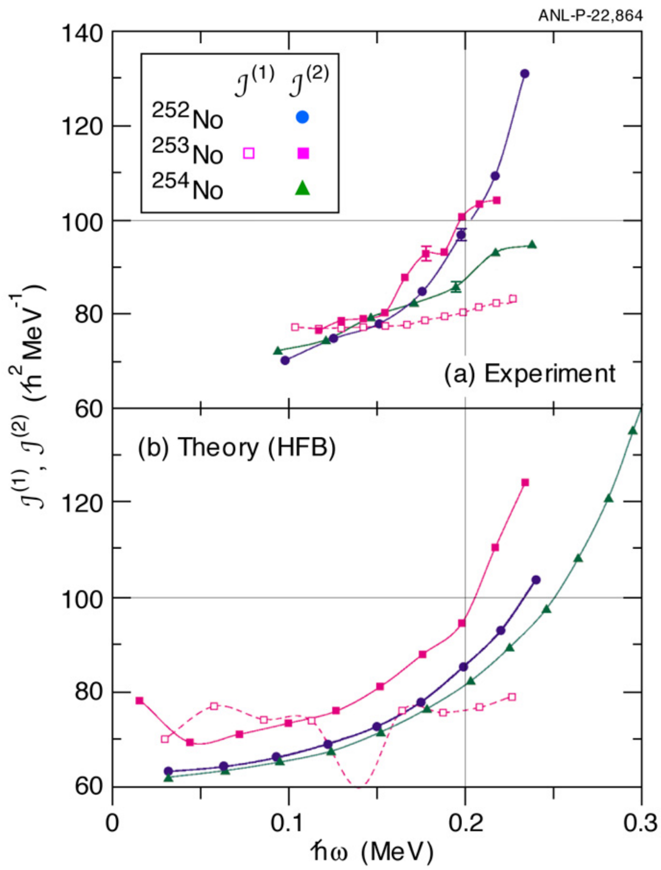

Fig. I-40. The moments of inertia $J^{(1)}$, for $J^{(2)}$ for the 7/2+[624] band in ^{253}No and $J^{(2)}$ for ^{252,254}No, given as a function of rotational frequency. (a) Experimental data; (b) results from SHFB theory, from Refs. 1 and 2. Typical error bars for $J^{(2)}$ are shown.