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Progress Report on

NUCLEAR SPECTROSCOPIC STUDIES

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I. Introduction

The experimental program in nuclear physics at the University of Tennessee, Knoxville, is led by Professors Carrol Bingham, Lee Riedinger, and Soren Sorensen, who respectively lead the studies of the exotic decay modes of nuclei far from stability, the program of high-spin research, and our effort in relativistic heavy-ion physics. Over the years, this broad program of research has been successful partially because of the shared University resources applied to this group effort. The proximity of the Oak Ridge National Laboratory has allowed us to build extremely strong programs of joint research, and in addition to play an important leadership role in the Joint Institute for Heavy Ion Research (JIHIR). Our experimental program is also very closely linked with those at other national laboratories: Argonne (collaborations involving the Fragment Mass Analyzer (FMA) and γ-ray arrays), Brookhaven (the RHIC and Phenix projects), and Berkeley (GAMMASPHERE). We have worked closely with a variety of university groups in the last three years, especially those in the UNISOR and now UNIRIB collaborations. And, in all aspects of our program, we have maintained close collaborations with theorists, both to inspire the most exciting experiments to perform and to extract the pertinent physics from the results.

The progress of our group has been made possible to a significant extent through the work of the research associates, visitors, and graduate students. The research associates in our group in the last year have been Walter Reviol in high-spin studies, David Morrison in relativistic heavy-ion physics, and in the far from stability program Brian Zimmerman initially and then Jan Wauters recently. Zimmerman assumed a permanent research position at the National Institute of Standards and Technology, and then Wauters came here from the University of Leuven in Belgium. In the past year Ming Zhang finished his research and received his Ph.D. in the far from stability program, and assumed a postdoctoral position at the University of Kentucky in medical physics, and Joe Kreke finished his Ph.D. in relativistic heavy-ion physics and assumed a teaching position at Mount Saint Mary's College in Emmitsburg, Maryland. Wilhelm Mueller continues his doctoral research in the high-spin aspects of Au nuclei, John Richards in the decay properties of light Pb nuclei, and Brad Smith in rotational bands in Tl nuclei. This experimental research group benefits greatly from the theoretical work led by UT Research Professor Jing-ye Zhang (supported partially from this grant) and the collaborations with the theory groups at UT and the Oak Ridge National Laboratory.

The state and the University of Tennessee have continued to support our research effort in substantial ways. For example, the Joint Institute for Heavy Ion Research brings a large flow of visitors (primarily in theory and in radioactive beam development) to the Oak Ridge/Knoxville area. These people benefit our research program greatly. The JIHIR is supported annually by a combination of UT, ORNL, and DOE funds through this contract, with the largest part coming from the University. A separate section discusses briefly the program and accomplishments of the institute for the last year.

II. Scientific Results

II.A. Properties of High-Spin States

II.A.1. Additional Experiments on ^{179}Au

W. F. Mueller, C. R. Bingham, W. Reviol, L. L. Riedinger, B. H. Smith, J. F. Wauters [UTK]; I. Ahmad, H. A. Amro, D. J. Blumenthal, M. P. Carpenter, C. N. Davids, S. M. Fischer, G. Hackman, D. J. Henderson, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, C. J. Lister, D. T. Nisius, D. Seweryniak [ANL]; W. C. Ma [Mississippi State].

Last year several transitions in ^{179}Au were discovered from an experiment with the Fragment Mass Analyzer (FMA) and 10 Compton-suppressed Ge detectors at the Argonne ATLAS facility. While the data were limited, they provided enough information to make a preliminary analysis. Five transitions believed to be in the yrast $\pi i_{13/2}$ band were established, as well as four decay transitions out of the band, although placement of these decay-out transitions are uncertain. The energy of the $21/2^+ \rightarrow 17/2^+$ transition is tentatively assigned to be 262 keV. Comparison with $21/2^+ \rightarrow 17/2^+$ transitions in ^{181}Au, ^{183}Au, and ^{185}Au (273, 283, and 287 keV respectively) indicates that the quadrupole deformation of Au nuclei is continuing to increase with decreasing neutron number. The maximum deformation was expected to occur between $N = 102 - 104$. Transition energy, however, is only one indicator of nuclear deformation. A second indicator in intruder bands such as the $\pi i_{13/2}$ is the bandhead energy. The data from this experiment, however, were too inconclusive to make an assignment of the bandhead energy of the $\pi i_{13/2}$ band in ^{179}Au.

An additional experiment was performed in November of 1995 to establish the bandhead energy of the $i_{13/2}$ band, as well as to study the many other expected features of this nucleus (e.g. $\pi h_{9/2} - f_{7/2}$ band mixing). The two-fold experiment was performed at the Argonne ATLAS facility using the AYE-ball array and the FMA with the parallel plate avalanche counter (PPAC), and a double-sided silicon strip detector (DSSD). AYE-ball consisted of eight 70% relative efficiency Compton-suppressed Ge detectors, nine 20-30% Compton-suppressed Ge detectors, one Compton-suppressed LEPS detector, and one non-suppressed LEPS detector.

The reaction chosen for this experiment was ^{124}Te(^{58}Ni,p2n) at a beam energy of 255 MeV. The first part of the experiment used a 0.385 mg/cm^2 ^{124}Te target supported with front and back layers of ^{12}C of thickness 0.010 mg/cm^2 and 0.040 mg/cm^2 respectively. For this part of the experiment, a total of ~1.5 million events were recorded consisting of either Ge-PPAC or PPAC-DSSD coincidences. This setup should enable the identification of prompt and delayed γ-rays in a particular nucleus by the M/q information from the FMA + PPAC system, Z-identification throught X-rays, and by the α-decay information obtained with the DSSD.

The second part of the experiment involved a 0.5 mg/cm^2 ^{124}Te target with a 60 mg/cm^2 Pb backing. In this part, an array of twelve neutron counters was used with the AYE-ball array. A total of ~100 million Ge-Ge coincidence events were recorded, a subset of which consisting of γ-γ events in coincidence with one or more neutron counters. Analysis of these new data is in progress.

II.A.2. Continuing Analysis of ^{181}Au

W. F. Mueller, J. M. Lewis, W. Reviol, L. L. Riedinger, C.-H. Yu† [UTK]; C. Baktash, J. D. Garrett, N. R. Johnson, I. Y. Lee,‡ F. K. McGowen [ORNL].

Analysis of data on ^{181}Au from the ^{150}Sm(^{35}Cl,4n) reaction using the Holifield 25 MV Tandem and the Spin Spectrometer with 19 Compton-suppressed Ge detectors has led to the establishment of several prolate deformed bands. A complete level scheme, showing these bands, is shown in Fig. II.A.2.1. Spin assignments and parity are based on angular correlation analysis and comparison of systematics with ^{183}Au and ^{185}Au. Band 2 can be identified as the favored signature of a structure built on the $\pi h_{9/2}$ single particle configuration. Theoretical calculations (Particle-Rotor and Cranked-Shell Models) indicate that the favored signature of the $\pi h_{9/2}$ band is relatively pure, but that unfavored $\pi h_{9/2}$ mixes with the favored $f_{7/2}$ band. This can be seen in Bands 1 and 3. On the basis of aligned angular momentum (see Fig. II.A.2.2), band 1 can be identified as being predominately of $\pi f_{7/2}$ character, whereas band 3 is mostly $\pi h_{9/2}$. In comparison with ^{183}Au and ^{185}Au, the $\pi f_{7/2}$ is lowest in energy for ^{181}Au, yet the $\pi f_{7/2}$ and $\pi h_{9/2}$ only weakly interact in ^{181}Au when compared with the heavier odd-A Au nuclei. There is only one weak transition from the $19/2^-$ level in band 1 to the $15/2^-$ in band 3. Additionally, there is very little visible perturbation of the levels in either band, yet in ^{183}Au and ^{185}Au the corresponding bands are clearly perturbed by the interaction. This smaller interaction in ^{181}Au may be the result that the $\pi f_{7/2}$ and $\pi h_{9/2}$ bands cross at a lower rotational frequency, and thus the coriolis interaction is not as great.

The spin labels for band 4 are speculative, as the 380 keV transition from band 4 to the $15/2^-$ level in band 3 was too weak to obtain an accurate DCO measurement. A possible assignment could be that band 4 is the unfavored signature of the $\pi f_{7/2}$ band. The behavior in alignment between band 1 and 4, however, is not consistent with this assignment. It may be that interaction with some unseen band has perturbed the alignment of band 4 sufficiently to cause this discrepancy.

Bark *et al.* [1] have studied the set of five positive-parity bands in ^{177}Re. Their conclusion is that none of these bands is the pure 1/2[660] band, and that this excitation happens to lie close to other positive-parity three-quasiparticle structures. By comparison, our group has seen in isotope ^{179}Ir only one $\pi = +$ band [2], as is the case also in ^{183}Au. It is clear that the $\pi i_{13/2}$ excitation comes lower in energy in Ir and Au as the Fermi level move up, and thus does not mix much with the higher-lying bands. Three-quasiparticle bands similar to those seen in ^{177}Re should also be present in the Ir and Au isotopes. Jin *et al.* [2] saw none of these in ^{179}Ir, but it is likely that bands 6 and 7 in ^{181}Au are candidates. The one-quaisproton $1/2^+$[660] configuration is clearly seen (Band 5). Due to the large alignment of this band, it becomes the yrast configuration for spins 21/2 – 49/2. Based on this, it is likely that an $i_{13/2}$ quasiproton is part of the nuclear structure of bands 6 and 7. As can be seen in the aligned angular momentum plot (Fig. II.A.2.2), band 6 undergoes a backbend at 0.30 MeV, which is at the same frequency as the $\nu i_{13/2}$ backbending observed in the $h_{9/2}$ and $f_{7/2}$ bands. Using blocking arguments, this precludes $i_{13/2}$ neutrons being involved in the quasiparticle nature before the backbend. The exact quasiparticle nature of bands 6 and 7, however, is not yet known.

The discovery of a strongly coupled band in ^{181}Au is the first for light odd-A Au nuclei. Linking transitions between the strongly coupled band and the rest of the level scheme have not been seen; however, X-ray energy and γ-ray multiplicity confirm that this band is in ^{181}Au and not a byproduct nucleus from the reaction. The strongly coupled nature and the lack of linking transitions, are indicative that the band is high-K. The $B(M1)/B(E2)$ branching ratios in this band are consistent with band being identified as high-K $\pi h_{11/2}$ $11/2^{+}[505]$. The spins and parity labels on this band are based on that assignment.

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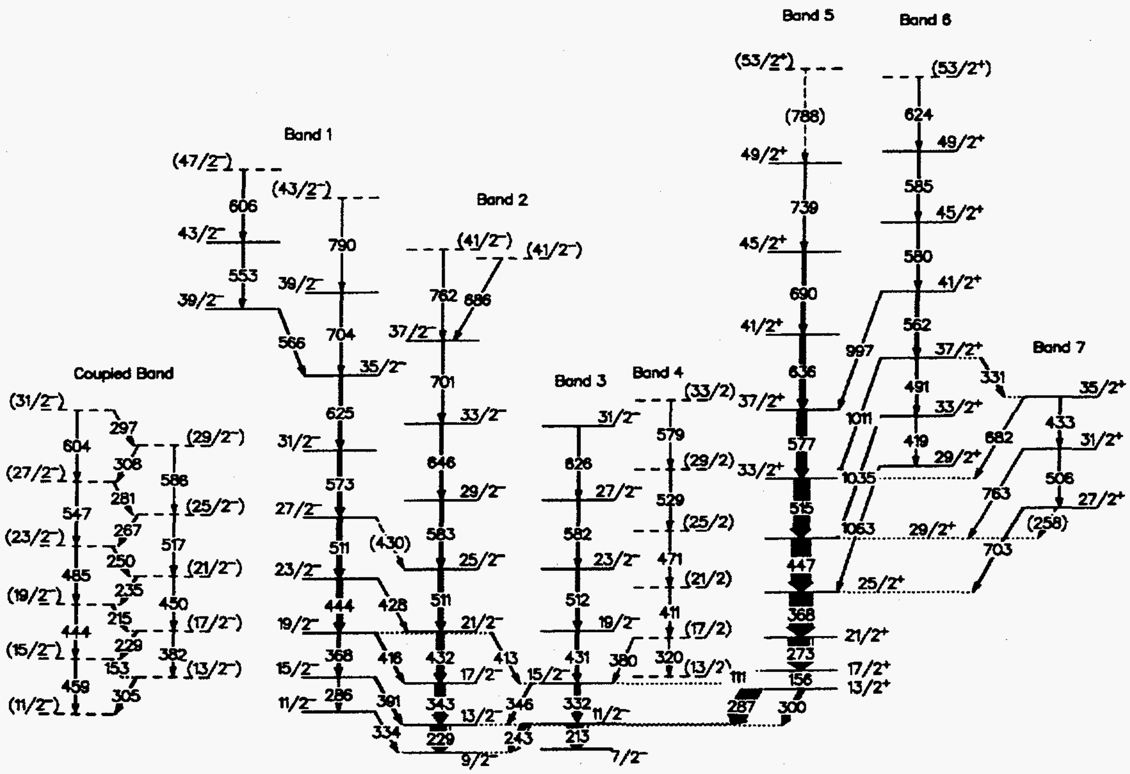

Figure II.A.2.1: Level scheme of ^{181}Au. The lowest level is set to 0, as a reference energy. The intensity of the γ-ray transition is represented by the width of the arrow.

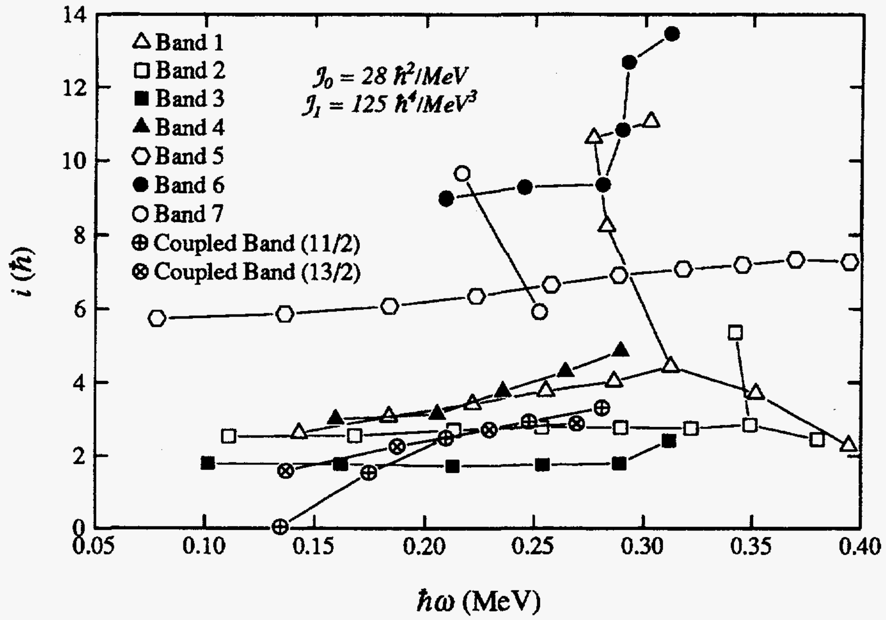

Figure II.A.2.2: Aligned angular momentum versus rotational frequency for rotational bands in ^{181}Au. The numbers in parentheses represent the lowest spin for the band represented.

II.A.3. Coexisting Shapes in ^{189}Tl

W. Reviol, L.L. Riedinger, W.F. Mueller, C.R. Bingham, B.E. Zimmerman [UTK];
T. Lauritsen [ANL]; C.-H. Yu [ROCHESTER]

For a study of normal and superdeformed bands in ^{189}Tl, we collected $2.8 \cdot 10^8$ triple and higher fold coincidences with Early Implementation Gammasphere (for details see [3]). These data have enabled us to extend the previously known [4] 9/2[505] and 1/2[660] bands and to newly establish three more bands, as already reported [5]. The proposed level scheme for the normal deformed states in ^{189}Tl is shown in Fig. II.A.3.1 (new bands are labeled 1a, 1b, and 5). Spin and parity assignments to energy levels are based on previous decay work and on our analysis of DCO ratios. Some of these assignments are tentative and given in parentheses. This scheme does not show the complete information on levels built on the $I^\pi = 13/2^+$ state but only the strongest cascade.

The lowest lying band, built upon the 9/2[505] isomer ($t_{1/2} = 1.4$ m) and labeled 1, is associated with an oblate deformed shape ($\beta_2 \sim 0.15$). This band is crossed by another strongly-coupled band (labeled 1a) establishing a sharp $(\nu i_{13/2})^2$ backbend. In this crossing region, another band of one signature (labeled 1b) feeds in which is most likely due to the oblate 1/2[550] (hole) configuration [3]. The decoupled band 4 is based on the prolate 1/2[660] intruder orbital ($\beta_2 \sim 0.27$). The structure on the left in the figure contains a decoupled band with $I^\pi \geq (9/2^-)$ labeled 5, which is proposed to be based on the prolate 1/2[541] intruder orbital. The decay out of this band proceeds mainly through a branch that feeds the known [6] $I^\pi = 3/2^+$ state, as indicated by coincidence relationships involving a 318 keV transition, and bypasses the 9/2[505] isomer. This $3/2^+ \rightarrow 1/2^+$ 318 keV transition is assumed to be a ground state transition which determines all level energies in the scheme. Such a decay pathway for high-spin states is a rather unique observation made possible by the resolving power of a new-generation γ-ray detector array.

Intensive search for superdeformed bands has revealed a weak signal of seven transitions in ^{189}Tl (367, 408, 448, 488, 527, 565, and 603 keV) with an average spacing of about 40 keV and estimated intensities in the order of 0.1 % of the yield of the 4n reaction channel. Due to the weakness of these intensities and the presence of a rather high background (mainly due to fission), it is difficult to determine in these data coincidence relationships between all these transitions to establish the presence of a band. The features of this weak signal fit to characteristics of other SD bands in the region in that the $\mathcal{J}^{(2)}(\hbar\omega)$ moments of this possible band in ^{189}Tl are increasing smoothly and with a similar slope as observed for the sets of bands in the ^{191,193}Tl isotopes based on the $\pi i_{13/2}$ [642]5/2 excitation [7, 8]. However, a candidate for a signature partner band in the ^{189}Tl data is not found. It is expected that a SD band in ^{189}Tl would be populated so weakly, considering the trend of SD band intensities in the isotopic chain of $^{189-192}$Hg (see *e.g.* [9]) together with the fact that SD bands are more weakly populated in Tl nuclei than in their Hg isotones. For a successful continuation of the superdeformation studies on light Tl nuclei, new ^{189}Tl data with higher statistics than in the present data set are necessary.

II.A.4. Alignment Additivity in the Two-Quasiparticles Superdeformed Bands of ^{192}Tl

S.M. Fischer, M.P. Carpenter, R.V.F. Janssens, B. Crowell, I. Ahmad, D.J. Blumenthal, T.L. Khoo, T. Lauritsen, D. Nisius [ANL]; W. Reviol W.F. Mueller, L.L. Riedinger, B.H. Smith [UTK]; B. Cederwall [LBL]

Six superdeformed (SD) bands were reported for this odd-odd nucleus in an earlier study by Liang et al. [10]. Two of the bands displayed a dynamic moment of inertia $\mathcal{J}^{(2)}(\hbar\omega) \simeq$ *constant* and this feature was attributed to double blocking of quasiparticle alignments in the neutron $j_{15/2}$ and proton $i_{13/2}$ intruder orbitals. This provided experimental evidence that the alignment of the high-N intruders is responsible for the smooth rise in $\mathcal{J}^{(2)}$ seen in most SD bands in this mass region. New results on ^{192}Tl have been obtained from a measurement with GAMMASPHERE consisting, at that time, of 36 Compton-suppressed Ge detectors (Early Implementation). High spin states in ^{192}Tl were populated with the ^{160}Gd(^{37}Cl,5n) reaction using a 178 MeV ^{37}Cl beam from the 88 inch Cyclotron. The ^{160}Gd target consisted of two self-supporting 0.5 mg/cm^2 foils. A total of $5 \cdot 10^8$ triple and higher fold coincidence events were recorded. The data were subsequently sorted into a three-dimensional histogram from which, in the analysis, double-gated one-dimensional spectra were created.

The main result from the search for SD bands are four $E2$ sequences, grouped into two signature partner pairs (bands A,B and C,D [11]). The assignment of these bands to ^{192}Tl is based on the observation of coincident yrast transitions in the nucleus requiring a detailed knowledge of the level scheme [12] (see also next section). Bands A, B and C correspond to bands 1, 3 and 5 of ref. [10], while band D is new to this work. Three of the bands reported in ref. [10] could not be confirmed. One of the reasons for misassignments in ref. [10] is a higher fission background since earlier the ^{192}Tl nucleus was studied in a (^{37}Cl,5n) reaction

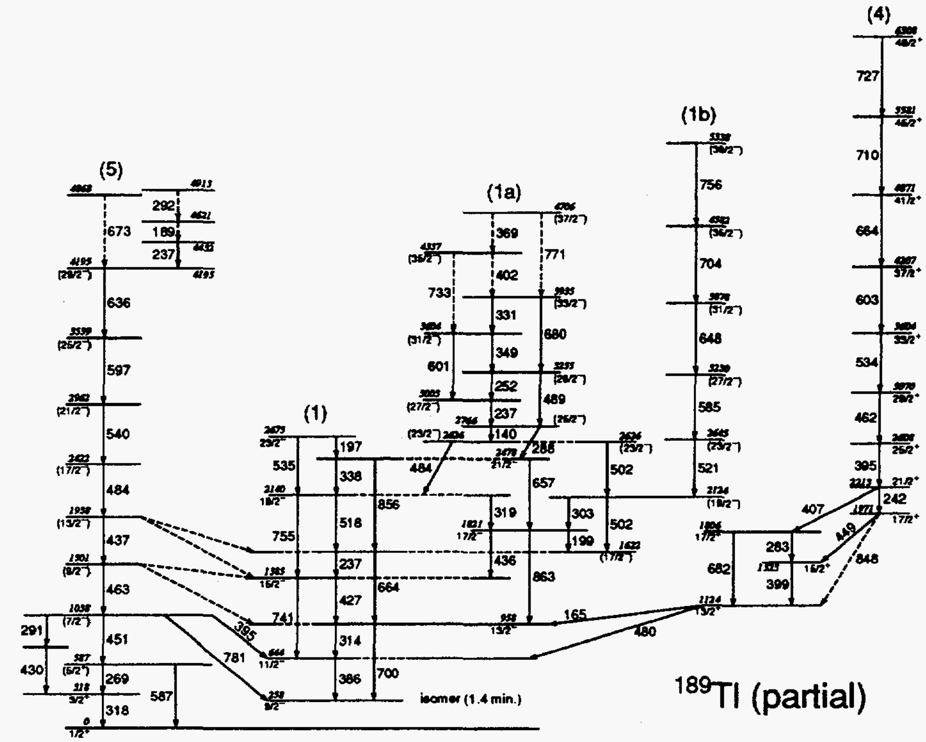

Figure II.A.3.1: Partial level scheme of ^{189}Tl from high-spin spectroscopic studies using the ^{156}Gd(^{37}Cl,4n) reaction. The band structures viewed as oblate and prolate bands are shown. Levels are labeled by the proposed spins, parities, and excitation energies (assuming the final state of the $3/2^+ \rightarrow 1/2^+$ transition [6] is the ground state).

at a higher bombarding energy. In Fig. II.A.4.1, the $\mathcal{J}^{(2)}$ moments of the four bands are presented as a function of rotational frequency. While bands C and D display a "typical" smooth rise in $\mathcal{J}^{(2)}$ with $\hbar\omega$, bands A and B are characterized by essentially constant $\mathcal{J}^{(2)}$ values. This difference was already noted in ref. [10] where the "flat bands" were assigned to the double intruder configuration $\nu j_{15/2} \otimes \pi i_{13/2}$.

This configuration assignment and the proposed assignment for bands C and D can be made firmer by comparing the alignments of the bands relative to a ^{192}Hg core with the alignments of the SD bands in odd-A neighboring nuclei known to be based on certain configurations. The alignments for bands A and B in ^{192}Tl, adapting the level spins from an educated guess, are shown in Fig. II.A.4.2 (a). These are compared in the same figure with $i(\hbar\omega)$ curves obtained by summing the individual contributions of the experimental one-quasineutron orbitals in ^{191}Hg [13] and one-quasiproton orbitals in ^{193}Tl [8], which form the appropriate two-quasiparticle bands, *i.e.* $j_{15/2} \otimes i^{f}_{13/2}$ for band B and $j_{15/2} \otimes i^{u}_{13/2}$ for band A (superscripts denote favored and unfavored signature). Fair agreement exists both in the magnitude and the variation of the alignment with frequency between the data and the computed values. Fig. II.A.4.2 (b) shows the alignments for bands C and D obtained for level spins derived from fits to $\mathcal{J}^{(2)}$ as described in refs. [14, 15]. Here, the summed alignments resulting from the coupling of bands 5 and 6 in ^{191}Hg [16] to the favored $i_{13/2}$ band in ^{193}Tl follow the trend for bands C and D fairly well. Thus, the bands C and D in ^{192}Tl are proposed to be based on the $5/2[512]\otimes i_{13/2}$ configuration. From these comparisons it is concluded that the concept of alignment additivity is applicable to SD bands in the mass 190 region, and that these alignments can be accounted for by considering quasiparticle excitations in a conventional way.

Interestingly, the $\mathcal{J}^{(2)}$ moments of band B display a long $\Delta I = 2$ staggering similar to the effect in the yrast SD band of ^{149}Gd [17]. While the staggering pattern in ^{194}Hg [18] is *possibly* the result of a band interaction scenario as described in a later section of this report, a straightforward band interaction picture of mixing of *e.g.* vacuum and two-quasiparticle aligned states is less likely for ^{192}Tl. Thus, the presence of an oscillation in band B might be particularly significant.

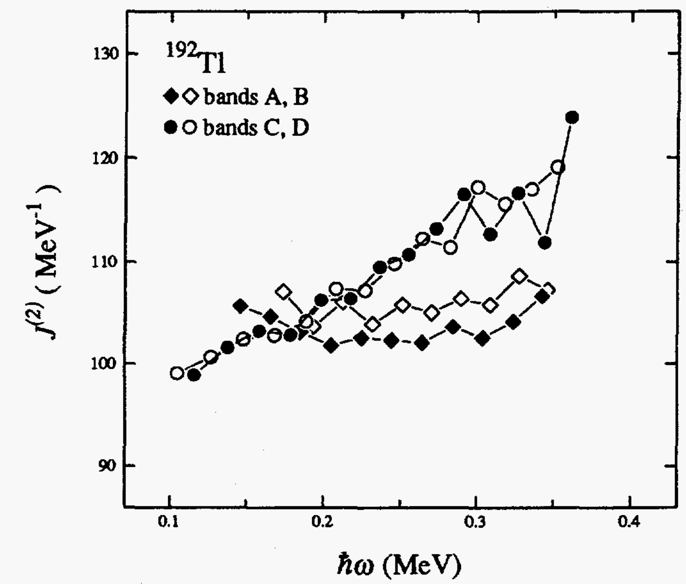

Figure II.A.4.1: Dynamical moment of inertia for the four SD bands observed in ^{192}Tl [11].

II.A.5. High Spin Studies of ^{192}Tl at Normal Deformation

B.H. Smith, W.F. Mueller, W. Reviol, L.L. Riedinger [UTK]; S.M. Fischer, M.P. Carpenter, R.V.F. Janssens, B. Crowell, I. Ahmad, D.J. Blumenthal, T.L. Khoo, T. Lauritsen, D. Nisius [ANL]; B. Cederwall [LBL]

The data taken for the study of superdeformed bands in ^{192}Tl (see previous section of this report) has also been used to study the yrast and near-yrast states of this nucleus in detail. From an analysis of the three-dimensional histogram (cube), we have built a new level scheme [12] shown together with the superdeformed bands in Fig. II.A.5.1. The proposed spin and parity assignments to the normally deformed states are preliminary. To make these

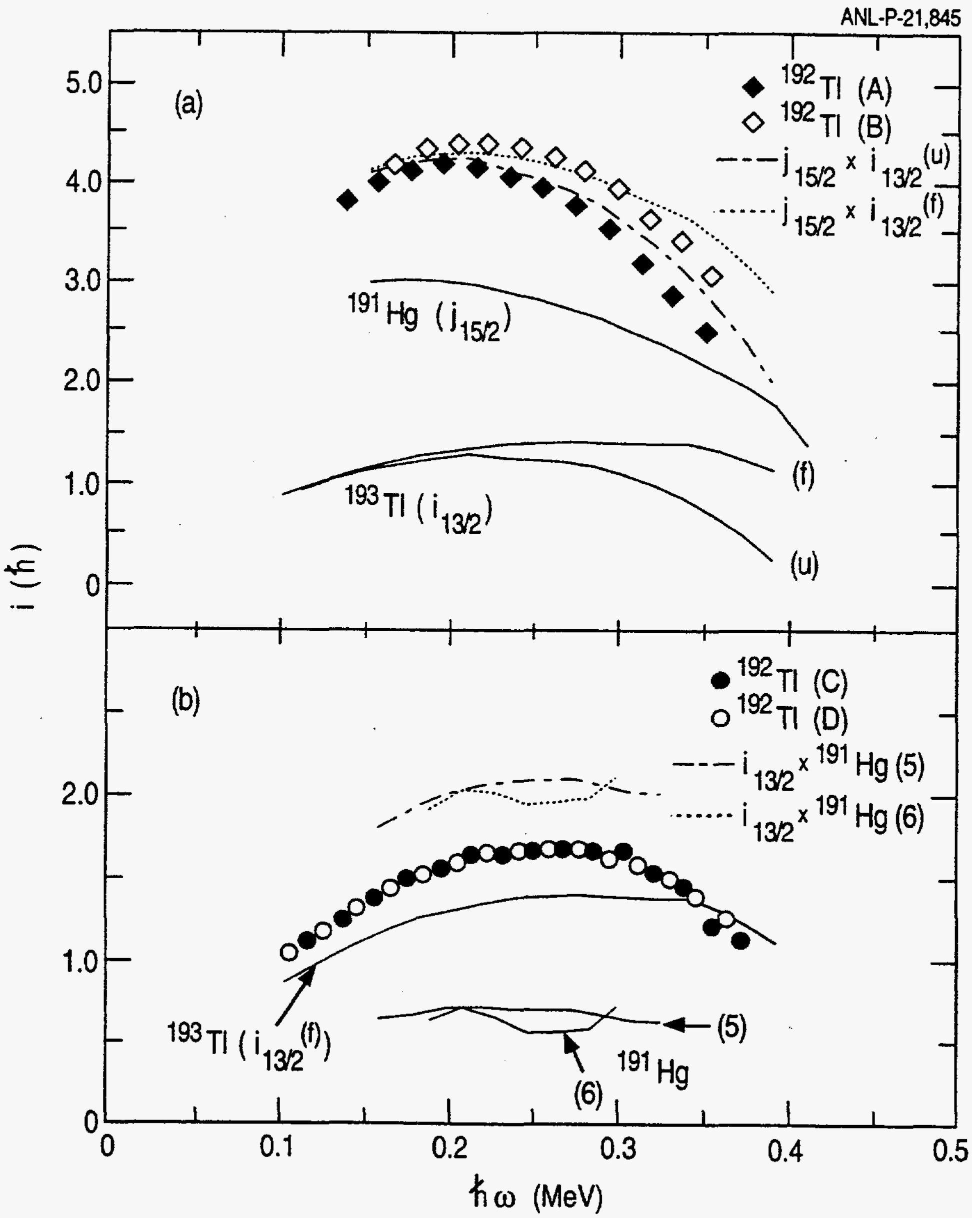

Figure II.A.4.2: (a): Alignments derived from the data for bands A and B in ^{192}Tl and comparison with curves based on alignments in neighboring nuclei. Solid curves: experimental alignments for the $j_{15/2}$ band of ^{191}Hg (band 1) and the favored (band 2) and unfavored (band 1) $i_{13/2}$ bands in ^{193}Tl. Dotted and dot-dashed curves: sums of these alignments for the configurations where the $j_{15/2}$ favored configuration is coupled to the two signatures of the $i_{13/2}$ configuration. (b): Same as (a) for alignments in bands C and D. In this case, the data are compared with configurations involving SD bands 5 and 6 in ^{191}Hg. This figure is taken from [11].

assignments more concrete, we have begun an analysis of the multipolarities of the γ-ray transitions by evaluating DCO (Directional Correlations from Oriented states) ratios. For this purpose a two-dimensional histogram (matrix) has been constructed with the energies of the events counted in one of the six 90° detectors along the x-axis and the energies of the events detected with any other non-90° counter on the y-axis.

The low-spin part of this level scheme is adapted from a previous work by Kreiner et al. [19]. Although a link between the 8^- state and the lower-lying $K^\pi = 8^-$ isomeric state ($t_{1/2}$ = 272 ns) is not observed in the data, it is evident that this isomer is populated strongly as indicated by the presence of a strong 250.6 keV γ-ray in coincidence with most transitions. Therefore, the lower limit for the K value of the observed levels is $6 - 8\hbar$ and the proposed spin assignments can be viewed as reasonable. The known strongly coupled negative parity band [19] (labeled band 1 in Fig. II.A.5.1) has been extended. This band is observed to be crossed by a new strongly-coupled band labeled $1a$, which extends the level scheme up to a spin of $24\hbar$ and an excitation energy of $\sim$ 5.2 MeV. The band structures labeled 2 and 3 are entirely new observations, each consisting of two signature partner sequences. The upper part of band 2 is linked to band 1 by relatively high-energy γ-rays with DCO ratios that are consistent with $E1$ multipolarity. This part of band 2 is linked to the bandhead sequence by a 136 keV γ-ray, which has been tentatively assigned as an $I \rightarrow I$ transition. Band 3 decays to lower lying states which are located in the crossing region of bands 1 and $1a$. There is evidence in the data for one more new band structure in ^{192}Tl which cannot be related to the scheme of strongly-coupled bands shown in Fig. II.A.5.1, nor can it be assigned to a neighboring nucleus. It is likely that these γ-ray transitions represent a decoupled band in ^{192}Tl.

For preliminary configuration assignments to bands 1, 1a, and 2, we assume that the odd-proton occupies an $h_{9/2}$ orbital, analogous to states in odd-A Tl neighboring nuclei above the $9/2^-$ isomer. This proton orbital is known to have a large influence on the shape of $A \sim 190$ nuclei which typically minimize in total energy at slightly oblate deformation with $\beta_2 \sim 0.15$. To identify the active neutron orbital involved, we inspect the experimental routhian energies shown in Fig. II.A.5.2 as function of rotational frequency. For comparison, $e'(\hbar\omega)$ plots for yrast bands in the neighboring ^{191,192}Hg nuclei [20] are included in the figure. While in ^{192}Hg the AB neutron pair undergoes a rotational alignment at a crossing frequency of 0.21 MeV, this crossing is blocked in ^{191}Hg by the odd neutron and instead a delayed BC crossing occurs at a frequency of 0.27 MeV. Very similar to the ^{191}Hg case is the crossing behavior of bands 1 and 1a in ^{192}Tl with $\hbar\omega_c \sim 0.26$ MeV and a similar alignment gain ($\Delta i \sim 9\hbar$). Thus, band 1 is proposed to be based on the $\pi9/2[505] \otimes \nu5/2[642]$ ($K = 7^-$) configuration and band 1a on the corresponding four-quasiparticle configuration ($K = 7^-$) $\otimes$ $(i_{13/2})^2$. These assignments agree with the interpretation for band 1 in ref. [19]. The $e'(\hbar\omega)$ plot for band 2 resembles the ^{192}Hg case, thereby excluding the excitation of a single $i_{13/2}$ neutron. Since band 2 interacts with band 1, it must also be high-K in nature. Most likely, band 2 is based on a $\pi9/2[505] \otimes \nu5/2[503]$ configuration with $K = 7^+$. This would be also the energetically favorable coupling of parallel proton and neutron spins according to the Gallagher-Moszkowski rule [21]. The two-quasiparticle configuration assignments for bands 1 and 2 are supported by an analysis of $B(M1)/B(E2)$ ratios. A comparison between experimental $B(M1)/B(E2)$ ratios and predictions obtained from the semi-classical model by Dõnau and Frauendorf [22, 23] for the same two-quasiparticle configurations indicates agreement between data and model for the $K = 7$ couplings.

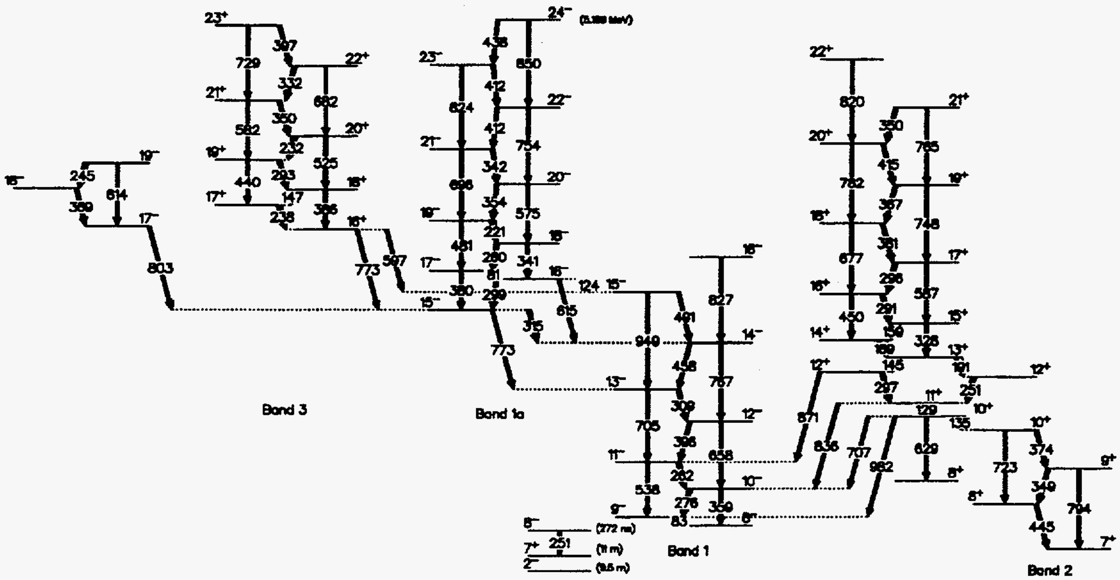

Figure II.A.5.1: Proposed level scheme for ^{192}Tl from high-spin spectroscopic work. The 7^+ and 8^- states are isomeric with half lives of 11 m and 272 ns respectively [19]. For the levels above these states, spin and parity assignments are tentative.

II.A.6. Bands in odd-odd ^{164}Tm – complete sets of couplings

W. Reviol, L.L. Riedinger, X.Z. Wang, J.-Y. Zhang [UTK]; H.J. Jensen, G.B. Hagemann, P.O. Tjøm, R.A. Bark, S. Leoni, T. Lönnroth, H. Schnack-Petersen, T. Shizuma, J. Wrzesinski [NBI]

Our recent NORDBALL experiment on ^{164,165}Tm (for details see [24], section II.A.6) has established more than 12 rotational-like band structures assigned to ^{164}Tm. Ten of these structures consist of two signature partner $E2$ sequences linked by $M1$ transitions. Three of these structures were observed previously [25], but only over a range of 10 - 12 spin units. A partial level scheme for ^{164}Tm is shown in Fig. II.A.6.1. For example, the bands labeled 3 and 4 have been found in the course of this work, while band 5 contains the sequences called "C" and "D" in ref. [25]. Like in other high-spin work on odd-odd nuclei, the decay out of the lower levels cannot be determined from experimental evidence only. Thus all proposed spin and parity assignments are uncertain. Nevertheless, most of the bands reported can be associated with either the $K^\pi = 1^+$ ground state (*e.g.* the low-K bands 3, 4 and 5) or the $t_{1/2} = 5.1$ m $K^\pi = 6^-$ isomer [25] (*e.g.* the high-K yrast band, labeled 6).

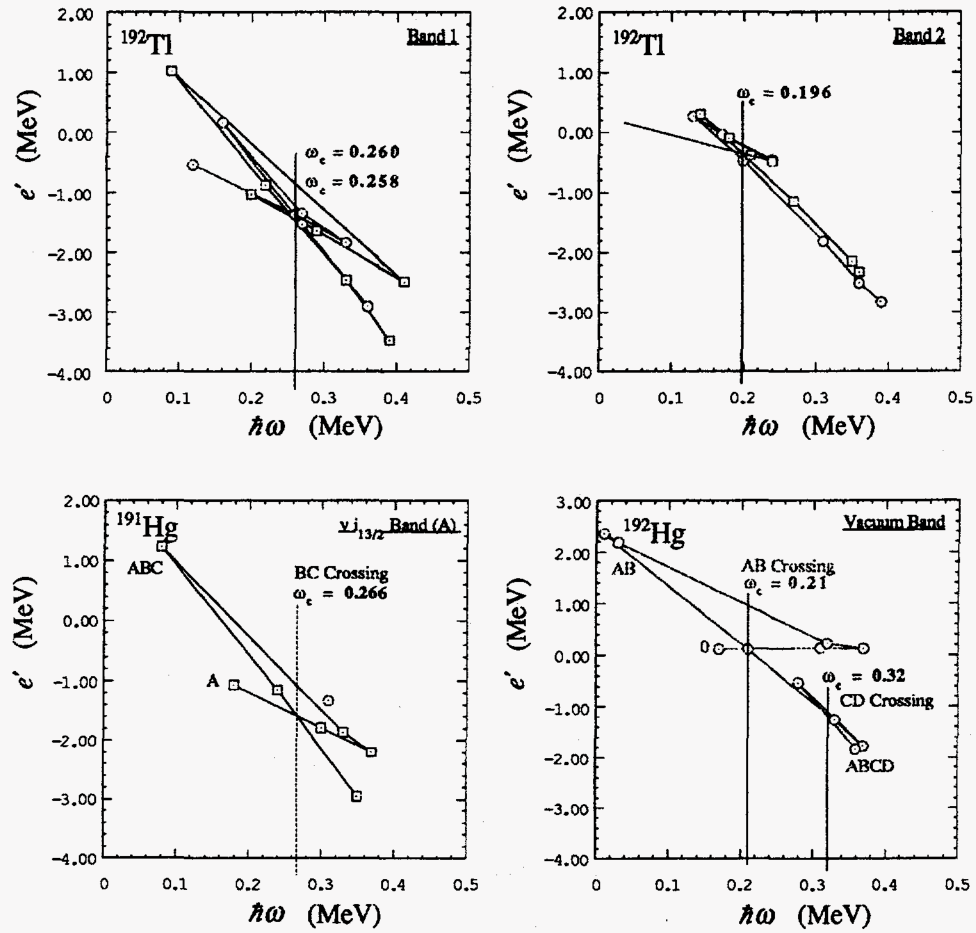

Figure II.A.5.2: Routhian energies versus rotational frequency for bands in ^{192}Tl and ^{191,192}Hg. The set of parameters $\mathcal{J}_0 = 8\ \hbar^2\ \mathrm{MeV}^{-1}$ and $\mathcal{J}_1 = 40\ \hbar^4\ \mathrm{MeV}^{-3}$ is used as a rotating reference.

To give an overview over the bands in ^{164}Tm, we summarize in table II.A.6.1 the Nilsson levels identified in the neighboring odd-A Tl isotopes and Er and Yb isotones and indicate which of the resulting proton-neutron couplings are proposed to be assigned to a band in the odd-odd nucleus. These assignments are based on intensity considerations, the presence of band crossings (only the bands 7 and 12 display a neutron AB alignment with $\hbar\omega_c \approx 0.25$ MeV), the degree of signature splitting, the relative sizes of the dynamic moments of inertia, and $B(M1)/B(E2)$ ratios. We do not concur with the $\pi h_{9/2} \otimes \nu i_{13/2}$ assignment to band 5 in reference [25], mainly for the following reason. The signature splitting of both of these orbitals is large in the adjacent odd-A nuclei ($\Delta e' \geq 160$ keV at $\hbar\omega = 0.15$ MeV) but the measured splitting for band 5 small ($\Delta e' = 8$ keV). Instead, we prefer to assign the favored signature of the $\pi h_{9/2} \otimes \nu i_{13/2}$ band to one of the "single" $E2$

sequences (band 9). As indicated in table II.A.6.1, we observe many complete sets of proton-neutron couplings in ^{164}Tm including both the parallel and the anti-parallel orientation of the individual spins (couplings with different K values). The energetically more favorable parallel coupling (Gallagher-Moszkowski rule [21]) is assigned to the stronger one, the anti-parallel coupling to the weaker one of both bands. This argument leads us to propose for the previously known band 1 (called "B" in ref. [25]) an ($K^\pi = 1^+$) 7/2[404]⊗5/2[642] assignment. In cases like the "doublet" bands 6 and 3, it is however obvious that the different K assignment is consistent with the different decay out of both bands. Another important observation is that most of the bands have a very small signature splitting ($\Delta e' \approx 0$ at $\hbar\omega =$ 0.15 MeV) and thus are predestined for comparisons with Tilted Axis Cranking (TAC) [26] model calculations.

Perhaps the most sensitive test for configuration assignments to our bands are the $B(M1)/B(E2)$ ratios extracted from experiment. The ratios obtained for bands 1, 2, 3, and 6 are shown shown in Fig. II.A.6.2. While larger magnetic moments for configurations involving the 7/2[523] proton orbital (bands 3, 6) than for configurations involving the 7/2[404] orbital (bands 1, 2) are expected, it is interesting that the $M1's$ are consistently larger for the configurations with low K than for the ones with high K-values. This difference is fairly well reproduced over the full $\hbar\omega$ range by the results from TAC calculations (performed in collaboration with S. Frauendorf) which are included in Fig. II.A.6.2. The success of this model appears particularly for the low-K couplings, for which the "standard" Dönau-Frauendorf formalism [22, 23] is not applicable. The TAC model provides also quantitative descriptions of $\Delta e'$ values and excitation energies of bands relative to each other that are in better agreement with the data than other models. Indeed, the TAC model is needed to describe newly-observed features in rare-earth nuclei.

The $B(M1)/B(E2)$ branching for band 6 shows a staggering between two consecutive spins up to a 50 % difference, which holds for a careful analysis of $E2/M1$ mixing ratios. This staggering is correlated with a very small but significant staggering in the signature splitting of the band (differences in $\Delta e'$ of 5 keV or less). Observation of this fine effect goes beyond our present understanding of phenomena in rotational bands.

II.A.7. Transition energy staggering and band interaction in rare-earth nuclei

W. Reviol, L. L. Riedinger [UTK]; H.-Q. Jin [ORNL].

Recently, $\Delta I = 2$ staggering effects in the $\mathcal{J}^{(2)}$ moments of inertia of superdeformed bands have been observed, *viz.* in ^{149}Gd by Flibotte et al. [17] and in ^{194}Hg by Cederwall et al. [18]. The authors of references [17, 18] applied higher order derivatives of the γ-ray transition energy, $\Delta^3 E_\gamma$ and $\Delta^4 E_\gamma$ respectively, to amplify these small-amplitude effects ($\sim$ 100 eV). We have performed a similar analysis for the normally deformed rare-earth nuclei from gadolinium to platinum [27]. We find that staggering effects of $\Delta I = 2$ type are present in these nuclei and are related to the interaction of a particular band with another one of the same parity and spin sequences (mixing). The second important observation is that the staggering patterns of both bands are in antiphase. However, the staggering amplitudes as a function of I (or E_γ) form a bell-shaped envelope which is different from the constant

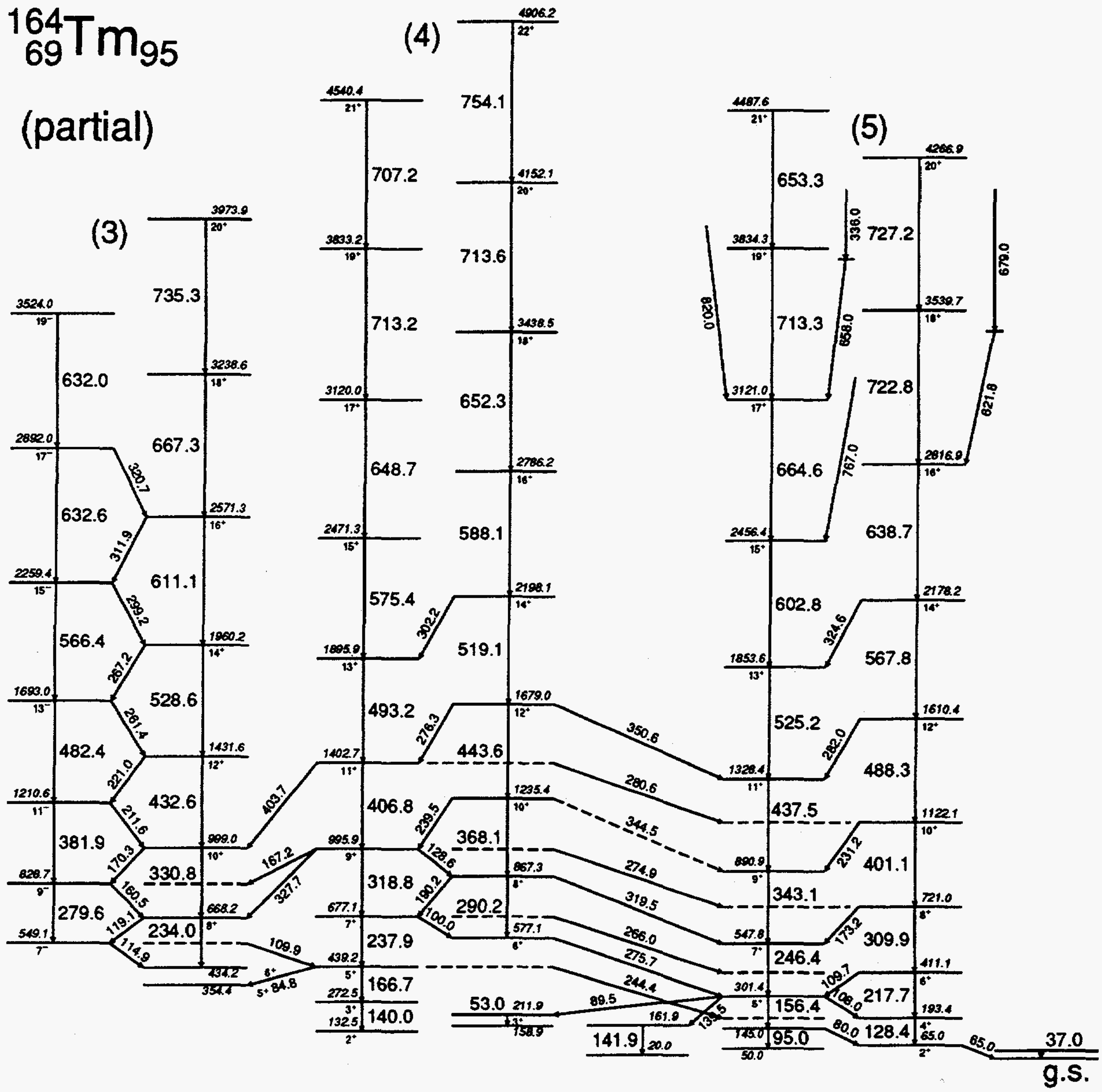

Figure II.A.6.1: Part of our proposed level scheme for ^{164}Tm obtained in the ^{150}Nd(^{19}F,5n) $E_{lab} = 85$ MeV reaction. These are the bands with presumably prompt decay to $K = 1^+$ ground state. The $E2$ sequences forming band 5 have been reported previously [25]. Spin and parity assignments to the band head states are uncertain, spin changes between levels are based on DCO ratios.

Table II.A.6.1: Expected proton-neutron configurations in ^{164}Tm and proposed assignments to the bands observed. Left columns: Known proton and neutron levels in neighboring odd-A nuclei labeled by their Nilsson quantum numbers and a symbol for spin "up" or "down". Right columns: Doublets of couplings for parallel and anti-parallel proton and neutron spins labeled by the $K = K_p \pm K_n$ value. In parenthesis, the number of the band label is given. The lower- and higher-lying K^π state is qualified.

Couplings			
		odd-odd Kπ	
p	n	lower ↑↑	higher ↑↓
7/2[523] ↑	5/2[523] ↓	1+ (g.s.)	6+ (#12)
7/2[404] ↓	5/2[523] ↓	6- (iso.,#7)	1-
1/2[411] ↓	5/2[523] ↓	3-	2-
1/2[541] ↓	5/2[523] ↓	3+ (#8)	2+
7/2[523] ↑	5/2[642] ↑	6- (#6)	1- (#3)
7/2[404] ↓	5/2[642] ↑	1+ (#1)	6+ (#2)
1/2[411] ↓	5/2[642] ↑	2+ (#5)	3+ (#4)
1/2[541] ↓	5/2[642] ↑	2- (#9)	3-
7/2[523] ↑	3/2[521] ↑	5+ (#11)	2+ (#10)

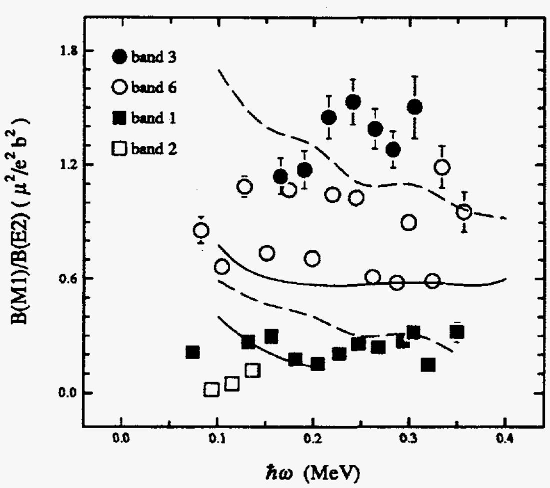

Figure II.A.6.2: Experimental $B(M1)/B(E2)$ ratios for the "doublets" bands 3 and 6 and bands 1 and 2 as a function of rotational frequency and comparison with calculations using the Tilted Axis Cranking model. Theoretical curves: dashed for low-K, full lines for high-K configurations (see text).

behavior of the staggering amplitude observed in *e.g.* ^{149}Gd.

As representative cases, sets of bands in ^{156}Dy [28] and ^{166}Yb [29] are chosen. In Fig. II.A.7.1, the staggering parameter

$$\Delta^3 E_\gamma(I) \;=\; 1/8[E_\gamma(I+3) - 3E_\gamma(I+1) + 3E_\gamma(I-1) - E_\gamma(I-3)]$$

is compared with the relative energy between the two bands as a function of I, indicating that the staggering effect is localized around a crossing spin I_c where the two bands come closest in energy. In most cases, both bands are connected by $E2$ interband transitions. We base our conclusions on those examples of staggering effects where the strength $|V_I|$ of the band interaction can be extracted from experiment. For cases with $|V_I| < 100$ keV (upbends excluded), the amplitude of the staggering increases with increasing interaction in a roughly proportional way.

For discussion, we use first a schematic picture for band interaction. This consists of two rigid rotor $E2$ cascades with one energy level, *e.g.* $I = 12$, shifted down by an amount ϵ and another $I = 12$ level in the second band shifted up by the same amount. The two model $E2$ cascades exhibit for the spins $I-6, I-4, I-2, I, I+2, I+4, I+6$ a staggering behavior

$$\Delta^3 E_\gamma \;=\; 0, \mp 1/8\epsilon, \pm 4/8\epsilon, \mp 6/8\epsilon, \pm 4/8\epsilon, \mp 1/8\epsilon, 0$$

(upper sign: band 1, lower sign: band 2) that resembles the oscillatory patterns shown in Fig. II.A.7.1 (b). The significance of this picture is that a staggering pattern in $\Delta^3 E_\gamma(I)$ is produced as a consequence of a change of one energy level or two transition energies propagating through formula (1). Secondly, we have performed two-band mixing calculations [30] with the interaction strength as a free parameter to fit the amplitudes of the experimental staggering patterns in normally deformed bands. With the experimental values $|V_I| =$ *constant* we obtain reasonable agreement between data and calculations. In Fig. II.A.7.1 (c), $\Delta^3 E_\gamma(I)$ patterns of calculated sequences for ^{156}Dy and ^{166}Yb are shown. The oscillation in the ^{156}Dy case is more symmetric with respect to I_c than in the ^{166}Yb case. This detail depends on the difference between the I_c value and the nearby spin. For I_c exactly between two level spins, a perfectly symmetric staggering is obtained. In practice, the shape of the staggering pattern can be used to determine quite precisely (within 1 $\hbar$) where two $\Delta I = 2$ sequences intersect.

The analysis of staggering effects in normally deformed bands is also used to make a comparison with the oscillations observed in a few superdeformed bands. Again, we use the schematic picture for band interaction (*cf.* expression (2)), but assume now a model $E2$ cascade that is twice perturbed at separate spins (spin regions) 8 $\hbar$ apart. The effect obtained in $\Delta^3 E_\gamma$ is shown in Fig. II.A.7.2 (c) for one band only. This situation could be due to interactions of a band with two different bands where energy levels in band 1 are accidentally shifted by a very similar amount in both crossing regions. For comparison, we include in Fig. II.A.7.2 also plots for those superdeformed bands and show as inset of Fig. II.A.7.2 (c) the $\mathcal{J}^{(2)}$ behavior of the model cascade. The plot for the model cascade resembles the experimental pattern for ^{194}Hg. The creation of a "flat" staggering pattern of a very particular band like the one in ^{194}Hg by its interaction with two other bands is a possibility to be considered in the present discussion of $\Delta I = 2$ effects in superdeformed bands.

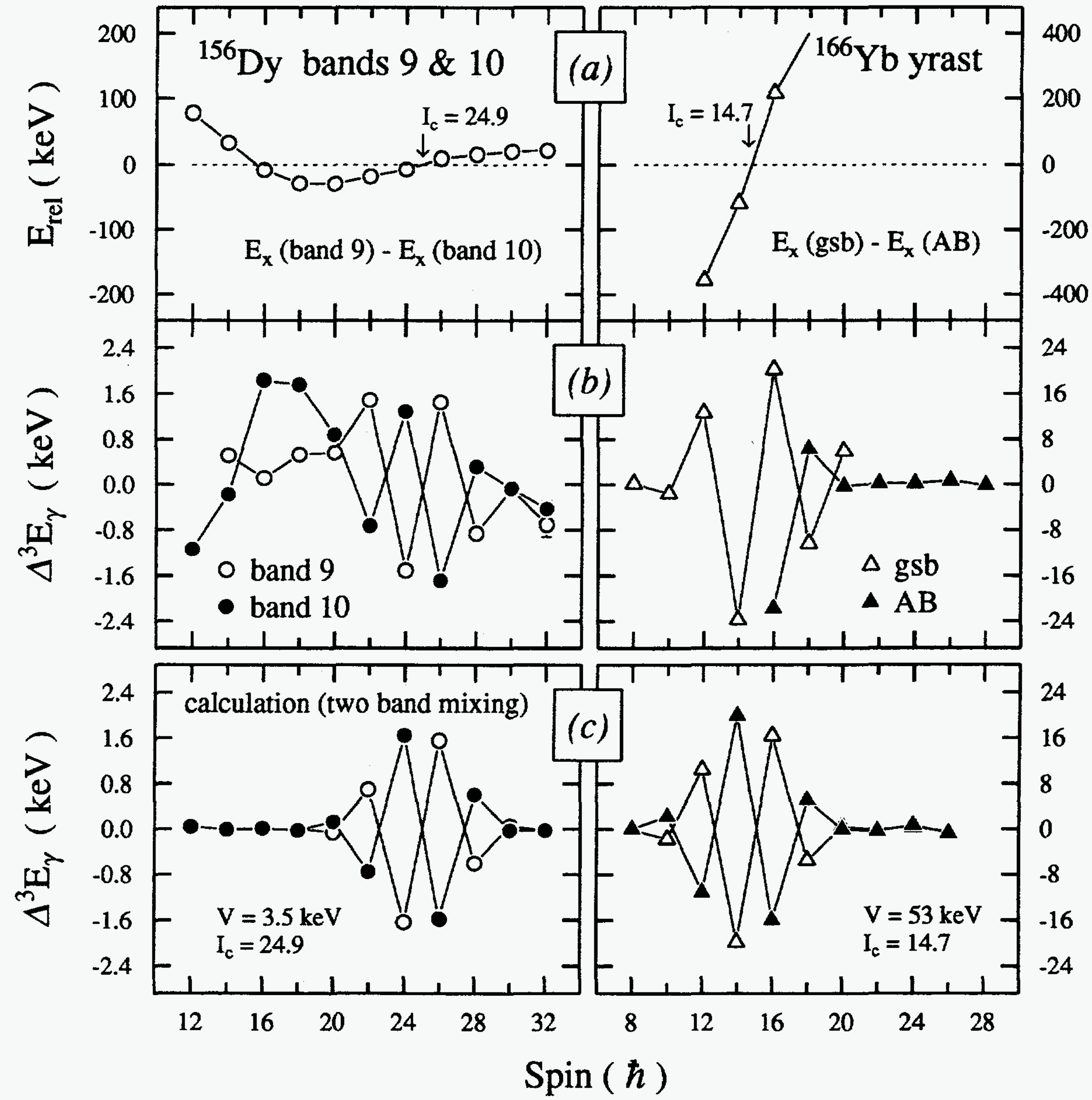

Figure II.A.7.1: (a) Difference in excitation energies E_{rel} for interacting bands and (b) energy staggering in representative cases: ^{156}Dy [28], ^{166}Yb [29]. (c) Fits to the $\Delta^3 E_\gamma(I)$ data using $\Delta I = 2$ sequences calculated with a two-band mixing model.

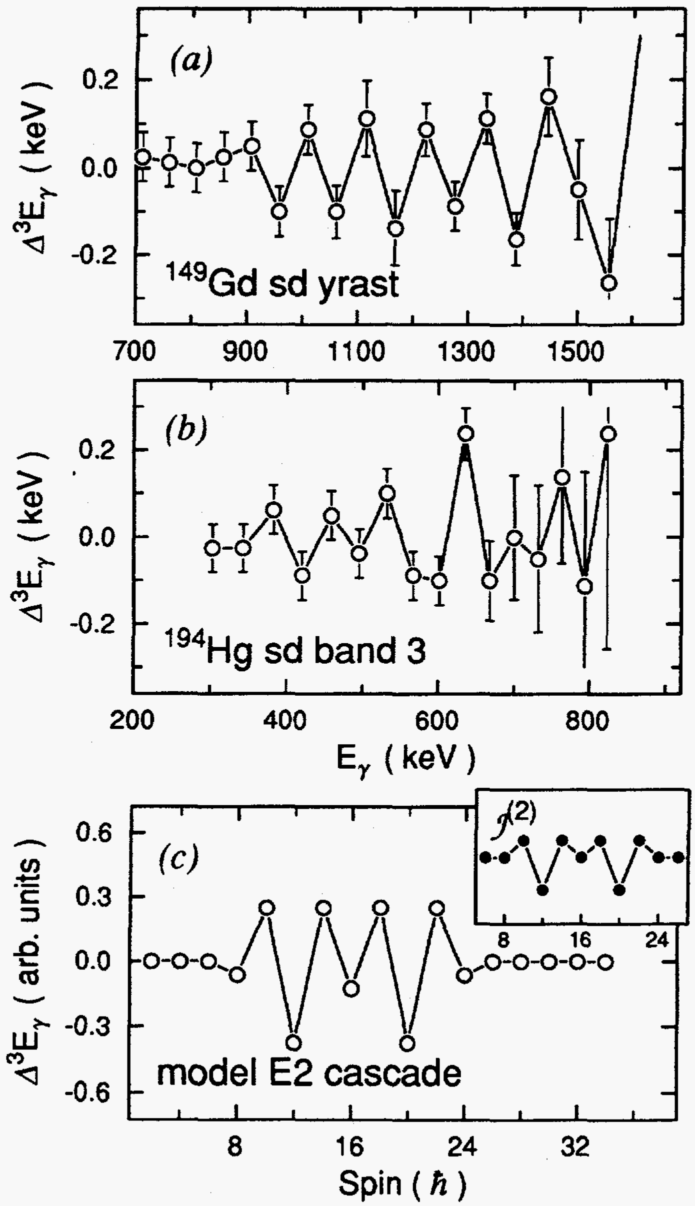

Figure II.A.7.2: $\Delta^3 E_\gamma(I)$ staggering patterns for superdeformed bands of (a) ^{149}Gd [17] and (b) ^{194}Hg [18] in comparison with that of an (c) $E2$ model cascade due to an energy shift of the spin levels $I = I_c, I_c + 8$ by the same amount. Inset: $\mathcal{J}^{(2)} vs. I$ for the model cascade. In part c, the ordinates of both graphs have arbitrary units in order to demonstrate the staggering effect qualitatively.

II.A.8. High-Spin States and K-Forbidden Decay in ^{172}Hf

D.M. Cullen, C.-H. Yu, R.W. Gray, M.J. Fitch, X.-H. Wang [ROCHESTER]; C. Baktash, N.R. Johnson [ORNL]; A.O. Macchiavelli, I.Y. Lee [LBL]; W. Reviol [UTK].

High-spin states in ^{172}Hf were populated with the ^{128}Te(^{48}Ca,4n) reaction at 200 and 214 MeV. The experiment was performed at the Lawrence Berkeley Laboratory using the GAMMASPHERE array with 36 detectors (Early Implementation) to measure the in-beam γ-rays. Double- and higher-fold coincidence events were collected, in total $3.2 \cdot 10^8$ events at 200 MeV and $2.5 \cdot 10^9$ unfolded events at 214 MeV.

The seven previously known rotational bands [31] in ^{172}Hf have been extended significantly, *e.g.* the yrast band from a highest-spin state of 34 $\hbar$ to a highest-spin state of 44 $\hbar$. In addition, five new band structures have been established. One of the newly-established structures, labeled "7" in reference [32], is a strongly-coupled band with an interesting decay-out path way. This band is likely to be built upon a $K^\pi = (14^+)$ bandhead state. The observed γ-decay of this state proceeds through three consecutive transitions with 142, 201, and 1256 keV, the latter feeding the $I^\pi = 12^+$ level of the $K = 0$ yrast band. In this decay scheme, the 1256-keV γ-ray represents a $\Delta K = (12)$ transition. The apparent breakdown of the K-selection rule may be due to a mixing of high-K components into the yrast band in the region of the first band crossing where the feeding takes place.

II.A.9. Statistical Analysis of Pairs of Rotational Bands in 'Odd and Even' Nuclei at Normal Deformation

I. Ragnarsson[Lund]; Jing-ye Zhang and L.L. Riedinger [UTK].

Identical bands (IBs) were first observed at superdeformation [33, 34], where transition energies in rotational bands are sometimes found to be surprisingly similar in adjacent nuclei. While it is for strongly deformed configurations that the best examples of identical bands have been observed, it has been found that also at normal deformation some rotational bands in even-even nuclei and their odd-even neighbors are very similar in moment of inertia, and these bands have been also referred to as identical [35, 36, 37, 38]. Before trying to find specific explanations for the identical bands, it seems important to clarify, however, if indeed there are more bands in odd nuclei which are very similar to their even neighbors than one would expect from "simple coincidence". Thus, for the differences between bands in odd and even nuclei, one would in general expect a smooth distribution [39] with some bands being identical or close to identical (this is provided that the distribution is not peaked at large differences and goes to zero when the bands are very similar). In our opinion, it is only in the case that there is a large surplus of very similar bands over this smooth distribution that this phenomenon becomes a real challenge and it becomes relevant to look for special explanations, for example special symmetries as reviewed in ref. [38].

In our study a sample of 234 pairs of normally deformed bands [37] in odd-Z nuclei and their $A-1$ even-even neighbors in mass region $A = 150-190$ with $Z = 66-79$ (data taken from [40]) was analyzed.

We have considered the distribution of the difference between rotational bands in odd-Z nuclei and their even "Z-1" neighbors. We have limited ourselves to the $A = 170$ region of nuclei where according to previous investigations, many so-called identical bands are present. We express the difference in the $R(\mathcal{J}^{(1,2)})$ number, where $R(\mathcal{J}^{(1,2)})$ expresses the relative difference in the first and second moment of inertia compared with what one would expect for rigid rotation. One can also note that $R(\mathcal{J}^{(1,2)})$ is close to the percentage change in the moment of inertia. Our main results are:

1. The distribution is centered around $R(\mathcal{J}^{(1,2)}) = 0$ but with a considerable width. Most odd-A partners of these similar bands are built on upsloping orbitals.

2. No special surplus of identical or close to identical bands is seen above the smooth distribution.

The distribution of differences is certainly somewhat dependent on how the difference is expressed in quantitative terms (e.g. the range of frequencies included; also our choice to consider absolute differences so that the contributions from different pairs of comparing states cannot be canceled because of their opposite sign). These dependences should not change our main conclusions. The fact that in this region of nuclei $R(\mathcal{J}^{(1,2)})$ is centered around zero suggests the presence of specific orbitals (upsloping) around the Fermi surface. Quantitative calculations in ref. [41] do also indicate that these orbitals tend to form bands which are close to identical to the even core bands. This is however only an effect *on the average.* Then, our second conclusion suggests that there are no other special features and thus no reason to look for other specific effects leading to a surplus of identical bands. We think it would be interesting to consider similar distributions in other regions of nuclei.

II.A.10. $\Delta I = 4$ Bifurcation: Origins and Criteria

Jing-ye Zhang, Yang Sun, and Mike Guidry [UTK]

The new γ-ray detector arrays have demonstrated that rotational sequences in certain superdeformed bands with angular momentum differing by two can split into two branches [17, 18, 42]. This is commonly called as $\Delta I = 4$ *bifurcation,* or $\Delta I = 2$ *staggering,* and has attracted considerable interest in the nuclear structure community (for instance, see refs.[43, 44, 41, 45, 46, 47, 48]. Because this phenomenon depends on the variation of E_γ values, the bifurcation appears as an oscillation in the dynamic moment of inertia, $J^{(2)}$ as well.

Intuitively, these observations suggest a fourfold symmetry in the nuclear system, corresponding to an invariance of the shape under rotations by $\frac{\pi}{2}$ [17]. This has motivated theoretical investigations that have included a C_4 symmetry piece in the Hamiltonian statically or dynamically, with the rotation axis either along or vertical to the symmetry axis [41, 46]. In another approach, the influence of $\Delta K = 4$ coupling through the inclusion of an I^4 operator in the Hamiltonian has been investigated [47].

Recently, we have proposed an alternative approach that is based on the angular momentum projected shell model [49]. We have shown that such staggering can emerge naturally in an angular-momentum preserving system when two almost isolated rotational bands are mixed by *ordinary two-body shell model interactions.* Angular momentum projection transforms intrinsic states to the laboratory system and shell-model configuration mixing provides coupling between different intrinsic K-states. The quantum mechanical interference of this projection and the associated configuration mixing can lead to $\Delta I = 4$ bifurcation in the resulting laboratory-frame spectrum. Under such a mechanism [49], there should be four distinct features in the resulting bifurcations:

1. The existence of this effect should be independent of the difference in K values between two bands which mix.
2. There is a "beat" envelope localized in the crossing region; the largest amplitude of the oscillation corresponds to where the two bands come the closest.
3. If the two bands that mix are well isolated from other bands, this bifurcation should be observed in both mixed bands with opposite phase structure.
4. There may exist phase reversals in a long oscillation sequence because the following band mixture occurs normally independent of the previous band crossing.

In summary, $\Delta I = 4$ bifurcation is an interesting and challenging phenomenon. Further investigation both from experimental and theoretical aspect is in progress actively in the nuclear structure community all over the world.

II.A.11. The Statistical Distribution of Inertial Parameters in Normally Deformed Nuclei

Jing-ye Zhang, Yang Sun, Mike Guidry [UTK] and Da Hsuan Feng [Drexel]

There is no published theoretical attempt to reproduce the global features of the experimental statistical distribution of moment of inertia before the present study, except a few theoretical calculations addressing some specific cases [50, 41, 51]. Such an endeavor might be expected to provide a strong test of a theory's ability to describe the general features of nuclear structure. In this paper we apply the Projected Shell Model [52] and the Cranking Model with particle number projection to the first such analysis for normally deformed nuclei.

The experimental sample used in the present statistical analysis consists of the yrast bands in even–even nuclei with Z = 66–78 and N = 86–116, a total of 2145 band pairs. We include in the data set all known spin states [40] up to the first band crossing, or up to I = 10^+, whichever comes first. For each possible pair, we evaluate the average absolute difference in the kinematic moment of inertia

$$\delta\mathcal{J}^{(1)} = \frac{1}{I_{\max}/2}\sum_{I=2}^{I_{\max}} \frac{|E_\gamma^I(1) - E_\gamma^I(2)|}{(E_\gamma^I(1) + E_\gamma^I(2))/2},$$

where the transition energy is $E_\gamma^I = E_I - E_{I-2}$, with (1) or (2) specifying the nucleus 1 and 2, respectively, and the average absolute difference in the dynamical moment of inertia

$$\delta\mathcal{J}^{(2)} = \frac{1}{(I_{\max}/2 - 1)}\sum_{I=4}^{I_{\max}} \frac{|\delta E_\gamma^I(1) - \delta E_\gamma^I(2)|}{(\delta E_\gamma^I(1) + \delta E_\gamma^I(2))/2},$$

where the $\delta E_\gamma^I = E_\gamma^I - E_\gamma^{I-2}$.

In order to emphasize in the test the global properties of the models, and to place the comparison between the two models on as equal a footing as possible, we have used a constant ground state deformation and pairing gap for each yrast band in all calculations.

From the comparison between the data with theoretical results for the statistical distribution in $\delta\mathcal{J}^{(1)}$ (Fig. II.A.11.1a), and $\delta\mathcal{J}^{(2)}$ (Fig. II.A.11.1b) one sees that the PSM gives very good overall agreement with the observations, except for an overprediction at extremely low values and a general underprediction at very large values of the discrepancy. Conversely, the cranking model results are in poor agreement with the observations, exhibiting a broad and rather flat distribution that is in strong contrast to the empirical distribution which peaks strongly near a value of about 20.

The good overall agreement between the data and the PSM results (and the corresponding poor agreement between the data and the cranking results) suggests that the shell model configuration mixing and the angular momentum projection implicit in the PSM are important in reproducing the experimental low-spin moment of inertia variation from one nucleus to another. However, there are some clear systematic discrepancies that are observed upon detailed comparisons with the observations, the PSM produces higher values than observed in the region of very small deviations and somewhat lower values than observed in the region of large deviations. This is presumably related to the simplicity of the PSM approach, which uses a basis truncated at a fixed deformation. Although the two-body correlations incorporated through the Hamiltonian in the subsequent diagonalization account for some amount of deformation fluctuation, we may generally expect the model to work better for well-deformed than for deformation-soft nuclei.

The much more serious failure of the simple cranking model to reproduce these statistical quantities may also be understood qualitatively in terms of known limitations of the model. The cranking model describes nicely many phenomena in high-spin physics such as band crossing, alignment and nuclear deformations (through potential energy surface [53] and total routhian surface [54] calculations), but it is known not to describe well the moment of inertia [55, 56, 57]. This is particularly true for the low-spin moments of inertia, which are dominated by Coriolis antipairing effects.

II.B. Study of Low-Energy Levels of Nuclei Far From Stability

In recent years, our study of nuclei far from stability has taken us to the limits of stability. At the limit, we have concentrated on two experimental techniques, proton radioactivity and α decay. In addition we have continued our study of shape coexistence phenomena in the light lead region via electron capture decay.

II.B.1. Proton Radioactivity Studies

Proton radioactivity of nuclear ground states and isomers is a somewhat novel decay mode which is only present for nuclei at the limits of nuclear stability. Nevertheless, it is one of

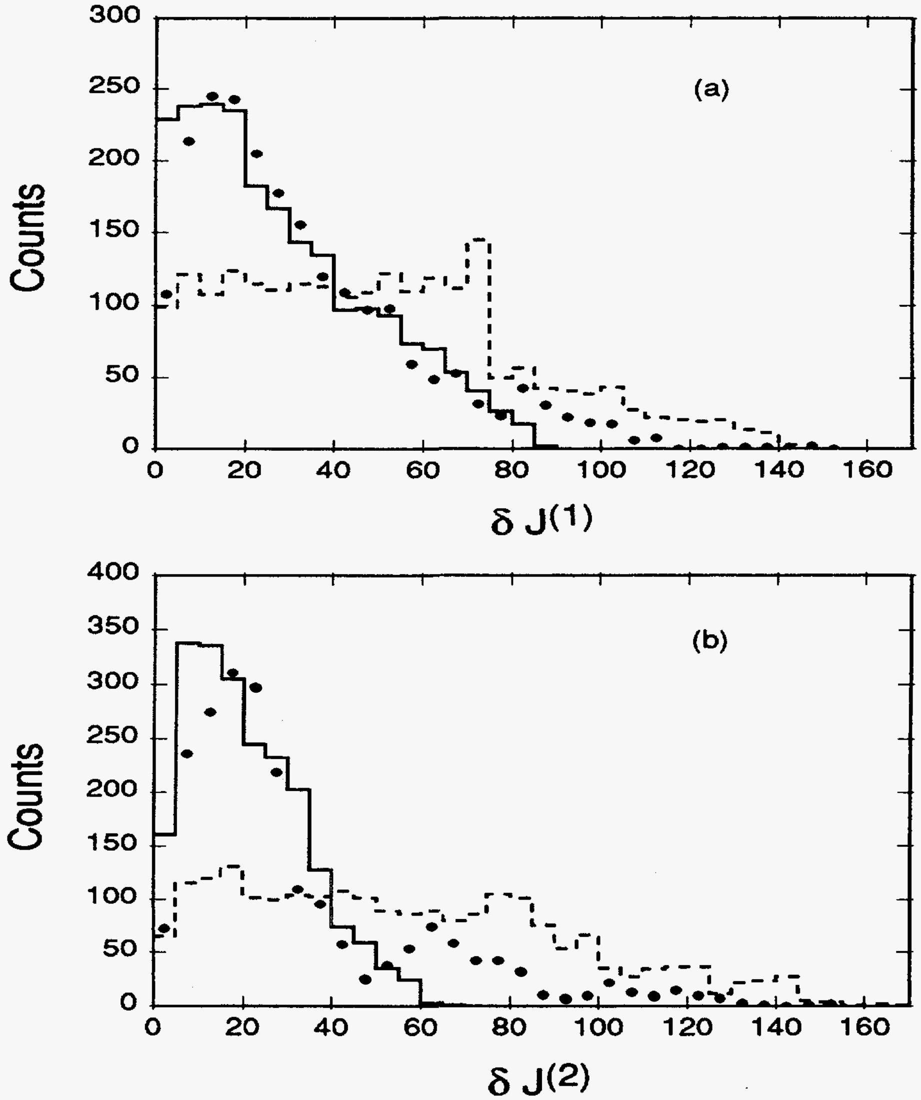

Figure II.A.11.1: Statistical distributions for the $\delta\mathcal{J}^{(1)}$(a) and $\delta\mathcal{J}^{(2)}$(b) in 2145 pairs of bands. Filled circles are experimental data; the solid line is the corresponding distribution from PSM calculations and the dashed line is the analogous distribution from Cranking Model calculations.

the simplest decay modes, resulting in the possibility to learn fundamental nuclear structure information due to the fact that the proton is one of the elementary constituents of the nucleus. Because of the difficulty of producing these nuclei and studying a rather delicate decay mechanism, very few cases have been studied previously.

Our studies have been concentrated largely at the Fragment Mass Analyzer (FMA) on-line to the ATLAS Accelerator at Argonne National Laboratory (ANL), in a collaboration with others from ANL, University of Edinburgh, and several other US universities. The FMA and the use of double-sided silicon strip detectors (DSSD) constitutes an ideal setup to study this decay mode of nuclei beyond the proton drip line. The proton emitters are produced by fusion- evaporation reactions of very proton-rich heavy ions. The FMA provides rapid separation of the evaporation residues from the beam and disperses the products in M/Q. A thin position-sensitive multi-wire proportional counter (MWPC) at the focal plane of the FMA and the DSSD positioned behind the MWPC can be used to identify the residue and follow its subsequent proton or α decay. By use of time stamps on the recoil and decay events, decays can be correlated with particular residues, and with the subsequent decay of the daughters, leading to positive identification of the different decay channels. Results from several of the experiments are given below.

We have been preparing for proton radioactivity experiments behind the focal plane of the Recoil Mass Separator (RMS) being installed at the Holifield Radioactive-Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL), again in collaboration with Edinburgh, ORNL, Louisiana State University (LSU), and the University of Maryland. A chamber has been designed and built in the LSU and UT shops. Two 40x40 DSSD's have been purchased by ORNL and UT and are awaiting installation at Oak Ridge. Amplifier systems to handle the hundreds of individual signals from the separate detector strips were built in Edinburgh and are currently being shipped to Oak Ridge. About 160 high resolution amplitude to digital converters (ADC) have been purchased with funds from ORNL and the University Radioactive-Ion Beam Collaboration and other electronics provided by the University of Maryland. Within the next month or so, the entire system will be assembled, tested, and adjusted in preparation for commissioning studies with the RMS, and later used in experiments with radioactive beams.

II.B.2. Proton Decay of an Intruder State in ^{185}Bi

C. N. Davids, H. T. Penttilä, D. J. Blumenthal, D. J. Henderson, and D. Seweryniak [ANL]; J. C. Batchelder [LSU]; C. R. Bingham and B. E. Zimmerman [UTK]; L. T. Brown [Vanderbilt], B. C. Busse [Oregon State]; L. F. Conticchio and W. B. Walters [Maryland]; T. Davinson, R. J. Irvine, and P. J. Woods [Edinburgh]; and K. S. Toth [ORNL]

This is the heaviest nuclide yet studied by detection of proton radioactivity of a ground state or isomer. The ^{185}Bi was produced by bombardment of a target of ^{95}Mo with a 410-MeV beam of ^{92}Mo. A single proton peak at an energy of 1.585 $\pm$ 0.009 MeV was observed in the particle spectrum from the A = 185 recoils, and was shown to be correlated with subsequent α decay of the daughter, ^{184}Pb, which conclusively identifies the proton emitter to be ^{185}Bi.

The observed half-life of the proton-decaying isomer is 44 $\pm$ 16 μs. The ground states of the odd-A Bi isotopes have an I^π of $9/2^-$, but an intruder $1/2^+$ state exists at low excitation in these nuclides, and is thus isomeric. The predicted half-lives of WKB barrier penetration calculations utilizing the formalism described by Hofmann [58] and the Becchetti-Greenlees optical potential [59] for l = 0 and l = 5 decays are 2.2 and 29000 μs, respectively. It is clear that the observed proton decay cannot be from the expected $h_{9/2}$ ground state of ^{185}Bi, and that it must be from the $s_{1/2}$ intruder state.

The $1/2^+$ state should be dominated by a $\pi(h_{9/2})^2(s_{1/2})^{-1}$ configuration, and thus the favored proton decay would be to the $\pi(h_{9/2})^2(s_{1/2})^{-2}$ configuration of ^{184}Pb. This intruder two-particle two-hole state in ^{184}Pb should exist primarily at an excitation energy of about 0.6 MeV. Proton decay to this state would have a barrier penetration factor approximately seven orders of magnitude smaller than proton decay to the ground state, and hence, with even a small admixture of the favored configuration in the ground state, decay to the ground state would dominate. By comparing the observed half-life to the calculated half-life for an $l = 0$ transition, we conclude that the ground state of ^{184}Pb has a mixing intensity of 5 ± 2 % of the 2p-2h intruder state.

These results have been accepted for publication in the Physical Review Letters [60].

II.B.3. Other Proton Emitters Discovered

C. N. Davids, B. B. Back, D. J. Blumenthal, D. J. Henderson, C. L. Jiang, H. T. Penttilä, D. J. Seweryniak, and A. H. Wuosmaa [ANL]; P. J. Woods, T. Davinson, R. J. Irvine, and R. D. Page [Edinburgh]; J. C. Batchelder and P. Joshi [LSU]; C. R. Bingham, J. D. Richards, and B. E. Zimmerman [UTK]; L. T. Brown and A. V. Ramayya [Vanderbilt]; B. C. Busse [Oregon State]; L. F. Conticchio and W. B. Walters [Maryland]; S. J. Freeman [Manchester]; M. Freer [Birmingham]; and K. S. Toth [ORNL]

- ^{161}Re– This new proton emitter in Re was discovered in some of the commisioning runs designed to confirm the earlier results on the decay of ^{160}Re. The results were reported in the recent ENAM95 conference in Arles, France [61].

- ^{165,166,167}Ir– These new proton emitters in Ir were observed in a very prolific 4-day run in which a ^{92}Mo target was bombarded with 356-MeV ^{78}Kr and separately with 384-MeV ^{78}Kr. The preliminary report of the results was made at the ENAM95 conference [62] and at the APS Nuclear Physics Division meeting in Bloomington, IN [63]. Two proton-decaying isomers were discovered in each of ^{167}Ir and ^{166}Ir and one was observed in ^{165}Ir. The five proton groups were positively identified by the correlated M/Q of the recoil and by correlation with the α decay of the corresponding Os daughters. As an example, Fig. II.B.3.1 shows a portion of the decay spectrum around 1 MeV from the DSSD when using the 356-MeV beam under several correlated conditions. In part (a) the total spectrum in the region from 500-2000 keV is displayed. The large continuum is due to the escape of α particles from the front of the DSSD and the small peak is a proton line. In part (b) the portion of the decay data correlated with a recoil at mass 167 is displayed. Since the proton emitter has a shorter half-life than most of the αs observed, additional filtering is provided by setting a short limit on the time between the recoil and decay as shown in part (c) which is the same as (b) but with correlation times limited to be less than 50 ms. Finally, after a decay occurs, one can correlate the decay with subsequent decay of the daughter. Part (d) shows the spectrum with the requirement that the next decay be the α decay of ^{166}Os and exhibits conclusively the proton decay of two isomers of ^{167}Ir. Preliminary analysis of these data has been carried out at Argonne and UT, final analysis and interpretation of the energies and half lives is in progress at Argonne.

- ^{171}Au– The proton radioactivity of ^{171}Au was observed in a bombardment of ^{96}Ru with ^{78}Kr. A single proton peak was observed and shown to be correlated with the subsequent α decay of ^{170}Pt. Its half-life is 1.7 ± 0.5 ms [63]. These data are currently under further analysis in Edinburgh.

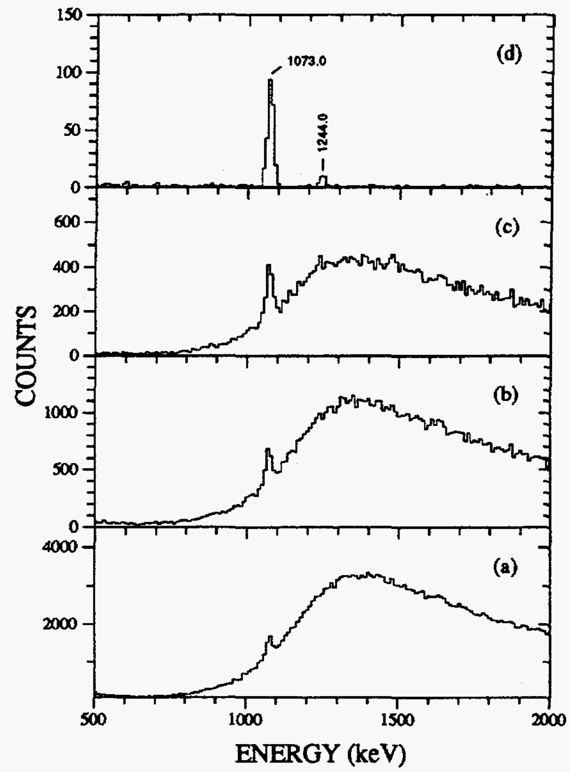

Figure II.B.3.1: Spectra gated on various correlations to display the protons from the decay of ^{167}Ir: (a) Total Spectrum, (b) Spectrum correlated with recoils of mass 167, (c) Spectrum of particles arriving within 50 ms of the mass 167 recoils, and (d) Spectrum of particles which were followed by the α decay of ^{166}Os.

Alpha Decay Studies Far From Stability

II.B.4. Interpretation of Fine Structure in ^{190}Pb α Decay

[J.D.Richards, C.R. Bingham, J. Wauters and B.E. Zimmerman [UTK]; K.S. Toth [ORNL]; Y.A. Akovali, H.K. Carter, J. Kormicki, P.F. Mantica [UNISOR] ; E.A. Henry, and J.A. Becker [LBL]; P. Joshi and E.F. Zganjar [LSU]

In our 1993 progress report, the fine structure in the α decay of ^{190}Pb to the 2_1^+ excited state of ^{186}Hg was discussed. Further careful analysis has, in addition, allowed us to determine the relative intensity of fine structure in α decay of ^{190}Pb to the 0_2^+ state of ^{186}Hg. In order to interprete the strengths of the fine-structure relative intensities we compute hindrance factors (HF) following the prescription of Rasmussen [64], while taking into account the centrifugal barrier for the $\delta l = 2$ transition. The HF value for the decay of ^{190}Pb to the 0_2^+ excited state of ^{186}Hg, 18(5) is similar in value to HF values for decay of ^{188,186}Pb to the 0_2^+ excited state of ^{184,182}Hg, which are 21(3), 21(4) respectively [65, 66]. This supports the interpretation that the 0_2^+ excited state in ^{186}Hg is a nearly pure π(2p-4h) state (mixing below 5 %), similar to the 0_2^+ excited state in ^{184}Hg and ^{186}Hg [65, 66], and in agreement with half-life measurements from the 0_2^+ state in ^{186}Hg by Joshi et al. [67].

In contrast the HF value for the α decay of ^{190}Pb to the 2_1^+ state in ^{186}Hg (HF=6) is low compared to the corresponding transitions from ^{188}Pb (HF=24) and ^{186}Pb (HF>29) [65, 66]. The strong variation in HF for α decay of ^{182,184,186}Hg towards the 0_2^+ state in ^{176,178,180}Pt (17,3.5,2.4) has been interpreted as due to the variation in mixing between the 0_1^+ groundstate and 0_2^+ state in Pt [66]. The change in HF for ^{186,188,190}Pb towards the 2_1^+ states in ^{180,182,184}Hg may signal similar change in the degree of mixing of the 2_1^+ with the 2_2^+ of the deformed band. Rotational band extrapolations of the high-spin members of the deformed band give >67% (^{182}Hg), 50% (^{184}Hg) and 4% (^{186}Hg). The strong increase in mixing can be seen nicely in the increased perturbation of the 2_1^+ near constancy and the parabolic behavior for the 2_2^+ state as they repel more and more due to mixing when approaching N=102. The increased component of the π(2p-4h) deformed configuration in the 2_1^+ state could then result in increased HF of the α decay towards this state, similar as the Pb and Hg decays to the 0^+ intruder state, explaining the HF behavior.

II.B.5. Search for Fine Structure in ^{192}Po α Decay

J. Wauters, C.R. Bingham, X.S. Chen, W. Reviol and B.E. Zimmerman [UTK]; N. Bijnens and M. Huyse [Leuven]; L.F. Conticchio and W.B. Walters [Maryland]; I. Ahmad, D.J. Blumenthal, C.N. Davids, R.V.F. Janssens and D. Seweryniak [ANL]; J.C. Batchelder and E.F. Zganjar [LSU]; H. Penttilä [Jyvaskyla] and B.C. Busse [Oregon State]

In the study of low-lying 0^+ states and shape coexistence in the lead region, the ^{188}Pb nucleus forms an especially interesting case. As in the heavier even Pb isotopes, a 0^+ excited state is expected at low excitation energy, which would be the bandhead of a shell-model intruder band [68]. These states have been observed down to ^{190}Pb. Furthermore, ^{188}Pb has attracted special interest since the observation of a prolate deformed band down to 2^+ in

Table II.B.5.1: half-life measurements of light Po isotopes

isotope	$T_{1/2}$(s) literature	$T_{1/2}$(s) this work
^{193g}Po	0.45(4)	0.34(3)
^{193m}Po	0.24(1)	0.210(15)
^{194}Po	0.394(4)	0.373(15)
^{195g}Po	4.64(9)	4.1(2)
^{195m}Po	1.92(2)	1.81(5)
^{196}Po	5.8(2)	6.06(35)

$^{186,188}Pb$ [69], [70]. Alpha decay has proven to be very well suited to study low-lying 0^+ states in the lead region [71]. The relative hindrances compared to the ground-state alpha decay gives information on the particle-hole character of the connecting states, and the mixing between excited 0^+ and ground state in parent and daughter nuclei. In the case of ^{192}Po, considerable mixing between the ground state and a 0^+ intruder state (not yet observed) is expected, both from level systematics of the neutron-deficient even-even Po isotopes, as from their ground state alpha-decay reduced widths [72]. This will most probably result in a hindrance factor smaller than one, a unique case.

In ^{188}Pb, the 0^+ intruder state can be expected around 550-600 keV, based on extrapolating the heavier Pb isotopes.

In a first experiment, carried out at the Fragment Mass Analyzer in Argonne National Laboratory, the alpha decay of ^{192}Po was studied using a ^{40}Ca beam on a ^{156}Gd target. Implants and alpha's were recorded using the DSSD in conjunction with the MWPC. A silicon detector and a LEPS detector were placed at the back of the DSSD to detect conversion electrons and characteristic X-rays following the alpha feeding to an excited 0^+ state. However, due to the fact that the beam consisted mainly of ^{40}Ar, too little statistics was acquired, insufficient to observe any weak alpha fine-structure transition from ^{192}Po. As this problem was not known for some time, an additional experiment was carried out using the $^{160}Dy(^{36}Ar,4n)$ reaction, with the same detector setup. The cross-section for ^{192}Po was measured to be 2.5 μb; nevertheless interesting results were observed, including:

- The half-lives of $^{193-196}Po$ were remeasured and are given in table II.B.5.1. Due to the poor enrichment of the ^{160}Dy target, all these isotopes were produced simultaneously. The half-life of ^{192}Po, 34(3) ms [73] is confirmed and approved to 33.4(14) ms.

- We confirmed the alpha-branching ratio of ^{190}Pb and the one of ^{188}Pb, by measuring the correlations between parent and daughter α decay. This now ends a long-standing discussion on the α branching ratios of the neutron-deficient even-even Pb nuclei and their implications on the stability of the Z=82 shell (see e.g. [74]).

- Fig. II.B.5.1 shows the total α spectrum (a), the α spectrum gated on mass 192 and with the condition that the time between implant and subsequent decay (T) is less than 200 ms (b), and same as (b) but with 200ms<T<400ms (c). From these spectra, the

α line at 6610(30) keV is observed only in correlation with a mass 192 implant and has a similar half-life behavior as the ground state α line of ^{192}Po. The other lines can be attributed to mass 193 and 194 contamination ($T_{1/2}$>200 ms) and ^{192}Bi ($T_{1/2}$=37 s). The 6610 keV line is an indication for the fine structure in the α decay of ^{192}Po feeding a 0^+ state in ^{188}Pb at 560(30) keV. The hindrance factor (HF) for this line compared to the ground state alpha line of ^{192}Po, is 0.9(4). The position of the 0^+ state at 560(30) keV would be in nice agreement with the extrapolations from heavier Pb isotopes, as mentioned in the introduction, for the π(2p-2h) 0^+ intruder state. The low hindrance factor follows the decrease as a function of decreasing neutron number: ^{198}Po: 2.8, ^{196}Po: 2.5 and ^{194}Po: 1.1. This is believed to be due to increased mixing in the very light Po isotopes and is also indicated by the low-energy level-scheme systematics of the even-even Po isotopes [72]: a deformed band intrudes to low energies with decreasing neutron number, and increasingly mixing with the ground-state band, possibly up to 58% for ^{192}Po [72]. Furthermore, the low HF is supported by the saturation of the α-reduced widths near 75 keV, instead of 200 keV [75]. The hindered α decay of the intruder π(4p-2h) component in the ground state Po α decay to the relatively pure Pb ground state will reduce the total α-decay strength of the light Po isotopes, resulting in lower δ^2 reduced widths.

The experiment shows that the setup at the FMA is very well suited for fine structure studies of very exotic nuclei. It is now important to confirm these indicative results on a solid basis with better statistics for two reasons: first to obtain α-electron coincidences correlated with mass 192 implants and with an electron energy above 450 keV, and coincidences between these alpha's and Pb KX-rays. Secondly, the HF should be determined to a better accuracy in order to draw further conclusions from it on the shape coexistence in ^{188}Pb and ^{192}Po. From a careful analysis of the cross-section data in this region, and in combination with a modified detector setup, using a silicon box in front of the DSSD (reducing the background from escaping alpha's and increase the total efficiency), a final experiment would yield up to 8 times higher production, sufficient to obtain unambiguous evidence for the fine structure in the α decay of ^{192}Po. This experiment is currently proposed at ANL.

II.B.6. New Platinum Isotopes Identified by α Decay

C. R. Bingham and B. E. Zimmerman [UTK]; K. S. Toth [ORNL]; J. C. Batchelder [LSU]; D. J. Blumenthal, C. N. Davids, H. T. Penttilä, and D. Seweryniak [ANL]; L. T. Brown [Vanderbilt], B. C. Busse [Oregon State]; L. F. Conticchio and W. B. Walters [Maryland]; and T. Davinson, R. J. Irvine, and P. J. Woods [Edinburgh]

The lightest platinum isotope known up to now, ^{168}Pt, was identified by Hofmann *et al.*[76] who measured its α-decay energy to be 6824(20) keV but did not report a value for its half-life. As part of an on-going investigation of short-lived proton and α-particle emitters, designed to obtain nuclear structure information near and beyond the proton drip line, we identified and measured the properties of the new isotopes ^{166}Pt and ^{167}Pt and measured the half-life of ^{168}Pt. These new nuclides were produced in the same runs used to produce the

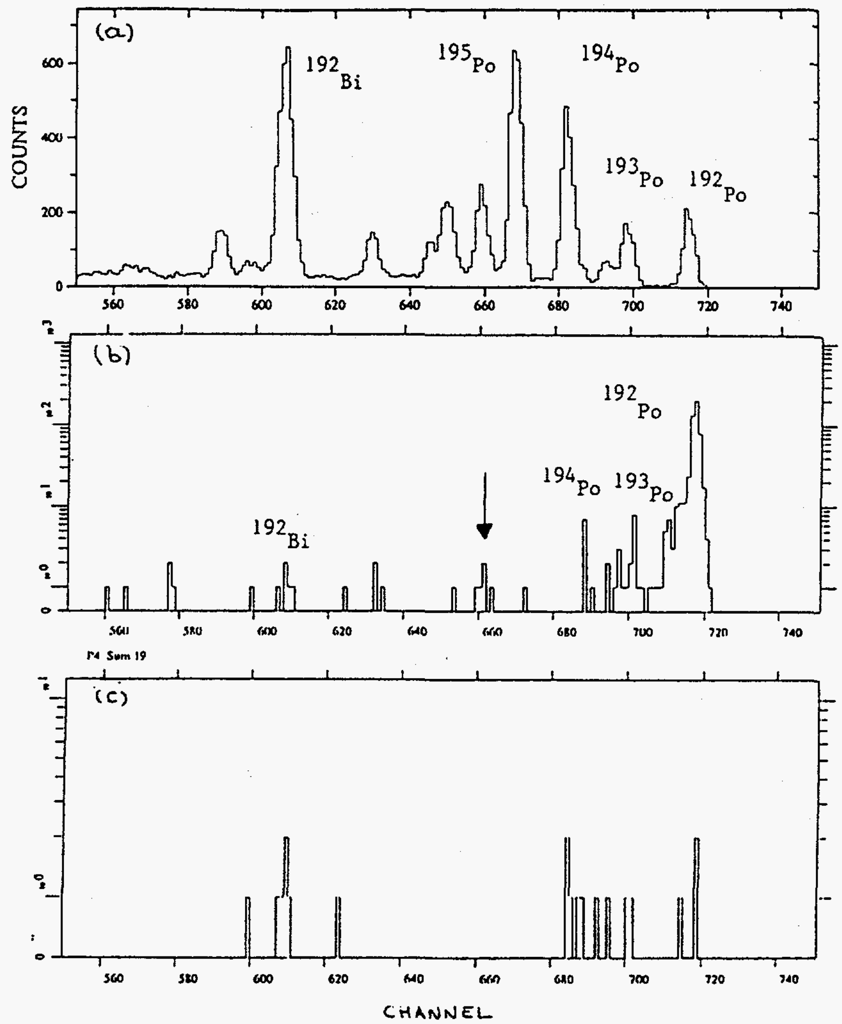

Figure II.B.5.1: a) Total alpha spectrum, b) alpha spectrum in correlation with mass 192 implants and with time between implant and decay less than 200 ms, and c) same as b) but with time between 200 and 400 ms.

Ir proton emitters discussed above. Decay energies between 0.5 and 10 MeV were recorded and hence, the new α lines were contained in the same dataset.

Spectra observed in our experiments were found to be dominated by α radioactivities with atomic numbers less than that of platinum (Z = 78). Nevertheless, based on α-decay-energy systematics, the expectation is that for a given mass number the platinum product should have the largest E_α value. Indeed, at 356 MeV there were two isolated α groups, 6832(10) and 6998(10) keV located at the higher-energy part of the total accumulated α-particle spectrum. The energy of the first of these agrees with the E_α value [6824(20) keV] assigned to ^{168}Pt by Hofmann *et al.*[76] while the previously unobserved 6998-keV peak is a good candidate for ^{167}Pt α decay. In Fig. II.B.6.1 (a) and (b) we show spectra gated by A = 168 and A = 167 recoils, respectively, and one notes that the new α is absent in (a) and is clearly emphasized in (b). Fig. II.B.6.1 (c) and (d) show the same mass-gated data but with additional restrictions, namely, correlations with the α decays of ^{164}Os [(c)] and ^{163}Os [(d)]. These two figures demonstrate unambiguously the assignments of the 6832- and 6998-keV peaks to ^{168}Pt and ^{167}Pt, respectively. We deduced a half-life of 1.8(4) ms for ^{168}Pt and 0.7(2) ms for the new isotope, ^{167}Pt.

Similar analysis of the spectrum accumulated at 384 MeV reveals a peak at 7.110(15) MeV which is correlated with A = 166 recoils and with the α decay of the ^{162}Os daughter. Based on this evidence we assign the previously unobserved 7110(15)-keV α peak to the new isotope ^{166}Pt; its half-life was determined to be 0.3(1) ms.

In a separate but concurrent experiment wherein ^{96}Ru was bombarded with ^{78}Kr to examine the decay properties of Au and Ir isotopes, ^{170}Pt was produced in a (2p,2n) reaction and its half-life was measured to be 14.7(5) ms. Our energy agrees with the previous determination of 6545(8) keV, but our half-life is about a factor of two larger than the (6^{+5}_{-2}) ms value of Hofmann *et al.*[76].

Table II.B.6.1 summarizes our ^{166,167,168,170}Pt data and compares them with previously available results. We have included in the table new information on ^{169}Pt and ^{171}Pt obtained in recent experiments [77] utilizing the Daresbury recoil separator; these data are also compared with published results.

The α-decay rates of the isotopes listed in Table II.B.6.1 were examined within the formulation of Rasmussen [64] together with the rates of some heavier Pt nuclides. Values of the reduced widths obtained are also given in Table II.B.6.1, along with error bars determined by calculating the barrier penetration factor utilizing the end points of the error bars on the half- lives and α branches. These reduced widths are plotted as a function of neutron number in Fig. II.B.7.1. Values resulting from the present experiment and recent measurements [77] for ^{169,171}Pt are shown as solid dots, while values calculated with previous data [78] are shown as open symbols. For the Pt nuclides between N = 91 and 93, the reduced widths indicated by solid symbols are seen to be significantly lower than those obtained from previous results [78] and more in line with values of heavier isotopes. Surprisingly, the reduced widths seem to stay between 100 and 150 keV all the way down to N = 88.

The observed α decay of the two new isotopes establishes new Q_α values of 7286(15) keV for ^{166}Pt and 7159(10) keV for ^{167}Pt. A slightly higher and more accurate number of 6998(10) was obtained for ^{168}Pt as compared with 6991(20) from the 1993 Atomic Mass Evaluation [79].

This work has been written up and will be submitted to the Physical Review for possible publication as a Rapid Communication after the other co-authors have had a chance to review the paper.

II.B.7. The α Decay of $^{162-166}$Os

C. R. Bingham and B. E. Zimmerman [UTK]; K. S. Toth [ORNL]; J. C. Batchelder [LSU]; D. J. Blumenthal, C. N. Davids, H. T. Penttilä, and D. Seweryniak [ANL]; L. T. Brown [Vanderbilt], B. C. Busse [Oregon State]; L. F. Conticchio and W. B. Walters [Maryland];

Table II.B.6.1: Alpha-decay energies, half lives, decay branches, and reduced widths of proton-rich platinum isotopes

	E_α(keV)	$T_{1/2}$(ms)	Branch	δ^2(keV)	Ref.
^{166}Pt	7110(15)	0.3(1)		105^{+70}_{-35}	present
^{167}Pt	6988(10)	0.7(2)		105^{+53}_{-29}	present
^{168}Pt	6832(10)	1.8(4)		128^{+49}_{-31}	present
	6824(20)				[76]
^{169}Pt	6678(15)	5±3		147^{+268}_{-65}	[77]
	6678(15)	$2.5^{+2.5}_{-1.0}$		294^{+259}_{-163}	[76]
^{170}Pt		14.7(5)		141^{+10}_{-13}	present
	6545(8)	6^{+5}_{-2}		346^{+208}_{-169}	[76]
^{171}Pt	6450(3)	25(9)		176^{+106}_{-50}	[76]
		43(3)		102^{+11}_{-9}	[77]

and T. Davinson, R. J. Irvine, and P. J. Woods [Edinburgh]
Peaks in our Pt α spectra due to the decay of $^{162-166}$Os were also analyzed for energies and half-lives, as well as α branches for the daughters of $^{166-168}$Pt through mother-daughter correlations. These results are given in Table II.B.7.1 and compared with previous results on record at the National Nuclear Data Center (NNDC). The half-life for ^{162}Os ($1.5^{+0.7}_{-0.5}$ ms) agrees within the errors with the previous result [78]. The half-life of ^{163}Os was determined for the first time to be 5.5(6) ms. The half-life for ^{164}Os [24(7) ms] is a bit less and much more precise than the previous value. The half lives for ^{165,166}Os agree with previous data, but have much smaller errors. The α branches for the three lighter Os nuclides (A = 162-164) were deduced from parent-daughter correlations with their Pt parents to be very near 1.0 in all three cases.

The present values of the reduced widths (δ^2)for Os isotopes basically agree with the previous results, but a major oscillation at N = 88 seems is smoothed out. The new results for both odd-A Pt and Os yield reduced widths that are about the same as those of the neighboring even-even isotopes, so that their hindrance factors (HF) are close to 1, indicating that the parent and daughter nuclei have the same spin and neutron configurations. The present Q_α values for $^{162-166}$Os 6786(10), 6678(10), 6473(10), 6337(8), and 6147(5) keV, respectively, compared with the following values listed in [79]: 6780(30), 6670(50), 6478(21), 6320(50), and 6130(6) keV.

II.B.8. The α-Decay Properties of ^{181}Pb

K. S. Toth [ORNL]; J. C. Batchelder [LSU]; C. R. Bingham, J. D. Richards, and B. E. Zimmerman [UTK]; L. F. Conticchio and W. B. Walters [Maryland]; C. N. Davids, D. J. Henderson, R. Hermann, H. Penttilä, and A. H. Wuosmaa [ANL]

The α-decay energy of ^{181}Pb has been reported as 7211 (10) keV [80] and 7044 (15) keV

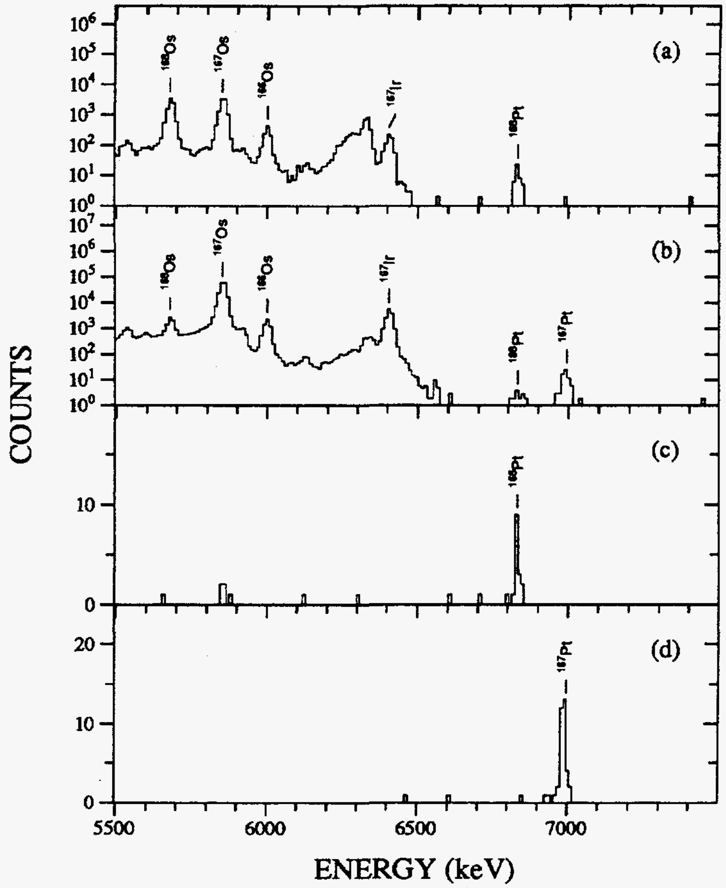

Figure II.B.6.1: Portion of the α spectrum taken at a bombarding energy of 356 MeV with various gates. a) A = 168 gate, b) A =167 gate, c) A = 168 gate correlated with α decay of ^{164}Os, and d) A = 167 correlated with α decay of ^{163}Os.

[81]. In the 1991 Atomic Mass Evaluations [79], the 7211-keV E_α was taken to be the ^{181}Pb ground state decay energy while the 7044-keV value was ascribed to the decay of an isomer in ^{181}Pb. This interpretation leads to an apparent pairing energy in ^{181}Pb which is significantly larger than values calculated with two separate formulae [79].

In a survey experiment to examine experimental yields for one- and two-nucleon evaporation products from symmetric cold-fusion reactions, ^{181}Pb was produced via the ^{90}Zr(^{92}Mo,n) reaction at the Argonne National Laboratory ATLAS accelerator facility. The FMA and DSSD were used to separate the activities and correlate decays with particular recoils. An α group at 7065 (20) keV in the A = 181 recoils was shown to be correlated with the subsequent decay via the ^{177}Hg 6580-keV α peak, and is thus assigned to the decay of ^{181}Pb. The half-life for the 7065-keV peak was measured to be 45 (20) ms. These new results therefore agree with the ^{181}Pb data reported in Ref. [81]. Furthermore, there was no indication of an α group at 7211 (10) keV, the energy reported by Keller *et al.* [80]. We interpret these results to indicate that the data used in the Atomic Mass Evaluation needs to be reexamined, and

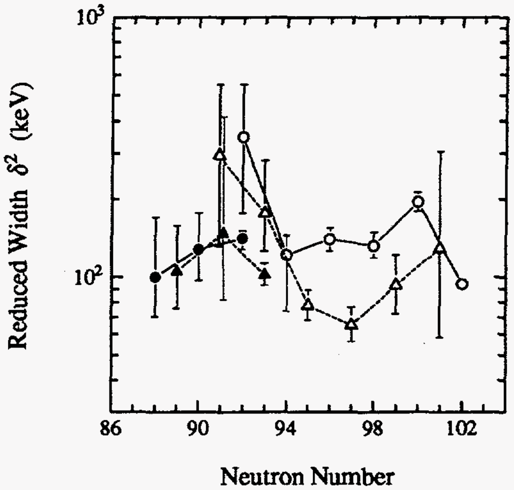

Figure II.B.7.1: Comparison of the reduced widths δ^2 obtained in the present work with earlier results. Circular symbols are used for even-even isotopes and triangles for odd-A isotopes. The solid points are from the present work except for ^{169}Pt and ^{171}Pt results taken from a recent still unpublished work [77].

Table II.B.7.1: Alpha-decay energies, half lives, decay branches, and reduced widths of proton-rich osmium isotopes

	E_α(keV)	$T_{1/2}$(ms)	Branch	δ^2(keV)	Ref.
^{162}Os	6618(10)	$1.5^{+0.7}_{-0.5}$	1.0	143^{+90}_{-53}	present
	6611(30)	1.9(7)	1.0	120^{+120}_{-51}	[78]
^{163}Os	6514(10)	5.5(6)	1.0	86^{+17}_{-15}	present
	6510(30)				[78]
^{164}Os	6315(10)	24(7)	~0.95	87^{+24}_{-17}	present
	6320(20)	41(20)	1.0(7)	55^{+72}_{-24}	[78]
^{165}Os	6183(8)	70(2)		100^{+11}_{-9}	present
	6164(10)	65^{+70}_{-30}	1.0(4)	127^{+131}_{-71}	[78]
^{166}Os	5999(5)	208(15)		121^{+38}_{-31}	present
	5983(6)	181(38)	0.72(13)	162^{+90}_{-58}	[78]

that perhaps the pairing energy for ^{181}Pb will fall more in line with expectations.

A manuscript has been written on this work and submitted to Phys. Rev. C for publication [82].

II.B.9. Study of ^{189}Bi and ^{190}Po α Decay

J. C. Batchelder and E. F. Zganjar [LSU]; K. S. Toth [ORNL]; D. M. Moltz, T. J. Ognibene, J. D. Powell, and M. W. Rowe [Berkeley]; C. R. Bingham and B. E. Zimmerman [UTK]

These experiments carried out at the Berkeley 88" Cyclotron complement our study of fine structure in the α decay of light Po isotopes. The ^{189}Bi was produced by bombarding ^{144}Sm with 215- and 225-MeV ^{48}Ti ions, whereas ^{190}Po was produced with the first of these reactions. Data were accumulated with the rapidly rotating recoil catcher wheel system at Berkeley, which has 12 Si detectors to view the wheel at various distances from the collection spot. (See Ref. [83] for a more complete description of the system.) Wheel speeds up to 500 rpm were used to study the decay of ^{189}Bi whereas speeds of 1000 and 1500 rpm were used to observe the shorter-lived ^{190}Po.

Details of our results for ^{189}Bi α decay can be seen in the already published short report [83]. Briefly, the decay energy of the ^{189}Bi^{m} ($\pi s_{1/2}$) α transition that proceeds to the ($\pi s_{1/2}$) ground state of ^{185}Tl was measured to be 7.30(4) MeV. This establishes the excitation energy of ^{189}Bi^{m} as 190(40) keV rather than the adopted value of 92(10) keV obtained from earlier measurements [6]. The new result indicates that the excitation energy of the ($\pi s_{1/2}$) intruder state in the light Bi isotopes plotted as a function of neutron number is leveling off to a minimum near the neutron midshell, similar to that of intruder levels in neighboring nuclei above and below the Z = 82 closed shell.

The α-decay energy and half-life of ^{190}Po were measured to be 7.49(4) MeV and $1.0^{+1.0}_{-0.4}$ ms, respectively. These compare with results from a GSI Progress Report [84] of E_α = 7482(20) keV and $t_{1/2} = 9.6^{+47}_{-4.4}$ ms. The two energies agree, but the two half-lives differ by a factor of about 10. While the earlier data yield an α reduced width which is much smaller than those of neighboring nuclides; the present energy and half-life result in a width that fits the overall α-decay-rate systematics in the mass region above the Z = 82 closed shell. The present work has been submitted to Phys. Rev. for publication [85].

II.B.10. Decay of ^{202}Fr and ^{204}Fr and the α-Decay Daughters

J. D. Richards, C. R. Bingham, B. E. Zimmerman [UTK]; Y. A. Akovali [ORNL]; W. B. Walters [Maryland]; P. K. Joshi and E. F. Zganjar [LSU]; I. Stone [Oxford]; O. Tengblad, M. Lindroos, and P. Van Duppen [ISOLDE] and the ISOLDE Collaboration

A report of production rates for various light nuclei produced at the ISOLDE facility with a ThC target and a positive surface ionization source was given in the progress report last year and at the ENAM95 Conference in Arles [86]. Some additional work on these data this year has revealed some new insights not discussed before and are briefly discussed here.

In Fig. II.B.10.1 the decay scheme of ^{204}Fr and its α-decay daughters is shown. The values that are primed were determined in earlier work by Huyse *et al* [87]; we have confirmed these within experimental uncertainty. We are reporting here new branching ratios for the decay of ^{204}Fr. The ec/β^+ branches for the 3^+ and 7^+ isomers were determined by counting γ transitions in ^{204}Rn, which were previously identified in an in-beam study [88]. Since no transitions were observed coming from levels with spin greater than 8^+, we assume that ec/β^+ decay from the 10^- isomer of ^{204}Fr is small. However, we do observe a new γ transition with an energy of 276.1(4) keV which matches the energy difference between the 10^- and 7^+ isomers of ^{204}Fr and with the same half-life as that seen from α decay of the 10^- isomer. On the basis of these data and encouraged by systematics, we assign this γ ray to an E3 transition between the two isomers. From the intensities of the isomeric transition and the α decay of the 10^- isomer we deduce the isomeric branch to be 30(8)%. Using this and the previously estimated half-life [87], we deduce a B(E3) of 5.4 $\times 10^{-4}$ Weisskopf units. This is somewhat larger than the upper limit found by Huyse *et al.* [87] for the same transition in ^{206}Fr ($< 5.2 \times 10^{-5}$ W.u.).

The E3 transition rates for the Fr isotopes discussed here and also for the α-decay daughters shown in Fig. II.B.10.1 [87] are about 5 orders of magnitude smaller than those in the trans-lead region with higher neutron numbers [89]. Since the energy differences of the 10^- and 7^+ isomers are very similar to the energy differences of the $13/2^+$ and $5/2^-$ neutron states ($1\nu i_{13/2}$ and $2\nu f_{5/2}$ single particle orbitals) in the odd-A Pb isotopes in this region, it is likely that the 10^- and 7^+ isomers are formed through coupling of these two neutron orbitals to the $\pi(h_{9/2})^n_{9/2}$ orbitals. The E3 transition between the two configurations would be j forbidden (Δj=4 > L=3). The extreme slowness of the E3 transitions indicates that the configurations are rather pure with little admixture of e.g. $\nu f_{7/2}$ coupled with the $h_{9/2}$ protons.

II.B.11. Electron Capture Decay Studies of ^{199}Bi and ^{193}Bi

M. Zhang, C. R. Bingham, J. Y. Zhang, and B. E. Zimmerman [UTK]; J. L. Wood [Ga. Tech.]; P. F. Mantica, L. Rayburn, and H. K. Carter [UNISOR]; P. K. Joshi and E. F. Zganjar [LSU]; S. Shastry [SUNY]; J. K. Deng and J. Kormicki [Vanderbilt]

Many details and results from this work have been included in the last three progress reports. M. Zhang finished his thesis early this year and received his PhD degree in May, 1995. He is currently working with the MRI group at the University of Kentucky Hospital. A long manuscript containing the many results of his thesis has been prepared and is in final revision for submission to Phys. Rev. for publication.

II.C. High Energy Heavy-Ion Physics

II.C.1. Introduction

A more detailed description of the physics goals of the high energy nuclear physics group can be found in the proposal "Studies of hot and dense nuclear matter" by S. Sorensen, K.

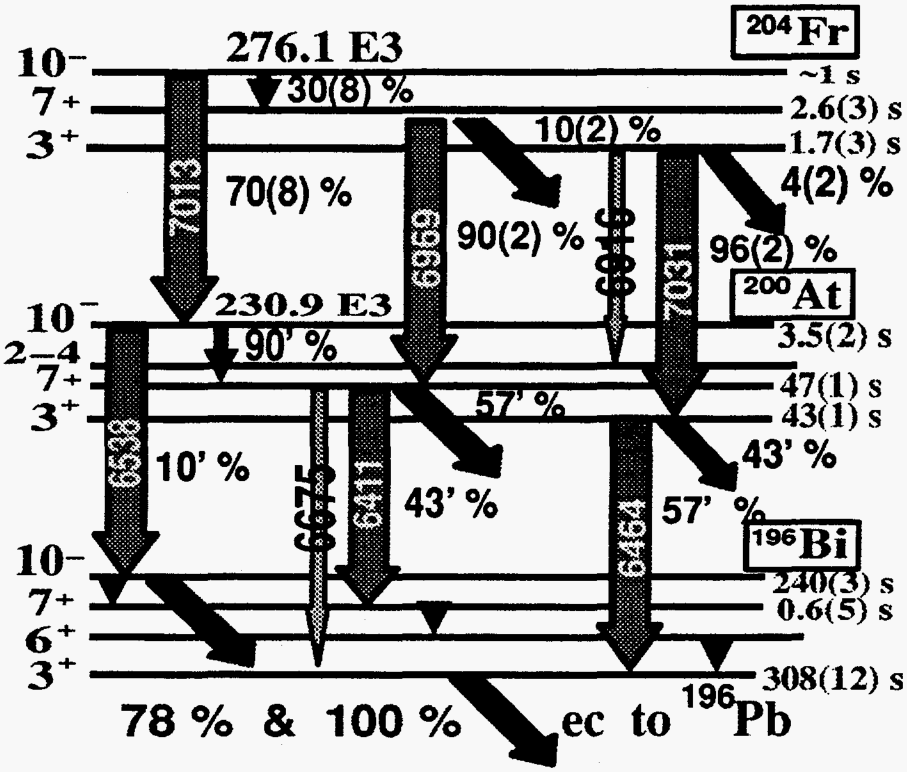

Figure II.B.10.1: Alpha decay scheme of the isomers of ^{204}Fr. Numbers taken from previous work [87] are shown primed and new numbers are shown unprimed. All the numbers agree with the present results within experimental uncertainties.

Read and F. Obenshain, which have been submitted to DoE on January 7, 1996. This proposal also contains detailed descriptions of the experiments we are currently involved with as well as descriptions of the work we have done within the last 3 years. We will therefore be fairly brief in this progress report.

II.C.2. The PHENIX Experiment at RHIC

An Dehai, Joe Kreke, Liu Qihang, Saskia Mioduszewski, Dave P. Morrison, Felix Obenshain, Victor Perevoztchikov, Ken Read, Soren P. Sorensen, Xu Rongsheng, Zhao Yan, and the PHENIX Collaboration

PHENIX is one of the two large experiments at the Relativistic Heavy Ion Collider currently under construction at BNL. The PHENIX experiment emphasizes detection of lepton pairs, photons, and identified hadrons over a wide range in p_T and mass.

In 1995 the PHENIX Collaboration has been busy with the construction of the detector. The magnet is nearly finished in Russia and will be shipped to USA in 1996, and most other subsystems is currently working on prototypes of the mechanical structures and the front-end electronics or have already started production of the final detector elements. The University of Tennessee has concentrated its efforts within PHENIX in two areas: a) The

Off-line Computing System and b) The Muon Arm.

The Off-line Computing System

The purpose of the PHENIX off-line computing system will be to provide all aspects of data and information handling that are not directly connected to the collection of data and the monitoring of the detector.

1995 was the first year where we had full funding from the RHIC construction budget. This enabled us to assemble a group of physicists and computer engineers at UT/ORNL dedicated to the design and implementation of the PHENIX off-Line system. Victor Perevoztchikov from IHEP, Protvino has a long experience in off-line systems from Delphi and the SSC and has been responsible for our data structures. An Dehai and Liu Qihang are computer engineers from IHEP, Beijing and have been responsible for our data base system and event displays. Yan Zhao is a computer engineer from China, who will start as a graduate student in the Department of Computer Science at UT in 1996. He has worked on the interprocess communication system. Dave Morrison is sharing his time 50/50 between the off-line system and the WA98 experiment and has been a major force in the design work and the implementation of the central controller process.

The main accomplishment this year was the design and first implementation of the PHENIX Event Processor (PEP). In the previous years we had compiled a large set of requirements, which we finally synthesized in a design. Since PEP will have to provide both for the large-scale event reconstruction facility running at the RHIC Computing Center and for the online and off-line analysis of the data done on individual workstations, we have chosen a very flexible design based on message passing between a set of independent processes.

PEP is organized around a controller process that keeps track of all the additional processes. The controller can start and stop them and decided which processes should serve a particular request. PEP is furthermore based on the client/server model, where each process is a server that performs a particular service. Examples of processes are: a) Data Operators which accepts event data structures and transforms them into new sets of data structures, b) GUI (Graphical User Interface) which communicates with the user, c) Data Base Server which handles all data base requests and d) Visualizer which provides for all the display of information, spectra and events.

PEP is very modular and we have gone to great length to try to incorporate as much third-party software as possible in order to increase the level of professionalism and cost-efficiency.

The communication between these processes is handled by PVM (Parallel Virtual Machine), which is a software package from UT/ORNL dedicated to handling parallel processing in large heterogeneous systems. All data structures are handled by the DSPACK package from University of Birmingham. The GUI is based on the TCL/TK freeware and for the event display we have chosen a French package called OnX.

The first version of PEP was ready around November 1 and contains most of the key modules, but still only in very rudimentary implementations. In order to help the collaboration in the transition from the current PISA/PISORP system to PEP we have transformed all the PISORP software from the Beam-Beam counter, so that it can serve as a template.

R&D Work for the PHENIX Muon Arm.

The purpose of the PHENIX muon arm is to enable the study of vector mesons decaying into dimuon pairs, to allow the study of the Drell-Yan process and charm production via $D\bar{D} \rightarrow \mu^+\mu^-X$, and to provide the muon detection in $D\bar{D} \rightarrow \mu e X$.

Full Scale Prototype Preparations A major milestone accomplished during the past year was to arrive at a feasible, cost-effective mechanical design for the PHENIX muon identifier panels and an associated installation plan. Because of the non-flatness of the steel absorber layers produced in Russia and the very limited longitudinal space between the muon magnet backplate and the north wall, there were severe constraints on the mechanical engineering design. This design was finalized during the past year. Final detailing remains to be done to allow for the electrical and gas services of the panels. The number and lengths of tubes in every panel and all panel dimensions have been determined. A feasible and satisfactory alignment scheme has been investigated. In order to test the design and optimize it for mass fabrication, considerable activity has taken place to prepare for construction of a full scale muon identifier prototype. The prototype will either be assembled at ORNL or in the new high bay area laboratory space our group occupies on campus.

Muon Identifier R&D We have performed a variety of R&D activities associated with the muon identifier technology (along with colleagues at ORNL and other institutions). These include beam tests ("RD94") performed at the GS to study Iarocci tube performance, testing of resistive plate counters (RPCs) and Iarocci tubes, and testing Iarocci tubes of various cross sectional dimensions with various gases. During the past year, our R&D program concluded that conventional limited streamer tubes satisfy most of our design criteria. However, in order to avoid dead time associated with the PHENIX muon arm level-1 trigger, we have performed R&D to develop Iarocci tubes with drift time intervals considerably smaller than 100 ns. We developed and tested tubes with channel widths of 5 and 6 mm, rather than the standard 9 mm. Also, we explored the use of fast gas mixtures, particularly those containing CF_4.

Muon Identifier Simulations A number of significant simulation results have been obtained this past year by us in collaboration with colleagues, especially on the potential negative effects of beam gas interactions. Beam gas is potentially a very serious background for the muon identifier LVL-1 trigger. We expect that specialized absorber shields located in the RHIC beam tunnel will be required to suppress this background. Approximately 20% of UA1 events satisfy the LVL-1 trigger algorithm described above. Thus, the false LVL-1 trigger rate due to central collisions (and neglecting beam gas) is 20% of 2 kHz. This is an acceptable contribution to the total LVL-1 bandwidth and will not introduce dead time. Moreover this background will be almost completely suppressed by LVL-2. An overall μ/π separation ratio of approximately 10^{-4} can be obtained after the LVL-2 trigger (or off-line) by means of imposing four requirements: (1) the muon identifier road must match to a track in the tracker, (2) the track in the tracker must extrapolate to within 40 cm of the vertex in the transverse plane, (3) the muon road must have the correct depth-momentum relation, and (4) the invariant mass of the reconstructed dimuon must exceed 1 GeV/c^2. In addition we are involved in the development of a new Monte Carlo beam gas event generator.

II.C.3. Relativistic Heavy-Ion Experiments at the CERN/SPS

D. P. Morrison, S. P. Sorensen and the WA98 Collaboration

During the past year, there has been significant progress made in the CERN WA98 experiment, the third generation of a series of experiments in which UT has played a major role investigating the physics of very high energy nuclear collisions. In the autumn of 1994 the experimental heavy-ion program at CERN achieved a significant and longstanding goal: the acceleration of ^{208}Pb ions to an energy of 160 GeV per nucleon. It has been anticipated that the collisions of these ions with a fixed target of ^{208}Pb will create large volumes of nuclear matter under conditions of extreme energy and baryon density. Among other things, it is hoped that these conditions will result in the production of a system of deconfined partons, the quark-gluon plasma.

The main UT responsibility in WA98, one which it shares with ORNL, is the calibration and operation of the Mid-Rapidity Calorimeter (MIRAC). This device was originally built and installed several years ago for experiment WA80, but it has been reconfigured for the present work. It has full azimuthal coverage over the pseudo-rapidity range, $3.0 < \eta < 5.2$. MIRAC is one of the main event characterizing detectors in the experiment. It provides a measure of the transverse energy (E_T) created in the collision and indirectly, therefore, a measure of the centrality of the event.

MIRAC is not only a trigger detector, however. Dedicated runs were taken in order to perform an investigation of transverse energy production with the Pb beam, and approximately 150,000 minimum bias Pb+Pb events were collected during the last running period. In order to aid in understanding the systematic increase in E_T production seen with the heavier beams and targets, a similar number of events were collected for Pb+Ni and Pb+Nb collisions. These data sets mean that WA98 is the only large CERN experiment with the ability to look at systematic changes as one goes to collisions of heavier and heavier nuclei using the Pb beam. This type of systematic approach has proved itself quite valuable in the past for making headway in understanding heavy ion physics with lighter projectiles. Because the calorimeter hardware is well understood and the analysis software is relatively mature, data from MIRAC has been able to produce some of the first physics results seen with the newly commissioned beam. Fig. II.C.3.1 shows preliminary results of the E_t spectrum seen in Pb+Pb collisions at 160 GeV/nucleon. This plot was shown at the Quark Matter '95 conference held in Monterey, CA at the beginning of 1995.

Another calorimeter has been added recently to the experiment alongside MIRAC. It was recycled from a previous experiment and has been rechristened the Backward Neutral Calorimeter (BNC). The BNC has only a limited azimuthal range, but extends the pseudo-rapidity coverage of WA98 by nearly 1.5 units. This device worked flawlessly during the recent run and its data will be combined with that of MIRAC in the near future.

Until recently, the construction, calibration and operation of the Zero-Degree Calorimeter (ZDC) was also the joint responsibility of ORNL and UT. For WA98, this responsibility has been officially taken on by a Russian team from Dubna—a task which severely strained

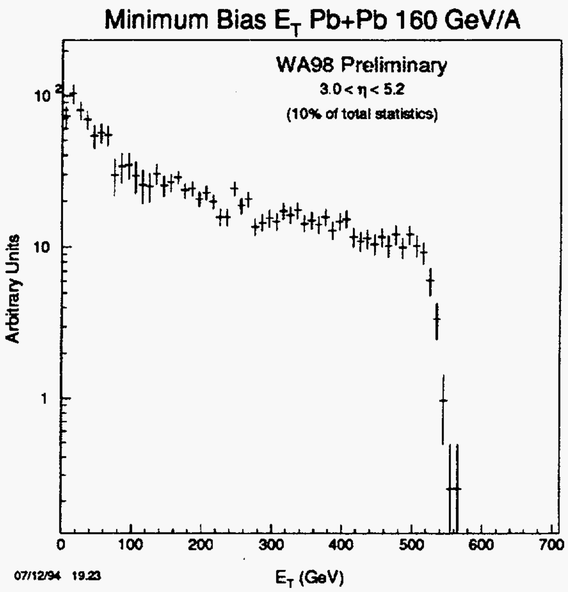

Figure II.C.3.1: Transverse energy distribution in 160 A·GeV/c $^{208}Pb+^{208}Pb$ collisions, as measured by MIRAC ($3.0 < \eta < 5.2$). For comparison, the maximum E_T seen in the previous WA80 S+Au measurements was approximately 200 GeV.

their experience and resources. UT and ORNL staff were able to shepherd the process along and help deliver a working detector in time for the needs of the collaboration. The data from this device serves as the principal determination of centrality in the off-line analysis, especially for symmetric systems such as Pb+Pb. Each full energy Pb ion that impacts the ZDC deposits 33 TeV.

One of the newest detectors in WA98 is the 10,000 module lead-glass (PbGl) array. This detector measures the energy and angular spectra of photons coming from the heavy-ion collisions. It is being used to make a high precision measurement of the fraction of photons directly emitted during a collision. The UT/ORNL designed digitization and readout system for the PbGl array has advanced the state of the art for analog electronics. Each module is connected to one channel of a sophisticated circular buffer analog memory which continuously samples the signal from a phototube. When a trigger signal is received, on-board ADC's digitize the stored analog samples. All the PbGl information is then multiplexed and sent to the data acquisition system via a relatively small number of ribbon cables. The large channel count of the PbGl array has presented many challenges, such as calibrating 10,000 channels, but these have been tackled quite effectively and the 1995 physics run was very successful.

In addition to the new experimental work being done on WA98, analysis continues to be done on the production of direct photons using the S+Au data collected as part of the WA80 experiment. The fundamental question being addressed by this work is whether there is photon production in nucleus-nucleus collisions in excess of what one expects from strictly thermal emission. This will have bearing on detailed models of the space-time development of the collision and the process of hadronization. The analysis has become quite sophisticated, with significant improvements in the understanding of all sources of systematic error. A paper on the results of this analysis has recently been submitted to Physical Review Letters.

In all, 1995 was a good year for WA98. Most significantly, all of the planned detectors were installed and tested, making the experiment fully operational. The data taking run in late 1995 went smoothly from the point of view of the experiment, with nearly 20 million events written to tape.

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IV. The Joint Institute for Heavy Ion Research

C. R. Bingham [UTK], J. D. Garrett [ORNL], and J. H. Hamilton [Vanderbilt]

The Joint Institute for Heavy Ion Research is a collaborative endeavor between the University of Tennessee, Vanderbilt University, and ORNL. About three-fourths of its funding comes from the State of Tennessee through the Science Alliance at the University of Tennessee. The remainder is provided by Vanderbilt University, DOE, and ORNL. The Joint Institute is housed in two buildings which are adjacent to the Holifield Facility.

It has continued to fulfill its mission as defined in its agreement between the three sponsoring institutes:

> "to promote and support heavy-ion research at the Holifield Facility by providing an intellectual center and physical support for researchers who work at the Holifield Facility, to the mutual benefit of sponsors and participants, in the field of heavy ion research."

This is done is three ways: 1) support of workshops and meetings, 2) support of guests, and 3) operation of a dormitory facility.

While there were several international conferences sponsored by the JIHIR in prior years, support during the current year was devoted more to informal discussion with visitors and several workshops and meetings aimed at startup of facilities and organizations. The meetings are listed in Table IV.1 which shows a total attendance of about 250 persons. The UNIRIB Organizational Meeting was held to organize members of about 12 university communities to effectively collaborate in the development of facilities and take advantage of new research opportunities presented by the developing radioactive ion beams at the Holifield Facility. The JIHIR hosted the HRIBF User's Workshop in which many exciting ideas regarding the new research program with radioactive beams at HRIBF were discussed, and furthermore aided in organizing small working groups to tackle some of the developmental work that must occur in order to carry out measurements at this facility. The Vanderbilt Summer Science Collaborative was a school to introduce undergraduate students to various scientific endeavors including nuclear structure studies at HRIBF. In addition to these meetings which we sponsored, many other meetings were held within our facility, including the regular ORNL Physics Division Seminars. The JIHIR is an attractive facility for small working meetings, and maintains an informal atmosphere where local scientists and visiting scientists can meet and react with each other in a most productive way to advance understanding of heavy-ion science.

Full or partial support was provided to the guests noted in Table IV.2. The average length of appointment during FY 1993 for the 72 guests was almost 4 months. A large effort was mounted in nuclear structure theory in support of physics that can be addressed with RIBs. Among the theory visitors supported this fiscal year were Sven Aberg, Jacek Dobaczewski, Da Hsuan Feng, Walter Greiner, Yang Sun, Tomasz Werner, and Witek

Table IV.1: Meetings sponsored by the JIHIR during FY 1992

Meeting	Date	Attendees	Chairmen
UNISOR Executive Meeting	Oct. 11, 1994	12	E. F. Zganjar
UNIRIB Organizational Workshop	Nov. 29,1994	25	E. F. Zganjar
ORISE Director's Meeting	Jan. 23, 1995	10	H. K. Carter
PHENIX On-Line Meeting	Feb. 15-17, 1995	50	G. Young
SERS Poster Meeting	Mar. 8, 1995	50	H. Payne
HRIBF User's Workshop	June 2-3, 1995	60	C. Gross
Vanderbilt Summer Science Collaborative	June 6-8, 1995	35	J. H. Hamilton
ORISE Director's Meeting	July 7, 1995	10	H. K. Carter

Nazarewicz up to the time that he was appointed to a permanent faculty position with our university. This group of theorists and several other visitors made significance progress in development of computational capacities of relevance to the HRIBF program. The nuclear theory effort at UTK/ORNL and the JIHIR visitor program comprises an important component in the study of nuclei near the proton drip line and in the region of astrophysical significance. A significant effort was made in the development of radioactive ion beam capability at Oak Ridge, with support of Juergen Breitenbach, Joe Dellwo, Antoni Piotrowski, Stig Sundell, and Hermann Wolnik for extended periods.

The dormitory was relatively less used this year since the HHRIF was not providing beams for users, but it was used to house some of the JIHIR visitors and other short-term guests in Oak Ridge for short-term developmental projects. It provided lodging for 60 guests who stayed for a total of 1388 person-nights.

Table IV.2: Guest scientists at the Joint Institute for Heavy Ion Research during the period of October 1994 - September 1995

Name	Institute	Length of Appointment
Aberg, Sven	Lund Inst. of Mathematical Phys. (Sweden)	2 months
Bailey, James	JIHIR/UT	1 year
Bennett, Jonathan	Univ. of North Carolina	1 week
Berggren, Tore	Lund Inst. of Technology (Sweden)	2 weeks
Bhatt, Kumar	Univ. of Mississippi	1 month
Blankenship, Jim	JIHIR/UT	1 year
Breitenbach, Juergen	Leuven (Belgium)	6 months
Casten, Rick	Brookhaven National Lab. (New York)	2 days
Chavez-Lomeli, Efrain	Univ. Nacional Autonoma de Mexico (IFUNAM)	5 weeks
Chen, Xue-Shi	Inst. of Nuclear Research (China)	10 months
Cwiok, Stefan	Warsaw University (Poland)	6 weeks
Daniels, Andrei	Joint Inst. for Nuclear Research (Russia)	1 month
Das, Jiban	Nuclear Science Centre (India)	1 year
Dean, David	Caltech	1 week
Dellwo, Joseph	JIHIR/UT	3 months
Di Bartolo, Gaetano	Inst. Nazionale Di Fisica Nucl., Catania (Italy)	7 months
Dobaczewski, Jacek	Warsaw University (Poland)	4 months
Engel, Jonathan	Univ. of North Carolina	4 days
Feng, Da Hsuan	Drexel University	1 week
Greiner, Martin	Inst. for Theoretische Physik (Germany)	1 month
Greiner, Walter	Inst. for Theoretische Physik (Germany)	3 weeks
Guber, Klaus	Inst. of Transurane (Germany)	1 year
Gupta, Mohini	University of Bombay	5 months

Table IV.2: cont. Guest scientists at the Joint Institute for Heavy Ion Research during the period of October 1992 - September 1993

Name	Institute	Length of Appointment
Haas, Bernard	C.N.R.S. (France)	2 weeks
Hackman, Gregg	McMaster University	2 days
Halbert, Melvyn	JIHIR/UT	9 months
Han, Xiao-Ling	Chung Yuan Christian University (China)	2 months
Harvey, Jack	JIHIR/UT	5 months
Horen, Daniel	JIHIR/UT	6 months
Howell, Calvin	Duke University	2 days
Huang, Jian	Drexel University	2 weeks
Huo, Junde	Jilin University (China)	3 months
Johnson, Noah	JIHIR/UT	9 months
Joshi, Paresh	Tata Inst. of Fund. Research (India)	3 months
Kahane, Sylvian	Nuclear Res. Center-Negev (Israel)	3 months
Keinonen, Juhani	University of Helsinki (Finland)	2 weeks
Kim, Hee	JIHIR/UT	1 year
Lamoreaux, Steve	Univ. of Washington	1 week
Lohwasser, Reinhard	Ludwig Maximilians Universitat(Germany)	2 months
Maruhn, Joachim	Univ. of Frankfurt (Germany)	1 week
Mezzacappa, Anthony	JIHIR/UT	10 months
McGowan, Francis	JIHIR/UT	1 year
Middleton, Jerry	Mississippi State University	1 week
Mueller, Paul	JIHIR/UT	6 months
Nazarewicz, Witek	Warsaw Univ. (Poland)	3 months
Nestor, Charles	JIHIR/UT	9 months
Oberacker, Volker	Vanderbilt University	1 month
Olive, Don	Campbellsville College	3 months

Table IV.2: cont. Guest scientists at the Joint Institute for Heavy Ion Research during the period of October 1992 - September 1993

Name	Institute	Length of Appointment
Ormand, Erich	JIHIR/UT	1 year
Piotrowski, Antoni	Soltan Inst. for Nuclear Research (Poland)	5 months
Rab, Shaheen	Kuwait Inst. for Scientific Research	6 months
Ravn, Helge	ISOLDE Facility, CERN (Switzerland)	2 weeks
Rohozinski, Stanislaw	Warsaw Univ. Inst. fur Th. Phys/ (Poland)	3 weeks
Rowley, Neil	Univ. of Manchester (United Kingdom)	1 week
Rykaczewski, Krzysztof	Warsaw University (Poland)	1 week
Saini, Surender	JIHIR/UT	3 months
Sandulescu, Aureliu-Emil	Romanian Academy (Romania)	4 days
Schmorak, Marcel	JIHIR/UT	1 year
Sousa, Dave	Eastern Kentucky University	3 weeks
Sun, Yang	Drexel University	9 months
Sundell, Stig	CERN (Switzerland)	4 months
Talbert, Willard	Amparo Corp. (New Mexico)	4 months
Thoennessen, Michael	Michigan State University	3 days
Tikkanen, Pertti	University of Helsinki (Finland)	2 weeks
Vallieres, Michel	Drexel University	1 week
Vidovic, Mario	Johann Wolfgang Goethe Univ.	3 months
Werner, Tomasz	Inst. of Theoretical Phys. (Poland)	1 year
Wollnik, Hermann	University of Giessen (Germany)	2 months
Wu, Cheng-Li	Chung Yuan Christian University (China)	2 months
Zeldes, Nissan	Hebrew University (Israel)	7 months
Zhang, Tian	Inst. of Applied Physics and Comp. Math. (China)	$3\frac{1}{2}$ months
Zhu, Yaoyin	Carnegie Mellon University	1 month

V. List of Publications

V.A. Papers Published or Submitted

1. "Competing Shapes in Light Tl Nuclei," W. Reviol, L.L. Riedinger, W.F. Mueller, J.M. Lewis, C.R. Bingham, Jing-ye Zhang, B.E. Zimmerman, *Physica Scripta*, **T 56** (1995) 167.

2. "Collectivity of Dipole Bands in ^{196}Pb," E.F. Moore, M.P. Carpenter, Y. Liang, R.V.F. Janssens, I. Ahmad, I.G. Bearden, P.J. Daly, M.W. Drigert, B. Fornal, U. Garg, Z.W. Grabowski, H.L. Harrington, R.G. Henry, T.L. Khoo, T. Lauritsen, R.H. Mayer, D. Nissius, W. Reviol, M. Sferrazza, *Phys. Rev. C* **51** (1995) 115.

3. "High Spin States in ^{94}Tc and the Shell Model Interpretation," S.S. Ghugre, S. Naguleswaran, R.K. Bhowmik, U. Garg, S.B. Patel, W. Reviol, J.C. Walpe, *Phys. Rev. C* **51** (1995) 2809.

4. "Search for Entrance Channel Dependence in the Population of Superdeformed Bands in ^{191}Hg," F. Soramel, T.L. Khoo, Ph. Benet, K.B. Beard, R.V.F. Janssens, I. Ahmad, I.G. Bearden, M.P. Carpenter, P.J. Daly, M.W. Drigert, B. Fornal, U. Garg, Z.W. Grabowski, T. Lauritsen, Y. Liang, R.H. Mayer, E.F. Moore, W. Reviol, D. Ye, *Phys. Lett. B* **350** (1995) 173.

5. "Lifetimes in ^{181}Ir and ^{187}Au: Enhanced Deformation of the $\pi i_{13/2}$ Intruder Orbital," J.C. Walpe, U. Garg, S. Naguleswaran, Q.-W. Ren, M.P. Carpenter, R.V.F. Janssens, I. Ahmad, I.G. Bearden, R.G. Henry, T.L. Khoo, T. Lauritsen W. Reviol, L.L. Riedinger, X.-Z. Wang, *Acta Physica Polonica B, Vol.* **26** (1995) p. 279.

6. "Lifetime Measurements in ^{120}Xe," J.C. Walpe, B.F. Davis, S. Naguleswaran, W. Reviol, U. Garg, Xing-Wang Pan, Da Hsuan Feng, J. X. Saladin, *Phys. Rev. C* **52** (1995) 1792.

7. "High-Spin States and K-Forbidden Decay in ^{172}Hf," D.M. Cullen, C. Baktash, M.J. Fitch, I. Frosch, R.W. Gray, N.R. Johnson, A.O. Macchiavelli, I.Y. Lee, W. Reviol, X.-H. Wang, C.-H. Yu, *Phys. Rev. C* **52** (1995) 2415.

8. "Universality of Symmetry and Mixed-Symmetry Collective Nuclear States," Bradley H. Smith, Xing-Wang Pan, Da Hsuan Feng, Mike Guidry, *Phys. Rev. Let.* **75** (1995) 17.

9. "Alignments, Shape Changes, and Band Terminations in ^{157}Tm," M. A. Riley, T. B. Brown, N. R. Johnson, Y. A. Akovali, C. Baktash, M. L. Halbert, D. C. Hensley, I. Y. Lee, F. K. McGowan, A. Virtanen, M. E. Whitley, J. Simpson, L. Chaturvedi, L. H.

Courtney, V. P. Janzen, L. L. Riedinger, and T. Bengtsson, *Phys. Rev. C* **51** (1995) 1234-1246.

10. "Statistical Analysis of Pairs Of Rotational Bands in 'Odd and Even' Nuclei at Normal Deformation," I. Ragnarsson, Jing-ye Zhang, and L. L. Riedinger, *Phys. Lett. B* **356** (1995) 423.

11. "Statistical Investigation of Factors Affecting Rotational Motion in Even-Even Nuclei," Jing-ye Zhang, N.V. Zamfir and R.F.Casten, *Phys. Rev. C* **51** (1995) R456.

12. "First observation of a Rotational Band in Odd Sn Nuclei: ^{111}Sn," D.R. Lafosse, D.B. Fossan, J.R. Hughes, Y. Liang, P. Vaska, M.P. Warning, Jing-ye Zhang, R.M. Clark, R. Wadsworth, S.A. Forbes, and E.S. Paul, *Phys. Rev. C* **51** (1995) R2876.

13. "$\Delta I = 4$ Bifurcation without Explicit Four-fold Symmetry" Yang Sun, Jing-ye Zhang and M. Guidry, *Phys. Rev. Lett.* **75** (1995) 3398.

14. "The Statistical Distribution of Inertia Parameters in Normally Deformed Nuclei," Jing-ye Zhang, Yang Sun, Mike Guidry and Da Hsuan Feng, *Phys. Rev. C* **52** (1995) R2330.

15. "Transition Energy Staggering and Band Interaction in Rare-earth Nuclei," W. Reviol, H.-Q. Jin, L.L. Riedinger, *Phys. Lett. B,* in print (1995).

16. "α-Decay rates for $^{181-186}$Au and $^{181-185}$Pt isotopes," C. R. Bingham, M. B. Kassim, M. Zhang, Y. A. Akovali, K. S. Toth, W. D. Hamilton, H. K. Carter, J. Kormicki, J. von Schwarzenberg, and M. M. Jarrio, *Phys. Rev. C* **51** (1995) 125.

17. "Excitation Energy of the $s_{1/2}$ Intruder State in ^{189}Bi," J. C. Batchelder, K. S. Toth, D. M. Moltz, T. J. Ognibene, M. W. Rowe, C. R. Bingham, E. F. Zganjar, and B. E. Zimmerman, *Phys. Rev. C* **52** (1995) 1807.

18. "Proton Decay of an Intruder State in ^{185}Bi," C. N. Davids, P. J. Woods, H. T. Penttila, J. C. Batchelder, C. R. Bingham, D. J. Blumenthal, L. T. Brown, B. C. Busse, L. F. Conticchio, T. Davinson, D. J. Henderson, R. J. Irvine, D. Seweryniak, K. S. Toth, W. B. Walters, and B. E. Zimmerman, *Phys. Rev. Lett.* submitted (1995).

19. "The α-Decay Properties of ^{181}Pb," K. S. Toth, J. C. Batchelder, C. R. Bingham, L. F. Conticchio, W. B. Walters, C. N. Davids, D. J. Henderson, R. Hermann, H. Penttila, J. D. Richards, A. H. Wuosmaa, and B. E. Zimmerman, *Phys. Rev. C* submitted (1995).

20. "Determination of the ^{190}Po α-Reduced Width," J. C. Batchelder, K. S. Toth, E. F. Zganjar, D. M. Moltz, T. J. Ognibene, J. D. Powell, M. W. Rowe, and C. R. Bingham, *Phys. Rev. C* submitted (1995).

21. "Identification of ^{166}Pt and ^{167}Pt and the Determination of the ^{168}Pt Half-Life," C. R. Bingham, K. S. Toth, J. C. Batchelder, D. J. Blumenthal, L. T. Brown, B. C. Busse, L. F. Conticchio, C. N. Davids, T. Davinson, R. J. Irvine, D. Seweryniak, W. B. Walters, P. J. Woods, and B. E. Zimmerman, *Phys. Rev. C* submitted (1995).

22. "Alignment Additivity in the Two-Quasiparticles Superdeformed Bands of ^{192}Tl," S.M. Fischer, M.P. Carpenter, R.V.F. Janssens, B. Crowell, I. Ahmad, D.J. Blumenthal, T.L. Khoo, T. Lauritsen, D. Nisius, W. Reviol, W.F. Mueller, L.L. Riedinger, B.H. Smith, B. Cederwall, *Phys. Rev. C,* submitted (1995).

23. "Effects of Intruder States in ^{179}Ir," H. Q. Jin, C. R. Bingham, M. P. Carpenter, V. P. Janzen, L. L. Riedinger, C. H. Yu, L. Zhou, P. B. Semmes, Jing-ye Zhang, M. A. Riley, C. Baktash, M. L. Halbert, N. R. Johnson, I. Y. Lee, and F. K. McGowan, *Phys. Rev. C* submitted (1995).

24. "Optimal Conditions for the Observation of $\Delta I = 4$ Bifurcation," Yang Sun, Jing-ye Zhang and Mike Guidry, subm. for publication.

25. "Production of η mesons in 200 A GeV/c S+S and S+Au Reactions", WA80 Collaboration, *Phys. Lett.* **B361** (1995) 14

26. "Relativistic Heavy Ion Collisions", S. P. Sorensen, *Encyclopedia of Science and Technology* McGraw-Hill, New York. (1995)

27. "Limits on the Production of Direct Photons in 200 A GeV ^{32}S+Au Collisions", WA80 Collaboration, *Phys. Rev. Lett.*, submitted Dec 1995.

28. " A Review of the Current Efforts of the Projected Shell Model in Nuclear Structure Physics " Da Hsuan Feng, Yang Sun, Jing-Ye Zhang and M. Guidry, proceedings of *II International Symposium on Heavy-Ion Physics and Its Applications*, Lanzhou, China, 8/29 – 9/1, 1995.

29. "On $\Delta I = 4$ Bifurcation: Origins and Criteria " Jing-Ye Zhang, Yang Sun and Mike Guidry, proceedings of *The 3rd Workshop of Nuclear Spectroscopy by Use of JAERI Tandem - Booster*, Tokai, JAERI, Japan, 7/27 – 7/28, 1995.

V.B. Theses

"Study of Shape Coexistence in ^{199}Pb and ^{193}Pb," M. Zhang, Ph.D. Thesis 1995.

"A Prototype Muon Identifier for PHENIX," Joe Kreke, Ph.D. Thesis, December 1995.

V.C. Abstracts at Meetings

1. "Variety of high-K and low-K Bands in ^{164}Tm," W. Reviol, L.L. Riedinger, X.Z. Wang, Jing-ye Zhang, H.J. Jensen, G.B. Hagemann, P.O. Tjom, R.A. Bark, S. Leoni, T. Lonnroth, H. Schnack-Petersen, T. Shizuma, J. Wrzesinski *Bull. Am. Phys. Soc.* **40(2)** 1995 p. 1005

2. "Level Structures at High Spins in Nuclei At and Near N=52," S.S. Ghugre, U. Garg, G. Smith, M.P. Carpenter, B. Crowell, R.V.F. Janssens, D. Nisius, W. Mueller, W. Reviol, L.L. Riedinger, R. Kaczarowski *Bull. Am. Phys. Soc.* **40(10)** 1995 p. 1607

3. "High Spin Studies in the First Well of ^{192}Tl," B.H. Smith, W. Mueller, W. Reviol, L.L. Riedinger, M.P. Carpenter, S.F. Fischer, R.V.F. Janssens, D. Nisius, T. Lauritsen *Bull. Am. Phys. Soc.* **40(10)** 1995 p. 1624

4. "$\pi h_{9/2} \pi f_{7/2}$ mixing in A $\leq$ 185 Nuclei from High Spin Spectroscopy," W. Mueller, W. Nazarewicz, W. Reviol, L.L. Riedinger, Jing-ye Zhang *Bull. Am. Phys. Soc.* **40(10)** 1995 p. 1631

5. "Superdeformation Studies of ^{192}Tl," S.M. Fischer, M.P. Carpenter, R.V.F. Janssens, I. Ahmad, D. Blumenthal, B. Crowell, T.L. Khoo, T. Lauritsen, C.J. Lister, D. Nisius, B. Cederwall, W. Mueller, W. Reviol, L.L. Riedinger *Bull. Am. Phys. Soc.* **40(10)** 1995 p. 1636

6. "New Heavy Proton Radioactivities," C. N. Davids, P. J. Woods, J. C. Batchelder, C. R. Bingham, D. J. Blumenthal, L. T. Brown, B. C. Busse, L. F. Conticchio, T. Davinson, S. J. Freeman, M. Freer, D. J. Henderson, R. J. Irvine, R. D. Page, H. T. Penttila, A. V. Ramayya, D. Seweryniak, K. S. Toth, W. B. Walters, A. H. Wuosmaa, and B. E. Zimmerman, **Int'l Conf. on Exotic Nuclei and Atomic Masses**, Arles, France, June 19-23, 1995.

7. "Proton Radioactivity Studies at the FMA," C. N. Davids, P. J. Woods, J. C. Batchelder, C. R. Bingham, D. J. Blumenthal, L. T. Brown, B. C. Busse, L. F. Conticchio, S. J. Freeman, M. Freer, D. J. Henderson, R. D. Page, A. V. Ramayya, K. S. Toth, W. B. Walters, A. H. Wuosmaa, and B. E. Zimmerman, H. Pentilla, **Int'l Conf. on Exotic Nuclei and Atomic Masses**, Arles, France, June 19-23, 1995.

8. "Study of ^{189m}Bi α-Decay," J. C. Batchelder, K. S. Toth, D. M. Moltz, T. J. Ognibene, M. W. Rowe, C. R. Bingham, E. F. Zganjar, and B. E. Zimmerman, **Int'l Conf. on Exotic Nuclei and Atomic Masses**, Arles, France, June 19-23, 1995.

9. "Decay Chains of ^{202}Fr and ^{204}Fr and α-Decay Branches," C. R. Bingham, J. D. Richards, B. E. Zimmerman, Y. A. Akovali, W. B. Walters, J. Rikovska, P. Joshi, E. F. Zganjar, M. Lindroos, O. Tengblad, P. Van Duppen, and the ISOLDE Collaboration, **Int'l Conf. on Exotic Nuclei and Atomic Masses**, Arles, France, June 19-23, 1995.

10. "The α-Decay Properties of ^{181}Pb," K. S. Toth, J. C. Batchelder, L. F. Conticchio, W. B. Walters, C. R. Bingham, J. D. Richards, B. E. Zimmerman, C. N. Davids, H. Pentilla, D. J. Henderson, R. Hermann, and A. H. Wuosmaa, **Int'l Conf. on Exotic Nuclei and Atomic Masses**, Arles, France, June 19-23, 1995.

11. "New Heavy Proton Radioactivities ^{165,166,167}Ir, ^{171}Au, and ^{185}Bi," C. N. Davids, B. B. Back, D. J. Blumenthal, D. J. Henderson, C.L. Jiang, H.T. Penttila, D. J. Seweryniak, A. H. Wuosmaa, P. J. Woods, T. Davinson, R.J. Irvine, R.D. Page, J.C. Batchelder, P. Joshi, C. R. Bingham, J.D. Richards, B. E. Zimmerman, L.T. Brown, A.V. Ramayya, L.F. Conticchio, S.J. Freeman, M. Freer, and K.S. Toth, *Bull. Am. Phys. Soc.* **40(10)** 1995 p. 1630.

12. "Excitation Energy of the $\pi s_{1/2}$ Intruder State in ^{189}Bi," J.C. Batchelder, E.F. Zganjar, K.S. Toth, D.M. Moltz, T.J. Ognibene, M.W. Rowe, C.R. Bingham, and B.E. Zimmerman. *Bull. Am. Phys. Soc.* **40(10)** 1995 p. 1631.

13. "α-Decay of new Pt Isotopes," C.R. Bingham, J.C. Batchelder, D. J. Blumenthal, L.T. Brown, B.C. Busse, L.F. Conticchio, C.N. Davids, T. Davinson, D.J. Henderson, R.J. Irvine, H.T. Penttila, D.J. Seweryniak, K.S. Toth, W.B. Walters, P.J. Woods, B.E. Zimmerman. *Bull. Am. Phys. Soc.* **40** 1995.

V.D. Invited Talks

C. R. Bingham

"The Discovery of Two New Isotopes, ^{166,167}Pt and Measurement of the halflife of ^{168}Pt," Meeting of the Southeastern Section of the American Physical Society, Tallahassee, FL, November 1995.

"Study of Fine Structure Effects in Particle Spectroscopy," Holifield Radioactive-Ion-Beam Facility Workshop, Oak Ridge National Laboratory, Oak Ridge, Tennessee, June 1995.

W. Reviol

"Very Deformed High Spin States in Nuclei near A = 110, 180 and 200," W. Reviol, Workshop on Research Opportunities with Secondary Beams at ATLAS, Argonne National Laboratory, January 1995.

L. L. Riedinger

"The Multiplicity of Shapes in Tl Nuclei," Workshop on Gammasphere Physics, Lawrence Berkeley National Laboratory, December 1-2, 1995.

S. P. Sorensen

"The Off-line Computer System of PHENIX," DOE TAC Review of the PHENIX Detector, Brookhaven National Laboratory, April 1995.

Jing-ye Zhang

"On $\Delta I = 4$ Bifurcation: Origins and Criteria " Jing-Ye Zhang, Yang Sun and Mike Guidry, The 3rd Workshop of Nuclear Spectroscopy by Use of JAERI Tandem - Booster, Tokai, JAERI, Japan, September 28-29, 1995.

V.E. Colloquia

C. R. Bingham

"Techniques in the Study of Nuclei at and beyond the Proton Drip Line Utilizing Double-Sided Silicon Strip Detectors," Oak Ridge National Laboratory, Oak Ridge, TN, October 1995.

W. Reviol

"New Rotational Band Phenomena in odd-odd ^{164}Tm," Lawrence Berkeley Laboratory, Nuclear Science Division, June 1995.

L. L. Riedinger

"Science and Technology in Tennessee - an American Example," Adlershof Technology Park, Berlin, March 1995.

"Federal and State Funding of Science and Technology in the U.S.," Rossendorf Research Center, Dresden, Germany, March 1995.

"Future studies of collective and single-particle effects in light Z=53-59 nuclei approaching the proton-drip line," Oak Ridge National Laboratory, Oak Ridge, TN, October 5, 1995.

S. P. Sorensen

"The Off-line Computing System in PHENIX," Institute of High Energy Physics, Beijing, China, May 1995

"The PHENIX Experiment at RHIC," Peking University, Beijing, China, May 1995

J. Wauters

"Alpha- and beta-decay studies in the Z=82 region," Oak Ridge National Laboratory, Oak Ridge, TN, November 29, 1995

Jing-ye Zhang

"$\Delta I = 4$ Bifurcation without Explicit C4 Symmetry," Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, July 11, 1995.

"Identical Band Phenomena," Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, August 2, 1995.

"$\Delta I = 4$ Bifurcation: Origins and Challenges," Physics Department, Tokyo University, September 1, 1995.

"Odd-odd Nuclei: TAC and PSM Calculations," RIKEN, Tokyo, September 4, 1995.

"Odd-odd Nuclei: Complexity and Richness," Tsukuba University, September 8, 1995.

"What is happening in Frontier of High Spin Physics," Institute of Modern Physics, Lanzhou, October 17, 1995.

"Recent Status of Nuclear Structure Physics at High Spin," Lanzhou University, October 26, 1995.

V.F. Nuclear Physics Group Seminars

"High-spin Intruder Physics At and Beyond the Sn Closed Shell," Victor Janzen, Chalk River, March 6, 1995.

"Novel Accelerator Targets for Positron Emission Tomography," Bill Alvord, CTI, April 28, 1995.

"Nuclear Astrophysics at HRIBF," Michael Smith, ORNL, December 20, 1995.