Progress Report on

NUCLEAR SPECTROSCOPIC STUDIES

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I. Overview

Overview

The Nuclear Physics group at the University of Tennessee, Knoxville (UTK) is involved in several aspects of heavy-ion physics including both nuclear structure and reaction mechanisms. While our main emphasis is on experimental problems involving heavy-ion accelerators, we have maintained a strong collaboration with several theorists in order to best pursue the physics of our measurements. During the last year we have led several experiments at the Holifield Heavy Ion Research Facility (HHIRF) and participated in others at Argonne National Laboratory. Also, we continue to be very active in the collaboration (WA93/98) to study ultra-relativistic heavy ion physics utilizing the SPS accelerator at CERN in Geneva, Switzerland and in a RHIC detector R&D project (PHENIX).

Our experimental work is in four broad areas: (1) the structure of nuclei at high angular momentum, (2) heavy-ion induced transfer reactions, (3) the structure of nuclei far from stability, and (4) ultra-relativistic heavy-ion physics. The results of studies in these particular areas will be described in this document in sections IIA, IIB, IIC, and IID, respectively. Areas (1), (3), and (4) concentrate on the structure of nuclear matter in extreme conditions of rotational motion, imbalance of neutrons and protons, or very high temperature and density. Area (2) pursues the transfer of nucleons to states with high angular momentum, both to learn about their structure and to understand the transfer of particles, energy, and angular momentum in collisions between heavy ions. An important component of our program is the strong emphasis on the theoretical aspects of nuclear structure and reactions. The theoretical effort is maintained in many cases through the close collaboration of members of our group with theorists from other institutions. The theory projects are largely concentrated on nuclear structure calculations, both from a collective model and a fermion dynamical symmetry point of view, but also include some work to investigate the mechanics of heavy-ion induced transfer of nucleons. These theoretical results are reported mainly in section IIE although some of the results are reported with the appropriate experimental contribution in IIA, IIB, or IIC.

The Joint Institute for Heavy Ion Research (JIHIR) is discussed in chapter III. The JIHIR has been a huge success; it greatly benefits our own research program through the flow of excellent visitors to the area and in the last year through sponsorship of six workshops that were of direct interest to our work.

The lists of publications, abstracts, and invited talks are given in chapter IV. In the past year, the research supported by the DOE contract has resulted

in the publication of 50 papers, with 15 others under review or ready for submission to journals. Twenty-seven abstracts were submitted to meetings, and 40 additional invited talks, papers, or lectures were presented.

The research described here is led by four full-time UTK faculty in the Department of Physics: Carrol Bingham (Prof.), Mike Guidry (Prof.), Lee Riedinger (Prof.), and Soren Sorensen (Assoc. Prof.). C.-L. Wu, a theorist from Jilin (China), has spent extended periods with our group during the last year; J.-Y. Zhang, a theorist from Lanzhou (China), and X. L. Han, an experimentalist from Jilin, have also been with us this year. In addition, Holger Jensen from the Niels Bohr Institute was a visitor to our group for 6 months in 1992, working on various aspects of our high-spin program. Several JI-HIR visitors have contributed to the theoretical effort (e.g., Witek Nazarewicz, Ramon Wyss, and Chao Weiqin) and to the experimental effort (N. Stone). Our experimental programs depend heavily on collaborations with experimentalists from ORNL (C. Baktash, J. D. Garrett, F. K. McGowan, K. S. Toth, M. L. Halbert, F. Plasil, R. L. Ferguson, T. Awes, F. E. Obenshain, and G. R. Young), University of Lund (I. Otterlund, H. A. Gustafsson, E. Stenlund, A. Oscarson, et al.), University of Münster (R. Santo, K.-H. Kampert, T. Peitzman, et al.), GSI, Darmstadt (H. Gutbrod, R. Schmidt), Georgia State University (G. Petitt), Vanderbilt University (C. Maguire), Los Alamos (P. L. McGaughey, P. Moss, et al.), VECC, Calcutta, India (B. C. Sinha, Y. P. Viyogi, et al.), with UNISOR personnel (H. K. Carter et al.), and with scientists from LSU (E. F. Zganjar et al.), Georgia Tech. (J. L. Wood et al.), Tennessee Tech. (Paul Semmes), University of Maryland (W. B. Walters), Lawrence Livermore Laboratory (E. A. Henry et al.), Texas A&M (H. A. Schuessler et al.), University of Rochester (D. Cline, et al.), and Argonne National Laboratory (M. P. Carpenter, C. N. Davids, R. V. F. Janssens, and T. L. Khoo). In view of the large number of collaborations in our work, we list the actual participants at the beginning of each report in this document.

Postdoctoral research associates and graduate students play a large role in the research described here. Currently, there are three postdoctoral research associates contributing to this research: X. C. He in the ultra-relativistic heavy ion physics program, Walter Reviol in the program to study high spin states, and B. E. Zimmerman in the program to study nuclei far from stability. Reviol replaced Chang-Hong Yu, who left in September to assume a faculty position at the University of Rochester. Hua Wu recently accepted the fourth postdoctoral position in the area of calculational nuclear physics and will devote time to writing programs to further utilize the FDSM in the detailed description

of nuclear structure. Zimmerman will take the lead on experiments utilizing recoil mass separators at other facilities and contribute to design of detection techniques to be used with the new facility in Oak Ridge. Reviol, in addition to leadership for in-beam experimentation, will devote time toward development of a miniball of particle detectors to be used in the center of a large γ -ray ball such as Gammasphere. At the present time we have eight graduate students working on some aspect of this research. M. Zhang, X. Wang, and J. Ding are supported fully by the DOE grant. J. Kreke, J. Lewis, J. D. Richards, B. Smith, G. Torshizi, and W. Mueller receive partial support from the contract and partial support from other university funds. In addition, seven undergraduate summer fellows (Leonard Jordan and Ivaylo Zlatev from Berea College, Georges Gauthier from University of Lyon, and Saskia Mioduszewski from University of North Carolina, Zack Eitzen from Maryland, Raymond Igharas from the University of Tennessee, and Ernest Perkins from South Carolina) worked with our group during the summer of 1992 on university funds.

The results of the research on the properties of high-spin states are detailed in section IIA of this report. There has been substantial progress in several areas of this program. We have emphasized the properties of high- j intruder orbitals at high spins in the past year. Calculations indicate that excitation of such intruder orbitals have a profound effect on the deformation of the nucleus, but it is not easy to test these deformation predictions in direct and accurate lifetime measurements. Thus, we have sought other indirect measures of the effect of intruder states on nuclear deformation, such as by analyzing the delay of standard band crossings (e.g., $\nu i_{13/2}$ rotation alignment) in these intruder bands and the signature splitting in a rotational band in odd- A and odd-odd nuclei.

We have taken the lead on two high-spin experiments at Holifield in the past year, one on the first spectroscopic study of ^{181}Au and the other on the measurement of lifetimes of states in ^{161}Lu . The latter directly attempts to measure the change in β_2 in the proton $h_{11/2}$ band before and after the $\nu i_{13/2}$ backbend, in order to observe the change induced by the high- j rotation alignment. The former provides the first observation of the $\pi h_{9/2}$ and $\pi i_{13/2}$ bands in the lightest Au isotope yet studied by in-beam spectroscopy. The presence of the $\nu i_{13/2}$ band crossing in the former structure but its absence in the latter is a clear indication that the deformation of the nucleus is indeed increased by the excitation of the $\pi i_{13/2}$ intruder state.

Our work on superdeformation has also progressed. We have completed analysis of the Oak Ridge and Argonne experiments that led to the discov-

ery of two SD bands in ^{191}Tl . This is the lightest Tl isotope for which such bands have been observed. These two SD bands are almost certainly the two signatures of the $\pi i_{13/2}$ band, and it is surprising to us how consistent is the “signature splitting” in this band between the three odd- A isotopes of Tl for which superdeformation has been found, $A = 191, 193$, and 195 . This is an indication of the stability of the deformation for this same structure for the three isotopes. We have also participated in the Argonne-led measurement of six SD bands in ^{192}Tl . These results are important, since among these six are two bands that do not show the common rise in moment of inertia among essentially all SD bands in the $A = 190$ region. This “flat” moment indicates to us that this band must have the $\nu j_{15/2}\pi i_{13/2}$ configuration, which blocks the postulated band crossings based on the rotation alignment of each of these high- j quasiparticles.

Also prominent in our progress in the high-spin program in the past year is the extensive work on signature splitting in rotational bands based on the $\nu i_{13/2}$ and $\pi h_{9/2}$ bands in deformed nuclei. The first detailed calculations of this quantity is reported and compared with experimental data.

Much attention has been drawn to our work on identical bands, i.e. rotational bands in adjacent nuclei with surprisingly similar moments of inertia. A *Physical Review Letter* explains our suggestion that the bands that best fit the identical-band criterion are built on orbitals that are down-sloping with deformation in the standard single-particle scheme. This leads us to suggest that a cancellation mechanism may be the reason for the identical-band phenomenon, i.e. a cancellation between the opposing effects of pairing and deformation changes for the down-sloping orbitals.

The results of the research utilizing transfer of nucleons between heavy-ions are detailed in section IIB of this report. No new experiments have been done in the heavy-ion transfer program over the past two years. We have had experiments approved, but have been unable to run them because of budgetary constraints that kept the Oak Ridge Holifield Accelerator from running coupled operations, and then because of the decision to convert Holifield to a Radioactive Ion Beams facility. Nevertheless, over the past year we have submitted four papers associated with the analysis of previously acquired data. These papers deal with possible evidence for a nuclear Josephson effect, anomalous population and structure observed in the 2-8 MeV excitation energy range, measurement of the probability of populating rotational states as a function of angular momentum in one and two-neutron transfer, and a search for a nuclear Berry phase effect (diabolical transfer). Most importantly, they establish the

foundation for next-generation experiments that that we shall propose for the new multidetector arrays and radioactive ion beam accelerators.

In our work at UNISOR (section IIC), work has progressed in the study of the transition region of nuclei between mass 180 and 200 via γ -ray and conversion electron spectroscopy and α -decay work. Much of our effort was focused on the study of shape coexistence in the light Pb nuclei; the analysis of data on the decay of ^{199}Bi to ^{199}Pb has established a much better known level scheme, the first excited state of which was unknown in the previous scheme. An excellent candidate for the $13/2^+$ member of the shape coexistent deformed band has been identified at an excitation energy of 1704.6 keV. Studies of α branches of the light Pb and Hg isotopes continued in order to solidify the values and determine the credibility of the claimed anomalies in the decay of the closed shell Pb nuclei. Our program of α decay study has continued through movement of experimental measurements to the Fragment Mass Analyzer at the ATLAS facility at Argonne.

In collaborative efforts, several experiments were performed at UNISOR utilizing the He^3/He^4 dilution refrigerator and new fast detector systems designed to measure picosecond half-lives. Preliminary results of some of these are discussed. In another collaborative effort shape coexistence in the light Tl isotopes was explored further through measurement of isotope shifts and quadrupole moments in ^{187}Tl via laser spectroscopy and interpretation of the results via Total Routhian Surface calculations and a Particle-Triaxial Rotor model.

The observation of superdeformed states in the high spin region has prompted several theoretical predictions relating to superdeformed nuclei. It has been predicted that the low-spin states of such a superdeformed nuclei in the light Hg-Pb-Po region will fall at an excitation energy of perhaps 3–5 MeV. For a few years now we have sought to observe low-spin members of such a band through their being fed by radioactive decay of various nuclides. During the last year we have reflected on the measurements, finished some of the extensive analyses, and published a few papers reporting the results, including very small upper limits for the branch of the beta decay to the 8^+ , 10^+ and 12^+ members of the SD band in ^{194}Pb . Also, plans were made to make another attempt to observe the low-spin SD band members in ^{198}Po or ^{194}Pb utilizing the isotope separator ISOLDE at CERN.

In the field of high energy nuclear reactions (sect. IID) our focus is more and more shifting towards preparations for the RHIC accelerator. As part of one of the largest RHIC collaborations, PHENIX, we have had overall

responsibility for all the simulations of the performance of PHENIX's muon detector. In collaboration with Los Alamos National Laboratory, Vanderbilt University, and Georgia State University we have demonstrated the muon arm's very good detection capabilities for decay muons from vector mesons ranging all the way from the ρ to the Υ . Especially, the large yields for the J/ψ will enable PHENIX to study the details of the suppression as function of centrality and transverse momentum.

We continue to take an active and leading role in the analysis of the large set of data from the WA80/93 collaboration at CERN. All the calorimeter data from the heavy ion runs have now been published, and in the last year we have worked on the analysis of the proton induced data. The emphasis of the analysis was initially on a careful evaluation of all the background sources, which are much more numerous for a proton beam than for a heavy ion beam. More recently, we have developed a new technique utilizing Gamma-function folding methods in order to understand how well the heavy ion transverse energy results can be understood as a simple superposition of binary nucleon-nucleon collisions. In parallel with this analytic approach we have also performed numerous comparisons with a variety of Monte Carlo codes.

We have also continued our investigation of the space-time evolution of high energy nuclear collisions in order to obtain more reliable estimates for the attained energy densities. Our results show, in a purely hadronic scenario, that the energy densities at CERN energies are probably only 50-75% of the values estimated from the Shuryak-Bjorken formula. With a formation time of 1 fm/c this will lead to maximal energy densities on the order of 1-1.5 GeV/fm³. Currently our interests are focused on developing methods for handling the sequencing of binary collisions in Monte Carlo codes, when the particle densities become very high.

Theoretical work that was directed toward understanding some of our data is reported in the experimental sections IIA, IIB, and IIC, but additional theoretical developments are discussed in section IIE. Our research effort in theoretical physics has produced a number of papers and ideas within the past year. The centerpiece of this effort has been the completion of the massive review article on the Fermion Dynamical Symmetry Model (FDSM) commissioned by *Advances in Nuclear Physics*. This paper is now in press. It runs to 325 pages (double-spaced) plus 75 illustrations, and represents the first comprehensive review of the FDSM. A second major accomplishment is the publication of the new extension of the FDSM idea to supershells and superdeformation (in press, *Annals of Physics*) that has been in development for the

past two years and represents an alternative to the usual cranking theory of superdeformation. In addition to these two long papers, we have published and submitted a number of other papers on a variety of topics: nuclear masses and astrophysics, transfer reactions, the dynamical Pauli effect, the origin of deformation, the origin of identical bands, and a critical discussion of whether evidence exists for quantized alignment in superdeformation.

We take pride in the observation that in several of these cases the FDSM result has triggered an intense debate, replete with spirited attacks in the journal and conference proceedings literature; this has been particularly true of the new results on superdeformation, on identical bands, on nuclear masses and astrophysics, and the dynamical Pauli effect. These debates have forced a critical re-examination of ideas with which nuclear physics has become too comfortable: on what physics may be lost in a mean-field approximation to a many-body system, on the meaning of an effective interaction in a truncated space, and on the difference between microscopic theory and phenomenology.

A modest effort has been maintained in CEBAF related theory through our partial support of Z. P. Li, who has worked both on nuclear structure and the non-relativistic quark model. This effort has produced three publications that are relevant to the development of the CEBAF research program.

The nuclear physics programs at the University of Tennessee and at the Oak Ridge National Laboratory continue to receive considerable support from the university and the state. Most of this support comes from the state through the Science Alliance, which is the first and largest of the Centers of Excellence funded by the State of Tennessee. The Science Alliance has supported the nuclear physics effort at UTK/ORNL in a variety of ways, including partial support of Holifield equipment purchases (Compton-suppressed Ge detectors, dilution refrigerator, and the Recoil Mass Spectrometer), partial support of graduate students in our group, undergraduate summer research appointments, support of our effort in the relativistic heavy-ion program at CERN, and the major part of the operating fund for the Joint Institute for Heavy Ion Research (JIHIR). Our group has contributed much to the operation of the JIHIR, but has also benefited from the visitors to the institute. The JIHIR is administered through UTK, which means that all of the visitors are paid and processed through our university offices. There have been a total of 60 visitors to the Joint Institute in the past year working in support of Holifield programs, some involving our group; the average length of these appointments was approximately 3 months. In addition the JIHIR was a major sponsor for six workshops and conferences that had significance in the development of nuclear structure theory in the

area and in the development of RIB-type facilities. The JIHIR has had a major impact on the vitality of nuclear physics in the state of Tennessee, and on the health of the field at an international level.

Concerning committee work in the community, Lee Riedinger continues to serve on the Nuclear Science Advisory Committee (NSAC), on the Executive Committee of the Division of Nuclear Physics (DNP) of the American Physical Society, and as chairman of the Nuclear Science Resources Committee in the DNP. At the University of Tennessee, he presently holds the position of Associate Vice Chancellor for Research on an acting basis. Carrol Bingham serves as vice-chairman of the UNISOR executive committee and as chairman of its Technical Committee, and is a council member of the Joint Institute for Heavy Ion Research and an Executive Council Member of the Southeastern Section of the American Physical Society. He helped to organize the *Workshop on the Production and Use of Intense Radioactive Ion Beams* at the Isospin Laboratory partially supported by the JIHIR in October, 1992. Mike Guidry was a co-chairman for two conferences partially sponsored by the JIHIR: 1) *Workshop on Microscopic Origin of Nuclear Deformation* and 2) *First Symposium on Nuclear Physics in the Universe*.

II. Scientific Results

II.A. Properties of High-Spin States

II.A.1. Superdeformed Bands in ^{191}Tl

S. Pilotte[†], C.-H. Yu*, H.Q. Jin[‡], J.M. Lewis, L.L. Riedinger [UTK]; M.P. Carpenter, R.V.F. Janssens, T.L. Khoo, T. Lauritsen, Y. Liang, F. Soramel** [ANL]; I.G. Bearden [Purdue]; C. Baktash, J.D. Garrett, N.R. Johnson, I.Y. Lee, F.K. McGowan [ORNL]

Two weakly populated sequences of regularly spaced transitions have been identified in ^{191}Tl . These bands exhibit many of the properties observed in other superdeformed nuclei in the Hg region. These two bands are assigned to the $\pi i_{13/2} [642]5/2$ configuration, in agreement with pairs of superdeformed bands seen in neighboring Tl nuclei.

High-spin states in mercury nuclei have been the object of much interest following the discovery of superdeformation in ^{191}Hg [1]. Approximately 34 superdeformed bands in 14 nuclei have now been reported in this region. The majority of these bands exhibit a small monotonic increase (of the order of 20%) in their dynamical moment of inertia over the range of observed rotational frequencies (≈ 0.2 – 0.4 MeV). The ^{192}Hg nucleus plays a central role in this region since it has a doubly-closed gap at $Z = 80$ and $N = 112$ for superdeformed (SD) shapes. ^{191}Tl is two neutrons below the $N = 112$ gap and has an additional proton outside the SD closed shell at $Z = 80$.

States in ^{191}Tl have been populated via the $^{159}\text{Tb}(^{36}\text{S},4n)$ reaction at 165 MeV. Initially, a beam from the Holifield Heavy Ion Research Facility at Oak Ridge National Laboratory was used. In a second experiment, the beam was provided from the ATLAS superconducting accelerator at the Argonne National Laboratory. At Oak Ridge, coincidence γ -ray events were collected with the Spin Spectrometer comprising 19 Compton-suppressed Ge detectors and 52 NaI counters. Approximately 200 million events were recorded in this way, and the data were subsequently analyzed with software cuts on a high fold of NaI elements. In the Argonne experiment, coincidence events were collected with an array of 12 Compton-suppressed Ge detectors and 50 BGO elements surrounding the target. In this measurement a fold $K \geq 6$ was required in the BGO array. Approximately 120 million events were written to tape. The initial Holifield experiment resulted in the detection of a weak signal of regularly spaced transitions. Since two bands were expected (both signatures of the $\pi i_{13/2}$ band, as in ^{193}Tl and ^{195}Tl), a second Holifield experiment was performed with the $(^{26}\text{Mg},4n)$ reaction in an effort to consolidate our initial findings. Unfortunately, not even the original SD sequence of γ -ray transitions could be reliably identified, possibly due to population of ^{191}Tl at too low angular momentum. The third experiment of the series was performed at Argonne

with the same ($^{36}\text{S}, 4n$) reaction: there a second superdeformed sequence was found along with the original band.

The characteristics of these bands agree very well within the systematics of other SD bands found in the Hg-Tl-Pb region. First, the dynamical moments of inertia of the proposed bands in ^{191}Tl increase with rotational frequency at a rate similar to that observed in the majority of SD bands in this region. It corresponds to a cascade of γ rays with a decreasing energy spacing from 40 keV at the bottom of the band to 33 keV for transitions of 600 keV decaying from higher spin levels. Secondly, their weak intensities of $\approx 0.4\%$ also follow the trend present in Hg nuclei, where the ^{190}Hg SD band is populated at 0.8% [2] which is lower than in the heavier isotopes usually populated at the 1 to 2% level. The SD bands reported in ^{192}Tl [3], ^{193}Tl [4], ^{194}Tl [5, 6] and ^{195}Tl [7] are more weakly populated than in their corresponding Hg isotones. Thirdly, the lowest transition of 377.8 keV indicates a decay out of the band at a higher rotational frequency than for the heavier isotopes. This behavior is analogous to that of ^{190}Hg , which has its lowest-energy transition at 360 keV. This last point agrees with a predicted reduction in the depth of the SD potential minimum with decreasing neutron number [8]. Experimentally, the γ -ray energy of the lowest observed transition of the Hg isotopes has a minimum at $N = 112$. The Pb isotopes also show the same trend in their first transition energies. They are generally lower than their Hg and Tl counterparts, indicating a decay out of band at very low spins. The ^{191}Tl bands agree very well with this systematic.

One approach to comparing superdeformed bands in various nuclei involves what has been called [9] the incremental alignment Δi , where differences in γ -ray energies of the nucleus of interest with those of a reference nucleus are compared with the increase in energy between successive transitions of the reference. For ideal strongly coupled bands, the resulting even-spin sequences will exhibit the same transition energies as the yrast band of the core whereas the odd-spin sequences are staggered at mid-energies. A detailed discussion on these aspects is presented in ref. [10]. Explicitly, the incremental alignments are defined as,

$$\Delta i = \frac{2 [E_{\gamma}^{\text{ref}}(I) - E_{\gamma}(I')]}{E_{\gamma}^{\text{ref}}(I) - E_{\gamma}^{\text{ref}}(I-2)} \quad (\text{II.1})$$

where I and I' represent the angular momenta of the levels in the reference band and the band of interest, respectively. E_{γ} and E_{γ}^{ref} are chosen to be the transitions closest in energy. The factor of two in the numerator comes from the fact that a difference in energy between two consecutive transitions

is accompanied by a change in angular momentum of $2\hbar$. The incremental alignment, Δi , is simply related to spins through γ -ray energy differences and takes the values $\Delta i = 0, 1$ and $\pm 1/2$ for even- A and odd- A nuclei, respectively.

Calculations indicate that $Z = 80$ and $N = 112$ shell gaps are both important at superdeformed shapes, $\beta_2 \approx 0.45$. Due to the stabilizing effect of these two gaps, the ^{192}Hg nucleus plays a central role as a reference nucleus. The yrast superdeformed configuration of the ^{192}Hg core is commonly designated by its high- N orbital configuration and labeled as $\pi 6^4\nu 7^4$ adopting the nomenclature of refs. [11, 12].

For ^{191}Hg the 111^{th} neutron is in the $\alpha = -1/2$, $N_\Omega = 7_{3/2}$ orbit (favored signature), this represents the yrast SD configuration, and the high- N content is $\pi 6^4\nu 7^3$. The Δi diagram (Fig. II.A.1.1a) for ^{191}Hg shows a strongly downsloping pattern, indicating a rotating core different than ^{192}Hg . In addition, two excited bands have been found in ^{191}Hg [13]. The absence of signature splitting suggests that these bands are built on the $[642]3/2$ neutron orbital. They follow very well the prescription for a valence neutron strongly coupled to the ^{192}Hg core exhibiting rather flat incremental alignments at $\Delta i = \pm 1/2$. This shows that these excited bands are similar in shape to ^{192}Hg and follow from the fact that they have the same high- N ($\pi 6^4\nu 7^4$) configuration as ^{192}Hg . The details in the $\mathcal{J}^{(2)}$ moments of inertia also support these assignments [1, 13]. The two superdeformed bands observed in ^{193}Tl agree well with the expected single-particle configurations [4, 7]. For Tl isotopes, the valence proton is placed in the $6_{5/2}$ $[642]5/2$ orbital just above the $Z = 80$ gap. The Δi plots (Fig. II.A.1.1) show a gradual increase relative to ^{192}Hg from $\pm 1/2$ starting values.

Data on ^{190}Hg and ^{189}Hg [2] each reveal only one superdeformed band. By contrast to the $A = 150$ region where SD features can be interpreted in terms of single particle excitations, the $A = 190$ region requires pairing to achieve any degree of success in explaining the different configurations in the framework of the cranked shell model. The superdeformed core for ^{190}Hg , despite being labeled by the same high- N configuration as ^{192}Hg , is apparently slightly different in deformation due to a significant change in the occupation probabilities of the high- N orbitals (since pairing plays some role). In ^{190}Hg and ^{189}Hg , the Δi values follow a downsloping trend relative to ^{192}Hg , reflecting this suggestion of different cores for these cases.

Clearly, we see that comparing nuclei having different high- N configurations is not justified and indeed not very helpful. We would like to investigate the response of these different cores under the influence of the same $6_{5/2}$ proton

Figure II.A.1.1: Incremental alignments for superdeformed bands of selected nuclei in the Hg-Tl region plotted relative to the appropriate core, either ^{190}Hg or ^{192}Hg .

orbital. To do so let us examine the incremental alignment Δi of ^{191}Tl relative to the ^{190}Hg core, in addition to ^{193}Tl and ^{195}Tl compared to their respective cores, ^{192}Hg and ^{194}Hg (Fig. II.A.1.1b). Also plotted are the incremental alignments of ^{189}Hg and ^{191}Hg yrast bands to illustrate the effect of changing to the more appropriate ^{190}Hg reference for the lighter isotopes. One common feature of all three Tl isotopes is an increase in Δi relative to their respective cores. Due to the intruder character of the $6_{5/2}$ proton orbital, deviation from the strongly-coupled scheme is to be expected since polarizing effects are likely to be present. The high- N content of $^{189,190}\text{Hg}$ and ^{191}Hg yrast bands is reduced

compared to ^{192}Hg (one $j_{15/2}$ neutron less) and thus the ability to resist the deformation-driving effect of the valence proton orbit could be reduced. The $6_{5/2}$ proton orbital drives the core to larger deformation in ^{191}Tl resulting in a greater increase in Δi for ^{191}Tl compared to ^{193}Tl . Recent results for ^{192}Pb [14], also shown in Fig. II.A.1.1b, seem to indicate that the 82^{th} proton does not influence the ^{190}Hg core significantly since the Δi slope is only marginally steeper. Other factors like pairing effects or structure details in the vicinity of the Fermi level could also be important.

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II.A.2. Double Blocking in the Superdeformed ^{192}Tl Nucleus

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A characteristic feature of superdeformed (SD) bands in the $A = 190$ region is the smooth increase of the dynamic moments of inertia $\mathcal{J}^{(2)}$ with the rotational frequency $\hbar\omega$, in contrast to the behavior in the $A = 150$ region. The most likely explanation for this rise is the combined alignment of pairs of quasiprotons and quasineutrons in $N = 6$ ($\pi i_{13/2}$) and $N = 7$ ($\nu j_{15/2}$) intruder orbitals, respectively, which results in a change of pairing [1]. Experimental evidence for this alignment picture is at present circumstantial. Clearly, the behavior of $\mathcal{J}^{(2)}$ in the SD bands of an odd-odd nucleus should be particularly revealing. If both the odd proton and the odd neutron occupy these high- N orbitals, the alignments should be blocked and, as a result, $\mathcal{J}^{(2)}$ should be constant with $\hbar\omega$.

The only odd-odd SD nucleus in the $A = 190$ region previously known was ^{194}Tl where six SD bands were located [2]. Encouraged by the recent discovery of two SD bands in ^{191}Tl [3] we have studied ^{192}Tl . The experiment was performed at the Argonne Tandem Linac Accelerator System using the γ -ray facility there, which consists of 12 Compton-suppressed Ge detectors and a $K = 50$ element BGO array. The states in ^{192}Tl were populated with the $^{160}\text{Gd}(^{37}\text{Cl}, 5n)$ reaction at beam energies of 178 and 181 MeV. A total of 100 million γ - γ coincidences for a hardware gate $K \geq 4$ were recorded at each beam energy. Data analysis showed the existence of six E2 bands with regular energy spacings $\Delta E_\gamma \sim 38$ keV in ^{192}Tl [4] indicative of superdeformation.

The $\mathcal{J}^{(2)}(\hbar\omega)$ values for the six bands are presented in Fig. II.A.2.1. For two of the bands shown in the upper panel (Fig. II.A.2.1a) and labeled as 3 and 4, $\mathcal{J}^{(2)}$ remains constant with $\hbar\omega$, while the other four SD bands display the more typical rise with $\hbar\omega$ (Fig. II.A.2.1b). A comparison between the $\mathcal{J}^{(2)}$ values for bands 3 and 4 and those of the odd-even neighbors ^{191}Hg (band 1) [6] and ^{191}Tl [3] (Fig. II.A.2.1a) indicates that, at the lowest frequencies,

the value of $\mathcal{J}^{(2)}$ is lower in the odd-even neighbors than in the two new SD bands. These results have been compared with cranked shell model calculations performed with the Warsaw-Lund code [7] using the parameters given in ref. 8. From there, the following conclusions can be drawn: (i) An alignment of an $N = 7$ neutron pair, which is predicted to occur in ^{191}Tl (and ^{192}Hg) for $0.15 < \hbar\omega < 0.3$ MeV is blocked in ^{192}Tl (and ^{191}Hg) when the odd neutron occupies the second $j_{15/2}$ orbital involved. (ii) An alignment of a pair of $N = 6$ protons is predicted to occur for $0.25 < \hbar\omega < 0.4$ MeV in ^{191}Hg (and ^{192}Hg). This alignment is also blocked in ^{192}Tl (and ^{191}Tl) when the proton occupies the third intruder $i_{13/2}$ orbital. (iii) At low frequencies, the calculations show that the occupation of both the $\pi i_{13/2}$ and $\nu j_{15/2}$ orbitals results in an additional contribution to $\mathcal{J}^{(2)}$ with respect to the odd-even neighboring nuclei. The calculated value ($107 \hbar^2 \text{ MeV}^{-1}$) for the double-blocked configuration discussed above, is also shown in Fig. II.A.2.1a, and agrees well with the data. On the basis of this comparisons, it is proposed that the SD bands 3 and 4 correspond to a configuration built on the favored ($\alpha = -1/2$) signature of the $\nu j_{15/2}$ orbital coupled to the two signatures ($\alpha = \pm 1/2$) of the $\pi i_{13/2}$ orbital, i.e., $\pi i_{13/2}(\alpha = \pm 1/2) \otimes \nu j_{15/2}(\alpha = -1/2)$. In fact, the data on bands 3 and 4 represent the first case where constant values of $\mathcal{J}^{(2)}$ have been observed in SD bands near $A = 190$, thereby providing strong evidence that the alignment of quasiparticles occupying the high- N intruder orbitals indeed plays an essential role in the evolution of $\mathcal{J}^{(2)}$ with $\hbar\omega$.

The four other SD bands in ^{192}Tl exhibit a rise in $\mathcal{J}^{(2)}$ with $\hbar\omega$ that is similar to that seen over the same frequency range in the odd-even neighbors, but significantly smaller than that observed in the even-even $^{192,190}\text{Hg}$ nuclei. This suggests that only one pair of high- N quasiparticles aligns in these four ^{192}Tl bands. Probably, the proton pair is involved, and the assignment proposed for all the four bands is $\pi i_{13/2}[642]5/2$ coupled to the $\nu i_{11/2}[642]3/2$ configuration which is the lowest lying neutron excitation in the SD minimum of ^{191}Hg (bands 2 and 3) [6]. This assignment is based on the following considerations: (i) The bands 1, 2 and 5, 6 are viewed as signature partners due to analogies with SD bands in the neighboring isotopes. The signature splitting for both pairs of SD bands increases with $\hbar\omega$ as expected for the $\pi i_{13/2}[642]5/2$ and $\nu i_{11/2}[642]3/2$ orbitals, and it seems that these splittings have been observed in the SD bands of $^{191,193}\text{Tl}$ [3, 5] and ^{191}Hg [6] as well. (ii) A comparison between the new SD bands and known bands in other nuclei in terms of the incremental alignment Δi as function of $\hbar\omega$ [9] can be taken into account. From the Δi values for the SD bands in ^{192}Tl computed for $^{190,191,192}\text{Hg}$ and $^{191,193}\text{Tl}$ as possible ref-

Figure II.A.2.1: Dynamic moments of inertia $\mathcal{J}^{(2)}$ versus rotational frequency $\hbar\omega$ for the six SD bands in ^{192}Tl . (a) The $\mathcal{J}^{(2)}$ values for bands 3 and 4 and, for comparison, $\mathcal{J}^{(2)}(\hbar\omega)$ for the two bands in ^{191}Tl and one band in ^{191}Hg shown as thick lines. The thin line displays results of cranked shell model calculations (see text). (b) The $\mathcal{J}^{(2)}$ values for bands 1, 2, 5 and 6. The lines are for guiding the eye.

ferences [4] only the one for a ^{191}Tl band are consistent with the systematics presented in ref. 9. According to these systematics the bands 2 and 5 would share the same $\pi i_{13/2}$ ($\alpha=\pm 1/2$) content as the SD bands in ^{191}Tl . Their signature partners, band 1 and 6 respectively, show smoothly decreasing values $\Delta i(\hbar\omega)$ which were in analogy to that seen in SD bands associated with the $\nu i_{11/2}[642]3/2$ orbital in ^{191}Hg [6]. Thus, one of the two pairs of bands (1,2 or 5,6) might correspond to the $\pi i_{13/2}[642]5/2(\alpha=1/2)\otimes \nu i_{11/2}[642]3/2(\alpha=\pm 1/2)$ configuration, while the other is associated with the unfavored $\pi i_{13/2}$ partner ($\alpha=-1/2$) coupled to the same neutron configuration.

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II.A.3. Shape Driving Effects In ^{191}Tl

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The data taken for the study of superdeformation in ^{191}Tl have also enabled an investigation of the normal deformed states of this nucleus in great detail. The data are from three experiments. The first experiment, $^{159}\text{Tb}(^{36}\text{S},4n)$ at a bombarding energy of 165 MeV, was performed at the Holifield Facility at ORNL using the Spin Spectrometer and 19 Compton-suppressed Ge detectors (CSS). The second, $^{169}\text{Tm}(^{26}\text{Mg},4n)$ at 128 MeV, was also performed at Holifield using the compact ball with 20 CSS's. Analyzing data from these two experiments has allowed us to extend the known level scheme of high-spin states [1] by more than 50 transitions. The third experiment was performed at the ATLAS facility at ANL with the same $(^{36}\text{S},4n)$ reaction as in the first experiment (see section A.1 of this report), and these data have been used so far to clear up coincidence relationships for some weak and/or contaminated transitions.

The level scheme is shown in Fig. II.A.3.1. It consists essentially of two branches with opposite parities. The spin and parity assignments of the newly observed levels are tentative and thus are given in parentheses. The negative-parity $E2$ -sequences based on the $9/2^-$ state [2] (and labeled 1) exhibit a rotational-like behavior and are viewed as being strongly coupled bands. The positive-parity branch, built on the $13/2^+$ state [3] appears to be more complex (structures 2 and 3). First, the level spacings do not show the smooth increase with spin that is usually associated with rotational-like behavior. Secondly, the crossover dipole transitions in this branch compete strongly with the $E2$ -transitions. Thirdly, above spin $19/2$ two different level structures coexist up to the highest spins observed in this work. The weaker one of both level structures consists of the 361, 354, and 409 keV *etc.* γ rays (structure 3) and has been found very recently. It is established totally from coincidence relationships, and at present the level ordering within this sequence is rather preliminary. Though most of the transitions linking to the stronger sequences in this branch are very weak (*e.g.* the 412 and 448 keV transitions), their existence helps to position the whole sequence in the level scheme.

The negative-parity $E2$ -sequences have been interpreted as nearly oblate ($\beta_2 \approx 0.15$, $\gamma \approx -57^\circ$) $\pi h_{9/2}$ bands in which a $\nu i_{13/2}$ band crossing occurs at $\hbar\omega_c \approx 0.22$ MeV (see ref. [4]). This agrees with comparable level structures in neighboring isotopes, *e.g.* ^{193}Tl [5], as well as in Hg-core nuclei [6]. The question and more interesting point, however, is the interpretation of the level structures built on the $13/2^+$ state. Two scenarios of interpretation exist assuming either a deformed or a nearly spherical shape of the nucleus. These alternatives are reflected by Total Routhian Surface (TRS) calculations [7]

Figure II.A.3.1: Partial level scheme for ^{191}Tl . Spin and parity assignments of new levels given in parentheses are tentative. Theoretical assignments of Nilsson orbitals are discussed in the text.

Figure II.A.3.2: Sample TRS plots for positive-parity configurations of ^{191}Tl . The frequency range shown is $0.089 \text{ MeV} \leq \hbar\omega \leq 0.403 \text{ MeV}$.

for positive-parity states in ^{191}Tl . Some results from these calculations are shown in Fig. II.A.3.2. At low rotational frequency ($\hbar\omega < 0.24 \text{ MeV}$) we see only a near-spherical minimum based on the $s_{1/2}$ configuration. When the rotational frequency increases, a new deformed minimum based on the $\pi i_{13/2}$ configuration tends to develop ($\beta_2 \approx 0.19$, $\gamma \approx -55^\circ$). A closer inspection of the level sequences built on the $13/2^+$ state seems to support this trend with increasing frequency (spin). In fact, at higher spin ($I > 19/2$) the energy spacings approach a somewhat more rotational-like $E_\gamma(I)$ behavior where the energies of the $E2$ transitions agree with the corresponding range $\hbar\omega > 0.24 \text{ MeV}$. Further, these transitions are bypassed by the level structure 3. It is

not unlikely that the near-spherical minimum is a continuation of the ground state $s_{1/2}$ [400]1/2 band which becomes energetically less favored at higher spin ($I > 19/2$) than a deformed minimum. In this context, structure 3 could be viewed as a weakly populated extension of these near-spherical level structures at higher spin. Structure 2, on the other hand, is thought to originate from the $i_{13/2}$ [606]13/2 configuration possibly coupled to a $(\nu i_{13/2})^2$ excitation. This picture is partially supported by systematics of band crossings in the mass region (“configuration crossing” behavior) which has been discussed in an earlier report [4]. It has to be addressed that data *and* model predictions for the positive-parity states are less indicative of rotational-like behavior than the information obtained for the negative-parity states. Alternatively, level structure 2 could be interpreted in terms of non-collective excitations associated with a near-spherical shape. While this possibility cannot be ruled out, at present we favor the first interpretation discussed.

Comparisons with neighboring nuclei are partially instructive. In ^{193}Tl a level structure of positive-parity states similar the structure 2 in ^{191}Tl has been observed, however, there it was interpreted as being single-particle like [5]. It is noteworthy to mention that the corresponding TRS diagrams are different from ^{191}Tl indicating in that case only one, near-spherical minimum in the whole frequency range under consideration. In ^{179}Ir , on the other hand, a similar type of “configuration crossing” behavior has been seen [8] also, however, in that case the orbitals involved are $\pi i_{13/2}$ and $\pi d_{5/2}$.

Future work on ^{191}Tl will consist of completing both the analysis of the DCO ratios and the $B(M1)/B(E2)$ transition strengths already in progress.

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II.A.4. Spectroscopic Study of ^{190}Tl

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As a byproduct of our study of ^{191}Tl described in the preceeding section we have significantly extended the level scheme of ^{190}Tl . This information has been extracted from the same data sets which were used for the off-line analysis of ^{191}Tl . For the Spin Spectrometer data, certainly a more suitable multiplicity gate could be used in order to enhance contributions from ^{190}Tl in the spectra. This will be a future part of the ongoing analysis for ^{190}Tl .

The preliminary level scheme is shown in Fig. II.A.4.1. Compared to the previously known scheme [1] more that 15 new transitions have been added. According to Kreiner et al. [1], the high spin levels are built on the known $I^\pi = 7^{(+)}$ isomeric state with a half-life of 750 μsec . They also proposed in a series of odd-odd Tl isotopes a few transitions in a $\nu i_{13/2}\pi h_{9/2}$ band, the bandhead of which is an isomer decaying to the 7^+ state. In ^{190}Tl , they observed only the 272, 280, and 382 keV transitions, feeding perhaps a bandhead of $I = 10$ or $11 \hbar$. Our data in preliminary analysis lead to $\Delta I = 1$ and 2 transitions in a band structure extending perhaps to $I = 17$ or $18 \hbar$. Other side feeding lines are also present. The systematics of the Hg-Tl region at $A \approx 185$ –195 show oblate-prolate shape coexistence with the oblate structures dominating the heavier nuclei and the prolate shapes beginning to become a factor with decreasing mass with $A \approx 188$ –189. We believe that ^{190}Tl is still too heavy to show prolate bands, and should behave in a more oblate manner. A final judgement, however, will be based on future advances of the data analysis.

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II.A.5. Intruder Orbits in ^{181}Au

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The study of configuration-dependent nuclear shapes is one of the most interesting topics in high spin nuclear structure physics. Particular interest centers on the study of the “shape driving” effects of the high- j , low- Ω intruder orbits, such as the low- Ω members of the $h_{9/2}$ and $i_{13/2}$ subshells. Nuclei appear to assume a larger quadrupole deformation when these “intruder” orbits

Figure II.A.4.1: Preliminary level scheme of ^{190}Tl . The bottom level is not the ground state, but rather the lowest energy state observed.

are occupied. A qualitative evidence for this “shape driving” effect is the shift of the $i_{13/2}$ neutron crossing to a higher frequency in the $\pi h_{9/2}$ configuration versus the other configurations. This feature has been commonly observed in the ${}_{71}\text{Lu}$, ${}_{73}\text{Ta}$, and some light ${}_{75}\text{Re}$ isotopes [1, 2, 3].

Recently, a systematic analysis [4] of experimental $i_{13/2}$ neutron band crossing frequencies indicates that the shape driving effect of the high- j intruder orbits is strongly Fermi level dependent. The proton $h_{9/2}$ $1/2[541]$ orbit loses its shape polarization effect when it is in the vicinity of the nuclear Fermi surface. A direct evidence for this is that the $i_{13/2}$ neutron crossing frequencies in the proton $h_{9/2}, 1/2[541]$ bands of odd- A ${}_{77}\text{Ir}$ nuclei are no longer shifted compared to those of the adjacent even-even cores, which suggests similar deformations for both the odd- A and even-even nuclei. Such a Fermi level dependence of the shift of neutron crossing frequencies can be understood, since the low- Ω $h_{9/2}$ state is a “half-particle, half-hole state” for the Ir isotopes. The occupation probabilities of this state are the same for both the even-even core and odd- A nuclei, even though the latter has this state occupied by the single particle. The shape “driving force” of the intruder orbit is therefore no longer significant.

Shape driving effects associated with the proton $i_{13/2}$ $1/2[660]$ orbit (another high- j , low- Ω orbit) do appear in the Ir isotopes, since the proton Fermi levels are sufficiently below this orbit. In all the measured Ir nuclei, the $\pi i_{13/2}$ bands exhibit proper intruder characteristics, i.e. the aligned angular momenta increase smoothly with $\hbar\omega$ without any obvious neutron band crossing through the spin region where the other configurations (e.g. $\pi h_{9/2}$ $1/2[541]$) exhibit the neutron crossing. This is indicative of a larger quadrupole deformation associated with the large β_2 driving force of the $1/2[660]$ orbit. A Holifield lifetime measurement of a transition in the $\pi i_{13/2}$ band of ${}^{179}\text{Ir}$ supports this suggestion [5].

In contrast to the pattern in the ${}_{77}\text{Ir}$ nuclei, the $\pi i_{13/2}$ band in heavier ${}_{79}\text{Au}$ isotopes no longer has clear evidence for its “intruder” characteristics. In ${}^{187}\text{Au}$, a band crossing is observed at a frequency of $\hbar\omega_c \approx 0.24$ MeV in the $\pi i_{13/2}$ band, which is attributed [8] to the excitation of a pair of $h_{9/2}$ quasiprotons; in ${}^{183,185}\text{Au}$, band crossings were observed [8, 9] in the $\pi i_{13/2}$ band at a frequency range of $0.25 < \hbar\omega_c < 0.35$ MeV. These crossings were tentatively attributed to the combination of $\pi h_{9/2}$ and $\nu i_{13/2}$ alignments. The occurrence of these band crossings in the $\pi i_{13/2}$ band in the heavier Au isotopes suggests that the shape driving effect of this intruder orbit is significantly reduced compared to that in the Ir and Re isotopes.

In analogy to the changing characteristics of the $\pi h_{9/2}$ $1/2[541]$ orbit from $_{71}\text{Lu}$ to $_{77}\text{Ir}$, it is natural to interpret the different behavior of the $\pi i_{13/2}$ $1/2[660]$ orbit in the $_{77}\text{Ir}$ and $_{79}\text{Au}$ isotopes as a similar Fermi level dependence of the shape driving effect due to the high- j , low- Ω orbits. That is, the $1/2[660]$ state is a strongly shape driving orbit in the $_{77}\text{Ir}$ isotopes but loses this effect when it is in the vicinity of the Fermi level, which is the case of the $_{79}\text{Au}$ isotopes.

In order to prove the above interpretation, it is necessary to extend the systematic analysis of Au nuclei to lighter isotopes. We performed recently an experiment to establish bands in ^{181}Au at the Holifield facility at Oak Ridge, using the Spin Spectrometer array of γ -ray counters. We used the $^{150}\text{Sm}(^{35}\text{Cl}, 4n)$ reaction to establish the first reliable level scheme of this nucleus at the edge of the region where ‘normal’ in-beam spectroscopy can be performed (without mass spectrometers or gating on emitted particles). Combined with the existing data on $^{187,185,183}\text{Au}$, our new data makes it possible to analyze systematically the role of intruder orbits in Au isotopes. The influence of the Fermi level on shape driving forces of the intruder orbits is also discussed together with the systematic trend of the $\pi i_{13/2}$ band in Ir and Re isotopes.

Although the data are still under analysis, some features of the level scheme enable us to make the following conclusions:

a) The alignment features of the $\pi i_{13/2}$ band in ^{181}Au show no obvious band crossing. Compared to the heavier Au isotopes (see Fig. II.A.5.1), in which band crossings are observed in this band, the lack of a band crossing in ^{181}Au suggests a increasing quadrupole deformation with decreasing neutron number.

b) Such a trend (the increasing deformation with decreasing N) can be understood, since the neutron Fermi levels of these nuclei are in the middle or upper portion of the $i_{13/2}$ and $h_{9/2}$ subshell. By decreasing neutron number, the nucleus loses the up-sloping orbits, thus increasing the quadrupole deformation.

c) TRS calculations also predict the same deformation trend for the Au isotopes (Fig. II.A.5.2).

d) On the other hand, the systematics for Ir and Re isotopes show no apparent change of $\pi i_{13/2}$ behavior from lighter to heavier isotopes (see Fig. II.A.5.3). This indicates that the shape associated with the $\pi i_{13/2}$ orbit is much more stable in the Ir and Re isotopes than that in the Au isotopes.

e) The different trends of the $\pi i_{13/2}$ band in Au and Ir indicate that the

Figure II.A.5.1: Aligned angular momentum versus rotational frequency for the $\pi h_{9/2}$ and $\pi i_{13/2}$ bands in ^{181}Au , ^{183}Au , ^{185}Au , and ^{187}Au .

Figure II.A.5.2: Trend of β_2 values from TRS calculations for isotopes of Re, Ir, and Au.

Figure II.A.5.3: Aligned angular momentum versus rotational frequency for the $\pi h_{9/2}$ and $\pi i_{13/2}$ bands in isotopes of Ir and Re.

nuclear shape associated with the $\pi i_{13/2}$ band is more stable in Ir isotopes than in Au isotopes. This may be the result of a Fermi level effect. In Ir isotopes, the $\pi i_{13/2}$ orbit is further from the Fermi level, whereas in Au, it is closer. The driving force of the $\pi i_{13/2}$ orbit is less when it is close to the Fermi level.

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II.A.6. Identical Bands at Normal Deformation

J.-Y. Zhang* and L.L. Riedinger

It has been known since 1958 [1, 2] that pairing correlations play a substantial role in the collective motion of nuclei. In odd- A nuclei, the pairing

correlation is reduced because of the blocking effect of the odd nucleon, which in turn increases the moment of inertia of the rotating nucleus. In general, the effective moments of inertia of odd- A nuclei exceed those of adjacent even-even nuclei by roughly 20%, although there are large variations, as summarized by Bohr and Mottelson [3]. This “effective” moment of inertia is simply the ratio of angular momentum (I) to rotational frequency (ω), which is now generally called the kinematic moment of inertia, $\mathcal{J}^{(1)}$ [4, 5], and is hereafter called “moment of inertia” (unless specified otherwise) for simplicity here. However, it has recently been found that there exist in nuclei of normal deformations “identical bands” which exhibit differences in moments of inertia more than an order of magnitude less than the typical value mentioned above, either between nearby even-even nuclei [6–8] or, especially, between odd- A nuclei and their even-even neighbors [9–12].

While the observation of superdeformed rotational bands was met by a significant degree of theoretical understanding, the discovery of identical bands, at both superdeformed and normal shapes, has been a real surprise. That is, the occurrence of rotational bands based on different configurations in different nuclei but exhibiting such identical moments of inertia presents real challenges to contemporary nuclear models. And, it is especially difficult to explain the fact that identical bands are found at normal values of deformation, where pairing effects are known to be strong. It has been our intent to refine the definition of identical bands and demonstrate that this phenomenon occurs for very special single-particle orbitals.

Different groups [6–12] have used different criteria for defining the existence of an identical band. It is very important to properly define crucial criteria, so that the least ambiguity is included in the identification of the identical bands.

The judgment of the identical nature of rotational bands depends somewhat on whether the kinematic ($\mathcal{J}^{(1)}$) or dynamic ($\mathcal{J}^{(2)}$) moments of inertia of adjacent nuclei are compared. The former is defined to be the ratio of angular momentum to rotational frequency, the latter the ratio of the variations of these two quantities. A rotational band with an aligned angular momentum exhibits differing $\mathcal{J}^{(1)}$ and $\mathcal{J}^{(2)}$ values, which could give a different conclusion concerning the identical nature of this band relative to that in a neighbor. We present here an analysis based on both moments, with emphasis on $\mathcal{J}^{(1)}$, because the influence of pairing and deformation variations on $\mathcal{J}^{(1)}$ are more clear. The possibility of a cancellation between these factors giving rise to the identical condition is easier to assess in the $\mathcal{J}^{(1)}$ analysis.

A direct and simple derivation of the relative deviation in the moment of inertia, $R(\mathcal{J}^{(1)})$, between two adjacent nuclei follows:

$$\mathcal{J}^{(1)} = \frac{I}{\omega} \quad (11.2)$$

$$\begin{aligned} \delta\mathcal{J}^{(1)} &= \frac{\mathcal{J}^{(1)}(A_1) - \mathcal{J}^{(1)}(A_2)}{\mathcal{J}^{(1)}(A_1)} = \frac{I(A_1) - I(A_2)}{\omega(A_1)} \bigg/ \frac{I(A_1)}{\omega(A_1)} \\ &= \frac{I(A_1) - I(A_2)}{I(A_1)} = \frac{i(A_1)}{I(A_1)} \end{aligned} \quad (11.3)$$

where A_1 and A_2 are the mass numbers for the odd- A and $A - 1$ (even-even) nuclei, respectively. The relative variation in the moment of inertia between two adjacent nuclei is thus the ratio of the angular momentum difference, i , to the angular momentum of the odd- A nucleus. It is necessary to average this angular momentum difference over N different states in a band to give a total measure of the relative variation in the moment of inertia:

$$R(\mathcal{J}_{\text{avg}}^{(1)}) = \frac{1}{N} \sum_{n=1}^N \frac{|i_n(A_1)|}{I_n(A_1)} \quad (11.4)$$

where the index n is the label of the state. The relative difference in the moment of inertia due to the variation in mass number, $R(\mathcal{J}_m)$, is used as a unit to evaluate the relative deviation of $\mathcal{J}^{(1)}$ between two adjacent nuclei:

$$R(\mathcal{J}_m) = \frac{A_1^{5/3} - A_2^{5/3}}{A_1^{5/3}}; \quad (11.5)$$

$R(\mathcal{J}_m)$ is around 1% in the mass region discussed. One possible criterion is then

$$R^{(1)} = \frac{R(\mathcal{J}_{\text{avg}}^{(1)})}{R(\mathcal{J}_m)} < 1.0 \quad (11.6)$$

which means that we are defining an identical band as one where *the average relative difference of the moment of inertia in two nuclei is less than $R(\mathcal{J}_m)$* (defined by eqns. 2-4).

Using this criterion, we have compared approximately 160 rotational bands (all bands with not less than three rotational transitions before the first backbending or sharp upbending) previously known for odd-proton nuclei in the region $A = 150-190$ and $Z = 67-77$ with yrast bands of their corresponding $A - 1$ even-even nuclei [9, 10]. Ten identical bands are found to

satisfy our definition. *It is clear that all of the identical bands found by our criterion correspond to particle states with the occupation of upsloping (with respect to quadrupole deformation) orbitals, $[404]7/2$ and $[402]5/2$, and occur mostly in the lutetium isotopes.*

Factors which influence the moment of inertia include pairing correlations, deformation (quadrupole, hexadecapole, triaxial, etc.), proton neutron interaction, and quasiparticle alignment. It has long been known that in the traditional pairing theory [2, 3] an odd nucleon always reduces the monopole pairing correlation via the blocking effect, consequently increasing the moment of inertia. It is reasonable to assume that to compensate or cancel this increase in the moment of inertia, there must be other factors which act to reduce $\mathcal{J}^{(1)}$ in these particular odd- A nuclei. One possibility is that the quadrupole deformation provides this compensating reduction of the moment of inertia. Of course, such a scenario is a necessary but not sufficient condition for observing identical bands, since the occurrence of identical bands requires a *precise* cancellation of the factors affecting the moment of inertia.

To test qualitatively this cancellation picture, we have performed a model calculation. The equilibrium deformation was found for different configurations in ^{171}Lu and ^{170}Yb at $\omega = 0$ through a potential energy surface calculation with normal BCS plus Strutinsky method [11]. Using these deformations, we then performed a self-consistent pairing calculation with particle number projection [12] at rotational frequencies of 0 and 0.15 MeV. It is found that, compared with the ground band in ^{170}Yb , the quadrupole deformation of ^{171}Lu decreases for the configurations $[404]7/2$ and $[402]5/2$, but increases for $[541]1/2$, the downsloping orbital. However, the proton pairing decreases for all configurations in ^{171}Lu . Consequently, for these upsloping configurations, deformation reduces and therefore compensates the effect of the reduction of pairing on the moment of inertia, as mentioned above. In contrast, for the downsloping configuration $[541]1/2$, both the reduction in pairing correlation and the increase in deformation result in a rise in the moment of inertia. Therefore, in general, compared to the yrast band in $A-1$ even-even nuclei, the band of an upsloping configuration in the odd- A nucleus has less increase in moment of inertia than the one of a downsloping configuration. In contrast, the $R^{(1)}$ values for the dominant downsloping configuration in this region ($[541]1/2$) are all large (19 to 68) compared to the values for the upsloping configurations, as expected in the cancellation picture discussed here.

Now let us consider a similar analysis based on the dynamic moment of inertia, $\mathcal{J}^{(2)}$. This quantity reflects the local characteristics of the effective

moment of inertia and is different from the kinematic moment ($\mathcal{J}^{(1)}$) when a band has an alignment, i . The above analysis of $R^{(1)}$ picks out those bands with small alignments compared to the even-even core nucleus. The question now is whether there are bands that have constant values of i and should be judged as identical to the core nuclei based on a $\mathcal{J}^{(2)}$ analysis. The criterion is set up in a manner analogous to that in eqns. (1-5):

$$\mathcal{J}^{(2)} = \frac{dI}{d\omega} \quad (11.7)$$

$$\begin{aligned} \delta\mathcal{J}^{(2)} &= \frac{\mathcal{J}^{(2)}(A_1) - \mathcal{J}^{(2)}(A_2)}{\mathcal{J}^{(2)}(A_1)} = \frac{dI(A_1) - dI(A_2)}{d\omega(A_1)} \bigg/ \frac{dI(A_1)}{d\omega(A_1)} \\ &= \frac{d[I(A_1) - I(A_2)]}{dI(A_1)} = \frac{di(A_1)}{2}. \end{aligned} \quad (11.8)$$

It is then necessary to average this relative angular momentum difference to give a total measure of the relative variation in the dynamic moment $\mathcal{J}^{(2)}$:

$$R(\mathcal{J}_{\text{avg}}^{(2)}) = \frac{1}{N} \sum_{n=1}^N \frac{|i_{n+1}(A_1) - i_n(A_1)|}{2} \quad (11.9)$$

$$R^{(2)} = \frac{R(\mathcal{J}_{\text{avg}}^{(2)})}{R(\mathcal{J}_{\text{m}})} < 1.0. \quad (11.10)$$

Once again all the identical bands found by this $\mathcal{J}^{(2)}$ criterion are based on upsloping configurations, and some are the same as those identified in the $\mathcal{J}^{(1)}$ analysis. An important finding is that the downsloping $[541]1/2$ bands still have $R^{(2)}$ values (3 to 51) much larger than those for the upsloping orbitals. So, even removing the possible influence of a sizable but constant alignment (which would give a large $R^{(1)}$ value) results in still rather large $R^{(2)}$ values in $[541]1/2$ bands and the conclusion that the identical bands are found only among the upsloping configurations. Baktash et al. [7, 8] also found that the identical bands are mostly associated with upsloping orbitals in this same $A = 150 - 190$ region.

From the results one can see that there is a continuous variation in the $R^{(1)}$ and $R^{(2)}$ values for the bands surveyed here. That is, there is no distinct gap between these values for identical compared to non-identical bands [6].

To summarize, the simple picture of a cancellation between the effects of a pairing reduction and a quadrupole deformation decrease must be considered as a possible explanation for the identical band phenomenon at normal

deformation.

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II.A.7. Calculation of Energy Signature Splitting

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Rotational bands of high- K have a “signature splitting,” i.e. an energy shift between the favored (lower) and the unfavored (upper) $\Delta I = 2$ components of the band, which is small or zero. However for the low- Ω components of a high- j shell, mixing with the $K = \frac{1}{2}$ orbital (which has signature splitting by definition) leads to a significant energy shift between the two signatures. Since this energy difference between signatures results from mixing between orbitals with Ω values differing by one unit, energy signature splitting depends on deformation, pairing, and Fermi level. Consequently, a comparison between measured and calculated signature splitting can provide an extremely sensitive test of nuclear models and the shape parameters used. A signature splitting analysis has been done previously by Shastry et al. [1]; we have expanded on their original experimental data, and will introduce a new method for calculating signature splitting.

Experimentally, $\Delta\epsilon'$ is extracted by taking the difference between the Routhian energies at a specific rotational frequency of the two signature partners in question ($\Delta\epsilon' = \epsilon'(\alpha_u) - \epsilon'(\alpha_f)$). In principle, $\Delta\epsilon'$ could be extracted in the same way from theoretical calculations of the Total Routhian Surfaces

(TRS) or the routhians from the Cranked Shell Model. The proper approach would be to calculate the total energy of the nucleus as a function of rotational frequency ω and quasiparticle configuration self-consistently in deformation and pairing, i.e. with each signature “blocked” in turn. At present, no code is available to allow this complex calculation. For this reason, we used an approach combining the results from three different programs: TRS [2], HFBC, and ENER00¹.

The total signature splitting is (or must be²) decomposed into two parts

$$\Delta\epsilon' = \Delta E_{\text{def}} + \Delta E_{\text{rot}}$$

where ΔE_{def} comes from the difference in bandhead energy due to a possible difference in deformation for the two signatures, and ΔE_{rot} results from the different dependence on the rotational frequency ω for the routhians $\epsilon'(\alpha_{u/f})$. The procedure³ we have used, can be split into three parts:

1. Use the TRS calculations to get the best possible estimate for the deformation parameters for both the unfavored and favored signature $\beta_2^{\alpha_{u/f}}$, $\beta_4^{\alpha_{u/f}}$ and $\gamma^{\alpha_{u/f}}$ at the rotational frequency ω_0 of interest.
2. Calculate the difference in bandhead energies (or vacuum energy at ω_0) for the two signatures, ΔE_{def} , with the program ENER00, using the deformation parameters obtained from the TRS calculations at frequency ω_0 . In these calculations the relevant configuration is blocked, the monopole pairing is calculated in a self-consistent way and the particle number equation is checked.
3. The final step is to run the Hartree–Fock–Bogolyubov theory based cranking code, HFBC, for each set of deformation parameters and blocking the corresponding configuration to obtain the second contribution, ΔE_{rot} . Like in step 2, pairing is calculated in a self-consistent way and the particle number equation is checked, but here also at each frequency step (model version IMODEL = 3).

The improvement in this three step calculation, compared to “traditional” ways of estimating $\Delta\epsilon'$ from Total Routhian Surfaces, is based essentially on

¹We received the codes, HFBC and ENER00 from W. Nazarewicz.

²The HFBC code can only be used for calculating quasiparticle energies relative to the vacuum, so the code can only be used to calculate the contribution ΔE_{rot} which results from rotation!

³This way of calculating $\Delta\epsilon'$ has been suggested by W. Nazarewicz.

Figure II.A.7.1: Deformation parameters (at $\hbar\omega = 0.2$ MeV) for the odd- N $\nu i_{13/2}$ signature partners of isotopes of Dy, Er, and Yb. These values were extracted from TRS calculations. The open symbols are the favored signature ($\alpha = \frac{1}{2}$), and the filled symbols are the unfavored signature ($\alpha = -\frac{1}{2}$).

two ingredients: *i*) a better treatment of pairing and blocking, realized by using the HFBC code, where pairing can be treated in a self-consistent way, and *ii*) numerical improvements based on more precise calculations of the single-particle level energies and wave functions, and also on removing interpolation errors in calculating ΔE_{def} compared to the TRS calculations, which are done on a relatively coarse deformation grid.

As a test for our method, signature splitting in known $\nu i_{13/2}$ rotational bands in Dy, Er, and Yb isotopes has been analyzed. For this analysis, $\Delta\epsilon'$ was extracted at $\hbar\omega = 0.2$ MeV, which is well below the first band crossing, so band crossing effects are negligible. The deformation parameters obtained from the TRS calculations are summarized in Fig. II.A.7.1.

The $\nu i_{13/2}$ sub-shell was a “natural” choice to test our method. Since it is the only positive parity sub-shell in the region, we would not have problems associated with crossings of other shell states. For example, most theoretical

codes presently used cannot trace a particular state through a bandcrossing. There were, however, other problems associated with the calculation of the Fermi level λ in cases with high level density in the vicinity of the configuration of interest. In such cases, the interactive procedure used for calculating λ and Δ in the pairing model (IMODEL = 3) that we had chosen to use would not converge and sometimes the program would “crash”. Thus ΔE_{rot} could not be obtained from these calculations. To avoid this problem, we tried to sacrifice the self-consistent pairing treatment. We have found that if we use a model with a frequency independent pairing that is calculated from normal BCS theory without blocking at $\omega = 0$ (IMODEL = 0), then we get almost the same results as for IMODEL = 3 (which has the blocking feature activated) even though the pairing is quite different. An additional advantage of using IMODEL = 0 is that the HFBC code ran successfully for all calculations.

Fig. II.A.7.2 shows the ΔE_{rot} resulting from IMODEL = 0 and the successful calculations of IMODEL = 3. The surprising agreement between the signature splittings calculated for these two pairing treatments might be explained by the fact that $\Delta\epsilon'$ is an energy difference between two routhians. Because of the similarity of the two models, and the problem of “crashing” in IMODEL = 3 we have based our calculations/results on IMODEL = 0. Also shown on Fig. II.A.7.2 are the ΔE_{def} values obtained from calculations done with ENER00. The contribution to $\Delta\epsilon'$ from ΔE_{def} is much smaller than the contribution from ΔE_{rot} in all cases. This is not unexpected, because the difference in deformation between the two signatures is quite small for all isotopes, as can be seen in Fig. II.A.7.1.

The comparison between measured and calculated signature splitting values is shown in Fig. II.A.7.3. The calculated $\Delta\epsilon'$ values are in excellent agreement with experiment, with the largest deviations being low in the shell. The results demonstrate that as neutron number increases, signature splitting decreases. This is expected, because with increasing neutron number $\nu i_{13/2}$ states of increasing K are occupied, which implies that there is a reduced mixing with the $\frac{1}{2}^+[660]$ configuration, and thus a reduced signature splitting. For example, the Fermi level for ^{155}Dy ($N = 89$) lies at the $K = \frac{1}{2}$ state, whereas $K = \frac{3}{2}$ for ^{157}Dy , giving rise to a smaller signature splitting for ^{157}Dy . It is also expected that smaller nuclear deformations produce a larger $\Delta\epsilon'$ for states with $K > \frac{1}{2}$, because a smaller deformation implies that there is a smaller distance between the $K = \frac{1}{2}$ and the higher K $\nu i_{13/2}$ members, which produces an increased mixing that results in an increased $\Delta\epsilon'$. For example, the quadrupole deformations obtained from TRS calculations for the favored signature ($\alpha_f = +\frac{1}{2}$)

Figure II.A.7.2: Calculated ΔE_{rot} and ΔE_{def} contributions, obtained from HFBC and ENER00 respectively (at $\hbar\omega = 0.2$ MeV), to $\nu i_{13/2}$ signature splitting in odd- N isotopes of Dy, Er, and Yb. The filled symbols are ΔE_{rot} calculated with blocking and self-consistent pairing (IMODEL = 3), the open symbols are ΔE_{rot} calculated without blocking or self-consistent pairing (IMODEL = 0), and the stars are ΔE_{def} .

of the $N = 91$ isotopes of Dy, Er, and Yb are $\beta_2 = 0.236$, 0.228, and 0.212 respectively. The corresponding experimental $\Delta\epsilon'$ for these nuclei are 0.303, 0.372, and 0.454 MeV, which follows the expected trend.

One possibility for the systematic deviations in the lower part of the $\nu i_{13/2}$ sub-shell is the sensitivity of the calculations to changes in deformation. Nuclei with λ low in the $\nu i_{13/2}$ sub-shell are less deformed than those higher in the shell (Fig. II.A.7.1). It is possible that the lighter nuclei studied ($A \sim 157$) may be more susceptible to small changes in deformation than the heavier nuclei. The dependence of the calculations on changes in pairing is another possibility. Tests of the HFBC code, from which ΔE_{rot} is obtained, showed that the results

Figure II.A.7.3: Experimental and calculated $\nu i_{13/2}$ signature splitting at $\hbar\omega = 0.2$ MeV for isotopes of Dy, Er, and Yb. The experimental data were extracted from the literature, and the calculated values were obtained using results from TRS, HFBC, and ENER00 calculations. The filled symbols are the experimental values, and the open symbols are calculated values.

are not sensitive to changes in deformation in either the light or heavy nuclei studied. ΔE_{def} is also relatively independent of changes in pairing as well (seen Fig. II.A.7.2). Initial tests of ENER00, which uses that same pairing calculation as HFBC, indicate that the results also depend relatively little on pairing, but, on the other hand, are very dependent on β_4 and perhaps on β_2 and γ as well. These tests of ENER00, however, are still preliminary.

In conclusion, despite the discrepancies between the experimental values and calculations low in the $\nu i_{13/2}$ sub-shell, this method of calculating signature splitting produces surprisingly accurate results.

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II.A.8. Signature Splitting for $\pi h_{9/2}[541]1/2^-$ Bands in Tm and Lu Isotopes

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The strongly shape driving $\pi h_{9/2}[541]1/2^-$ intruder configuration with $\alpha_f = +1/2$ exhibits some anomalous, and so far unexplained, features concerning the crossing frequency ($\hbar\omega_c$), the aligned angular momentum (i_x), and interaction strength at the alignment of the first pair of $i_{13/2}$ quasineutrons in several odd- Z rare-earth nuclei [1, 2, 3]. Besides the problems at the band crossing it has been known for a while that the moments of inertia and quadrupole moments can be difficult to understand within the mean-field picture. To understand these problems it is important to get new and additional information about the $\pi h_{9/2}$ configuration and find new ways of testing the model predictions for this configuration. One extremely important way to gain new insight is to measure electromagnetic matrix elements, since they can give the most detailed information about the nuclear structure. Unfortunately these are rather difficult experiments and the resulting uncertainties are often larger than 10–20%. So it is important to find other ways to test model predictions of $\pi h_{9/2}$ properties. The high-spin group at UTK has, during the past few years, looked for different ways to understand similar problems for other intruder configurations in the rare-earth region. One way is to look at the energy signature splitting, $\Delta\epsilon' = \epsilon'(\alpha_u) - \epsilon'(\alpha_f)$. The signature splitting has the nice advantage that it is easy to measure experimentally and the uncertainty is small, because it is calculated from level energies, $E(I)$, that can be measured with an accuracy typically better than a few tenths of a keV.

In the preceding report it is described how a new way of calculating $\Delta\epsilon'$ has been tested and used with success for neutron $i_{13/2}$ configurations in the rare-earth region. The total signature splitting, at a given frequency ω_0 , has contributions from two parts: $\Delta\epsilon' = \Delta E_{\text{def}} + \Delta E_{\text{rot}}$, where ΔE_{def} comes from the difference in band-head energies (or vacuum energy at ω_0) due to a difference in deformation for the two signatures, and ΔE_{rot} results from the different dependence on the rotational frequency ω for the routhians $\epsilon'(\alpha_{u/f})$. We refer

N	Nucleus	$\Delta\epsilon'$ [keV]			Nucleus	$\Delta\epsilon'$ [keV]		
		100	150	200		100	150	200
94	^{163}Tm			469	—			
96	—				^{167}Lu	266	359	439
98	^{167}Tm	288	401	479	^{169}Lu	295	413	502
100	^{169}Tm	338	457	(532)	^{171}Lu	337	456	544
102	—				^{173}Lu	365	485	(578)
104	—				^{175}Lu	403	(517)	

Table II.A.8.1: Experimental signature splitting for the $\pi h_{9/2}$ band of thulium and lutetium isotopes.

to the preceding report for a description of the used procedure. In parallel to this on-going analysis we have tried to extend the analysis to the available data for $\pi h_{9/2}[541]1/2^-$ bands in the odd- Z thulium and lutetium isotopes. Table II.A.8.1 gives a summary of the known data. The signature splitting is extracted at a rotational frequency equal to 100, 150 and 200 keV, using experimental routhian plots.⁴ The unfavored signature is poorly known and is only established high enough in spin for a few heavier Re, Ir and Au isotopes, except for the presented data. The Re, Ir and Au isotopes have not yet been included in the analysis. The large signature splitting for the $[541]1/2^-$ band causes the population of the unfavored signature to be quite weak, compared to the favored band. Furthermore, a large signature splitting may cause the decay from the unfavored band to take place via (irregularly spaced) $M1$ transitions competing with the stretched $E2$'s, thereby complicating the decay pattern. This explains why the unfavored signature partner is known in relatively few cases.

Before presenting the results, we would like to discuss some points of interest—or difficulty—in the calculations. In the analysis of the odd- N case we have a unique parity intruder state $\nu i_{13/2}$. This implies that it is relatively easy to extract the deformations from the TRS [4] calculations for these configurations, because there will be no mixing with other configurations of the same parity. In the odd- Z case we have other negative parity states $\pi h_{11/2}[523]7/2^-$ (and for the heavier rare-earth nuclei also $\pi h_{11/2}[514]9/2^-$ and $\pi h_{11/2}[505]11/2^-$), that are mixing with the $\pi h_{9/2}$ configuration, and for some deformations and some frequencies they cross the $\pi h_{9/2}[541]1/2^-$ band. This

⁴It should be mentioned that even though the experimental uncertainty on the level energies, $E(I)$, often is less than 0.5 keV, the whole procedure of extracting the signature splitting introduces an additional uncertainty on $\Delta\epsilon'$ that we estimate to be of the order of 3–5 keV.

Figure II.A.8.1: Extracted deformation parameters β_2 , β_4 and γ for favored and unfavored signatures of the $\pi h_{9/2}$ band in thulium and lutetium isotopes at rotational frequency 200 keV.

makes the extraction of deformation parameters more difficult and the results less reliable. In an attempt to reduce this problem, we have used a new and unreleased code, written by R. Wyss [4], that is designed to distinguish between high and low- K configurations, making use particularly of the difference in signature splitting and alignment for high and low- K configurations. The program makes the results more reliable. There are two basic uncertainties related to the extracted deformation parameters.

1. Theoretical uncertainties in the TRS calculation itself, mainly caused by the selection of a “central nucleus” for the mesh. This problem has been discussed by W. Nazarewicz et. al. [5] and they found that typical uncertainties for β_2 and β_4 usually do not exceed 0.007 and 0.002 respectively. Axial symmetry was assumed in that paper so no uncertainty was given

for γ .

2. Uncertainties related to the procedure of extracting data from the TRS mesh, especially when levels are mixing and/or crossing. In the odd- Z case we have been facing this problem. We estimate that the uncertainties for β_2 and β_4 are of the same order of magnitude as the theoretical uncertainties.⁵ For the triaxiality parameter γ we estimate that $\Delta\gamma \sim 1 - 2^\circ$.

In addition to these uncertainties, we have learned that the extracted deformation parameters also depend on the pairing used in the TRS calculations. The ytterbium mesh has been done for different values of both the neutron and proton pairing. Within reasonable variations of Δ_p we found that the deformation parameters differ only a few percent. In the discussion of the results we will use the following resulting theoretical and procedural uncertainties, $\Delta\beta_2 = 0.008$, $\Delta\beta_4 = 0.0025$ and $\Delta\gamma = 1.5^\circ$. The deformation parameters for the favored and unfavored signatures of the $[541]1/2^-$ band for the Tm and Lu isotopes can be seen in Fig. II.A.8.1.

Crossing levels, between configurations with the same parity and signature, are a problem for the HFBC code, when calculating the ΔE_{rot} part, since the crossing causes a discontinuous change in the pairing at the crossing frequency. The code is not yet developed to trace a specific configuration and the blocking procedure implies that a different configuration is blocked before and after a crossing, which again implies that the pairing is calculated for different configurations before and after the crossing. In some cases the calculations even crash! It has not been possible to get around this serious problem, and it has led us to look at the splitting at different frequencies to avoid the crossing. We have even tried to sacrifice the self-consistent pairing treatment and have found the interesting result, that if we use a model with a frequency independent (IMODEL= 0) pairing (calculated from normal BCS theory without blocking at $\omega = 0$) then we get almost the same results as for IMODEL = 3 (which has the blocking feature activated), even though the pairing is quite different. The result is illustrated for Tm and Lu at $\hbar\omega = 200$ keV in Fig. II.A.8.2. It is seen that in the calculated cases the maximum difference between the results for IMODEL = 3 and IMODEL = 0 is 3.9% and 2.8% for

⁵We want to emphasize that this is only valid for the Tm and Lu isotopes. For the Re and Ir isotopes—where more states are mixing and the nuclei are more γ -soft—we have learned that the uncertainties are quite a bit larger!

Figure II A.8.2: Comparison of $\pi h_{9/2}$ signature splittings, ΔE_{rot} , calculated with the IMODEL = 0 and 3 options for thulium and lutetium isotopes at rotational frequency 200 keV. The ΔE_{def} part is also shown.

Tm and Lu respectively.⁶ The surprising agreement between the signature splittings calculated in these two options might be explained by a cancellation effect, since $\Delta\epsilon'$ is the difference between two routhians. The IMODEL = 0 code has the very nice advantage that the calculations are faster, it is easy to run and it does not crash! After realizing this, we have based our calculations/results on IMODEL = 0 whenever we have problems with IMODEL = 3.

In Fig. II.A.8.2 we have also shown the calculated ΔE_{def} part. The contribution to the total signature splittings $\Delta\epsilon'$ from ΔE_{def} is seen to be strongly dependent on the neutron number N for the thulium isotopes, and much larger than the ΔE_{def} part for the lutetium isotopes, that have a rather constant (and negligible) value except for the lighter isotopes. The dramatic difference in ΔE_{def} between thulium and lutetium isotopes can be understood qualitatively as a consequence of the larger difference in β_2 and β_4 between the unfavored and favored signature for the thulium isotopes compared to the lutetium isotopes, see Fig. II.A.8.1.

⁶We have tested a third model, IMODEL = 1, which treats the pairing at $\omega = 0$ in the same way as IMODEL = 0, but the particle number equation is checked in addition and a model dependence of Δ_p versus ω can be used. Again we get a good agreement between the three models.

Figure II.A.8.3: Comparison of experimental and calculated $\pi h_{9/2}$ signature splitting for thulium and lutetium isotopes at rotational frequency 200 keV. Only IMODEL = 0 calculations are shown.

The results of our analysis are summarized in Fig. II.A.8.3, which shows experimental and calculated signature splittings for the Tm and Lu isotopes at rotational frequency 200 keV. On the figure we have only shown the IMODEL = 0 results. Before discussing the large differences between theory and experimental data it is necessary to examine the dependence of ΔE_{def} and ΔE_{rot} on the deformation parameters and the used pairing treatment.

We have learned that the extracted deformation parameters are almost constant against reasonable variations in the pairing used in the TRS calculations. We have also learned (see Fig. II.A.8.2) that the self-consistent pairing treatment in IMODEL = 3—that was expected to do a better job—does not change ΔE_{rot} significantly compared to the used standard BCS pairing in IMODEL = 0. Finally we have tested the dependence of ΔE_{def} on the used monopole pairing strength and again we found a surprisingly weak dependence. Even though the pairing Δ_p in some critical cases changed by almost 50% the observed change in ΔE_{def} was less than a few keV. So we can conclude from our analysis that $\Delta \epsilon'$ is almost independent of the pairing for the nuclei studied. It is known that higher multipole pairing can be important, especially for deformation driving configurations as the studied $\pi h_{9/2}[541]1/2^-$ configuration. So a future improvement of the calculations might be to include the quadrupole pairing.

We have tested the dependence of both ΔE_{def} and ΔE_{rot} on the deformation parameters for a few isotopes. For ΔE_{rot} we found that a variation of the deformation parameters within the discussed uncertainties on β_2 , β_4 and γ gives a variation in ΔE_{rot} less than typically 2% for $^{161,163,167}\text{Tm}$. ΔE_{def} has so far only been tested for ^{163}Tm and we found a strong dependence of the band-head energies on β_2 and β_4 , and a negligible effect from γ . This implies that even relatively small uncertainties on β_2 and β_4 can result in large uncertainties on ΔE_{def} . The analysis gave a total uncertainty on ΔE_{def} equal to ~ 150 keV, with contributions from $\Delta\beta_2 = 0.008$, $\Delta\beta_4 = 0.0025$ and $\Delta\gamma = 1.5^\circ$ equal to ~ 96 keV, ~ 117 keV and ~ 12 keV respectively. We still need to estimate the uncertainties for other isotopes, but the remarkable result for ^{163}Tm clearly proves that a very critical point in our analysis is the deformation parameters.

To improve the accuracy in the calculations more accurate deformation parameters is strongly needed. The effect of using monopole pairing only is an other possibility that must be examined. Finally we want to mention that it has already been shown [6] that the effect of including coupling to various vibrational modes in the calculations can easily change the signature splitting with as much as 100 keV.

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II.A.9. Signature Splitting in Odd–Odd Nuclei

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The deformation-driving effects of intruder states have been studied by analysis of various types of data on rotational bands in rare-earth deformed nuclei. The sensitivity of four measurables (bandhead energy, $B(E2)$ value, neutron $i_{13/2}$ crossing frequency, and signature splitting) to increased deformation in an intruder band is now clear through the work of our group and others. In the previous two sections we have discussed in some detail the analysis of signature splitting systematics for bands in odd- N and odd- Z nuclei. Here we discuss the extension of this analysis to bands in odd-odd nuclei, both at normal and super deformations.

The discussion here is focused on the proton intruder states, $h_{9/2}$ and $i_{13/2}$, throughout the rare-earth region of normal deformation, and then on the $\pi i_{13/2}$ band as a “spectator” in superdeformed bands in Tl. The calculated single-proton level ordering shows that the $K = 1/2$ $h_{9/2}$ level, $1/2[541]$, is clearly an intruder state (*i.e.* above the proton Fermi surface) for deformed (β_2 around 0.2) nuclei with $Z = 60$ (Nd) through 76 (Os), while the corresponding $i_{13/2}$ state retains its intruder status through Hg ($Z = 80$). However, at superdeformed shapes (β_2 around 0.5) there are four protons in the $i_{13/2}$ orbitals for Hg, which removes its status as an intruder orbital. For those cases, it is the $j_{15/2}$ neutron orbital that seems to have the largest shape-driving tendencies.

The signature splitting of the $\nu i_{13/2}$ band is an easily measurable quantity related to the deformation of the nucleus. The amount of signature splitting is deduced for such bands by plotting the energies in the rotating frame of the nucleus and extracting the difference in Routhian energies at a certain rotational frequency, $\hbar\omega = 0.2$ MeV. We have extracted these quantities, $\Delta\epsilon'$, from all known $\nu i_{13/2}$ bands in odd- A odd- N nuclei, as discussed in a previous section of this report. The trend of signature splittings is quite smooth, being large low in the $\nu i_{13/2}$ shell ($N = 89$) and decreasing steadily as the neutron Fermi level increases through the $i_{13/2}$ shell. This trend is shown for the upper part of this region ($N = 99$ –107) in Fig. II.A.9.1.

Even for a given neutron number, there is a strong variation in the $\Delta\epsilon'$ value for different values of Z in Fig. II.A.9.1. This results from the varying deformation, β_2 , for these isotones. For example, TRS calculations [1] yield β_2 values of 0.282, 0.277, and 0.258 for the $Z = 70, 72$, and 74 $N = 99$ isotones, the larger deformation giving rise to the smaller splitting. This is an important point for addressing the deformation driving properties of intruder

states. That is, the coupling of the $\pi h_{9/2}$ intruder orbital to the $\nu i_{13/2}$ structure forms a band (usually yrast) in odd-odd nuclei. If the intruder state changes the deformation of the nucleus, then the $\nu i_{13/2}$ signature splitting in the odd-odd nucleus should change compared to the adjacent odd- A nuclei, as is the case in Fig. II.A.9.2. Note that the $\Delta\epsilon'$ value for the $\nu i_{13/2}\pi h_{9/2}$ band in ^{172}Ta is reduced from an expected value of 74 keV (that value on the $N = 99$ curve for $Z = 73$) to an actual value of 29 keV, which could suggest a 5% increase in β_2 . Note also that the $\Delta\epsilon'$ decrease for odd-odd Re is still present (i.e. the $\pi h_{9/2}$ state is still a deformation-driving intruder orbital), but largely disappears for four known odd-odd Ir isotopes (two, ^{180}Ir and ^{178}Ir , from our measurements [2]). This correlates with the loss of intruder status by the $\pi h_{9/2}$ orbital, reflected also in the agreement in the $\nu i_{13/2} \hbar\omega_c$ values in the $\pi h_{9/2}$ band of Ir nuclei, compared to the even-even cores. Thus, the measured $\Delta\epsilon'$ values in odd-odd nuclei do indeed reflect the change in shape induced by the coupling of the $\pi h_{9/2}$ intruder orbital to the $\nu i_{13/2}$ structure.

The superdeformed bands in the Hg region are generally thought to have a high- j composition of four protons in $i_{13/2}$ orbitals and two neutrons in $j_{15/2}$ levels (e.g., see [8]). It should be possible to do an analysis of signature splittings for the superdeformed bands now known in various isotopes of Hg and Tl in a manner similar to that described above. One difference is that the absolute energies of the levels are not known in the superdeformed cases. All one can measure at this time is the energies of the two sequences of $E2$ γ -ray energies, which are assumed to be related signatures of a strongly coupled superdeformed band. Until the next generation of 4π detectors is available, one can only make this association of γ -ray cascades into a strongly coupled band and hope that there are only a few confused cases. Since it is impossible to extract an actual signature splitting in these cases, we define instead an energy shift, ΔE , based on the average of two consecutive energies in one sequence to the comparable energy in the other signature:

$$\Delta E = E_\gamma(I \rightarrow I-2) - 1/2[E_\gamma(I+1 \rightarrow I-1) + E_\gamma(I-1 \rightarrow I-3)]$$

This quantity could be very different than the actual signature splitting, and thus one must be careful in the use of it. With this caution in mind, we attempt to systematize this quantity for the known superdeformed bands in Hg and Tl nuclei, as shown in Fig. II.A.9.2.

Note first the essentially identical behavior for the superdeformed bands in the three odd- A Tl isotopes. In each case, these represent the two signatures of the $\pi i_{13/2} 5/2[642]$ band [9, 10, 11], and so the consistency is logical. For

Figure II.A.9.1: Energy signature splittings, $\Delta e'$, for the $\nu i_{13/2}$ bands in odd- A odd- N nuclei and for the $\nu i_{13/2} \pi h_{9/2}$ bands in odd-odd nuclei. The values are extracted at $\hbar\omega = 0.20$ MeV from literature data on bands in these various odd- A nuclei, and from Kreiner et al. [3] for ^{172}Ta , Venkova et al. [4] for ^{180}Re , Slaughter et al. [5] for ^{182}Re , Yu et al. [2] for ^{178}Ir and ^{180}Ir , Kreiner et al. [6] for ^{182}Ir , and Kreiner et al. [7] for ^{184}Ir .

comparisons to the others, all three Tl isotopes show a ΔE of around 6 keV at a transition energy of 600 keV. By comparison, the three sets of bands in the Hg isotopes represent smaller energy shifts at 600 keV. The bands in ^{191}Hg are assigned [12] to the $\nu i_{11/2}$ $3/2[642]$ orbital, in ^{193}Hg to $9/2[642]$ $\nu i_{13/2}$ [13], and in ^{194}Hg likely to the coupling of this $\nu i_{13/2}$ orbital to neutron $5/2[512]$ ([14]). There is little signature splitting found in the calculations for any of these orbitals, and thus it is logical that the resulting ΔE values would be smaller than those in odd- A Tl.

The values of the energy shifts for ^{194}Tl are shown in Fig. II.A.9.3, assuming the same association of energy cascades into bands as done by the original authors [15]. While none of the ΔE values is large, it is probably safe to conjecture that the pair with the largest values (called band 3 in Fig. II.A.9.3) are associated with the odd- A structure with the largest shift, $\pi i_{13/2}$. The two signatures of this orbital are coupled to the only signature of the $\nu j_{15/2}$ orbital, $3/2[761]$, observed in ^{193}Hg [13]. The reduction of the ΔE for this ^{194}Tl band from 6 keV at 600 keV (the measured value for the $\pi i_{13/2}$ bands in odd- A Tl) to

Figure II.A.9.2: Energy shifts, ΔE , for known superdeformed bands in Hg and Tl: ^{191}Tl [9], ^{193}Tl [10], ^{195}Tl [11], ^{191}Hg [12], ^{193}Hg [13], and ^{194}Hg [14].

not more than half that could be due to a deformation increase caused by the intruder orbital, $\nu j_{15/2}$. As with the systematic shown for normal-deformed bands in Fig. II.A.9.1, a deformation increase reduces the signature splitting of the “spectator” orbital. By comparison, the other two sets of bands in ^{194}Tl could be associated with one signature of $\pi i_{13/2} 5/2[642]$ coupled to the two signatures of the neutron $9/2[624]$ and $5/2[512]$ orbitals, since both of these have small ΔE in Hg nuclei (as discussed above).

This analysis of energy shifts between possible signature partners gives a suggestion of quasiparticle assignments that unfortunately cannot be checked currently by other means. The pattern of the moments of inertia is rather similar for the six observed cascades [15]. Eventually more measurements will give the details necessary to test the assignments suggested here.

The situation in ^{192}Tl is more complex. One association of the six newly observed bands produces three structures with energy shifts shown in Fig. II.A.9.4. As discussed by Liang et al. [16], an analysis of the moments of inertia of the six cascades suggest the set labeled 2 in our Fig. II.A.9.4 and called bands 3 and 4 there [16] should be assigned to $\nu j_{15/2} \pi i_{13/2}$ due to

Figure II.A.9.3: Energy shifts, ΔE , for known superdeformed bands in ^{194}Tl [15].

the unique flatness of the second moment as a function of frequency (double blocking of the expected crossing based on each of these orbitals). And this agrees with the trend discussed above, as the level of ΔE is reduced from the “expected” values for $\pi i_{13/2}$ (as in odd- A Tl) due to the deformation increase caused by the intruder orbital, $\nu j_{15/2}$.

The confusing aspects of ^{192}Tl correspond to the other structures labeled 1 and 3 in Fig. II.A.9.4. Using 600 keV as the point of comparison, these two structures have ΔE values *larger* than any measured in adjacent odd- A nuclei. If one associates these two bands with the couplings of $\pi i_{13/2}$ 5/2[642] with $\nu i_{11/2}$ 3/2[642], then it is difficult to explain such significant changes from the smaller ΔE values observed for each in adjacent nuclei. This would suggest a *decrease* in the deformation of the nucleus to produce an *increase* in the energy shifts in odd–odd ^{192}Tl . That would be difficult to understand, but the association of the cascades into strongly coupled bands is probably too premature to allow one to make strong conclusions from this.

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II.A.10. Lifetimes in ^{161}Lu Measured with Recoil Distance Method

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High spin states of ^{161}Lu are populated using the $^{120}\text{Sn}(^{45}\text{Sc},4n)^{161}\text{Lu}$ reaction with a 205 MeV ^{45}Sc beam provided by the Oak Ridge National Laboratory. A plunger was used to stop the recoils at various distances and the γ -rays were detected by the compact array of 20 Compton-suppressed Ge detectors. Gamma gamma coincidence events were taken at target-stopper

distances of 17, 30, 60, 85, 140, 210, and 320 micrometers. At each distance about 30 million double or higher fold events were accumulated.

Previously two rotational sequences were established [1] in ^{161}Lu , and high spin lifetimes in this nucleus were measured [2] with the DSAM technique. Large energy signature splitting was found in the low spin portion of the $\pi h_{11/2}$, $9/2[514]$ band. Similar splitting was also observed in the heavier lutetium isotopes and lighter $N = 90$ isotones. This phenomenon has been interpreted as the evidence for triaxiality and small quadrupole deformations occurring at low spin due to the occupation of an up-sloping $h_{11/2}$ proton. Among the known odd- Z $N = 90$ isotones, ^{161}Lu exhibits the largest energy signature splitting, and was predicted [3] to have the largest triaxiality and smallest quadrupole deformation. To verify this predication, absolute transition rates must be determined by lifetime measurements.

We measured lifetimes of lower-spin states in ^{161}Lu using the Recoil Distance Method with the above stated reaction. Doppler Shifted γ -ray peaks were measured in the four forward (45°) and four backward (135°) angle detectors. The remaining 12 detectors were used for setting gates. The large number of Ge detectors allowed us to obtain good statistics at each distance. As a result we were able to set gates above the transition of interest to obtain one-dimensional spectra for RDM analysis. This allows us to exclude side-feeding completely from the spectra, making the final results more accurate.

The obtained spectra are in the process of being analyzed with the RDM computer code at Oak Ridge National Lab. Fig. II.A.10.1 shows an example of the Doppler shifted γ -ray spectra (at a target-stopper distance of 85 micrometers) by gating on transitions above the states of interest.

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Figure II.A.10.1: Doppler shifted γ -ray peaks observed at forward and backward angles for the 605 keV, 673 keV and 658 keV transitions in the yrast band of ^{161}Lu . The spectrum is gated on a single transition above these three transitions.

II.B. Nuclear Structure and Reactions with Heavy Ions

II.B.1. Search for Diabolical Pair Transfer*

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This paper reports on the first experimental search for diabolical pair transfer in nuclear systems. While early calculations predicted measurable effects due to the presence of a diabolical point, later refinements made after the experiment was performed, have led to the conclusion that the effect of the diabolical point will be much smaller than first thought.

Using the system $^{156}\text{Gd} + ^{206}\text{Pb}$, nucleon-pair transfer was studied for both diabolical (^{154}Gd) and non-diabolical (^{158}Gd) cases and compared with a four-band calculations. Good agreement is obtained between the experimental results and the calculation. No clear evidence of diabolic pair transfer was seen within the sensitivity range of the experiment. The diabolical point between ^{156}Gd and ^{154}Gd is assumed to be close to angular momentum 18; thus probably there was insufficient inelastic excitation prior to the pair transfer to reach the backbending spin required to sense the sign of the interaction matrix elements around the diabolical point. However, the results of the present experiment suggest that the experimental method and theoretical calculations are adequate to observe the diabolical pair transfer if a lower spin diabolical point is studied.

* Summary of paper submitted to *Physical Review C*.

II.B.2. Anomalous Population of Excited States in Transfer Reactions with Very Heavy Ions*

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Total energy and multiplicities for γ -ray de-excitation following two-neutron pickup reactions on ^{164}Dy and ^{162}Dy targets with a ^{116}Sn beam yield two unexpected results. (1) There is a strong bias toward population of states at 2–4 MeV of excitation energy for the ^{164}Dy target relative to the ^{162}Dy target, and a smaller but still substantial bias in the 4–8 MeV range. (2) Within the total energy resolution of the Spin Spectrometer, there is evidence for strong bumps in the excitation energy in the range 2–6 MeV that are much more pronounced for the reaction with the ^{164}Dy target than for the ^{162}Dy target. These effects are illustrated in Fig. II.B.2.1 and Fig. II.B.2.2.

Figure II.B.2.1: Total energy spectrum for $^{164}\text{Dy}(^{116}\text{Sn}, ^{118}\text{Sn})^{162}\text{Dy}$.

Figure II.B.2.2: Total energy spectrum for $^{162}\text{Dy}(^{116}\text{Sn}, ^{118}\text{Sn})^{160}\text{Dy}$.

Calculations based on HFB and RPA methods suggest the possibility of such structure, but not the substantial differences observed between neutron numbers 98 and 96 for the deformed collision partner. We have discussed some starting points for possible theoretical explanations of the dramatic dependence on neutron number. New experiments have been proposed to extend the present observations, and we have indicated ways to test alternative theoretical descriptions of such experiments.

* Abstract of paper submitted to *Phys. Lett. B*.

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II.B.3. Possible Evidence for a Nuclear Josephson Effect*

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In this paper we have discussed possible evidence for a nuclear Josephson effect that could be provided by modern particle- γ coincidence techniques employing multidetector γ -ray arrays. In Fig. II.B.3.1 we display a representative Ge spectra in which known peaks of various transfer channels are marked. Discrete lines are observed corresponding to as many as six transferred particles. The peaks correspond to the ground-band $4^+ \rightarrow 2^+$ transition of the rare earth daughter transfer product.

In Fig. II.B.3.2 the total energy spectrum for these transfer channels, for inelastic scattering, and for one-neutron transfer on an adjacent odd-mass target are shown. Notice the pronounced shift of the population to very low excitation energy as the number of transferred particles is increased. This is the *opposite* behavior that one would expect from phase-space arguments, and suggests the presence of strong correlations at low excitation energy.

To summarize, the data suggest many of the features expected for a Josephson supercurrent:

1. We observe in Ni + Dy reactions at near-barrier energies peaks in the γ -ray spectrum that are at the correct energy (typically within a keV) for the $4^+ \rightarrow 2^+$ transition for the deformed daughter product in a variety of multinucleon transfer channels.
2. It appears possible to separate the contribution to these peaks from inelastic excitation of target contaminants by comparing the angular dis-

Figure II.B.3.1: Ge spectra indicating transitions in multiparticle transfer channels.

Figure II.B.3.2: Total energy spectra for inelastic scattering and for various transfer channels.

tribution of the proposed transfer peaks with that of Coulomb excitation of the target contaminants at forward angles.

3. The data analysis has been confined to scattering angles where the cross section is observed to be within 10% of Rutherford, the data have been gated on the quasielastic region from the time-of-flight information, and the data have been gated on detected neutron multiplicity zero. This should almost completely exclude large energy-loss collisions from the data set.
4. We observe a peaking of the total energy spectrum at low energies that becomes more pronounced as the number of transferred particles is increased. This peaking is a possible signature of strong pairing correlations in the low-lying states of the colliding ions. Careful investigation suggests that this peaking cannot all be accounted for by an incorrect background subtraction, or by an incorrect subtraction of inelastic excitation of target contaminants. A more bothersome possibility is that such peaking might be attributable to an incomplete separation of neutrons to the Spin Spectrometer total energy information. We cannot exclude this probability entirely with the present data set.

Thus, we suggest that the data presented here are compatible with a nuclear Josephson effect. We stop short of claiming proof because the present data set has low statistics and a limited number of cases. However, we believe that the tests we have applied must be satisfied if a Josephson effect exists, and that a more complete set of data on a variety of systems using the methods discussed here with the next generation of multidetector arrays will allow a definitive test of whether a nuclear Josephson effect exists and what its characteristics are.

* Summary of paper submitted to *Phys. Rev. C*.

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Figure II.B.4.1: Individual state probabilities for direct population in one and two-neutron pickup reactions, and for inelastic scattering reactions.

II.B.4. Probabilities for the Direct Population of High-Spin States in Transfer Reactions

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Probabilities are measured for directly populating the ^{160}Dy yrast band as high as the 18^+ state in one and two-neutron transfer reactions with very heavy ions. Examples are shown in Fig. II.B.4.1. Significant deviations from the corresponding probabilities for inelastic scattering are observed. The probabilities for two-particle transfer decrease rapidly with the angular momentum of the collective state populated in the Dy nucleus, contrary to expectations based on standard theories.

The technique demonstrated is a general one that allows a systematic study of such rotational excitation patterns in deformed nuclei. Theory suggests that such measurements could be indicators for important nuclear structure effects in the transfer reactions. For example, they could indicate angular localization on the deformed nuclear surface of orbitals participating in the transfer, or modification of pairing matrix elements by collective angular momentum.

* Brief summary of paper submitted to *Phys. Rev. C*.

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II.B.5. The Polarized Structure Function of the Nucleon in the Resonance Region*

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In this paper, we show how the Drell–Hearn–Gerasimov (DHG) sum rule in the real photon limit can be generalized to electroproduction, and related to the sum rules in the deep inelastic scattering. A general Q^2 dependence for the polarization function is discussed, particularly in the resonance region. The resonance $P_{33}(1232)$ plays a very important role in this region; in particular, it saturates the DHG sum rule for neutrons in the $SU(6) \supset O(3)$ basis. We show that the information from the polarized structure function in the low Q^2 region, where the baryon resonances play a dominant role, provides a very important probe of the spin-flavor structure of the nucleon.

* Abstract of paper in press, *Phys. Rev. D*.

II.B.6. First Symposium on Nuclear Physics in the Universe

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The *First Symposium on Nuclear Physics in the Universe* took place on Sept. 24–26, 1992, at the Oak Ridge Museum of Science and Energy; Mike Guidry and Mike Strayer were co-chairmen. It was jointly organized by ORNL, Drexel University, The University of Tennessee, Vanderbilt University, and Friedel Thielemann of the Harvard Smithsonian Center for Astrophysics. It is anticipated that this will be the first of a series of similar symposia to be held every two years that will serve as a forum to survey the field of nuclear astrophysics, to facilitate cross-disciplinary understanding among astrophysics, nuclear physics, and atomic physics, and to promote research of mutual interest in these fields.

Perhaps the most unique feature of the symposium was the gathering of over one hundred scientists from several distinct disciplines: astrophysicists, observational astronomers, and experimental and theoretical nuclear and atomic physicists. A central theme of the conference was the formation of the

elements, with the physics of supernova and related nuclear physics being the dominant topic. There were also significant talks on primordial element production and the physics implied in normal star evolution and the accompanying neutrino physics. Finally there were excursions into the gravitational n -body problem and the dark matter problems, and discussions of atomic and nuclear physics relevant to the interface between these disciplines and astrophysics. The conference proceedings are being readied for publication by Adam Hilger, Ltd.

**II.C. Study of Low-Energy
Levels of Nuclei Far
from Stability**

II.C.1. Study of Shape Coexistence in Odd-A Pb: Decay of Mass-Separated ^{199}Bi

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Shape coexistence in odd- A nuclei in the Pb region has been extensively studied from both an experimental and theoretical viewpoint [1]. Because the protons occupy levels near the $Z = 82$ closed shell and the neutrons occupy levels near the middle of the $N = 126$ shell, there is the possibility that nearly spherical and deformed states arising from the excitation of protons across the $N = 82$ shell can coexist at low energy in this region. In odd- A Pb isotopes, the $13/2^+$ deformed excited states arising from the coupling of the $i_{13/2}$ state to the deformed intruder bandhead have been found in $^{195,197}\text{Pb}$ [2, 3]. The goal of the present work was to compile a more complete decay scheme for ^{199}Bi to aid in the systematic study of odd- A Pb isotopes in this region.

The decay of ^{199}Bi was studied utilizing the University Isotope Separator at Oak Ridge (UNISOR) on-line to the Holifield Heavy-Ion Research Facility tandem accelerator. Ions of ^{199}Bi were produced by bombarding a 53 mg/cm² stack of Re foils with a 155-MeV ^{16}O beam and collected on a moving tape collector which moved the activity to a measurement station around which were placed three Ge γ -ray detectors and a Si electron detector. Multiscaled conversion electron and γ -ray singles data, as well as γ - γ and γ -electron coincidences, were collected.

From the data, a total of 286 transitions were attributed to the decay of ^{199}Bi , of which 149 transitions were placed in the level scheme. A total of 120 new transitions and 33 new levels were added to the previously adopted scheme. Since the ground-state spins of ^{199}Pb and ^{199}Bi are $3/2^-$ and $9/2^-$, respectively, the bulk of the decay proceeds to the first excited $5/2^-$ state. Previous studies revealed no ground-state transitions, but proposed instead an upper limit of 9.3 keV for the first excited state. We have deduced via the 1022.8 keV and 1034.0 keV gates and 1146.4 keV and 1157.5 keV gates, that each pair of these decay from the same state to both the ground and first excited states. The first set of these is shown in Fig. II.C.1.1. This establishes that the energy of the first excited state is 11.2 keV. The low energy portion of the level scheme is shown in Fig. II.C.1.2.

The electron singles and coincidence data allowed for the determination of 86 (47 new) conversion coefficients and the observation of transitions with enhanced $E0$ intensity, which is interpreted to be the signature of shape-

Figure II.C.1.1: Portion of coincidence spectrum gated on the 1034 and 1023 keV γ rays. Background has been subtracted.

coexistent states. We have observed a 1268.1 keV transition which decays to the 436.5 keV $13/2^+$ state, which is the first positive-parity excited state. The observed α_k value is 1.3 times larger than that expected for an $M1$ transition. Thus, the state at 1704.6 keV is proposed to be the deformed bandhead, which, as seen in Fig. II.C.1.3, fits well with the systematics of the neighboring Pb isotopes. Other $E0$ transitions suggest possible deformed states at 1573.9, 1754.4, and 1937.2 keV.

Figure II.C.1.4 shows level systematics of the deformed 0_2^+ states in even-even Pb nuclides along with the deformed $13/2^+$ states in odd- A Pb (including that proposed for ^{199}Pb). The systematic trend of increase in excitation energy as one moves away from mid-shell is observed for both the $2p-2h$ state and the single-particle state coupled to the $2p-2h$ state. This is consistent with the prediction that the energy of the “intruder” $2p-2h$ state decreases as the number of valance neutrons increases due to the $p-n$ interaction.

Figure II.C.1.2: Low-energy portion of the level scheme populated in the β decay of ^{199}Bi . Levels below 1.55 MeV are shown.

Using a simple deformed Nilsson potential:

$$V = -\kappa h\omega_0[2l \cdot s + (l_t^2 - \langle l_t^2 \rangle)]$$

and using standard values [4] for κ and ω_0 , we have calculated the excitation energies for the $i_{13/2}$, $f_{5/2}$, $p_{3/2}$, and $p_{1/2}$ states for odd- A Pb nuclides with $A = 193$ –205. As can be seen in Fig. II.C.1.5, there is good agreement between the experimental and calculated values. It is not quite understood, however, why the slope of the calculated $p_{1/2}$ levels is much greater than those experimentally observed. The calculations do reproduce the crossing of the $p_{1/2}$ and $f_{5/2}$ orbitals at $A = 205$, at which point the $p_{1/2}$ orbital becomes the ground state. The crossing of the $p_{3/2}$ and $f_{5/2}$ at $A = 199$ is also reproduced.

- [1] J. L. Wood et al., *Phys. Rept.* **215** 101 (1992).
- [2] J. C. Griffin et al., *Nucl. Phys.* **A531** 401 (1991).
- [3] J. Vanhorenbeeck et al., *Nucl. Phys.* **A531** 63 (1991).
- [4] T. Bengtsson and I. Ragnarsson, *Nucl. Phys.* **A436** 14 (1985).

Figure II.C.1.3: Portion of the level scheme observed in the decay of ^{199}Bi showing levels in relation to the nearly spherical $13/2_1$ level.

II.C.2. Re-investigation of the α Decay of ^{188}Pb

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Earlier work on the α decay of the light Pb isotopes has shown decay rates that are surprisingly high when compared with the rates for the decay of Hg isotopes [1]. Recent work from Leuven [2] reported an upper limit for the α -decay branch for ^{188}Pb that was lower than the values used in the earlier discussion [1]. Recently, an extensive dataset was taken on the decay of ^{188}Pb with the primary goal of finding superdeformed states in ^{188}Hg and ^{184}Hg [3]. We have reanalyzed the data to determine the α -decay branching ratio and also to examine α decay to excited states in ^{184}Hg .

In earlier work on the decay of $^{194,196,198}\text{Po}$, the α decay to the first excited 0^+ states of the respective Pb daughters was found to proceed with a high

Figure II.C.1.4: Energy systematics for the deformed 0_2^+ states in even-even Pb and deformed $13/2_2^+$ states in odd-A Pb nuclides. Energy values are relative to the lowest level with the same spin.

probability [4]. These first excited 0_2^+ levels in both Pb and Hg have been interpreted as two particle-two hole states that come low in excitation by having a deformation significantly different from the ground state. Thus, we also examined the data to see if the corresponding α decay to the 0_2^+ of ^{184}Hg is significant. Unfortunately, the first 2_1^+ of ^{184}Hg is too close to the 0_2^+ to enable complete separation of possible α peaks to these two levels, as indicated in Fig. II.C.2.1. However, we can establish an upper limit for the α -decay population of the 0_2^+ state.

The ^{188}Pb activity was produced by bombarding ^{180}W with a beam of ^{16}O from the Holifield Heavy Ion Research Facility. The mass 188 products were separated utilizing the UNISOR on-line separator and collected onto an automated tape-transport system. Every 50 seconds the collection spot was moved to a counting station equipped with a Ge(Li) γ -ray detector and a

Figure II.C.1.5: Experimental (solid) and calculated (dashed) energy levels for $i_{13/2}$, $f_{5/2}$, $p_{3/2}$, and $p_{1/2}$ states for odd- A Pb nuclides with $A = 193$ – 205 .

cooled Si(Li) electron detector. The Ge(Li) spectrum was used to search for γ rays and X-rays from the decay of ^{188}Pb , while the Si(Li) spectrum contained electrons and α particles from the source. Due to the very efficient production and separation of ^{188}Tl , the observation of γ rays from ^{188}Pb was difficult. Only two transitions were observed, and from systematics we conclude that they both proceed to the ground state of ^{188}Tl .

The rate of α decay was determined by measuring the number of α particles observed during the experiment. The detector was calibrated by assuming the efficiency for detection of α particles was the same as that for detection of electrons. The electron detection efficiency was determined by measurement of the number of K electrons observed for well-known $E2$ transitions in the spectrum and comparing this with the number expected based on the number of γ rays corresponding to the same transitions. The α -decay spectrum is shown in Fig. II.C.2.2 and reveals peaks due to the ground-state to ground-state tran-

Figure II.C.2.1: Schematic energy level diagram showing the possible α decays studied here and the transitions observed in the EC/β^+ decay of ^{188}Pb .

sitions from ^{188}Pb and the daughter ^{184}Hg . In addition, a peak is noted in the vicinity of the energy corresponding to decay of ^{188}Pb to the first excited 0^+ and 2^+ states, as indicated in the figure. The peak above the large peak is due to a drift problem during the experiment; unfortunately, this problem camouflages some of the observed fine structure, but it was taken into account in our analysis.

The rate of the EC/β^+ decay from ^{188}Pb is needed to calculate the α -decay branch. Two methods were used to obtain this rate: 1) add the intensities of γ rays proceeding to the ground state of ^{188}Tl and correct for the internal conversion of these transitions, 2) measure the number of K_α X-rays from Tl and relate these to the number of EC/β^+ decays. Since the second method requires corrections due to K -shell electron holes produced by internal conversion, it is obvious that the accuracy of both of these methods depends on knowing a rather complete decay scheme. However, the missing intensity

Figure II.C.2.2: Alpha-particle spectrum observed from the mass 188 sources. One peak results from the decay of the daughter, ^{188}Hg .

tends to decrease the calculated rate of EC/β^+ for method 1 while it increases the calculated rate from method 2. Thus, the two methods should result in upper and lower limits for the α branch deduced. From method 1 we deduce an upper limit for the α branch of $33 \pm 6\%$ and from method 2 a lower limit of $11 \pm 2\%$. These values can be compared with values of 15–22% from Ref. [1] and $\leq 10\%$ from Ref. [2].

The α counts in the vicinity of the expected peak for transitions to the

0_2^+ were corrected for the detector drift problem and assumed to be the upper limit on the number of such transitions detected. In this way, the upper bound for the α decay of the ground state of ^{188}Pb to the 0_2^+ was found to be $(9 \pm 2) \times 10^{-4}$ of the decay to the ground state. Using the prescription of Rasmussen [5], barrier penetrabilities were calculated and reduced widths (δ^2) deduced. From these we obtain the hindrance factor ($H.F.$) for population of the 0_2^+ as

$$H.F. = \frac{\delta^2(0_1^+)}{\delta^2(0_2^+)} \geq 23 \pm 3.$$

A recent preprint from Leuven [6] reported $H.F.$'s of 21(2) for the α decay to the 0_2^+ state and 37(7) for decay to the 2^+ state. Since we cannot separate the population of these two transitions (see Fig. II.C.2.2), we cannot compare our result directly with theirs. However, if we use their $H.F.$'s and calculate penetrabilities for $L = 0$ and $L = 2$ α -decay transitions, we conclude that approximately 1/4 of our intensity would be to the 2^+ state. With this assumption the hindrance factor for population of the 0_2^+ state would be about 31, which is slightly higher than the value reported in Ref. [6].

The hindrance factor for the α -decay population of the 0_2^+ state in ^{184}Hg is quite large compared to other known $0^+ \rightarrow 0^+$ transitions and is much larger than those for the corresponding transitions to the 0_2^+ of the Pb isotopes [4]. The large $H.F.$ for the population of the 0_2^+ in ^{184}Hg is a result of the fact that this level contains a large 2 particle-4 hole component in its wavefunction and thus it cannot be easily populated by the simple emission of an α (2 protons and 2 neutrons) from the closed shell nucleus ^{188}Pb .

- [1] K. S. Toth et al., *Phys. Rev. Lett.* **53** 1623 (1984).
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- [3] Y. A. Akovali et al., *Bull. Am. Phys. Soc.* **34** 1816 (1989).
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II.C.3. Search for the α Decay of ^{190}Hg and the α -Decay Branches of ^{186}Hg and ^{188}Hg

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In a discussion [1] of α -decay half-lives of even-even nuclei in the lead mass region it was noted that Hg isotopes appear to have decay rates that are slower than those of Pb nuclides. This result is unexpected since there should

be a hindrance effect of the $Z = 82$ closed shell on the Pb α -decay half-lives. We decided to provide additional data on the subject by re-measuring the α branching ratios of the two heaviest known Hg α emitters, namely ^{186}Hg and ^{188}Hg , since for each of these isotopes only one experimental determination of its α branch was available. As part of the investigation we also attempted to identify the α decay of ^{190}Hg .

Natural tungsten was bombarded with ^{12}C ions from the Holifield Heavy Ion Research Facility 25-MV tandem accelerator. Three bombarding energies were selected in turn to maximize yields for the Hg nuclides, and the UNISOR on-line isotope separator was used to mass separate reaction products. These were collected on a movable-tape system which was programmed to transport radioactivities to an array of α -particle and γ -ray detectors following a preset collection time. Collection and counting times were optimized for the half-life of the mercury nuclide being investigated. The Ge γ -ray detectors were calibrated for energy and absolute efficiency with an NBS standard Eu source while the Si(Au) α -particle detector was calibrated with ^{240}Pu and ^{244}Cm sources whose absolute disintegration rates were known.

Figure II.C.3.1 shows the α -particle spectra recorded at $A = 186$ [part (a)], $A = 188$ [part (b)], and $A = 190$ [part (c)]. For ^{186}Hg the intensities of the strong 112.1 and 251.5 keV γ rays were used together with the adopted [2] decay scheme to calculate the isotope's (EC+ β^+)-decay strength. By comparing this intensity with that of the 5094 keV α transition [see Fig. II.C.3.1(a)] the ^{186}Hg α branch was deduced to be 1.8×10^{-4} . This branch agrees with the previously available [2] value of 1.6×10^{-4} . For ^{188}Hg the most intense γ -ray transition (66.7 keV) is obscured by K X-rays and we are currently evaluating intensities for the other, much weaker, ^{188}Hg γ rays with which to determine the (EC+ β^+)-decay strength. In the meantime, based on the adopted [3] decay scheme, we converted our $K_{\alpha 1}$ and $K_{\beta 2}$ X-ray intensities to a number related to the ^{188}Hg (EC+ β^+)-decay strength. From this and the intensity of the 4610 keV α transition (see Fig. II.C.3.1(b)) we deduced a preliminary ^{188}Hg α branch of 4.2×10^{-7} that agrees with the available [3] value of 3.7×10^{-7} . In Fig. II.C.3.1(c) we indicate by an arrow the expected location of the ^{190}Hg α peak if its energy is indeed 4043 keV as predicted [4] from systematics. The $A = 190$ data were accumulated for two days but no α group was seen in the vicinity of that energy. The ^{190}Hg (EC+ β^+)-decay strength was determined based on the isotope's adopted [4] decay scheme and the intensity of its strongest γ ray, 142.6 keV. We then deduced an upper limit of 3.4×10^{-9} for the ^{190}Hg α branch by assuming that a peak with 5 counts

Figure II.C.3.1: Alpha-particle spectra recorded for mass-separated sources produced in $(^{12}\text{C} + ^{\text{nat}}\text{W})$ bombardments.

close to the predicted energy would have provided us with clear evidence for the α decay of ^{190}Hg . The previously available upper limit [4] is 5×10^{-7} .

- [1] K. S. Toth et al., *Phys. Rev. Lett.* **53** 1623 (1984).
- [2] R. B. Firestone, *Nucl. Data Sheets* **55** 583 (1988).
- [3] B. Singh, *Nucl. Data Sheets* **59** 133 (1990).
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II.C.4. Study of Platinum Nuclei with the ATLAS Fragment Mass Analyzer

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The fragment mass analyzer (FMA) [1] at the Argonne National Laboratory has recently undergone a series of commissioning tests using beams from the ATLAS facility. One such test involved the study of short-lived neutron-deficient α -emitting platinum isotopes produced in ^{32}S irradiations of ^{144}Sm . Following their traversal through the FMA, fusion reaction products were implanted in a Si(Au) detector placed behind a parallel plate avalanche counter (PPAC) located at the focal plane of the FMA. The subsequent α -particle decays of these recoils were then investigated, with spectra recorded during both bombarding and counting intervals. During the counting intervals a beam sweeper was used to deflect the ^{32}S ions off the ^{144}Sm target. The M/q resolution of the FMA was found to be about one part in 350. Excellent beam rejection was accomplished by means of a time-of-flight measurement between the PPAC and the surface barrier detector.

Two bombarding energies, 164 and 200 MeV, were used to emphasize the production of (^{173}Pt and ^{172}Pt) and of (^{171}Pt and ^{170}Pt), respectively. The half-lives of ^{173}Pt and ^{172}Pt were determined to be 290(60) ms and 110(20) ms in agreement with values adopted [2, 3] for the two isotopes. In Fig. II.C.4.1 we show the spectrum accumulated in the 200 MeV irradiations when the beam was both on and off the ^{144}Sm target. While the α peaks of ^{171}Pt and ^{170}Pt are clearly present in Fig. II.C.4.1, one sees the low cross sections encountered for these extremely proton-rich ($^{32}\text{S},5\text{n}$) and ($^{32}\text{S},6\text{n}$) reaction products. For ^{171}Pt half-lives of 40(10) ms and 20(6) ms have been reported [4]; our estimate of ~ 45 ms favors the first of these two values. In the case of ^{170}Pt , only three α -decay events were observed when the beam was deflected off the target. Since they were all registered in the first 10-ms time bin of the 80-ms counting

interval used in the $A = 171$ and $A = 170$ measurements, our results support the one available half-life determination [5] for ^{170}Pt , namely 6_{-2}^{+5} ms. We plan to have an experiment in the near future wherein the bombarding and counting times will be optimized to obtain a better half-life measurement for ^{170}Pt to improve our understanding of α -decay rates in this mass region.

- [1] C. N. Davids and J. D. Larson, *Nucl. Instrum. Methods* **B40/41** 1224 (1988).
- [2] V. S. Shirley, *Nucl. Data Sheets* **54** 589 (1988).
- [3] W. Gongqing, *Nucl. Data Sheets* **51** 577 (1987).
- [4] V. S. Shirley, *Nucl. Data Sheets* **43** 127 (1984).
- [5] S. Hofmann et al., *Z. Phys.* **A299** 281 (1981).

II.C.5. Alpha Decays of Light Uranium Isotopes

K. S. Toth, H. J. Kim, and J. W. McConnell [ORNL]; C. R. Bingham [UTK]; and D. C. Sousa [Eastern Kentucky]

With the use of a velocity filter, the α -particle decays of ^{224}U and ^{225}U were studied in ^{19}F bombardments of ^{209}Bi . The data obtained for these two isotopes are compared with those of previous investigators, and the α -decay rates of $^{222,224,226}\text{U}$ are discussed within the context of partial α half-lives for even-even nuclei with $Z \geq 84$. This work was recently published [1] and a reprint is included in the accompanying volume.

- [1] K. S. Toth et al., *Phys. Rev. C* **45** 856 (1992).

II.C.6. Search for Low-Spin Superdeformed States in Nuclei

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A number of collaborative efforts to locate the low-spin superdeformed levels in nuclei in the Hg-Tl-Pb-Po region are discussed briefly in this section. No new experiments were carried out during the last year, but some of the earlier data have been further analyzed and two publications [1, 2] have resulted. Copies of these are included in the accompanying bound set of reprints and preprints.

Figure II.C.4.1: Alpha-particle spectrum of reaction products implanted in a Si(Au) detector following their traversal through the ATLAS fragment mass analyzer.

Although much information is available on superdeformed (SD) states at high spin in nuclei (for a summary see Ref. [3]), except for the fission isomers in the actinide region, low-spin SD states have not been observed. Efforts have been made to locate these levels in a number of Hg and Tl nuclei through population via radioactive decay. To date we have not obtained evidence that the SD states are indeed populated via decay; we have established upper limits for the branch of the decay going to known SD states in ^{194}Pb [1].

During the past year we have formed a collaboration to make yet another search for low-spin SD states in nuclei below mass 200 utilizing the radioactive isotope separator facility (ISOLDE) at CERN. It is our contention that the SD bands observed in-beam extend to lower spins in the higher mass part of the mass 190 region. For example, in ^{194}Pb the SD band is known down to the 6^+ level, whereas for the Hg SD bands the lowest known level has a spin of ~ 10 . Calculations [4] shown in Fig. II.C.6.1 reveal that the SD minimum in the potential energy curves is somewhat deeper as one goes toward the higher mass isotopes, thus making the probability of population of low-spin states trapped in these minima larger for the higher mass ones. We propose to search for low-spin SD states in ^{198}Po and/or ^{194}Pb in an ISOLDE experiment. The proposal was presented to the SPSC PAC in March, 1992 and was granted provisional approval, contingent on some preliminary tests to confirm that the facility is indeed suitable for carrying out the experiment.

- [1] M. A. Stoyer et al., *Phys. Rev. C* (accepted for publication).
- [2] C. R. Bingham et al., *Nucl. Inst. Meth. Phys. Res.* (accepted for publication).
- [3] X.-L. Han and C.-L. Wu, *At. Data and Nucl. Data Tables* **52** 43 (1992).
- [4] W. Satula et al., *Nucl. Phys.* **A529** 289 (1991).

II.C.7. Nuclear Magnetic Dipole and Electric Quadrupole Moments of ^{187}Tl from Laser Spectroscopy and their Interpretation in the Strutinsky and Particle-Plus-Rotor Models

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Collinear laser spectroscopy in ^{187}Tl has been carried out at the UNISOR separator at Oak Ridge. Heavy-ion produced neutral isotopes were excited from the metastable $4p\ ^2P_{3/2}$ level populated in a charge-exchange reaction with Na. The excitation at $\lambda = 535\text{ nm}$ to the $7s\ ^2S_{1/2}$ level, using Doppler tuning, is followed by the radiative decay to the Tl ground state via a $\lambda = 377\text{ nm}$ transition. This transition is observed using a fiber optics light

Figure II.C.6.1: Potential energy curves versus β_2 deformation for even-even Hg, Pb, and Po Isotopes, calculated by Satula, et al. [4]

collection system. The signal of ^{187}Tl was observed during a run using ion beam intensities on the order of 8×10^4 ions/s. The hyperfine constants, the isomer shift, as well as the moments and the change in mean-square charge radius between the $I = 1/2$ and $I = 9/2$ states for ^{187}Tl , as extracted from the data, are listed in Table II.C.7.1.

A comparison of the results with those obtained for the heavier odd-Tl isotopes shows that the nuclear moments show little variation with mass number. A slight decrease from $\mu = 3.91(1)\mu_N$ for $A = 193$ to $\mu = 3.79(2)\mu_N$ for $A = 187$ is observed for the magnetic moments of the $I = 9/2$ states whereas those for the $I = 1/2$ states are constant within the experimental error between $A = 201$ and $A = 187$ ($\mu \approx 1.59\mu_N$). The values of the Q_s increase slowly between $Q_s = 2.20(2)\text{b}$ at $A = 193$ and $Q_s = 2.43(5)\text{b}$ at $A = 187$. We have carried out particle-triaxial-rotor (PTR-WS) and mean-field calculations, yielding Total Routhian Surfaces (TRS), for finding the deformation of ^{187}Tl . These calculations were able to successfully describe systematics in isotopic shape variations in the neighboring Pt, Au and Hg isotopes. TRS's were calculated using the deformed mean-field approach with a Woods-Saxon potential, a Strutinsky shell correction, and a monopole pairing force. The ground-state deformation parameters from the TRS calculations served as input to the subsequent PTR-WS calculation to obtain more detailed spectroscopic properties. (Both methods employ identical Woods-Saxon potentials.)

Minima in the Total Routhian Surfaces at oblate deformations of $|\beta| = 0.074$ ($1/2^+$) and $|\beta| = 0.158$ ($9/2^-$) are observed. The latter value is in good agreement with the deformation found from our experimental Q_s using the strong coupling scheme ($\beta = 0.15$) justified for isotopes with oblate shape for $Z = 81$. The difference in deformation between the ground and the metastable states indicated from the TRS's ($\delta\beta^2 = 0.019$) is somewhat larger than the $\delta\beta^2 = 0.012$ found from the isomer shift using the relation $\delta < r^2 >_{\text{def}} = 3/5R^2(5/4\pi)\delta\beta^2$, where $R = 1.2A^{1/3}$. The moments calculated in the PTR-WS approach with the PTR parameters as an input, as well as the values obtained after optimization of the deformation parameters, are included in Table II.C.7.1. The moments are already well reproduced (within $\approx 10\%$) with the deformation parameters taken directly from the TRS calculations. Slight adjustments of the parameters increase the agreement further. For the $I = 1/2$ state, an increase of β to 0.1, required to fit the magnetic moment, leads to a $\delta\beta^2$ of 0.015.

In summary, the moments of ^{187}Tl are not distinctly different from those of the heavier odd isotopes. They are well explained by the TRS and PTR-WS

Table II.C.7.1: Hyperfine parameters, moments and deformation parameters for ^{187}Tl . The code letters in the second column refer to (a) experimental values, (b) results from PTR-WS calculations with deformation parameters from the Total Routhian Surfaces, and (c) results from PTR-WS calculations after optimization.

I^π	C	$A(^2S_{1/2})$ [GHz]	$A(^2P_{3/2})$ [MHz]	$B(^2P_{3/2})$ [GHz]	μ [μ_N]	Q_s [b]	β_2	β_4	γ
$1/2^+$	a	11.7(5)	253(9)		1.55(6)				
	b				1.74		0.074	-0.005	57°
	c				1.57		0.10	-0.005	60°
$9/2^-$	a	3.163(5)	64(2)	-2.71(2)	3.79(2)	-2.43(5)			
	b				3.30	-2.27	0.16	-0.004	50°
	c				3.57	-2.49	0.16	0.07	60°

calculations that assume oblate shape with very moderate deformation.

II.C.8. Lifetimes of the 0_2^+ Configuration in ^{186}Hg and ^{188}Hg

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Coexisting bands of quite different deformations in $^{184,186,188}\text{Hg}$ have been known for some time from in-beam reaction [1, 2] and radioactive decay [3, 4] studies. The latter work also observed electric monopole ($E0$) transitions in these neutron-deficient Hg isotopes and precipitated the evolution of this region into a classic example of widely-occurring, nearly degenerate, nuclear shape coexistence. A direct measure of the mixing of coexisting shapes in even-even nuclei is the $E0$ strength between the intruder state and the ground state [5]. Changes in the nuclear radius lead to non-vanishing values for the monopole strength function, $\rho(E0)$; to measure $\rho(E0)$ experimentally, all that is needed is a measurement of the partial half-life of the level. These Hg isotopes present a unique challenge to the measurement of lifetimes in the picosecond range since the complexity of the decay demands a triple coincidence.

A lifetime measurement system developed at UNISOR [6] was used to mea-

Table II.C.8.1: Lifetimes and Monopole Strength Parameters

Nucleus	$E(0_2^+)$ keV	$T_{(1/2)}(0_2^+)$ ps	$E0$ branch	$T_{(1/2)p}(0_2^+)$ ps	$\sigma^2(E0)$ $\times 10^3$	V_0 keV	$E(2_2^+)$ keV	$T_{1/2}(2_2^+)$ ps
^{188}Hg	824	288 ± 63	$\geq 58\%$	288^{+207}_{-63}	$5.5^{+1.5}_{-2.3}$	73^{+9}_{-18}	881	199 ± 44
^{186}Hg	523	≥ 52	$\geq 72\%$	≤ 72	≥ 32	≥ 111	620	66 ± 37

sure the lifetimes of the 0_2^+ configurations in ^{186}Hg and ^{188}Hg . For ^{186}Hg , the $(\beta^+-X)-e^-$ triple coincidence, where X represents the X-ray following internal conversion of the associated e^- , was used to determine the lifetime of the 0_2^+ state. This unique system has been thoroughly described in Ref. [7]. The lifetime for the 0_2^+ level in ^{188}Hg was measured using the triple coincidence $(X-X)-e^-$, where the first X represents the K X-ray following the electron capture and the second is the same as above. The associated 2_2^+ -level lifetimes are determined in a similar manner. The mixing matrix element V_0 , calculated using the formalism of Kantele [8] are 73^{+9}_{-18} keV for the level in ^{188}Hg and ≥ 111 keV for the level in ^{186}Hg . These results are presented in Table II.C.8.1.

- [1] N. Rud, D. Ward, H. R. Andrews, R. L. Graham and J. S. Geiger, *Phys. Rev. Lett.* **31** 1421 (1973).
- [2] D. Protel, R. M. Diamond and F. S. Stephens, *Phys. Rev. Lett. B* **102** (1974).
- [3] J. H. Hamilton et al., *Phys. Rev. Lett.* **35** 562 (1975).
- [4] J. D. Cole et al., *Phys. Rev. Lett.* **37** 1185 (1976).
- [5] K. Heyde and R. A. Meyer, *Phys. Rev. C* **37** 2170 (1988).
- [6] P. K. Joshi et al., *Nucl. Instrum. Methods Phys. Res.* (submitted).
- [7] J. Kantele, *Nucl. Instrum. Methods Phys. Res.* **A271** 625 (1988).
- [8] J. Kantele, *Heavy Ions and Nuclear Structure*, Harwood Academic Pub. (1984) 391.

II.C.9. Spins and Magnetic Dipole Moments of New Isomers in ^{184}Au by Time Integral and Time Resolved Nuclear Orientation

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The existence of isomerism in ^{184}Au has been established in on-line studies at the NICOLE facility, ISOLDE, CERN, and confirmed in a previous UNISOR experiment. The detection of a highly converted $M3$ transition of 68 keV indicates that, provided no other transition is involved in the isomeric decay,

the two levels involved have the same parity and a spin difference of three. Low temperature nuclear orientation studies have been made at NICOLE in an attempt to learn the spins and moments of the long-lived states, but these efforts were hampered by the fact that there was no direct Au beam at ISOLDE so the activity was produced following implantation of ^{184}Hg ($t_{1/2} = 30.6$ s). The decay of ^{184}Au is complex, as revealed by a previous detailed study [1] at UNISOR. Many levels in the daughter ^{184}Pt are fed indirectly through both isomer and ground-state decay, making it difficult to extract information concerning the individual hyperfine interactions of the parents.

In the current study we have used the direct UNISOR ^{184}Au beam produced by the reaction of ^{12}C on ^{181}Ta at 150 MeV. It is known that the production ratio of the two long-lived states in this reaction differs from the ratio obtained from the Hg decay.

The experiment was divided into three sections. In the first, ^{184}Au activity implanted into a prepared iron foil was oriented at temperatures down to 14.5 mK. Accurate anisotropy measurements were made on all transitions in the combined decay of the low- and high-spin isomers of ^{184}Au . Taking advantage of the detailed decay scheme study done at UNISOR, these measurements will yield level spin and gamma transition properties in the daughter ^{184}Pt as well as helping to establish the hyperfine interactions of the long-lived orienting states.

The second stage of the experiment saw the first use at UNISOR of the pulsed beam implantation method known as Time Resolved On-Line Nuclear Orientation (TR-OLNO) [2] to observe the growth of orientation of the ^{184}Au activity as the nuclei relax, cooling to the Fe foil lattice temperature through the Korringa conduction electron relaxation mechanism. The relaxation time is a sensitive measure of the nuclear g -factor and, taken together with conventional orientation, can yield both the spin and moment of the oriented state. The activity was pulsed using a controlled beam stopper in the focal plane of the separator to give implantation for a period of 40 s followed by relaxation and decay for 216 s, the operation being repeated cyclically. Spectra taken during each of 32 successive 6-s time frames were added in successive cycles to allow observation of the growth of the anisotropy with good statistical quality. Data were taken with the dilution refrigerator at 16.7 mK and also at 1 Kelvin, the latter to study the decay of unoriented activity.

Finally, measurements were made on the spectroscopy beam line to improve knowledge of the half-lives of the long-lived states in ^{184}Au and to rule out the presence of additional isomers, which would be revealed only through

Figure II.C.9.1: Time resolved nuclear orientation of the ^{184}Au 363 keV transition.

the detection of highly converted low-energy transitions.

The data are still being analyzed in detail. Provisional TR-OLNO results, giving clear evidence for relaxation in ^{184}Au , are shown in Fig. II.C.9.1.

[1] Y. Xu et al., ORNL Progress Report 1992.

[2] N. J. Stone, *Nucl. Instrum. Methods Phys. Res.* **B70** 556 (1992).

II.C.10. Nuclear Orientation of ^{113}Sb

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Using the technique of On-Line Nuclear Orientation (OLNO), we have attempted to measure the magnetic dipole moment of the $5/2^+$ ground state of ^{113}Sb at the UNISOR/NOF. This was accomplished by depositing beam

from the UNISOR mass separator into an Fe foil soldered to the cold finger of the UNISOR/NOF $^3\text{He}/^4\text{He}$ isotope dilution refrigerator. By varying the temperature and observing the resulting anisotropy, it is possible to extract the moment from a fit of the data.

Four Ge γ -ray detectors were placed at the four 90-degree positions outside the refrigerator cryostat. In addition, two plastic scintillator detectors were placed in front of the 0° and 180° γ detectors to measure the anisotropy of positrons emitted in the decay of ^{113}Sb . Data were collected at warm (> 100 mK) and cold temperatures, including one data set in which the beam was shut off and the baffle to the beam closed to allow for an even colder temperature to be achieved. The direction of the applied magnetic field was also reversed at one point during the experiment.

Because of the low cross section for production of ^{113}Sb only the two strongest γ rays, the 332 and 498 keV, could be analyzed and poor statistics yielded anisotropies with large errors. In all, only three temperature points for the 332 keV line and four points for the 498 keV line were calculated. Fits were then attempted of these anisotropy versus temperature data. Using the tables of Krane [1] and Shaw and Stone [2] and mixing ratios recently measured via the $(\alpha, 2n\gamma)$ reaction [3], the values for Q_k , U_k , and A_k were determined and used as the input to the fitting program. The fits resulted in a value of the dipole moment of 1.7 n.m., which is roughly half the expected value of 3.5 n.m. for a $d_{5/2}$ proton in this region. However, the large errors in the data points combined with uncertainties in the level scheme could account for such a discrepancy.

The advantage of measuring β^+ anisotropies is that the odd B_k terms can be determined. This is important because of the larger sensitivity of these terms to differences in temperature and because of their ability to determine the sign of the moment (which is impossible in γ -ray measurements). Figure II.C.10.1 shows the anisotropy of the positrons as a function of spectrum number (each spectrum represents a 10 minute count). Because of the relationship between the observed positron anisotropy and the direction of the hyperfine field that interacts with the moment, it is possible to conclude that the sign of the moment is positive. The field reversal and subsequent change in direction of the anisotropy serves as a check of the system. This positive sign of the moment is consistent with that for a $d_{5/2}$ proton.

Further analysis of the β anisotropy data is currently in progress. Although apparently only two or three temperature points are available, it may be possible to set a limit on the value of the moment by comparing the exper-

Figure II.C.10.1: Plot of positron anisotropy vs. run number (representing 10 minute counts) for the decay of ^{113}Sb .

imental data to anisotropies predicted by theory for various moment values.

- [1] K. S. Krane, *Tables of Coefficients for Analysis of Angular Distribution of Gamma radiation from Oriented Nuclei*, Los Alamos Scientific Report LA-4677 (1971).
- [2] T. L. Shaw and N. J. Stone, *Atomic Data and Nuclear Data Tables* **42** 189 (1989).
- [3] I. N. Vishnevskii, Y. N. Lobach, I. A. Malyuk, I. P. Tkachuk, V. V. Trishin, and R. M. Shevaga, *Izvest. Ak. Nauk SSSR, Ser. Fiz.* **55** 2166 (1991).

II.C.11. Determination of Signs of Nuclear Moments by Beta Asymmetry Measurements

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We have recently applied the measurement of β^+ asymmetries to determine the signs of the magnetic moments of the ground states of ^{114}Sb and ^{116}Sb . Using the UNISOR/NOF, plastic scintillator detectors were placed outside the cryostat at 0° and 180° relative to the applied magnetic field, in a manner as described above. The anisotropies observed in the decay of these nuclei allowed for the assignment of a positive moment, consistent with the suggestion that these states are members of the $\pi d_{5/2}\nu s_{1/2}$ configuration [1]. Furthermore, comparison of the data with theoretically determined curves of anisotropy versus temperature for a moment value of 2.71 n.m. confirms the previous measurement for the magnetic moment of ^{116}Sb [2].

[1] B. E. Zimmerman et al., *Hyper. Int.* **75** 117 (1992).

[2] V. R. Green et al., *Phys. Lett.* **B177** 159 (1986).

II.C.12. Nuclear Orientation and Spin-Lattice Relaxation in ^{116}Sb

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The phenomenon of spin-lattice relaxation (SLR) is of great importance when dealing with the on-line nuclear orientation (OLNO) of very short-lived nuclei. In such experiments, nuclei are implanted with energies of several keV into a collection foil which is maintained at some cold (below 100 mK) temperature. The nuclei are generally not in thermal equilibrium with the collection foil and it is necessary for the nuclei to exchange energy with the foil lattice ("relax") in order to attain equilibrium. The time required for this to occur is the spin-lattice relaxation time. Since the angular distribution function

$$W(\theta) = \sum_{k=\text{even}} B_k U_k A_k Q_k P_k(\cos\theta)$$

depends on the populations of the magnetic sublevels through the B_k coefficients, any attenuation in the populations caused by incomplete relaxation

prior to decay of the oriented state will result in an attenuation in the angular distribution. This will result in erroneous values of the magnetic dipole moment, which can be extracted from anisotropy data.

The Corringa Law, which relates the SLR time (τ_{SLR}) to the lattice temperature (T_L) and the Corringa constant (C_k) for the experimental conditions under which such experiments are conducted is given by [1]

$$\tau_{\text{SLR}} = \frac{4C_k}{3T_L}$$

and is valid when the lattice temperature is greater than the interaction temperature (defined by the splitting of the magnetic sublevels by a magnetic field). In order to test this relationship, the odd-odd nucleus ^{116}Sb was oriented via OLNO. Since the moment was previously measured by NMR [2] (a technique not influenced by SLR) and the level scheme well established, an accurate theoretical curve of anisotropy as a function of temperature without accounting for SLR could be calculated and compared to one obtained from experiment.

Based on the lifetime and magnitude of the dipole moment, the expected attenuation in the orientation for ^{116}Sb should be on the order of less than 25%. Thus, the Corringa Law is confirmed if only a small deviation between the experimental data and the theoretical curve is observed. We oriented ^{116}Sb on-line by depositing beam from the UNISOR mass separator into an Fe target mounted to the cold finger of the UNISOR/NOF $^3\text{He}/^4\text{He}$ isotope dilution refrigerator. The temperature was varied by adding small amounts of heat to the refrigerator mixing chamber. Four temperature points were obtained during the experiment and were normalized to warm (above 100 mK) data.

Figure II.C.12.1 shows this curve along with the experimental data; as can be seen, there is good agreement within experimental limitations. One such limitation is an error in the calculated temperature due to a problem with the thermometer, which could cause a shift in the data along the x axis. In general, however, the Corringa Law has been demonstrated to give a reasonable description in this particular case.

- [1] E. Klein, in *Low Temperature Nuclear Orientation* (ed. by N. J. Stone and H. Postma), North-Holland, Amsterdam, 1986.
- [2] V. R. Green et al., *Phys. Lett.* **B177** 159 (1986).

Figure II.C.12.1: Plot of anisotropy vs. $1/T$ for the 1293 keV γ ray observed in the decay of ^{116}Sb . The dashed curve represents calculated anisotropies without accounting for SLR.

II.C.13. Decay of Mass-Separated ^{114}Te

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Recent systematic investigations of light odd-odd Sb nuclei [1, 2, 3] have been successful in extending or improving their level schemes and has facilitated identification of members of many of the proton-neutron multiplets which arise from the coupling of the odd proton and neutron in these nuclei. To aid in extending this study, we have investigated the structure of energy levels populated in the β/EC decay of ^{114}Te ($t_{1/2} = 15$ m) using the mass separator at UNISOR.

Products of the reaction of 230 MeV ^{32}S on a ^{92}Mo target were separated by mass and deposited in a mylar tape which could be moved sequentially to two shielded counting stations. Multiscaled γ singles, normal electron singles, and γ - γ and electron- γ coincidences were collected. These data, together with those collected from a recent experiment at Debrecen using the $(p,n\gamma)$ reaction, allowed for the assignment of many new transitions, internal conversion

coefficients, levels, and spins.

Figure II.C.13.1 shows the low-energy portion of the present level scheme. Although the analysis is still in progress, it is possible to assign configurations to some of the lower-lying levels. In particular, the 3^+ ground state has been shown by a magnetic dipole measurement [4] to be a mixture of the $\pi d_{5/2}\nu s_{1/2}$ and $\pi d_{5/2}\nu g_{7/2}$ configurations, with the level at 27.5 keV possibly being the other member of the $\pi d_{5/2}\nu s_{1/2}$ doublet. Although the spin assignment is not yet definite, the most likely candidate for the 1^+ member of the $\pi d_{5/2}\nu d_{3/2}$ multiplet is the level at 46.0 keV.

Calculations are currently being carried out using the odd-odd Truncated Quadrupole Phonon Model (OTQM) of Paar, which is identical to the Interacting Boson-Fermion-Fermion Model (IBFFM).

- [1] Z. Gacsi, T. Feynes, Z. Dombradi, S. Brant, and V. Paar, *Phys. Rev. C* **44** 642 (1991).
- [2] J. Gulyas et al., *Phys. Rev. C* **46** 1218 (1992).
- [3] T. Feynes and Z. Dombradi, *Phys. Lett. B* **275** 7 (1992).
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II.C.14. Lifetime Measurements in $^{118,120}\text{Xe}$: Non-Saturation of $B(E2)$ Strength in Mid-Shell Xe Isotopes

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The experimental electromagnetic transition rate between the ground state and the first excited 2^+ state in the even-even Xe isotopes below $N = 82$ appears to saturate [1] as mid-shell neutron number is approached. This saturation effect has been considered a result of the filling of neutron orbitals [2] which contribute very little to the total quadrupole moment. It has also been reproduced in the IBM-2 through the introduction of Pauli factors [3] into the operators of the IBM-2 Hamiltonian. More recent measurements using the Recoil Distance Doppler Shift (RDDS) technique employing Differential Decay Curve Analysis [4] have determined the mean lifetime of the levels in $^{120,122,124}\text{Xe}$ to be shorter than that reported [1], suggesting there is no saturation of $B(E2)$ values at mid-shell.

We have measured the lifetimes for levels in $^{118,120}\text{Xe}$ populated through the β^+/EC decay of $^{118,120}\text{Cs}$ produced at the Holifield Heavy Ion Research Facility. The major motivation for these new measurements was the employment of a different experimental technique to determine the lifetimes for the

Figure II.C.13.1: Low-energy (levels below 800 keV) portion of level scheme observed in the decay of 15 m ^{114}Te . The log ft values were only calculated for levels receiving more than 5% of the total decay feeding.

first 2^+ level in these nuclides, and to attempt to resolve the discrepancy in the RDDS lifetime measurements [1] for the level in ^{120}Xe .

Samples of $^{118,120}\text{Cs}$ were produced as recoils from the heavy-ion reaction between a ^{92}Mo target and a 175-MeV ^{32}S beam. Data were collected using the new UNISOR picosecond lifetime system. The system is composed of a 0.3 cm thick NE-111A plastic scintillator $\Delta E\beta$ detector mounted on a Philips XP-2020 photomultiplier tube (PMT) and a 1.3 cm thick conical BaF_2 crystal

mounted on a Philips XP-2020Q PMT for γ detection [4]. These detectors were placed face-to-face in vertical positions relative to the beam line. Two Ge detectors were also incorporated into the system, and were placed face-to-face in horizontal positions.

Shown in Fig. II.C.14.1 are the time-to-amplitude conversion (TAC) spectra for coincidences between β rays and the 322 keV 2_1^+ to 0_1^+ transition in ^{120}Xe , and for coincidences between β rays and the 338 keV 2_1^+ to 0_1^+ transition in ^{118}Xe . The resulting lifetimes were determined using the centroid shift method, where the reference “prompt” TAC’s were constructed by gating on the region of the BaF_2 γ -ray spectrum just above the full-energy peak of interest. The use of a background gate as the reference TAC ensures that Compton events from higher energy γ rays will not influence the lifetime measurement. Since there is no dependence of the centroid position on γ -ray energy in the BaF_2 detector for the energy region from 250 to 700 keV, as determined from prompt curve calibration measurements using ^{24}Na , the difference in the centroid position of the full-peak and background gates directly yields the lifetimes of the 2_1^+ levels for $^{118,120}\text{Xe}$.

The lifetimes for the first 2^+ level in these nuclides were determined to be 63 ± 6 and 64 ± 4 ps for ^{118}Xe and ^{120}Xe , respectively. Although the result presented here for the lifetime of the level in ^{118}Xe agrees with the adopted lifetime value [1], the lifetime value for the same level in ^{120}Xe is nearly a factor of two lower than the adopted value. The result for ^{120}Xe , however, is within the error limit of the most recent RDDS measurement by the Cologne group [4], who have reported a lifetime value of 75 ± 7 ps for the first excited 2^+ state in ^{120}Xe .

The resulting values for $B(E2; 0_1^+ \rightarrow 2_1^+)$ are shown in Fig. II.C.14.2 for the new measurements and also for previous measurements that are given in Ref. [1]. The $B(E2) \uparrow$ presented here for the lifetime of the 2_1^+ level in ^{118}Xe agrees with the adopted value [1]; however, the $B(E2) \uparrow$ value for the same level in ^{120}Xe is nearly a factor of two lower than the adopted value. Our new results for ^{120}Xe , however, are within the experimental uncertainty of the most recent RDDS measurement by the Cologne group [4], which is also shown in Fig. II.C.14.2.

Our new measurements, along with the most recent measurements from the Cologne group, suggest that there is no saturation of $B(E2; 0_1^+ \rightarrow 2_1^+)$ for the mid-shell Xe isotopes. To the contrary, these new $B(E2) \uparrow$ data imply that there is a steady increase until mid-shell neutron number is reached, after which the $B(E2) \uparrow$ values begin to decrease. This is clearly illustrated in

Figure II.C.14.1: Delayed and prompt TAC spectra for the measurement of the centroid shift for the 2_1^+ to 0_1^+ transitions in (a) ^{118}Xe and (b) ^{120}Xe .

Figure II.C.14.2: Most recent experimental $B(E2)^\dagger$ values for the Xe isotopes below $N = 82$ compared to recent theoretical calculations predicting saturation at mid-shell.

Fig. II.C.14.2. This is in agreement with the isotope shift data [5] available for the Xe isotopes below the $N = 82$ closed shell where the observed shift is linearly dependent on neutron number at least through $N = 68$. Since the occupation of the relatively “flat” Nilsson orbitals by neutron numbers $64 \leq N \leq 70$ does not allow for a large increase in the $B(E2)$ values for the Xe isotopes around mid-shell neutron number [2], it may prove important to consider the contribution from the proton $[404]9/2$ Nilsson orbital. This is a strongly up-sloping Nilsson orbital, which is indeed close to the Fermi surface for the mid-shell nuclides in this mass region (where $\beta \geq 0.25$), as reflected in the ground-state intruder character of the odd- Z nuclides ^{119}Cs .

Discussions of this topic with A. Dewald, S. Raman, W. Nazarewicz and I. Hammamoto are gratefully acknowledged.

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II.C.15. Magnetic Moment Measurements in Mirror Nuclei

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We have recently joined a collaboration headed by N. Benczer-Koller [Rutgers] aimed at measuring nuclear dipole moments of ground and excited states of mirror nuclei in the $f_{7/2}$ shell. These measurements are to be carried out at the Argonne Fragment Mass Analyzer (FMA) by NMR applied to nuclei polarized by passage through thin tilted foils.

The first part of this program was to test the production rates of the nuclei to be studied, namely ^{43}Ti and ^{45}V . Using the $^{12}\text{C}(^{32}\text{S},n)^{43}\text{Ti}$ and $^{12}\text{C}(^{35}\text{Cl},2n)^{45}\text{V}$ reactions, the challenge was to see how well the FMA could separate the products of a highly inverted reaction from the primary beam. Such separation is required due to the delicate nature of the tilted foils. The run was successful, indicating that production rates of 2000 cpm could be maintained in the detectors to be used in the experiment with excellent rejection of the primary beam.

The next part of the project will deal with the development of the apparatus (tilted foil chamber, beam line, stopper, etc.) and subsequent polarization of the nuclei to determine if a large enough effect can be achieved. The final part will consist of destruction of the polarization by NMR to determine the moment if a large enough polarization is observed.

II.D. High Energy Heavy-Ion Physics

II.D.1. Transverse Energy and Forward Energy Production in a High-Energy Nuclear Collision Model¹

J.-Y. Zhang, X. He, C. C. Shih, S. P. Sorensen, and C.-Y. Wong [ORNL]

Distributions of transverse energy, forward energy, and $dE_T/d\eta$ from 60A GeV and 200A GeV ^{16}O -induced and 200A GeV ^{32}S -induced nuclear collisions with Al, Cu, Ag, and Au are calculated by a high-energy nuclear collision model and compared to recent experimental data from the WA80 Collaboration at CERN. The high-energy nuclear collision Monte Carlo model, which is based on the concept of independent multiple nucleon–nucleon collisions, describes the experimental data well at forward rapidity and mid-rapidity.

¹ Abstract of published paper: *Phys. Rev. C* **46**, 748 (1992).

II.D.2. Hadronic Model for the Space–Time Development of High-Energy Nuclear Collisions

S. P. Sorensen and W.-Q. Chao*

Since 1986 the UT Nuclear Physics Group has, as part of the CERN WA80 collaboration, accumulated a large amount of calorimeter data from high-energy nuclear collisions. Most of these data have now been analyzed and published. In an attempt to better understand the physics underlying the data, we have started a theoretical attempt to model the space–time development of high-energy nuclear collisions. The emphasis in the model has been put on investigating how much information about the attained energy densities can be obtained from the available data on transverse and forward energy.

The model is based on a completely hadronic scenario in which the energy lost in the binary collisions between the initial nucleons is used to generate pions with transverse momentum p_T and rapidity distributions obtained from free nucleon–nucleon collisions. The pions emerge after a formation time τ_0 in their own rest frame. The subsequent rescattering between nucleons and pions is treated with special care by a novel method, which is Lorentz-frame independent.

We find that the maximal energy density at SPS energies [$\sqrt{s} < 20$ GeV] is 30–50% smaller than predicted by use of the Bjorken formula. This is caused by the finite collision time of approximately 1 fm/c, which is comparable to the formation time. At RHIC energies the collision time will be much smaller, and the energy densities will be closer to the Bjorken model predictions. These considerations assume that no rescattering is taking place.

Figure II.D.2.1: The longitudinal space and time development of the local energy density in a central collision of 200A GeV $^{32}\text{S} + ^{197}\text{Au}$.

If the rescattering is turned on, the measured transverse energies change considerably, but the maximal energy density does not change substantially. This is because the maximal energy density is reached early in the collision before rescattering has any effect.

We have also made systematic studies of the effects on the energy density of different formation times, stopping powers, bombarding energies, and colliding nuclei. Figure II.D.2.1 shows a typical development of the energy density as a function of the time and longitudinal coordinate.

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II.D.3. Status Report of WA80 Proton Data Analysis

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In the previous year the WA80 collaboration has published two calorimeter measurements on transverse and forward energy distributions [1]. The experimental setup consisted of a midrapidity calorimeter (MIRAC) and a zero degree calorimeter (ZDC). The reactions included 60 GeV/c oxygen and 200 GeV/c oxygen and sulphur beams bombarding several different targets at CERN SPS. Further analysis of the WA80's 200 GeV/c proton data taken in 1988 will provide additional understanding of the reaction mechanisms in high energy collisions.

The experimental minimum bias cross sections have been compared with the FRITIOF 1.7 calculations and Glauber theory predictions (see Table II.D.3.1). All the cross sections and spectra have been corrected for background effects by subtracting the normalized results from runs on an empty-target aluminium frame. The background corrections to the uncorrected minimum bias (MB) cross sections are typically between 20% and 30% and only affect the E_T spectra for extremely peripheral events (i.e., E_T less than 2.5 GeV).

Preliminary results of the transverse energy E_T spectra (seen in MIRAC) were obtained for several different target nuclei: ^{12}C , ^{27}Al , $^{\text{nat}}\text{Cu}$, $^{\text{nat}}\text{Ag}$, and ^{197}Au (see Fig. II.D.3.1).

The MIRAC covered a pseudorapidity range of $1.6 < \eta < 6.0$, and it had a full azimuthal coverage in the pseudorapidity interval $2.4 < \eta < 5.5$ for the WA80's proton and heavy-ion runs. The pseudorapidity distributions were also obtained with different event selection criteria and were fitted by using a Gaussian distribution. The results clearly indicated the target mass dependence. The distribution is shifted backward further in pseudorapidity space with a higher target mass. This is consistent with the WA80's heavy-ion data [1]. Figure II.D.3.2 shows the minimum bias $dE_T/d\eta$ distribution for all five targets. The Gaussian fits are given in Table II.D.3.2.

Several parameterization have been tested to fit the E_T spectra by using the single- and double-gamma distributions [2, 3]. The single-gamma distribu-

Table H.D.3.1: Comparison of the WA80 p-*A* MB cross section with FRITIOF 1.7 and Glauber theory predictions.

Target	MBCross Section (mb)		
	Fritiof	Glauber	WA80
C	221.5	235.3	245.9
Al	402.0	410.3	351.0
Cu	755.8	756.3	809.9
Ag	1103	1085	1178
Au	1701	1628	1760

Table H.D.3.2: $dE_T/d\eta|_{\max}$, $\bar{\eta}$ (centroid) and σ_η determined from Gaussian fits to the $dE_T/d\eta$ distributions (minimum bias).

Target	$dE_T/d\eta _{\max}$ (GeV)	$\bar{\eta}$	σ_η
C	2.14 ± 0.14	2.87 ± 0.09	1.54 ± 0.12
Al	2.25 ± 0.17	2.67 ± 0.12	1.61 ± 0.14
Cu	2.51 ± 0.20	2.53 ± 0.13	1.58 ± 0.13
Ag	2.73 ± 0.32	2.39 ± 0.15	1.59 ± 0.14
Au	3.09 ± 0.44	2.15 ± 0.20	1.63 ± 0.14

tion (with three parameters) does not fit the E_T spectra well. A better fit to the E_T spectra can be reached with the double-gamma distribution, but two additional free parameters are introduced in the fit procedure. A clear physical interpretation of these parameters is lacking. A further approach has been proposed to fit the E_T spectra, with which both the nuclear collision “geometry” (probability of binary collisions) and the energy degradation of the incident proton passing through a target nucleus have been taken into account. The advantage of this method is that the E_T spectra of the elementary nucleon-nucleon collision can be extracted and then used for construction of heavy-ion E_T spectra. The probability of having n binary collisions is calculated from the Glauber multiple collision theory [4, 5, 6]:

Figure II.D.3.1: Transverse energy spectra (minimum bias) for 200 GeV/c proton induced reactions on ^{12}C , ^{27}Al , $^{\text{nat}}\text{Cu}$, $^{\text{nat}}\text{Ag}$, and ^{197}Au targets. The error bars reflect the statistical error only, and the spectra are corrected for distortions caused by background events.

$$P(n) = \int d\mathbf{b} \mathcal{P}(n, \mathbf{b}) \quad (\text{II..1})$$

$$\mathcal{P}(n, \mathbf{b}) = \binom{A}{n} [T_A(\mathbf{b})\sigma_{\text{NN}}]^n [1 - T_A(\mathbf{b})\sigma_{\text{NN}}]^{A-n} \quad (\text{II..2})$$

The first factor on the right-hand side of the latter equation represents the

WA80 200 GeV proton

Figure II.D.3.2: Target dependence of $dE_T/d\eta$ in 200 GeV proton-induced minimum bias collisions. The lines are the Gaussian fits.

number of ways of finding n collisions out of A possible nucleon-nucleon collisions. $\mathcal{P}(n, \mathbf{b})$ is the probability of having n multiple collisions at the impact parameter $\mathbf{b}$. $\sigma_{NN} = 30$ mb is the free nucleon-nucleon inelastic cross section. $T_A(\mathbf{b})$ is the normalized thickness function for the target nucleus A and is defined as

$$T_A(\mathbf{b}) = \int \rho(\mathbf{r}) dz_A \quad (\text{II.3})$$

$$\mathbf{r} = \mathbf{b} + z_A \quad (\text{II.4})$$

where ρ is the nucleus density distribution, which is the same as the one used in [1], and z_A is the longitudinal coordinate. The E_T distribution is then formulated as

$$\frac{d\sigma}{dE_T} = \sigma_{\text{tot}} \sum_{n=1}^A P(n) f_n(\beta, p_n, E_T) \quad (\text{II.5})$$

where $P(n)$ is given by Eqn. (II.1), and f_n is the convoluted Gamma distribution. Since the Gamma distribution has an elegant convolution property if its slope parameter β (see below) is kept a constant, it has been assumed that the E_T spectra given by binary collisions are modeled by Gamma distributions, all with the same slope parameter. By doing so, $f_n(\beta, p_n, E_T)$ is then easily written as

$$f_n(\beta, p_n, E_T) = \frac{\beta}{\Gamma(p_n)} (\beta E_T)^{p_n-1} e^{-\beta E_T} \quad (\text{II.6})$$

where $\Gamma(p_n)$ is the Gamma function and β is the slope parameter mentioned above. The other parameter, p_n , plays an important role in this new parameterization scheme: it reflects the energy degradation of the incident proton while passing through the target nucleus A . Following the above assumption, it is not difficult to find that the average E_T given by the first binary collision is $\langle E_T \rangle^{(1)} = p^{(1)}/\beta$; for the second binary collision $\langle E_T \rangle^{(2)} = p^{(2)}/\beta$, etc. (note that the parameter β is the same for all collisions). The average E_T from n binary collisions will be given as

$$\begin{aligned} \langle E_T \rangle_n &= \frac{p_n}{\beta} \\ &= \frac{p^{(1)}}{\beta} + \frac{p^{(2)}}{\beta} + \cdots + \frac{p^{(n)}}{\beta} \\ &= \langle E_T \rangle^{(1)} + \langle E_T \rangle^{(2)} + \cdots + \langle E_T \rangle^{(n)}. \end{aligned} \quad (\text{II.7})$$

Because of the energy loss of the incident proton after each binary collision, we simply have $\langle E_T \rangle^{(1)} > \langle E_T \rangle^{(2)} > \cdots > \langle E_T \rangle^{(n)}$. Since the exact expression for $\langle E_T \rangle^{(i)}$ is unknown, several functional forms of p_n have been tested; it has been found that of these the following expression gives the best χ^2 fit and at the same time has a simple physical consideration linked with it:

$$\begin{aligned} p_n &= \sum_{i=1}^n \alpha^{i-1} p_1, \\ p_1 &= p^{(1)}. \end{aligned} \quad (\text{II.8})$$

Table II.D.3.3: The parameters of the convoluted single-gamma distribution obtained by fitting the WA80's minimum bias E_T spectra with $E_T(\text{low-cut}) > 2.75$ GeV.

Target	σ_{tot}	β	p_1	α	$\chi^2/\text{d.o.f}$
C	227	2.7	10.4	0.38	3.3
Al	334	2.4	8.8	0.36	2.0
Cu	783	2.4	8.5	0.41	11.8
Ag	1140	2.2	8.1	0.40	6.1
Au	1732	2.3	7.8	0.45	51.4

Here a new parameter α (less than 1.0) is introduced that implies the incident proton experiences the same fractional energy loss in each binary collision. There are four free parameters in this parameterization: (a) σ_{tot} , the integral of the E_T spectra in the fitted region; (b) β , the slope parameter; (c) p_1 , related to the average energy contributed from first nucleon-nucleon collision, i.e., $\langle E_T \rangle^{(1)} = p_1/\beta$; and (d) α , the energy degradation factor after each NN collision. Figure II.D.3.3 shows a preliminary χ^2 fit with the WA80's E_T spectra for all five target cases. These fits are quite good except for the Au target where the high E_T tail is over estimated. The extracted parameters are tabulated in Table II.D.3.3.

The essence of the above convolution parameterization is to separate the nuclear collision “geometry” from the dynamics. This separation “*allows experimental measurements to be used to derive the fundamental E_T spectrum of the elementary collision process, which is then used as the basis of the analysis of a nuclear scattering*” [2]. The search for constructing the heavy-ion E_T spectra from our p- A results is currently being undertaken.

In addition, some Monte Carlo code predictions have been compared with our data and will be tested in further data analysis.

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Figure II.D.3.3: Convoluted gamma distribution fits of E_T spectra. See text for details.

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II.D.4. Slow Singly-Charged Fragment Production in 200 GeV/c Hadron-Nucleus Interactions

WA80 Collaboration - (see name list in section II.D.3.)

The great interest recently shown in multiparticle production mechanisms in nucleus-nucleus collisions at ultrarelativistic energies has revived the importance of hadron-hadron and hadron-nucleus collisions. The gross features of the data obtained in the nucleus-nucleus collisions at these high energies can be understood in terms of the collision geometry. One way to get additional knowledge of the underlying mechanisms is to study hadron-hadron and hadron-nucleus interactions. This knowledge is needed when making more detailed extrapolations to the nucleus-nucleus reactions. The characteristic features of hadron-nucleus collisions should in principle be a helpful tool when extracting effects induced by the surrounding nuclear medium. Once the incident hadron has undergone the first collision it is no longer acting as a free hadron but appears as an excited state of hadronic matter whose characteristics are not very well known. It is generally believed that most of the hadronization takes place outside of the nuclear medium and that cascading in the nuclear medium is rather limited [1]. The hadrons emitted in these collisions can be divided into two classes, those produced in the reaction (mainly pions) and slow target-associated fragments. In this report the results from a study of singly-charged fragments are used to address the significance of target mass dependence and the question of whether or not there is a cascade in the nuclear medium.

The data were taken with the WA80 experimental setup [2] at the CERN SPS on proton and pion induced reactions at 200 GeV/c. The results discussed here were obtained by using the Plastic Ball spectrometer [2] covering the target rapidity region ($-1.7 < \eta < 1.3$). Each of the 655 detector modules is a particle identifying telescope with a ΔE (CaF₂) and E (plastic) detector; these are read out via one common photomultiplier (using the Phoswich technique). These telescopes have the capability of fully identifying $Z = 1, 2$ fragments from 30–250 MeV/ A , with the extension of up to 400 MeV for protons. Above this energy the contamination of pions is too severe to have an acceptable separation between these and the protons.

Multiplicity distributions of N_f slow singly-charged fragments (hereafter referred as to slow protons) with energies $30 A \text{ MeV} < E < 400 A \text{ MeV}$ emitted in the target rapidity region ($-1.7 < \eta < 1.3$) for proton and pion induced interactions can be seen in Figs. II.D.4.1 and II.D.4.2. The distributions have been corrected for background contributions (from no-target runs). To study

Figure II.D.4.1: Distribution of N_f slow singly-charged fragments from proton induced reactions on a variety of targets ranging from carbon to gold. The curves are fits, made with the GCM.

the shapes of the distributions in more detail a simple “Geometric Cascade Model” (GCM) [4] was adopted. This model gives a fairly good description of the spectra for all the target cases with only one free parameter, the average number of fragments produced in a single struck target nucleon, $\langle N_f \rangle_{\nu=1}$. The fits are also shown (lines) in Figs. II.D.4.1 and II.D.4.2.

The dependence of $\langle N_f \rangle_{\nu=1}$ as a function of target mass is given in Fig. II.D.4.3. The values are similar for both proton and pion induced reactions. This is expected because the difference in cross sections has been removed when extracting $\langle N_f \rangle_{\nu=1}$.

The angular and energy distributions of slow protons have also been studied. It is found that the angular distribution shapes are relatively well described by the form $\exp(\kappa \cos \theta)$, with the parameter κ being roughly 0.8 for heavier targets but larger for lighter ones. That the lighter targets have a more forward peaked structure is easily understood, as they are not large enough for a cascade to saturate. For the heavier targets κ is rather constant, indicating that the intranuclear cascade is almost fully developed in copper with only a small change found when going to heavier targets. Similar studies have

Figure II.D.4.2: Distribution of N_f slow singly-charged fragments from pion induced reactions on a variety of targets ranging from carbon to gold. The curves are fits, made with the GCM.

been performed for hadron induced reactions on emulsions at widely different energies where it has been found that κ has a value of 0.96, independent of the energy [4]. Figure II.D.4.4 shows the angular distributions together with VENUS model comparisons for both C and Au targets. The extracted κ values from VENUS model calculations are twice as big as those obtained from the data.

The slow proton energy distributions are found to be well described by the form $\exp(-E/E_0)$ in the energy interval of 80–400 MeV. (The reason for the energy cutoff at 80 MeV is that the energy is not unambiguously determined in the region of 30–60 MeV. However, this cutoff does not affect the results for the N_f and θ distributions discussed above.) We observed the angular dependent energy spectra that are shown in Fig. II.D.4.5 for three θ -bins. The angular dependence is stronger in the VENUS calculation, but the shapes are the same. The data exhibit a much stronger intranuclear cascade than does VENUS, in agreement with the conclusion from proton angular distributions. No clear target mass dependence has been found.

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Figure II.D.4.3: $\langle N_f \rangle_{\nu=1}$ as a function of the target mass A . The line represents the function $A^{1/2}$.

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II.D.5. Emission of Slow Protons in Relativistic $^{16}\text{O} + A$ Interactions

WA80 Collaboration – (see name list in section II.D.3.)

Slow singly-charged fragments, predominantly protons, were measured and identified with the Plastic Ball detector [1] over angles from 30° to 160° . Due to the high particle density in the most forward part, the analysis has been restricted to particles emitted with angles larger than 60° . The data was taken with a minimum bias trigger.

Multiplicity distributions of N_f slow singly-charged fragments are shown in Fig. II.D.5.1. The measured yields are very similar for 60 and 200 A GeV, except for low N_f values where the 60 A GeV data have slightly higher cross sections.

Figure II.D.4.4: The angular distributions for proton induced reactions on C and Au. The lines are fitted exponentials.

The similarities of the data from the two energies strongly support the idea that the emission of slow fragments is dictated by the nuclear geometry. When values of N_f extracted at a given level of cross section for the different targets are studied, it is observed that these values scale for small cross sections. An overall target dependence of roughly $A_T^{2/3}$ is observed, but the exponent seems to increase with target mass.

The form of the angular distribution of slow protons is found to be well described by the parameterization $C e^{\kappa \cos(\theta)}$, in agreement with earlier observations [2]. The ratio of the distributions for the two energies can be seen in Fig. II.D.5.2a. A similar plot for the energy distributions is given in Fig. II.D.5.2b. The figures show that both energies have essentially the same shape of distributions.

The slopes of the angular distribution, κ , extracted from exponential fits provide information about the cascading and rescattering processes within the target. Large values of κ correspond to a small amount of rescattering, whereas smaller values are related to a larger cascade. In Fig. II.D.5.2c the target dependence of κ is shown. As can be seen in the figure κ decreases with increasing target mass, indicating a cascade that grows with increasing

Figure II.D.4.5: The energy distributions for proton induced reactions on Au for three θ -bins. The lower panel shows the VENUS calculation. The lines are fitted exponentials.

amount of surrounding matter. Points from proton induced interactions [3] are included in the figure and show a similar target dependence although the values are somewhat smaller. In Fig. II.D.5.2d extracted values of κ are plotted as a function of centrality, characterised by the energy flow at zero degrees, E_{zd} . In central interactions with a moderately large target the spectator essentially vanishes, whereas in peripheral interactions a large part of the target is left as a spectator. This is the reason for the rise seen for the copper data in Fig. II.D.5.2d. The trend is different for the gold data. A much weaker centrality dependence is observed there, clearly indicating that the spectator part of the gold nucleus is sizable, even for small impact parameters. Furthermore, no difference is observed as the incident energy is changed.

The above results clearly indicate the important role played by the spectator part of the target nucleus. Here the main cascading and rescattering take place and thus these effects are, for smaller targets, predominantly seen in peripheral interactions. Figure II.D.5.2c shows that in proton induced interactions the κ values are reduced compared to the corresponding values for oxygen induced interactions. This is qualitatively what should be expected

Figure II.D.5.1: Multiplicity distributions of N_f slow fragments in 200 (symbols) and 60 (histogram) A GeV ^{16}O induced reactions.

due to the larger spectators left over from a target struck by a proton.

- [1] A. Baden et al, *NIM.* **203** 189 (1982).
- [2] M. Adamovich et al. (EMU01 collaboration), *Phys. Lett.* **B230** 175 (1989); *ibid.* **B262** 369 (1991); I. Otterlund et al., *Nucl. Phys.* **142B** 445 (1978).
- [3] R. Albrecht et al. (WA80 collaboration), to appear in *Z. Phys. C*.

II.D.6. Inclusive Photon Transverse Momentum Distributions from Ultrarelativistic Heavy-ion Collisions at 60 A and 200 A GeV/c at the CERN-SPS

WA80 Collaboration (see name list in section II.D.3.)

New results on inclusive photon transverse momentum p_T distributions from ultrarelativistic nucleus-nucleus and proton-nucleus collisions have been measured with the lead glass calorimeter SAPHIR in the WA80 experimental setup [1]. The present data include corrections imposed by the high particle densities found in heavy-ion collisions. These corrections tend to change the slopes

Figure II.D.5.2: a: Ratio of angular distributions of slow protons in ^{16}O -Au collisions; b: ratio of energy distributions of slow protons in ^{16}O -Au collisions; c: target mass dependence of κ ; d: centrality dependence of κ .

of the p_T distributions and provide an overall increase of the absolute photon yield.

The inclusive photon p_T distributions from central and peripheral events for different systems are shown in Fig. II.D.6.1. The events are selected for a high or low charged-particle multiplicity measured in the streamer tube detectors. The selection contains 10% of the minimum-bias cross section for the central, and 30% for the peripheral, events. Also shown are the results of $dN/dp_T \sim \exp(p_T/T)$ parameterizations in the range of $0.5 \text{ GeV}/c \leq p_T \leq 2 \text{ GeV}/c$.

The inclusive photon p_T distributions have been compared with predictions from the FRITIOF models 1.7 and 7.0, and with VENUS 3.07 where rescattering of secondary particles is considered. It is found that both FRITIOF versions and VENUS without rescattering fail to reproduce the p_T distributions while VENUS with rescattering fits the data better but overshoots at large val-

Figure II.D.6.1: Inclusive photon p_T distribution from central and peripheral events. The lines show the results from $dN/dp_T \sim \exp(p_T/T)$ parameterizations in the range of $0.5 \text{ GeV/c} \leq p_T \leq 2 \text{ GeV/c}$.

ues of p_T . This is an indication that rescattering is necessary to explain the behaviour of the photon p_T distributions.

The high photon statistics allow us to perform an η -dependent analysis of the photon p_T distribution. The SAPHIR has an η coverage from 1.5 to 2.1. One particular cause of a systematic error that has to be corrected carefully for this analysis is the effect of the high particle density, which varies not only with the centrality but even more pronouncedly with the η rings in each event. Figure II.D.6.2 shows the $\langle p_T \rangle_{\gamma,400}$ values of minimum-bias 200 A GeV/c $^{16}\text{O} + \text{Au}$ data as a function of the pseudorapidity η from uncorrected and corrected photon p_T spectra. The quantity $\langle p_T \rangle_{\gamma,400}$ is defined as

$$\langle p_T \rangle_{\gamma,C} = \left[\frac{\int_C^\infty p_T \frac{dN}{dp_T} dp_T}{\int_C^\infty \frac{dN}{dp_T} dp_T} \right] - C$$

where C is the lower p_T cutoff, which is determined by the efficiency of the photon reconstruction that drops significantly at low photon energies. This mean value has the advantage of being equal to the slope parameter T in the case of a pure exponential distribution. A clear rise is observed for large values of η (small laboratory angle θ). Since midrapidity for the 200 A GeV $^{16}\text{O} + \text{Au}$ system is 3.0, this indicates that the $\langle p_T \rangle_{\gamma,400}$ values increase for regions closer to midrapidity.

Further analysis is underway to study $\langle p_T \rangle_{\gamma,400}$ dependence as a function of the centrality, $1 + E_{\text{ZDC}}/E_{\text{beam}}$, and the correlation between $\langle p_T \rangle_{\gamma,400}$ and entropy density.

- [1] H. Baumeister et al., *Nucl. Instr. and Meth.* **A292** 81 (1990).

Figure II.D.6.2: $\langle p_T \rangle_{\gamma,400}$ values from minimum-bias 200 A GeV/c $^{16}\text{O} + \text{Au}$ data as a function of the pseudorapidity η .

II.D.7. CERN WA93 and WA98 Experiments

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The CERN WA93 experiment is the successor to the WA80 experiment in which UT has participated since 1984. The primary purpose of WA93 is to extend

the data set obtained by WA80 and, in addition, to implement new detector systems commissioned primarily for use in the upcoming WA98 experiment. WA98 will be the successor to experiment WA93, and will be performed using the lead beams at CERN. It was described in reference [1] under the title "Proposal for a Large-Acceptance Hadron and Photon Spectrometer".

During this reporting period, two WA93 runs have taken place. The first run was carried out in October and November 1991, and the second run took place in April 1992. The primary change in WA93 relative to WA80 is the removal of the Plastic Ball and the addition of a large magnet ("Goliath") needed for particle tracking, which is performed by means of multi-step avalanche counters (MSAC's). In addition, a photon multiplicity detector (PMD) built by Indian members of the collaboration was also commissioned. The UT and the ORNL designed and built Mid-Rapidity Calorimeter (MIRAC) and Zero-Degree Calorimeter (ZDC), as well as the nearly 4000-element lead-glass photon detector, were retained from experiment WA80 for operation in WA93. Prior to the first WA93 run, the radiation-damaged scintillator of the ZDC had to be replaced since its performance had degraded to an unacceptable level. The radiation damage was a result of the combined effect of the continuous low-level uranium activity from the ZDC absorber plates, as well as the higher level radiation doses received from the full intensity heavy-ion beams stopped in the ZDC. The replacement of the ZDC scintillator plates turned out to be a difficult (and expensive) operation due to the presence of uranium oxide powder from the corroded depleted-uranium absorber plates.

The first WA93 run (October–November 1991) was only a partial success. This was, in part, due to the fact that the new detector systems had not been thoroughly studied in test beams and some (e.g., MSAC's) did not perform as expected. It was also partly due to numerous beam delivery problems. The second WA93 run (April 1992) was much more productive than the first. However, while the performance of the MSAC's continued to improve during the run, their efficiency never exceeded 80%. Nevertheless, during both runs a large amount of photon data was obtained.

In early April 1992, the SPSL Committee approved the P260 proposal, leading to experiment WA98. This approval, however, was extended to only part of the experiment (photon measurements). The committee withheld approval of the tracking portion of the proposal, pending presentation of results from the WA93 runs.

The actual design of WA98 continues to undergo changes. MIRAC will continue in operation but will be reconfigured. The size of the lead-glass

array will be expanded to 10,000 elements, and the ORNL/UT-designed monolithic electronics will be installed on it for readout. A larger PMD will also be constructed, and the Plastic Ball will be reinstalled. The ZDC will be decommissioned and replaced by a calorimeter capable of withstanding the increased exposure to radiation damage that will take place with lead beams. It is expected that experiment WA98 will first be operated in 1994.

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[1] *Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1991*, ORNL-6689, p. 80.

II.D.8. Monte Carlo Simulations of the WA98 Calorimeter Performance

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An intensive preparation for the upgraded WA80/93/98 experiment [1, 2] has been ongoing for several months. Among the detectors to be employed in the WA98 setup (the experiment is expected to be first operated in the spring of 1994), a newly configured mid-rapidity calorimeter (MIRAC) and a new zero-degree calorimeter (ZDC) will play very important roles in collision event classifications and the measurement of reaction energy flow. In order to optimize the performance of the MIRAC and the ZDC, a set of simulations for different calorimeter configurations have been carried out using the FRITIOF 1.7 event generator. Also, a complementary charge measurement via zero degree Cherenkov counter has been simulated.

The simulations have been focused on three aspects: a) to make the best possible central collision trigger; b) to make the best possible peripheral trigger; c) to extract as much "physics" as possible from the calorimetry measurements. In order to simulate the effects of a magnetic field, a p_t kick of 600 MeV for Z/A equal to unity has been assumed. The magnitude of the

p_t kick is based on a field mapping measurement in the setup of the WA93 experiment.

Zero Degree Calorimeter

In the simulations, the ZDC is situated 50m from the target. An ideal ZDC geometry has been assumed to absorb all particles having a scattering angle, after magnetic field deflection, of less than 0.3 degree. The energy resolution is given by $\sigma/E = 40\%/\sqrt{E}$, and the deposited energy is randomized according to a Gaussian distribution. Since ZDC had a severe radiation (beam) damage in the WA80 and the WA93 experiments, several scenarios have been considered in the simulations regarding the existence of a hole of 1cm in diameter at the center of the ZDC. The simulation shows that the new ZDC without a hole will not provide a better peripheral or central trigger than MIRAC. Centrally, it performs similarly to MIRAC. Peripherally, it suffers the well-known (from the WA80 experiment) problem of the beam tail region. The ZDC with a hole poses a serious problem, since the physics of the projectile fragmentation is essentially unknown. Figure II.D.8.1 shows the Z/A ratio of the fragments as a function of the impact parameter. For peripheral collisions the ZDC will in some cases detect everything, as if there were no hole at all, but sometimes it will allow some large fragments through the hole and will record only a small energy. It would therefore be extremely difficult to know how to set a trigger (basically how to put a gate on the E_{ZDC} signal) in order to select peripheral events.

One must conclude that, for the reasons given above, a new ZDC, with or without a hole, is not recommended as a peripheral trigger. For central events the ZDC will not perform as a better trigger device than the MIRAC does.

Zero Degree Cherenkov Counter

The zero degree Cherenkov Counter (ZD Cherenkov) is assumed to produce a signal for all of the charged particles passing through it. In the simulations it is situated one meter in front of the ZDC and has a complete coverage of all particles having a scattering angle, after magnetic field deflection, of less than 0.3 degree. A perfect resolution for the ZD Cherenkov has been assumed, but this assumption is not crucial to our conclusions.

A fundamental problem in the interpretation of this detector is that the degree of beam fragmentation is unknown. With no beam fragmentation the signal in the detector will be proportional to $Z_{\text{spectator}}^2$, but if the beam fragments into many pieces and these pieces have relative distances larger than a

Figure H.D.8.1: Z/A ratios of beam fragments vs. impact parameter.

few Angstroms, then the signal will be proportional to the sum of each Z_{fragment}^2 , which can be significantly lower than $Z_{\text{spectator}}^2$. Two extreme scenarios have been considered. Figure H.D.8.2 shows the $Z_{\text{spectator}}^2$ (total charge Z^2) and total charge Z (all fragments with $Z = 1$) as a function of the impact parameter b . A realistic detector will record a signal somewhere between those of the above two scenarios. The simulations show that for peripheral collisions a large range of signal will be recorded in the ZD Cherenkov, and this will thereby reduce the value of this detector as a peripheral trigger device. The conclusion is that the Zero Degree Cherenkov Counter will be inferior to the MIRAC as a trigger device, both for peripheral and central collisions.

Figure II.D.8.2: Charge measurement (Z^2 and Z) of the Zero Degree Cherenkov counter vs. impact parameter b .

Mid-Rapidity Calorimeter

The MIRAC is situated at half the distance of the ZDC from the target (i.e., at 25m) in our simulations. All three detectors mentioned above are aligned along the beam direction when the magnetic field is off. The energy resolution for the MIRAC is the same as for the ZDC, $\sigma/E = 40\%/\sqrt{E}$, and the deposited energy is also randomized according to a Gaussian distribution.

The MIRAC has the advantage of not absorbing the beam or any beam fragments. This makes the understanding of the signal recorded in this detector much easier. From the WA80 experiment it was learned that the MIRAC is the best central trigger device for asymmetric collisions, and from the WA93

experiments it was found that it also performs very well as a peripheral trigger device.

There are seven different geometries of the MIRAC that have been simulated, ranging from linear deployments of all five sixpacks (each pack has a front face area of $20\text{cm} \times 120\text{cm}$) to idealized annular arrangements with different inner and outer radii. Each geometry will be referred to here by its IDCODE. For example, the linear deployments of all five sixpacks corresponds to an IDCODE of 1200 (see Table II.D.8.1). Most of these configurations perform as well as or better than the ZDC or the Cherenkov detector, both as peripheral and central triggers.

Table II.D.8.1: Summary of the MIRAC simulations for all configurations.

<i>Geometry</i>	<i>IDCODE</i>	η_{max}	η_{min}	E_{Tmax}	<i>Events</i>
1000	5.5	3.5	500	2000
1100	2.9	2.8	90	2000
1200	5.5	2.1	300	2000
1300	3.5	2.4	150	2000
1400	5.5	2.8	500	2000
1500	3.7	2.8	250	2000
1600	5.5	2.5	600	2000

Among the seven geometries of Table II.D.8.1 three cases have been considered closely, as they seem to be the most practical.

- A closepack configuration (IDCODE = 1300): This may be the easiest to

analyze and gives the best calorimeter behaviour, but it has a lack of ϕ symmetry.

- A two-arm configuration (IDCODE = 1500): An intermediate scenario, it gives a left-right symmetry, but still lacks full ϕ symmetry.
- An extended WA80/93 MIRAC geometry (IDCODE = 1400, 1600): In this configuration, a $40 \times 10 \text{ cm}^2$ hole is opened along the beam line in order to avoid beam hits. This scenario gives good ϕ -symmetry and measures the largest fraction of the total transverse energy, which might be an important asset. On the other hand, the response of the innermost towers will be difficult to ascertain. The inclusion of another calorimeter (IDCODE = 1600 configuration) will enhance the performance of each of the cases mentioned above, as it can be seen from Table II.D.8.1 that geometry 1600 measures more energy and has a bigger rapidity coverage.

In conclusion, independent of the geometry it is chosen, the MIRAC is the best peripheral and central trigger device.

[1] WA93 proposal: CERN/SPS 90-14, SPSC/P252, May 1990.

[2] Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1991, ORNL-6689, p. 80.

II.D.9. Preconceptual Design of PHENIX Experiment for RHIC

PHENIX Collaboration – a complete list of authors is given at the end of this article

The PHENIX Preliminary Conceptual Design Report (PCDR) was submitted to Brookhaven National Laboratory and RHIC management on June 29, 1992. Subsequent reviews by the BNL/RHIC Technical Advisory Committee and Program Advisory Committee were held in August and September, 1992, respectively. The collaboration will submit a formal Conceptual Design Report to BNL in January, 1993, with the intent to begin final engineering and construction of PHENIX by the latter part of 1993.

The PHENIX collaboration consists of about 275 scientists, engineers, and graduate students from 41 institutions in 10 countries. The collaboration is still growing.

The PHENIX collaboration at RHIC was formed under a common interest to measure as many potential signatures of the quark gluon plasma (QGP) as possible, to see if any or all of the physics variables show a simultaneous anomaly due to the formation of the QGP. We have concentrated our efforts on electromagnetic radiation and selected aspects of hadron emission from relativistic heavy-ion collisions. We emphasize the importance of searching in parallel for several markers of deconfinement, our hypothesis being that formation of the QGP will have many identifying marks, with no single signal assured of success. A key theme is the measurement of continuum electromagnetic radiation from the strongly-interacting system created in the collision. This radiation is observed in the form of real and virtual photons (via $\gamma^* \rightarrow l^+l^-$, $l = e$ or μ). They will be sensitive to this continuum from the high p_T and m_T range above 4 GeV, where perturbative QCD should serve as a quantitative point of reference, down through the range from 1–3 GeV and below, where radiation from a QGP is expected to be largest. Creation of a plasma with a large latent heat or large initial temperature will result in large amounts of radiation emitted. Similarly, they would be sensitive to a system with a long-lived mixed phase, the more so the higher the QCD critical temperature happens to be. We will also detect l^+l^- decays of vector mesons, a particularly useful class of hadrons for probing the matter created at RHIC and sensing changes in it. In the hadron sector, we will perform measurements of $\pi^\pm$ and $K^\pm$ spectra, measurements of small Δq correlations, and measurements of specific decays such as $\phi \rightarrow K^+K^-$. This gives us capabilities to observe strange particles ($K^\pm$) and particles carrying strange quarks (ϕ, η). The production of both types of particles is predicted to be modified in the presence of a plasma or mixed

phase with temperature T approaching m_s , the strange quark mass. We will also study two-particle correlation measurements, which yield information on the space-time size and shape of the system at hadronization. Observation of a particularly large system or one exhibiting a shape asymmetry, characteristic of a long hadronization time, would be expected to be correlated with observing significant thermal electromagnetic radiation (e.g., in the form of copious photon emission at $p_T \sim T_{\text{crit}}$). By measuring hadrons, we can also test ideas concerning the expected chiral-restoring transition of strongly interacting matter via comparison of $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ decay channels, which requires a comparison of lepton and hadron decay modes under the same set of reaction conditions.

We will search for a QGP through the programmatic study of a broad array of potential signatures as a function of energy density in both $A + A$ and $p + A$ collisions. Since some of the potential signatures involve rare processes and small effects, we designed the detector to be capable of taking data at the highest luminosities expected to be provided at RHIC. An isometric view of the PHENIX detector, as proposed in the PCDR, is shown in Fig. II.D.9.1.

We have chosen an axial field magnet with two opposing electron detectors in order to have uniform p_T acceptance for dielectrons. Electrons and positrons are detected by this two-arm spectrometer, each arm subtending 90° in azimuth (ϕ) and ± 0.35 units in pseudorapidity (η), roughly equivalent to a polar angle (θ) acceptance of $\pm 20^\circ$ centered at θ equal to 90° . The solid angle of each arm is 0.94 sr. Within this aperture, which is to be fully active for electrons, are subsets for photons ($\Delta\phi = 45^\circ$, $\Delta\eta = \pm 0.35$ for Pb glass and $\Delta\phi = 90^\circ$, $\Delta\eta = \pm 0.15$ for CsI or BaF2) and for hadrons ($\Delta\phi = 30^\circ$, $\Delta\eta = \pm 0.35$). For muons, a cone within θ equal to 37° around the beam direction is instrumented.

The detector consists of two magnets and a number of detector subsystems, which are summarized in Table II.D.9.1. It will use the Major Facility Hall (MFH) at RHIC for final assembly and operation. Beneficial occupancy of the MFH in January 1994 is required in order to complete the detector for operations in September 1997.

Figure H.D.9.1: Overview of the PHENIX detector showing the location of detector subsystems.

Table II.D.9.1: Summary of the detector subsystems for the standard version of PHENIX.

Element	$\Delta\eta$	$\Delta\phi$	Ch#	Purpose, special features, etc.
Magnet: central	± 0.5	360°		1.0 Tm for ++; 0.41 Tm for $\pm$
muon	1.1-2.5	360°		0.95 Tm for $\eta = 2$; 0.41 Tm for $\eta = 1.3$
Beam-beam	$\pm 3.1-4$	360°	0.1K	Start timing, on-line vertex decision
Si strip	± 2	120°	23K	$dN/d\eta$, accurate vertex decision
Si pad	$\pm 1.6-3.8$	360°	23K	$d^2N/d\eta d\phi$
Drift chambers	± 0.35	$90^\circ \times 2$	13K	Good momentum resolution, $\Delta m/m = 0.4\%$ at the ϕ
Pad chambers	± 0.35	$90^\circ \times 2$	47K	Pattern recognition, tracking for non-bend direction
TE chambers	± 0.35	$90^\circ \times 2$	43K	Pattern recognition, dE/dx and TRD
RICH	± 0.35	$90^\circ \times 2$	6.4K	Electron ID and tracking, PM tube based
TOF	± 0.35	30°	2K	$\sigma < 100$ ps; good hadron ID
EM Cal	± 0.35	$90^\circ \times 1.5$	18K	Good e/π separation
Pb-glass	± 0.35	45°	10K	Photon detection
CsI/BaF ₂	± 0.05	90°	3K	High resolution photon detection
Muon chambers	1.1-2.5	360°	17K	Tracking for muons
Muon identifier	1.1-2.5	360°	10K	Steel absorbers and streamer tubes for μ /hadron separation

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II.D.10. PHENIX Muon Spectrometer

PHENIX Collaboration – (see name list in section II.D.9.)

A muon endcap-spectrometer, with large solid angle acceptance and high rate capability, is proposed for the PHENIX detector at RHIC to detect muon pairs with broad kinematical coverage. Muon pair detection appears to offer a tractable solution for lepton-pair detection at rapidities greater than one. Muon pairs can span a range in invariant and transverse mass from 1 to 10 GeV/ c^2 . This approach, using an endcap spectrometer with full azimuthal coverage at forward rapidity, y , also allows us to obtain useful counting statistics in the mass region above 4 GeV/ c^2 , where perturbative QCD should be applicable. We can then move to lower mass using the same detector to examine the regime where nonperturbative effects and plasma may be seen. This spectrometer could also be used for measurements of the A_{target} , p_T , and x_F dependences of lepton-pair emission in p- A collisions. These measurements take advantage of the unique capabilities of RHIC to provide p- A collisions at high $\sqrt{s}$. Such studies can shed light on modifications of structure functions in nuclei and are an integral part of a program seeking to understand lepton-pair and photon emission in A - A collisions.

Several authors [1] have suggested that there may be a modification of properties of vector mesons immersed in dense strongly-interacting matter. These include changes in mass, width, branching ratio, and yield of vector mesons. One suggestion for demonstrating deconfinement is the observation of suppression of the yields for certain heavy vector mesons.

The proposed spectrometer will detect vector mesons over a large range of rapidity ($1 < y < 3$) and p_T (0 GeV/ c up to the statistics limit, which should be > 5 GeV/ c for the J/Ψ). The acceptance and resolution are sufficiently good to measure the cross section not only for J/Ψ and Ψ' , which are expected to be suppressed, but also for Ψ production, which is expected to be a “control” for vector meson suppression due to size effects.

Vector-meson suppression depends on the local energy density and, thus, screening radius; therefore, an experiment requires large rapidity coverage in order to take advantage of the variation of $dE_T/d\eta$ with rapidity. Measurements at several values of $\sqrt{s}$ will be necessary to observe a large variation in the maximum $dE_T/d\eta$ for a given system. Good statistics are needed, which implies large acceptance. The need for large acceptance becomes acute for lower $\sqrt{s}$, since the luminosity at RHIC decreases there, as does the lifetime for intra-beam scattering. Suppression effects should disappear at sufficiently high p_T , because the $q\bar{q}$ pair leaves the plasma before it can separate to a radius at which screening affects formation of the relevant state. This behavior is usually predicted to occur at p_T around 5 GeV/c, again placing a premium on acceptance if “control” points are to be accessible experimentally.

The muon endcap spectrometer consists of three main sections: a hadron absorber thick enough to remove most hadrons but thin enough to permit good mass resolution and kinematic acceptance, a magnetic spectrometer providing good acceptance and mass resolution of $< 2\text{--}3\%$, and a muon identifier to complete rejection of hadrons to the 10^4 level or better.

The purpose of the absorber is to attenuate the hadronic flux entering the tracking region to acceptable levels. The particular design depends upon the magnet chosen for PHENIX. The axial-field magnet has steel pole tips at forward rapidities $|y| \geq 1.0$ and for the present design it is $\sim 4\lambda$ thick. This serves as the hadron absorber. If further calculations of the field configuration in the central spectrometer section indicate that some of the steel could be removed from the $|y| \geq 1.0$ region, it would be preferable to replace as much of this steel as possible with other materials; for example, a low- Z material such as Al_2O_3 could be used for the first $2\text{--}3\lambda$ in order to minimize the multiple-scattering which dominates the resolution below 3 GeV/c² invariant mass. Simulations indicate that tracking through the magnet is not a problem since the integrated effect of the field is less than the effect of multiple scattering. Leakage calculations indicate that $1\text{--}2\lambda$ of copper will have to be added to the steel in order to reduce shower leakage into the muon tracking chambers to an acceptable level.

The shower products exiting the pole tip are dominated by soft e^+ and e^- and gammas, which can be easily suppressed by installing 10 radiation lengths of lead after the pole tip. Whether a graded absorber or a monolithic one of steel is used presently depends upon magnet developments.

Following the absorber is the muon tracking region. This consists of a large magnet and tracking chambers. The magnet being designed at the

Figure II.D.10.1: A section of the dimuon spectrometer is shown in relation to the main axial field magnet (see PHENIX write-up). The iron yoke of the main magnet serves as the muon inner absorber. The muon magnet and tracking chambers are shown on the right. The muon identifier is the last element of the spectrometer.

present time is shown in Fig. II.D.10.1 and gives nearly complete acceptance in ϕ . It is a piston and lamp shade configuration where the magnetic field is radial everywhere along the beam line. The polar angle acceptance depends on the configuration of the poles for the central region magnet and the muon magnet design. It includes all polar angles in the range $8.75^\circ < \theta < 37^\circ$.

The tracking chambers, as presently conceived, use drift chamber technology, which may be most suitable with the radial geometry. The chambers would be arranged in three stations, each with 6 detector planes. As an alternative, wire chambers with strip and/or pad readout could be constructed with the wires parallel to the field direction. It is likely that the wire chambers can be constructed with fewer radiation lengths of material, say, less than two percent.

Behind the tracking system will be a second hadron absorber for muon identification. This system will consist of steel layers interspersed with either proportional or streamer tubes. These may be read out using pads or by digital strips positioned along and normal to the wire direction. Which method is preferable (or necessary) depends upon further study related to the ability of any given system to connect a deep hit in the muon-identifier with the correct particle out of the several dozen present in the tracking section.

The inner absorber will eliminate most of the background in the muon spectrometer portion of the detector. However, several percent of the hadrons, particularly pions, will not be absorbed and will be detected in the outer absorber. In addition, some secondaries from showers starting late in the absorber will also enter the tracking section, as will a significant number of neutrons. Thus, the outer absorber must function as a "muon identifier", capable of discriminating between muons and the background of pions and other hadrons. The ideal muon identifier will be composed of > 6 layers of absorber plates alternating with gas proportional tubes or streamer tubes. The exact configuration of plates needs to be optimized, but at least 10l are needed. Our Monte Carlo studies indicate that the muon identifier needs effective pattern recognition in order to reject hadrons at the level required. The front layers may have to be instrumented with streamer tubes with pad readout in order to obtain good three-dimensional pattern recognition and to associate a hit deep in the muon identifier with the correct particle entering, since there are several dozen particles entering the forward muon identifier per event. It may be possible to instrument the deep layers in a less expensive manner with proportional tubes in alternating x and y layers with readout in yes-no mode, because the showers caused by hadrons are dilute there. We hope that directional information from deep hits is sufficient to resolve which entering particle matches the deep hit, because that would allow us not to instrument the first $2-3 \lambda$ of the muon identifier, which would save considerable money. We will study this design issue to optimize performance versus cost.

We have investigated the ability of the muon identifier to provide a fast trigger signal by making Monte Carlo studies using as few as two parameters, neither of which would require a long time to process, either in terms of signal collection times or calculation times. We find that satisfactory results are obtained by using only two parameters: total number of hits and deepest plane registering a hit. Our Monte Carlo results indicate that more than 95% of the pions can be rejected while rejecting only about 10% of the muons over the range from 1 to 10 GeV. We will study this topic further in order to

improve the acceptance for the muons. Additional cuts on tracking chamber hits and a vertex constraint would be applied before a muon candidate would be accepted. Tagging muons at trigger level is most important in reducing interaction rates for p- A and low mass A - A cases, as well as for peripheral Au + Au collisions.

- [1] T. Matsui and H. Satz, *Phys. Lett.* **B178**, 416 (1986); B. Svetitsky, *Phys. Lett.* **B227**, 450 (1989); *The Nuclear Equation of State, Part B: QCD and the Formation of the Quark-Gluon Plasma*, ed. by W. Greiner and H. Stocker, Plenum Press, New York, 1989, p. 257.

II.D.11. Monte Carlo Simulations of the PHENIX Detector at RHIC

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The design of the PHENIX detector for RHIC is currently in an intensive simulation phase in order to evaluate and optimize the detector elements and the experimental configuration within the constraints of a fixed construction budget. In general, two rather different simulation approaches are followed depending on the issues to be addressed. A standardized approach is to use the GEANT simulation package that can track the particles of simulated events in full detail through all of the active and inactive media of the experiment. This approach is extremely useful in order to evaluate the expected performance of the detector elements themselves, as deployed in the detector configuration, with full events. It is also useful in order to investigate sources of background, as might be produced by particles showering in portions of the detector. Such a GEANT-based simulation framework called PISA, which includes the full PHENIX geometry, has been set up by C. F. Maguire of Vanderbilt University. However, due to the extremely large particle multiplicities at RHIC and the large amount of CPU time necessary to track all particles fully, it is generally not feasible to simulate fully more than a few thousand events using GEANT. Since the emphasis of the PHENIX experiment is to concentrate on electromagnetic probes that have low count rates, this generally means that many millions of events must be simulated in order to approach the level of significance where physics will be done. For this reason, a second simulation approach is to use efficient Monte Carlo generators in which the physics signals and the backgrounds are parameterized appropriately in order to make parametric studies of the physics performance for various detector options.

Such efficient Monte Carlo simulations have been described previously for analysis of the photon detection results within PHENIX [1]. The simulation

code that was developed for this purpose has been adapted to simulate either the electron-pair or muon-pair performance of the PHENIX experiment. The code uses an efficient event generator that produces only those particles that decay to produce leptons in the final state, and that include backgrounds that might be identified falsely as leptons. The code has been implemented on the ORNL Intel/i860 Hypercube in order to obtain sufficient numbers of simulated events in short (~ 1 - to 2-day) simulation runs.

Results of such simulations for the electron-pair measurement within PHENIX are shown in Fig. II.D.11.1. The results are shown for 12.8×10^6 central Au + Au events in which a multiplicity of $dN/dy = 375$ has been assumed for each pion charge state. This corresponds to about three days of running at RHIC at design luminosity. The PHENIX detector electron coverage consists of two arms, each subtending 90 degrees in ϕ with a 45-degree opening between the arms and covering the pseudorapidity region of $|\eta| < 0.35$. Electrons are assumed to be tracked and identified if their momentum exceeds 100 MeV/c; softer electrons are trapped in the central magnetic field. For these simulations it has been assumed that, according to design, pions will be misidentified as electrons with 10^{-4} probability and that 0.5% of the photons will convert to e^+e^- pairs and not be eliminated by means other than a pair-mass cut. The results of Fig. II.D.11.1 show the invariant mass spectrum for opposite-sign electron pairs after imposing a Dalitz pair rejection criterion in which all electrons that form an opposite-sign pair with invariant mass less than 50 MeV/c² are eliminated from the pair list. This Dalitz rejection criterion has been optimized through such Monte Carlo studies. It is observed that the electron-pair invariant mass spectrum is dominated by a large combinatorial background that is seen to be attributed mainly to the background due to Dalitz electrons. This is the case in spite of the attempted rejection of Dalitz pairs. In fact, the Dalitz rejection provides a background suppression by about a factor of three only, due to the fact that many of the electrons to be associated to a Dalitz pair fall below the 100-MeV electron threshold or out of the detector acceptance. The results indicate the importance of finding a method to improve the rejection of Dalitz pairs. Currently under investigation is the question of whether or not it is feasible to include an inner detector to identify electrons whose momentum is below the electron arm threshold in order to improve the Dalitz rejection capabilities.

The results of Fig. II.D.11.1 are shown integrated over the transverse momentum of the pair. In Fig. II.D.11.2 the simulation results are analyzed quantitatively for the ρ , ω , and ϕ resonances as a function of the transverse

Figure M.D.11.1: Simulation of electron-pair measurements in the PHENIX detector at RHIC for 12.8×10^6 central Au + Au events. The solid curve is the same in each panel and shows the expected experimental result for the invariant mass spectra for opposite-sign pairs. In the upper left panel, the true pair signal is shown by the dashed curve in which the ρ , ω , ϕ , and J/ψ resonances can be seen on top of a continuum due to DD decays. No ρ - ω mixing is assumed. The like-sign pair combinatorial mass distribution is shown by the dashed curve in the upper right panel. In the lower left panel the contribution of true opposite-sign electron pairs from Dalitz decays of the π^0 and η is shown by the dashed curve. It is seen to fall several decades below the combinatorial spectrum; only the latter can be measured. The dotted curve indicates the combinatorial background due to a Dalitz decay electron with any opposite-sign electron, while the dashed indicates the same for all combinations of Dalitz electrons only. The lower right panel shows the contribution to the combinatorial background due to misidentified electrons (e.g., charged hadrons) with anything (dashed curve) or misidentified electrons paired with themselves (dotted curve).

momentum of the resonance. It is seen that due to the large combinatorial backgrounds, the peak/total ratios for these resonances are quite low for transverse momenta below about 2 GeV/c. Only the J/Ψ resonance appears without combinatorial background. As a result of these combinatorial backgrounds, the statistical errors for extracting the resonance cross section from the large background (equal to, $\sqrt{(2-Q)/(QN)}$, where Q is the peak/total ratio and N is the number of counts in the peak) are quite modest, even with the large number of accumulated events and even though the yields in the peaks are themselves large. The conclusion to be drawn from these simulations is that with the PHENIX electron detection system as presently designed, extracting the ρ and ω resonance production via their electron-pair decay will be quite difficult for central Au + Au collisions at RHIC. The extraction of the ρ production cross sections is probably not possible, and by implication, neither will be the more difficult extraction of thermal electron pairs due to decay of virtual photons. In order to improve the PHENIX electron-pair measurement substantially, it would be necessary to increase the electron detection coverage significantly, which is not feasible financially, or to improve the Dalitz rejection capabilities in order to eliminate this overwhelming background.

- [1] "Monte Carlo Simulations of Photon Measurements for the PHENIX Detector at RHIC," *Phys. Div. Prog. Rep. for Period Ending Sept. 30, 1991*, ORNL-6689, p. 96.

II.D.12. Simulations of the Performance of the PHENIX Muon Detector

PHENIX Collaboration -- (For a complete list of authors, see article "Preconceptual Design of PHENIX ...")

At the current stage in the development of the PHENIX detector for the RHIC accelerator, large-scale Monte Carlo simulations are of great importance for the evaluation of the performance of the various detector components. At UT we have been responsible, in collaboration with ORNL, Georgia State, Vanderbilt, and Los Alamos, for the simulation of the muon detector. This detector consists of a tracking element with a lamp shade magnet, followed by a large, instrumented block of steel serving as a muon identifier.

The early work was focused on evaluating the acceptance and dimuon invariant mass resolutions. The current detector design will accept all muons with scattering angles between 9 and 35 degrees with energies above 2 GeV. At the same time, pions and kaons with the same kinematics will be suppressed by $\approx 3 \times 10^4$. Based on the measured positions of the muons in three drift

Figure II.D.11.2: The expected performance of the PHENIX detector electron-pair measurement as a function of the pair transverse momentum for the ρ (open circles), ω (closed circles), and ϕ (open squares) resonances for 12.8×10^6 central Au + Au events. The results were analyzed after Dalitz pair suppression by first eliminating all electron candidates that form an opposite-sign pair with pair mass less than 50 MeV. The upper left panel shows the peak/total ratio integrated over the region of $\pm 2\sigma$ about the peak. The upper right panel shows an estimated (comparing runs with/without Dalitz rejection) efficiency that the Dalitz rejection does not reject true pairs. The lower left panel shows the accepted true yield as a function of transverse momentum. The lower right panel indicates the statistical uncertainty to extract the true yield after background subtraction.

chambers and the vertex position, determined by the vertex detector, we have developed a novel method for determining the momentum vector at the vertex. The method is based on a Chebyshev polynomial expansion in the measured quantities. It is especially well suited for second-level trigger purposes, since it is very fast and does not require any fitting.

The tracking of particles through the detector will impose three problems: (1) correlation of hits within the drift planes of a tracking station, (2) correlation of hits between tracking stations, and, finally, (3) correlations between tracks found in the muon identifier and the spectrometer. At the moment, we have solved problem (1) and are working on (2). The algorithm used for solving problem (1) is based on the principal component method and seems to be able to handle hit densities of up to 15-20%. We anticipate hit densities of 5-10% from our GEANT studies.

The whole feasibility of the muon detector hinges on the magnitude of the vector meson yield compared to the underlying combinatorial background of muons originating from sources other than vector meson decay or correlated dimuon production. The most important source is decay muons from pion decay. Through GEANT calculations at Vanderbilt and Los Alamos and high-gain Monte Carlo simulations at ORNL, we have found that even if the combinatorial background will be a most annoying feature, the signal-to-noise ratio will still be above 1 for invariant masses from 3 GeV and up.

Figure II.D.12.1 shows the invariant dimuon mass distributions for both all unlike-sign accepted muon pairs and the original signal consisting of vector mesons and Drell-Yan pair. No background is present at the Y . The J/Ψ is clearly seen above the background, whereas the Ψ' just makes it. The ρ and ϕ seem to be completely covered below the background, but one is able to recover their yield to within 10-20% by performing the proper background subtraction based on like-sign muon pairs. We note that no cuts to remove background muons have been made in this spectrum.

Figure II.D.12.1: Invariant dimuon mass distributions. See text for details.

II.D.13. Calorimeter Optimization Experiment(RD-10/RD-45 Project)

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The RD10 calorimeter optimization experiment conducted at the AGS at Brookhaven National Laboratory in the spring of 1991 resumed this spring under the project designation RD-45. This year's objective concentrated on iron absorber studies with calorimeter thicknesses of 4.8 and 8.2 λ . The layout of the RD-45 experiment was the same as for RD10, with the exception of the

addition of a third Cerenkov counter. This counter was placed between the beam hodoscopes, as close as possible to the calorimeter, and was used to better identify pions, thus reducing the number of misidentified decay muons incident on the calorimeter. Incident particle momenta were 1.5, 2, 3, 4, 6, and 8 GeV/c for the thinner calorimeter and 3, 4, 6, and 8 GeV/c for the thicker calorimeter. Because of the low leakage count rate with the relatively thick calorimeter configurations, the secondary level muon trigger was not implemented, and only the 4-inch lead curtain was used at the four highest energy runs. Secondary level triggers did include the electron trigger and the leakage trigger; a minimum bias (no secondary) trigger was also used for survey and normalization purposes.

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II.D.14. Limited Streamer Tubes for Muon ID

H. J. Kim, F. E. Obenshain, J. G. Kreke, and G. R. Young [ORNL]

Limited Streamer Tubes (LST) are the leading detector candidate for the muon identification section of the PHENIX detector. We have purchased 160 LST's from a commercial vendor for evaluation. The tubes are 8.4 cm wide and 148 cm long; they are being evaluated at the test facility that was set up during the summer of 1992. These LST's are rugged, reliable, simple, and inexpensive, and are widely used in experiments where charged-particle detection over large surface area is required, e.g., in hadron calorimeters, muon identifiers, etc. The magnitude and shape of cosmic-ray, gamma-ray, and beta-particle induced pulses from the plastic LST (supplied by Hodotector, Inc., of Houston, Texas) observed at the test facility are in good accord with expected results. Having completed the evaluation of detector characteristics and having determined the performance to be satisfactory, these LST's are being instrumented into a ten-layer muon identifier, interleaved with steel plates. Once assembled and thoroughly tested using cosmic rays, this prototype muon identifier will be taken to the AGS facility of Brookhaven National Laboratory for in-beam test experiments. We will study range, trajectory, shower pattern, and shower size

for relativistic charged particles that traverse or partially traverse the ten-layer detector at the AGS. We plan to utilize results from this study to design the muon identifier of the PHENIX experiment at RHIC.

II.E. Theoretical Nuclear Physics

II.E.1. Some General Constraints on Identical Band Symmetries*

M. W. Guidry [UTK]; M. R. Strayer [ORNL]; C.-L. Wu [JIHIR, UTK, and Drexel]; and D. H. Feng [Drexel]

In this paper we argue on general grounds that nearly identical bands observed for superdeformation and less frequently for normal deformation must be explicable in terms of a symmetry having a microscopic basis. We assume that the unknown symmetry is associated with a Lie algebra generated by terms bilinear in fermion creation and annihilation operators. Observed features of these bands and the general properties of Lie groups are then used to place constraints on acceptable algebras. Additional constraints are placed by assuming that the collective spectrum is associated with a dynamical symmetry, and by examining the subgroup structure required by phenomenology. We observe that requisite symmetry cannot be unitary, and that the simplest known group structures consistent with these minimal criteria are associated with the Ginocchio algebras employed in the Fermion Dynamical Symmetry Model. However, our arguments are general in nature, and we propose that they imply model-independent constraints on any candidate explanation for identical bands.

* Summary of paper submitted to *Physics Letters B*.

II.E.2. The Fermion Dynamical Symmetry Model (Review)*

C.-L. Wu [JIHIR, UTK, and Drexel]; D. H. Feng [Drexel]; and M. W. Guidry [UTK]

We have completed a major review paper on the Fermion Dynamical Symmetry Model (FDSM) for *Advances in Nuclear Physics*. In this review we have described a fundamentally new approach to nuclear structure physics. Although the FDSM stands in a rich tradition of symmetry-based theories, the kinds of dynamical symmetries and the manner in which they are used in the FDSM are unique. Previous applications of group theoretical methods to nuclear structure physics have resulted in two general classes of models. The first has a solid microscopic foundation, but is limited in applicability. The second has a less transparent microscopic foundation, but in its phenomenological applications it is descriptive of broad ranges of nuclear structure. The FDSM attempts to combine the positive attributes of both these classes, while avoiding their difficulties: it is a truncated shell model, so its microscopic pedigree is well defined, but its dynamical symmetries appear to be rich enough to encompass the basic features observed for nuclear structure in medium and heavy mass nuclei. Indeed, the examples and discussion presented in the re-

view give strong reason to believe that all of low-energy nuclear structure may be explicable in these terms.

After an introductory chapter, the second and third chapters deal with the mathematical formulation of the model, its dynamical symmetry limits, and the comparison with the Interacting Boson Model; Chapter 4 discusses the relationship with the geometrical model; Chapter 5 gives a variety of quantitative calculations of physical quantities; Chapter 6 discusses and provides extensive evidence for a new principle of collective motion termed the Dynamical Pauli Effect; Chapter 7 discusses the relationship of the FDSM to a microscopic particle-rotor model and to the traditional cranking model; Chapter 8 deals with the application of the FDSM principle to extended valence spaces termed supershells, and the application of the resulting theory to superdeformation; Chapter 9 provides a compact summary, and some provocative remarks concerning the role of microscopic dynamical symmetries in nuclear structure physics.

The emphasis in the present review is on the dynamical symmetry limits of the model and on perturbation theory about those limits. However, we lay the groundwork for, and give initial examples of, numerical computation of symmetry-breaking terms that will constitute the next stage of development for the FDSM.

* Summary of review paper in press, in *Advances in Nuclear Physics*.

II.E.3. Nuclear Superdeformation and the Supershell Fermion Dynamical Symmetry Model*

C.-L. Wu [JHIR, UTK, and Drexel]; D. H. Feng [Drexel]; and M. W. Guidry [UTK]

The one major shell fermion dynamical symmetry model (FDSM) has been extended to multiple shells. We term the resulting theory the supershell-FDSM (SFDSM). Many basic features of superdeformation emerge naturally from the SU_3 fermion dynamical symmetry of this model. It is found that the dynamical Pauli effect plays a vital role in the formation of low-lying superdeformed states, and provides a simple criterion for predicting where SD strength is most likely to occur. As an example, we show in Fig. II.E.3.1 a map of optimal regions for superdeformation that was obtained using general symmetry principles and simple estimates of single-particle energy effects that do not require detailed calculations.

The SFDSM suggests that many-body correlations that are discarded in the usual mean-field theories are responsible for the widespread occurrence of

identical bands in superdeformation. In this model the superdeformed ground band is not the usual unaligned band, but a D -pair aligned (DPA) band that sharply crosses the excited bands. We propose that the DPA band may be a key to understanding many superdeformation properties, including the sudden decay-out of superdeformed yrast intensity.

We argue that the dynamical Pauli effect also produces gaps in the deformed single-particle spectrum. Therefore, the usual contention that the stability of superdeformed shapes is associated with such gaps is given a fundamental interpretation: the gaps do not “cause” superdeformation. Instead, the dynamical Pauli effect produces gaps in the single-particle spectrum at precisely those points where it stabilizes superdeformed shapes: the gaps are symptoms, not causes.

Thus, we argue that the features of superdeformation are evidence for striking symmetries governing the dynamics of the many-fermion nuclear system. We suggest that these symmetries are so powerful that even symmetry-breaking terms such as pairing or the lifting of single-particle degeneracy are not able to substantially modify many basic symmetry-limit results.

Finally, we emphasize that the theory presented in this paper is a self-contained description of superdeformation that is an alternative to that of standard mean-field theories. We offer a new perspective that has many relations with the corresponding mean-field picture, but that in the final analysis stands independently as a comprehensive description of superdeformation physics.

* Summary of paper in press, *Annals of Physics*.

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II.E.4. The Fermion Dynamical Symmetry Model and Identical Bands*

M. W. Guidry [UTK]; C.-L. Wu [JHIR, UTK, and Drexel]; and D. H. Feng [Drexel]

We describe a new model of superdeformation based on an extension of the Fermion Dynamical Symmetry Model to supershells. The resulting theory is a microscopic, many-body approximation to the spherical shell model. Dynamical symmetries of the model lead to a microscopic particle-rotor model for which it is difficult for the single-particle energies to break the rotational dynamical symmetry, and for which reference moments of inertia are independent of particle number for localized regions of superdeformation. Microscopic estimates of expected symmetry-breaking terms suggest that these features may survive in a realistic Hamiltonian. This would provide an immediate microscopic explanation of the identical bands observed in many superdeformed

Figure II.E.3.1: A map of the most likely regions of superdeformation.

nuclei. Further approximations lead to a mean-field cranking picture in which this feature is lost, suggesting that identical bands are essentially a many-body effect.

Thus, in this paper we propose a solution of the identical band puzzle that departs substantially from the traditional viewpoint. In essence the proposed solution turns the problem on its head: identical bands are a puzzle because of our habit of thinking in mean field and liquid-drop terms. The more correct many-body physics underlying the problem favors identical bands; it is only symmetry-breaking that keeps identical bands from being more prevalent than they are. Therefore, the more profitable question to ask is why there are so few identical bands in nature. The fact that the symmetry we propose is based on the microscopic shell structure elevates the preceding statements above the level of a tautology: the microscopic basis of the symmetry allows a realistic estimate of symmetry-breaking terms. In this picture there is no fundamental difference between normal and superdeformations with respect to

identical bands. The only difference is quantitative: symmetry-breaking terms are more efficient for normal deformation than for superdeformation, and thus are more effective in obscuring the tendency toward identical bands favored by the symmetry of the collective motion.

Thus, we propose that the nuclear many-body problem can exhibit more stability in macroscopic quantities such as moments of inertia than that expected from the corresponding mean field approximation because such approximations discard important correlations present in the many-body problem. This idea assumes added weight because of the present assertions that the traditional mean field approach can be derived from the FDSM approach, and that it is precisely the approximations required to accomplish this that destroy the identical band properties. Therefore, the present conjectures suggest that the identical band problem may be tangible evidence for nuclear structure effects that go beyond the mean field.

* Summary of paper submitted to *Physical Review C*.

II.E.5. The Dynamical Pauli Effect*

M. W. Guidry [UTK]; C.-L. Wu [JHIR, UTK, and Drexel]; and D. H. Feng [Drexel]

In this paper the Dynamical Pauli Effect (DPE) of the Fermion Dynamical Symmetry Model (FDSM) is reviewed, and a variety of experimental predictions associated with the DPE are tested against available data. An example is shown in Fig. II.E.5.1. We conclude that there is strong empirical evidence from a variety of observations in support of this effect, and we suggest new experiments that can test its pervasiveness. In particular, unequivocal tests could be provided by observations of fundamental properties such as electromagnetic transition rates in nuclides that are presently unknown. Such information might become available from radioactive ion beam experiments.

It is suggested that the Dynamical Pauli Effect is a fundamental principle of many-body physics that unifies many well-known but seemingly independent properties of collective nuclear systems. For example, we argue that there is a direct link between the Dynamical Pauli Effect and the appearance of gaps in the deformed single-particle spectrum such as the ones found at nucleon numbers 98 and 152 at normal deformation, and nucleon number 64 in superdeformation.

We have shown that Dynamical Pauli Effects can often be given a simple physical interpretation in terms of a mean-field approximation to the underlying many-body theory. For example, the representation constraints for the

SU_3 dynamical symmetry of the FDSM have been shown by coherent state techniques to translate into Pauli forbidden regions of the beta-gamma deformation plane. This is directly related to the occurrence of gamma degrees of freedom in such systems. Although we have attached simple physical interpretations to Dynamical Pauli Effects by utilizing such approximations, these effects arise at the many-body level of the symmetry theory before such simplifications are made; thus, they transcend the mean-field approximations that we have employed to express them in more familiar language.

* Summary of paper submitted to *Annals of Physics*.

II.E.6. Network Calculations for the Production of Heavy Elements

R. Igharas and M. W. Guidry [UTK]; D. Dean and M. R. Strayer [ORNL]; and F.-K. Thielemann [Harvard]

Understanding the synthesis of the elements is a major goal of nuclear astrophysics. Light element synthesis in the Big Bang and the production of elements up to iron in the hydrogen burning stage of a star are much better understood than the later neutron-capture stages. The latter occur well within the last 10% of the star life cycle, and occur catastrophically. Therefore, extremely accurate hydrodynamical calculations are necessary to describe the non-equilibrium scenarios that occur, in particular the shock formation and propagation that are believed to expel the outer envelopes of the star. It is in these circumstances of high temperature and neutron fluxes that the synthesis of the heavier elements is thought to occur; the two non-equilibrium processes of importance are the s- and the r-processes.

The advent of radioactive ion beam physics implies a possibility of enhanced data quality for some input to element-production calculations, and improved theories for the extrapolation of the additional quantities required in such calculations that cannot be measured. Likewise, there are unprecedented opportunities for high-performance computation promised by the new generation of massively-parallel supercomputers. Accordingly, it is an appropriate time to evaluate the status of element-production calculations. The network codes describing the production of heavy elements in supernovae and explosive stellar burning processes have accreted over two decades and do not generally represent state of the art computation. Discussions with F. Thielemann (Harvard), J. Truran (U. Chicago), and J. Cowan (U. Oklahoma) have convinced us that there is a need for a new network code for element production that incorporates modern computational methods, and is optimized to take advan-

Figure II.E.5.1: Collective quadrupole reduced transition rates for even-even rare earth nuclei as a function of neutron valence pair number. Calculations are shown using the full fermion symmetry of the FDSM (solid lines) and in the boson approximation to this FDSM symmetry, which neglects the restrictions on representations implied by the Pauli principle (dashed line). The difference between these curves is the Dynamical Pauli Effect.

tage of the new generation of supercomputers and the increased accuracy and volume of input data that could become available in the next decade.

We have initiated a project to develop such a code. The project is still in a developmental stage, with the present effort centered on evaluating algorithms for the most efficient solution of the network of differential equations describing the production of heavy elements. Once an algorithm is adopted, we intend to write a new code for solution of this problem that will be particularly well suited to parallel systems such as the Hypercube.

The environments in which the s- and r-processes take place are of the utmost importance for the predicted element production. The calculations performed so far have normally decoupled the nucleosynthesis processes from the hydrodynamical calculations; the hydro output in terms of the neutron density, nuclei densities, and temperature profiles are parameterized as a function of time and assumed as input in the nucleosynthesis codes. While this can be justified energetically, the occurrence of heavier nuclei could affect the highly unstable shock formation and propagation through a modification of the opacity to the various energy transport mechanisms. Further, a dynamical coupling between the nucleosynthesis processes and the hydrodynamics will ascertain further the exact location of nuclear formation.

In a separate contribution to this progress report we describe the initiation of a program to calculate supernova explosions using multi-dimensional relativistic hydrodynamics. In the longer term, we may contemplate coupling the relativistic hydrodynamic code to the network code described in this contribution to produce a self-consistent calculation of element production in a supernova event.

II.E.7. Development of Relativistic Hydrodynamics for Heavy-Ion and Astrophysics Applications

Z. Eitzen [MARYLAND]*; D. Dean and M. R. Strayer [ORNL]; and M. W. Guidry [UTK]

The advance of computer technology has made it increasingly possible to perform calculations involving complicated nonlinear equations, particularly those exhibiting strong discontinuities such as shock fronts. The macroscopic equations of astrophysics, whether appearing in cosmology, stellar structure or diffuse matter, tend to fall in this class. The difficulty of describing phenomena involving multiple time and distance scales, and strong discontinuities, frequently leads to the patching together of somewhat discordant models for different regimes. The Oak Ridge theory section has developed numerical

methods for relativistic hydrodynamics that can be readily adapted to modeling supernovae and other explosive stellar processes in a more unified manner. In particular we might hope to relax the customary assumptions of spherical and cylindrical symmetry. These codes are readily adaptable to massively parallel architectures, allowing us to contemplate large three-dimensional lattices. Thus we hope to apply sufficient computer power to significantly advance the state of supernovae and nucleosynthesis modeling.

We have initiated such a program to adapt the relativistic hydrodynamics code to the calculation of supernova explosions without imposing the usual assumption of spherical symmetry. As an initial step in this adaptation, the code has been applied to calculations of relativistic heavy-ion collisions on Cray computers, and a version incorporating gravitation has been tested on the Hypercube.

We are presently discussing a collaboration to perform such calculations with S. Bruenn from Florida Atlantic University and A. Mezzacappa from the University of North Carolina. We anticipate that such two-dimensional calculations of supernova explosions would allow possible effects of angular momentum and corresponding anisotropies to be studied in the core collapse and bounce.

* UT summer Science Alliance student.

II.E.8. Optimum Pairs: A Novel Way to Portray Collective Motion within the Shell Model*

C.-L. Wu [JHIR, UTK, and Drexel]; H.-T. Chen [Chung-Yuan Christian University, Chungli, Taiwan, ROC]; and D. H. Feng [Drexel]

A pair component analysis of shell model wavefunctions suggests that the many-body wavefunction can be expressed as a simple direct product of fermion pairs, provided the structure and spins of the pairs are chosen properly. Such pairs are termed "Optimal Pairs". A generalized pair field method (GPFM) is proposed for solving many-body problems in this basis. It is demonstrated that for both the vibrational (pairing interaction) and rotational (pure $Q \cdot Q$ interaction) limits, the GPFM gives either exact or excellent approximations to the exact shell model solution for the single- j case. The more general case remains to be tested. The most attractive feature of this method is that it does not require diagonalization of huge matrices, thereby avoiding the dimensionality problems of the traditional shell model approach.

* Summary of paper submitted to *Physical Review Letters*.

II.E.9. Heavy-Ion Transfer Reactions to High-Spin States in the Particle–Rotor Model*

R. W. Kincaid and M. W. Guidry [UTK]; H. Scheeter [UTK, and Federal University, Rio de Janeiro, Brazil]; S. Landowne [Argonne National Lab]; R. Donangelo [Federal University, Rio de Janeiro, Brazil]; and G. Leander [deceased]

In this paper we present a model of one-neutron transfer reactions appropriate for cases in which one of the collision partners is deformed. The model considers rotational excitation due to the Coulomb field in the entrance channel, neutron transfer between the two nuclear surfaces at the distance of closest approach, and additional rotational excitation in the final channel. The Coulomb excitation processes are described within the sudden-limit approximation using classical-limit theory, and the transfer is described in terms of spectroscopic amplitudes obtained with the particle–rotor model.

We have applied this model of transfer to the $^{58}\text{Ni} + ^{161}\text{Dy}$ and $^{116}\text{Sn} + ^{161}\text{Dy}$ one-neutron pickup reactions – cases for which data are available. The calculations indicate that transfer into both ground and two-quasiparticle excited bands takes place and that the distribution of population in the ground band and two-quasiparticle states is in reasonable agreement with the data. Figure II.E.9.1 shows a typical result. In particular, one sees that the population of the excited quasiparticle states leads to larger average angular momentum than that for the ground band. This is a characteristic feature of the data. These results represent the first quantitative description of such experimental observations.

* Summary of published paper, *Physical Review C*.

II.E.10. Nuclear Superdeformation Data Tables*

X.-L. Han [UTK and JHPR] and C.-L. Wu [JHPR, UTK, and Drexel]

Tables are compiled that list the measured gamma-ray transition energies of 57 superdeformed bands. The corresponding rotational frequencies, dynamical moments of inertia, tentative spin assignments, static moments of inertia, and available transition quadrupole moments are also tabulated. Plots of the first and second moments of inertia versus frequency are given for each superdeformed band. A sample entry is displayed in Fig. II.E.10.1.

* Summary of paper published in *Atomic Data and Nuclear Data Tables* **52**, pp. 43-108 (1992).

Figure II.E.9.1: Calculated probabilities for transfer to the ground band and superband of ^{160}Dy by one-neutron pickup in the reaction $^{58}\text{Ni} + ^{161}\text{Dy}$ at a laboratory energy of 270 MeV.

II.E.11. The Average Nucleon Number Density in Intrinsic States of the FDSM $SU(3)$ Symmetry*

L.-A. Wu [Jilin University and UTK]; M. W. Guidry [UTK]; C.-L. Wu [JIHIR, UTK, and Drexel]; and D. H. Feng [Drexel]

By using the general definition of the nucleon number density, a formula for the nucleon number density in the $u = 0$ representations of the Sp_6 symmetry of the Fermion Dynamical Symmetry Model is derived. By comparing with corresponding expressions for the geometrical model, a deformation parameter of the FDSM can be expressed as a function of the SU_3 representation. For the ground-state rotational band the result can be expressed analytically. This result provides the relative negative sign between the quadrupole operator and the SU_3 generator. The resulting formalism allows a relationship to be established between the deformation parameters of the geometrical model

Figure H.F.10.1: Superdeformed rotational band for ^{192}Hg .

and the FDSM; thus, it constitutes a microscopic derivation of the deformation parameter and density formula of the geometrical model from a symmetry truncated shell model. These developments allow a representation of the dynamical symmetry $Sp_6 \supset SU_3$ in coordinate space in terms of the average density. Such results should be of utility in applying the algebraic FDSM to data that are conveniently visualized in terms of spatial density distributions.

* Brief summary of manuscript submitted to *Phys. Rev. C*.

II.E.12. The Polarizing Effect of $SO(6)$ Symmetry in the Fermion Dynamical Symmetry Model*

L.-A. Wu [UTK and Jilin University]; C.-L. Wu [JHIR, UTK, and Drexel]; M. W. Guidry [UTK]; and D. H. Feng [Drexel]

In this paper we address the polarizing influence of a system of SO_6 symmetry that is coupled by a quadrupole–quadrupole interaction to another independent system. The nature of such a system is important in the Fermion Dynamical Symmetry Model, which proposes that the rare-earth neutrons favor a dynamical symmetry $Sp_6 \supset SU_3$ while the rare-earth protons favor a symmetry $SO_8 \supset SO_6$, and that the neutrons and protons are strongly coupled by a quadrupole n–p interaction.

We demonstrate that γ -soft rotation, which is the geometrical characteristic of an SO_6 symmetry, may be viewed as a rotation in a set of continuous variables $(\theta, \varphi, \psi, \gamma)$ instead of the set (θ, φ, ϕ) of the usual rotational group SO_3 . The quadrupole–quadrupole interaction between the two coupled systems violates this symmetry, breaking it to the smaller symmetry SO_3 . This may be understood as the addition of an explicit symmetry breaking term to the Hamiltonian of a system whose ground state exhibits spontaneous symmetry breaking. In physical terms, if the quadrupole–quadrupole coupling is sufficiently strong, this selects a preferred direction for the variable γ (the explicit symmetry breaking), and the generalized rotation in the space $(\theta, \varphi, \psi, \gamma)$ is reduced to a rotation in the usual space (θ, φ, ψ) .

For the example of an SU_3 symmetry coupled to the SO_6 that is relevant for the structure of the rare-earth nuclei, the SU_3 symmetry favors axial symmetry with $\gamma = 0$ (if the ground state is a symmetric representation). Thus, the n–p quadrupole interaction breaks the rotational symmetry in the space $(\theta, \varphi, \psi, \gamma)$ down to axially symmetric rotations in the space (θ, φ, ψ) . This explains why the coupled $SO_6 \times SU_3$ system can behave as if it had an effective SU_3 symmetry, even though no formal dynamical symmetry exists, and

provides a justification for the previous numerical results of Wu and Vallieres [1] that indicated effective dynamical symmetries for such coupled systems.

We have constructed a Hamiltonian that can be separated into two parts: one associated with the collective motion and the other with an intrinsic motion, and we have obtained a microscopic expression for the γ -potential governing the collective motion. The corresponding equation of motion has been solved for some simple cases. These calculations are equivalent to solving a Bohr Hamiltonian with the β degree of freedom constrained to a fixed value, but with a microscopic expression for the γ -potential.

* Brief summary of paper accepted for publication in *Nuclear Physics A*.

[1] H. Wu and M. Vallieres, *Phys. Rev. C* **39** 1059 (1989).

II.E.13. Symmetry and the Origin of Nuclear Deformation*

M. W. Guidry [UTK] and C.-L. Wu [JIHIR, UTK, and Drexel]

In this paper, evidence is presented that the systematic features of nuclear deformation are determined primarily by filling of the normal-parity shell model orbitals of the valence shells, and that abnormal-parity orbitals play crucial but subsidiary roles. This contradicts much standard folklore concerning deformation, but is in accord with the point of view underlying the Fermion Dynamical Symmetry Model.

We also discuss an analogy between the origin of nuclear deformation as a spontaneous breaking of the rotational symmetry and the origin of masses in elementary particle physics resulting from a spontaneous loss of the gauge symmetry. We discuss a simple mechanical example and examples from other fields of physics illustrating that deformation is a non-perturbative effect; thus it cannot be obtained by adding one polarizing particle at a time outside closed shells.

We argue that the deformation systematics of the FDSM are consistent with those of the Nilsson model and that in the FDSM the n-p quadrupole residual interaction is responsible for deformation. The same principles applied to superdeformation indicate that abnormal-parity orbitals have a much more direct influence on superdeformation than on normal deformation.

* Summary of paper to be published in *J. Mod. Phys.*

II.E.14. FDSM Effective Interaction for Actinide Nuclei*Z.-P. Li,¹ M. Guidry,^{1,2} C.-L. Wu,^{1,3,4} X.-L. Han,^{1,3} D. H. Feng,⁴ and M. Kirson⁵

A systematic study of collective motion in the actinide region using the Fermion Dynamical Symmetry Model (FDSM) is presented. An effective interaction for the symmetry-truncated SD subspace of the FDSM is obtained by global fits to the ground state masses and first 2^+ excitation energies. This effective interaction is shown to reproduce global systematics for low-spin states of even-even actinide nuclei.

These results represent a first step toward a full shell model calculation in heavy nuclei. They demonstrate that it is possible to obtain a set of effective interaction parameters in the truncated FDSM space that give a good global description of a variety of data in the actinide region. Some parameter details may change when we include configuration mixing and symmetry breaking terms, and there will be additional parameters to be determined associated with high-spin interactions. Nevertheless, we may expect that these results will serve as guidance and a reasonable starting point for more comprehensive calculations.

* Summary of paper submitted for publication *Phys. Lett. B*.

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II.E.15. A New Microscopic View of Nuclear Deformation*Z.-P. Li,¹ M. W. Guidry,^{1,2} C.-L. Wu,^{1,3,4} and D. H. Feng⁴

The microscopic origin of deformation for heavy nuclei is discussed. Evidence is presented that for normal nuclear deformation it is the interactions in normal-parity valence orbitals that are of primary microscopic importance. We have suggested that the conventional wisdom invoking the filling of abnormal-parity orbitals as the cause of deformation is grounded in conceptual misunderstandings and is in essence a tautology, not an explanation. The abnormal-parity orbitals play important roles in deformation systematics, but (1) they are not the primary source of deformation, and (2) the most significant role played by the abnormal-parity orbitals in deformation systematics is not their splitting in the deformed field but rather their very *existence* in the valence shell.

We argue that the deformation systematics of the Fermion Dynamical Symmetry Model are consistent with those of the deformed shell model, and that the FDSM is consistent with the contention that neutron-proton quadrupole interactions are responsible for deformation. Finally, it has been suggested that application of the same principles to superdeformation leads to a qualitatively behavior for abnormal-parity orbitals; thus they play a more direct role in superdeformation than in normal deformation.

We are well aware that the basic assertions of this paper challenge strongly entrenched folklore; nevertheless, we are convinced that much of this folklore does not have a defensible microscopic basis, and that the alternative ideas we have presented merit serious consideration. These ideas have been motivated by the Fermion Dynamical Symmetry Model, but most of our arguments do not invoke assumptions that are specific to the FDSM. Therefore, we expect them to have a validity extending beyond the dynamical symmetry considerations that first gave them impetus.

* Summary of paper submitted for publication, *Phys. Rev. C*.

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II.E.16. Is There Objective Evidence for Quantized Spin Alignment in Superdeformed Nuclei?*

C.-L. Wu [UTK and Drexel]; D. H. Feng [Drexel]; and M. W. Guidry [UTK]

It is impossible to determine spins for superdeformed bands by fitting the γ -transition energies alone. It is necessary to introduce a model. By using a variable moment of inertia (VMI) model one can estimate spins but cannot rule out the possibility of a $\pm\hbar$ uncertainty. Therefore, no objective evidence exists requiring the presence of quantized spin alignment in superdeformed nuclei. An alternative hypothesis that all superdeformed nuclei in a given mass region have the same VMI core, and thus essentially no alignment until high- N Coriolis effects become significant, seems to explain the present data.

* Abstract of paper published in *Phys. Rev. CC46*, 1339 (1992).

II.E.17. Suppression of Two-Particle Transfer by a Dynamical Mottelson–Valatin Effect*

Z.-P. Li,¹ M. Guidry,^{1,2} C.-L. Wu,^{1,3,4} D. H. Feng,⁴ and R. Donangelo^{3,5}

The Fermion Dynamical Symmetry Model has been used to calculate the probability for two particle transfer as a function of collective angular momentum in deformed nuclei. We find that the two particle transfer may be significantly reduced at modest values of the collective angular momentum because of the Coriolis antipairing and dynamical Pauli effects, even though the effective gap parameter may remain large. This may be viewed as a dynamical form of the Mottelson–Valatin effect in which the gap parameters remain finite but the two-body transfer matrix elements are suppressed by the influence of the collective angular momentum. It has been suggested previously that this effect is responsible for the VMI effect, for the small fluctuations of $B(E2)$ values around the crossing point between ground band and the CAP band, and for g -factor angular momentum systematics; however, none of these effects are as dramatic as the one we show here. Because such behavior has not been predicted by traditional theories of nuclear structure, it is important both to test these ideas experimentally, and to determine whether modifications of standard theories can lead to such effects. Because the proposed effect occurs at relatively low angular momentum, it should be accessible experimentally in heavy-ion transfer reactions studied with large γ -ray arrays of the kind described in ref. [1].

* Summary of paper submitted to *Phys. Rev. C*.

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² Oak Ridge National Laboratory.

³ Joint Institute for Heavy Ion Research.

⁴ Drexel University, Philadelphia.

[1] C. Y. Wu, W. von Oertzen, D. Cline, and M. W. Guidry, *Ann. Rev. Nucl. Part. Sci.* **40** 285 (1990).

II.E.18. Electroproduction of the Roper Resonance as a Hybrid State*

Z.-P. Li [UTK]; V. Burkert [CEBAF]; and Z.-J. Li [CEBAF and VPI]

We derive the Q^2 dependence of the helicity amplitudes of the Roper resonance assuming that it is (1) a radially excited q^3 state, and (2) a q^3G hybrid baryon. Our study shows that for a hybrid baryon assignment the magnitude of the transverse helicity amplitude decreases rapidly as Q^2 increases, and

the longitudinal helicity amplitude vanishes. This behavior is quite different from the predictions of the q^3 quark potential model, which assumes a radially excited q^3 assignment. Comparison with data shows that the hybrid interpretation of the Roper is favored. Future experiments at CEBAF should be able to clearly distinguish between these two possible assignments.

* Summary of paper published in *Phys. Rev. C* **46**, 70(1992).

II.E.19. Effective Heavy Quark Theory*

F. E. Close [Rutherford Appleton Laboratory] and Z.-P. Li [UTK]

We show how heavy quark effective theory, including $1/M_Q$ corrections, may be matched onto dynamical quark models by making a specific choice of K_μ , m , and v_μ in the $p_\mu = mv_\mu + K_\mu$ expansion. We note that Wigner rotations of heavy quark spins arise at $O(p^2/m^2)$ in non-relativistic models but at $O(\Lambda_{QCD}/M_Q)$ or $O(\text{velocity-transfer})$ in HQET and so are necessary for a consistent treatment.

* Summary of paper published in *Phys. Rev. B* **289**, 143(1992).

II.E.20. Microscopic Nuclear Masses and their Astrophysical Implications*

R.-P. Wang [Drexel]; F.-K. Thielemann [Harvard]; D. H. Feng [Drexel]; and C.-L. Wu [Drexel, ORNL, and UTK]

Highly accurate level densities are predicted using masses derived from the microscopic Fermion Dynamical Symmetry Model. New features of this model predict a significantly different location of the astrophysical r-process path in the actinide region from that of the traditional mass model.

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III. Development and Organizational Projects

Development and Organizational Projects

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

Full or partial support was provided to the guests noted in Table III.1. The average length of appointment during FY 1992 for the 60 guests was over 3 months. The primary effort was made with the purpose of assisting in the creation of a nuclear structure theory effort at ORNL/UT. The mainstay of this effort was support for a senior nuclear structure theorist (Witek Nazarewicz) and support for a postdoctoral research associate (filled by Ramon Wyss until April 1992).

In line with the goal of establishing a strong nuclear structure theory effort, we have encouraged the proposal for DOE funds for theory in support of future experimentation at HHIRF when it becomes a Radioactive Ion Beam (RIB) facility. We have allotted \$50,000 of our previously approved funds and requested an additional \$20,000 from the Science Alliance to strengthen this expanding theoretical effort. We are happy that the proposal has been approved and funded; the new theory effort and the JIHIR will be important components in the study of nuclei near the proton drip line and in regions of astrophysical significance.

Support was provided for the meetings noted in Table III.2. *The International Symposium on Reflections and Directions in Low Energy Heavy-Ion Physics* celebrated operation of twenty years for UNISOR and ten years for the Joint Institute for Heavy Ion Research. Speakers at this two-day symposium reflected, in part, on the accomplishments in low-energy, heavy-ion science and emphasized the new directions and opportunities to be explored with low-

energy, heavy-ion facilities. Areas covered included properties of nuclei far from stability, high-spin states, hot dipoles, transfer, reaction mechanisms, and atomic physics. A final session focused on research at new facilities, such as one with radioactive ion beam capabilities, and on a new generation recoil mass spectrometer.

Among the developments reported at *The Second International Conference on On-Line Nuclear Orientation and Related Topics* were new initiatives to search for violations of parity and time-reversal invariance in nuclei, successful theoretical approaches leading to the understanding of $E2/M1$ mixing ratios and $M1$ moments, and the latest advances in the application of nuclear magnetic resonance to oriented nuclei. Also reported was a wealth of new spectroscopic information obtained from on-line nuclear-orientation measurements using both gamma-ray and particle detection.

The Workshop on the Microscopic Origin of Nuclear Deformation consisted of lectures on various aspects of nuclear deformation. Subjects covered included the role of proton-neutron interactions, the comparison and relation between shell model, algebraic, and geometrical pictures of nuclear deformation, and the phenomenon of spontaneous symmetry breaking. The goal was to summarize the present knowledge of the origin of nuclear deformations, and also discuss new directions in this field of research.

The purpose of *The International Workshop on Nuclear Structure Models* was to review and evaluate various theoretical approaches to nuclear structure. The first part of the workshop consisted of formal, but pedagogical, presentations on ten different groups of nuclear structure models. The second part of the workshop was devoted to evaluations of the different models.

The Satchlerfest had talks which highlighted major advances in the areas of direct, inelastic, particle-transfer, and fusion reactions, as well as dispersion relations, semiclassical scattering, effective interactions, optical models, and giant resonances. It was fitting that this meeting commemorated the 65th birthday of Ray Satchler who has been one of the major contributors to these areas over several decades.

The program of *The First Symposium on Nuclear Physics in the Universe* emphasized the new interface between astrophysics, nuclear physics, and atomic physics that is promised by radioactive ion beam facilities. This was particularly timely as the Holifield Facility is in the process of converting to this area of research.

Finally, the dormitory provided lodging for 230 guests who stayed for a total of 1425 person-nights.

Table III.1: Guest scientists at the Joint Institute for Heavy Ion Research during the period of October 1991–September 1992

Name	Institute	Length of Appointment
S. Aberg	Lund Univ. (Sweden)	6 weeks
A. Balantekin	Univ. of Wisconsin	5 days
K. Bhatt	Univ. Mississippi	17 days
J. Blankenship	ORNL/JIHIR	1 year
M. Brack	Univ. of Regensburg (Germany)	10 days
A. Bulgac	Michigan State Univ.	10 days
P. Butler	Univ. of Liverpool (England)	1 week
A. Champagne	Univ. of North Carolina	2 days
E. Chavez-Lomeli	Nat. Univ. of Mexico (Mexico)	7 months
D. Cullen	Univ. of Liverpool (England)	11 months
J. Dellwo	Univ. of Tennessee	2 months
J. Dobaczewski	Warsaw Univ. (Poland)	1 month
J. Draayer	Louisiana State Univ.	1 week
A. Faessler	Univ. Tubingen (Germany)	1 week
D. Feng	Drexel Univ.	1 week
S. Frauendorf	NBI (Denmark)	4 days
G. Gattoff	ORNL	11 months
J. Goerres	Univ. of Notre Dame	2 days
A. Goodman	Tulane Univ.	1 week
W. Greiner	Univ. of Frankfurt (Germany)	3 days
S. Gupta	Bhabha Atomic Res. Centre (India)	3 weeks
I. Hamamoto	Lund Univ. (Sweden)	10 days
K. Heyde	Inst. for Nuclear Physics (Belgium)	1 week
I. Hughes	JET Joint Undertaking (England)	8 months
V. Irby	Univ. of Missouri	9 months
R. Janssens	ANL	1 day
M. Korolija	Ruder Boskovic Inst. (Yugoslavia)	1 year
V. Madsen	Oregon State Univ.	5 months
C. Mahaux	Univ. of Liege (Belgium)	2 weeks
J. Maruhn	Univ. of Frankfurt (Germany)	19 days
F. McGowan	ORNL	1 year
J. Mueller	Univ. of Frankfurt (Germany)	1 year

Table III.1: (cont.) Guest scientists at the Joint Institute for Heavy Ion Research during the period of October 1991–September 1992

Name	Institute	Length of Appointment
P. Mueller	Univ. of Illinois	1 year
W. Nazarewicz	Warsaw Univ. (Poland)	1 year
V. Oberacker	Vanderbilt Univ.	1 week
T. Otsuka	Univ. of Tokyo (Japan)	3 days
V. Pashkevich	JINR (Russia)	10 days
S. Pittel	Univ. of Delaware	1 day
S. Rab	Kuwait Inst. Sci. Res. (Kuwait)	4 months
A. Ray	Texas A&M Univ.	3 months
S. Rohozinski	Warsaw Univ. (Poland)	10 days
S. Saini	ORNL	1 year
K. Schmid	Univ. of Tübingen (Germany)	10 days
M. Schmorak	ORNL	1 year
M. Schulz	Univ. of Missouri	13 days
M. Smith	California Inst. of Tech.	2 days
J. Stone	Oxford Univ. (United Kingdom)	1 month
N. Stone	Oxford Univ. (United Kingdom)	1 month
D. Stracener	Washington Univ.	3 days
S. Szymanski	Warsaw Univ. (Poland)	6 weeks
F. Thielemann	Harvard Univ.	1 day
M. Vallieres	Drexel Univ.	11 days
R. Vogelaar	Princeton Univ.	2 days
M. Wiescher	Univ. of Notre Dame	2 days
D. Winchell	Univ. of Pittsburgh	1 year
R. Wyss	Royal Inst. of Tech (Sweden)	8 months
P. Zeijlmans	Utrecht Univ. (The Netherlands)	11 months
V. Zelevinsky	NBI (Denmark)	10 days
J. Zhang	Inst. of Modern Phys. (China)	1 year
W. Zhao	Inst. of High Energy Phys. (China)	3 months

Table III.2: Meetings sponsored by the JIHIR during FY 1992

Meeting	Date	Attendees	Chairmen
<i>International Symposium on Reflections and Directions in Low Energy Heavy-Ion Physics</i>	October 14–15, 1991	120	J. H. Hamilton
<i>Second International Conference on On-Line Nuclear Orientation and Related Topics</i>	October 16–19, 1991	75	K. S. Krane
<i>Workshop on Microscopic Origin of Nuclear Deformation</i>	November 25, 1991	30	D. H. Feng M. W. Guidry W. Nazarewicz
<i>Workshop on Nuclear Structure Models</i>	Mar. 16–25, 1992	64	R. Bengtsson J. P. Draayer W. Nazarewicz
<i>Satchlerfest: A Symposium on Nuclear Reactions</i>	April 15–16, 1992	50	M. R. Strayer
<i>First Symposium on Nuclear Physics in the Universe</i>	September 24–26, 1992	100	M. W. Guidry M. R. Strayer

IV. List of Publications

1. "The Polarized Structure Function of the Nucleon in the Resonance Region," Z. P. Li, accepted for publication, *Phys. Rev. D*.
2. "Isotope Shift Measurements on the Neutron-Deficient Thallium Isotopes," F. Buchinger, H. A. Schuessler, E. C. Benck, H. Iimura, Y. F. Li, C. R. Bingham, and H. K. Carter, *Hyperfine Interactions* **75** (1992) 367.
3. "Alpha Decays of Light Uranium Isotopes," K. S. Toth, H. J. Kim, J. W. McConnell, C. R. Bingham, and D. C. Sousa, *Phys. Rev. C* **45** (1992) 856.
4. "Nuclear Moments of the Neutron-Deficient Thallium Isotopes," H. A. Schuessler, E. C. Benck, F. Buchinger, H. Iimura, Y. F. Li, C. R. Bingham, and H. K. Carter, *Hyperfine Interactions* **74** (1992) 13.
5. "Search for Population of Superdeformed States in ^{194}Pb Using ^{194}Bi α^+ -decay," M. A. Stoyer, E. A. Henry, J. A. Becker, R. W. Hoff, A. Kuhnert, D. Manatt, T. F. Wang, J. Breitenbach, M. Jarrio, J. L. Wood, Y. A. Akovali, C. R. Bingham, M. Zhang, P. Joshi, H. K. Carter, J. Kormicki, and P. F. Mantica, *Phys. Rev. C* **47** (1993) 76.
6. "First Results from the Fragment Mass Analyzer at ATLAS," C. N. Davids, I. Ahmad, B. B. Back, I. G. Bearden, R. R. Betts, K. Bindra, C. R. Bingham, D. J. Blumenthal, R. Broda, M. P. Carpenter, P. Chowdhury, W. Chung, B. Crowell, P. J. Daly, B. Fornal, S. J. Freeman, M. Freer, J. Gehring, Z. W. Grabowski, D. J. Henderson, R. Henry, R. V. F. Janssens, T. Lauritsen, Y. Liang, C. J. Lister, R. H. Mayer, D. M. Moltz, D. Nisius, A. V. Ramayya, J. D. Robertson, F. Scarlassara, P. Spolaore, F. Soramel, and W. B. Walters, **Proceedings of the 6th International Conference on Nuclei far from Stability**, Bernkastel-Kues, Germany, July 19-24, 1992.
7. "Investigation of Proton-Rich Platinum and Mercury Isotopes with the Fragment Mass Analyzer at ATLAS and the Isotope Separator at UNISOR," K. S. Toth, C. N. Davids, Y. A. Akovali, B. B. Back, K. Bindra, C. R. Bingham, H. K. Carter, W. Chung, Y. Hatsukawa, D. J. Henderson, T. Lauritsen, P. F. Mantica, D. M. Moltz, A. V. Ramayya, J. D. Robertson, and W. B. Walters, **Proceedings of the 6th International Conference on Nuclei far from Stability**, Bernkastel-Kues, Germany, July 19-24, 1992.
8. "Search for Low-Spin Superdeformed States in Nuclei," C. R. Bingham, M. Zhang, J. A. Becker, E. A. Henry, R. W. Hoff, A. Kuhnert, M. A. Stoyer, T. F. Wang, Y. A. Akovali, P. Joshi, T. S. Lam, D. Rupnik, E. F. Zganjar, J. Breitenbach, M. Jarrio, J. L. Wood, H. K. Carter, P. F. Mantica, and J.

Kormicki, *Nucl. Instru. and Meth. in Physics Research* (April, 1993) (in press).

9. "Lifetime of the 0_2^+ Configuration in ^{186}Hg and ^{188}Hg ," P. K. Joshi, S. J. Robinson, P. F. Mantica, E. F. Zganjar, D. Rupnik, R. L. Gill, W. B. Walters, H. K. Carter, C. R. Bingham, J. Kormicki, A. V. Ramayya, and W. C. Ma, **Proceedings of the 6th International Conference on Nuclei far from Stability**, Bernkastel-Kues, Germany, July 19-24, 1992.

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11. "Lifetime Measurements in $^{118,120}\text{Xe}$," P. F. Mantica, P. K. Joshi, S. J. Robinson, E. F. Zganjar, R. L. Gill, W. B. Walters, D. Rupnik, H. K. Carter, J. Kormicki, and C. R. Bingham, **Proceedings of the 6th International Conference on Nuclei far from Stability**, Bernkastel-Kues, Germany, July 19-24, 1992.

12. "The α -Decay Properties of Light Uranium Isotopes," K. S. Toth, H. J. Kim, J. W. McConnell, C. R. Bingham, and D. C. Sousa, **Proceedings of the 6th International Conference on Nuclei far from Stability**, Bernkastel-Kues, Germany, July 19-24, 1992.

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18. "Heavy-Ion Transfer Reactions to High-Spin States in the Particle-Rotor Model," R. W. Kincaid, H. Schechter, M. W. Guidry, S. Landowne, R. Donangelo, and G. Leander, *Phys. Rev. C* **46** (1993) .
19. "The Origin of Identical Bands," M. W. Guidry, C.-L. Wu, and D.H. Feng, submitted to *Phys. Rev. C*.
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21. "The Polarizing Effect of SO(6) Symmetry in the Fermion Dynamical Symmetry Model," L.-A. Wu, D.-L. Wu, M. W. Guidry, and D. H. Feng, submitted to *Nucl. Phys. A*.
22. "Anomalous Population of Excited States in Transfer Reactions with Heavy Ions," C. Y. Wu, X. T. Liu, M. W. Guidry, C. R. Bingham, D. Cline, T. Czosnyka, A. E. Kavka, W. J. Kernan, and S. P. Sorensen, submitted to *Phys. Lett. B*.
23. "Possible Evidence Indicating a Nuclear Josephson Effect," M. W. Guidry, X. T. Liu, C. Y. Wu, C. R. Bingham, D. Cline, T. Czosnyka, A. E. Kavka, and W. J. Kernan, submitted to *Phys. Rev. C*.
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27. "A New Microscopic View of Nuclear Deformation," Z. P. Li, M. W. Guidry, C.-L. Wu, and D. H. Feng, submitted to *Phys. Rev. C*.
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41. "Tracking Intruder States," L. L. Riedinger, W. F. Mueller, and C.-H. Yu, **Proceedings of Int. Conf. on Nucl. Struc. at High Angular Momentum**, Ottawa, Canada, May 1992, to be published.
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43. "Effects of Intruder States in Ir Nuclei," H. Q. Jin, C. R. Bingham, M. P. Carpenter, V. P. Janzen, L. L. Riedinger, C. H. Yu, L. Zhou, P. B. Semmes, J. Y. Zhang, M. A. Riley, C. Baktash, M. L. Halbert, N. R. Johnson, I. Y. Lee, and F. K. McGowan, to be submitted to *Physical Review C*.
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57. "Intermittency in $^{32}\text{S}+\text{S}$ and $^{32}\text{S}+\text{Au}$ Collisions at the CERN SPS," M. A. Bloomer, P. Jacobs, R. Albrecht, T. C. Awes, P. Beckmann, F. Berger, D. Bock, R. Bock, G. Claesson, G. Clewing, R. Debbé, L. Dragon, A. Eklund, R. L. Ferguson, S. Fokin, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, O. Hansen, M. Hartig, G. Hoelker, J. Idh, M. Ippolitov, K. H. Kampert, K. Karadjev, B. W. Kolb, A. Lebedev, H. Loehner, I. Lund, V. Manko, B. Moskowitz, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, F. Plasil, A. M. Poskanzer, M. Purschke, H. G. Ritter, B. Roters, S. Saini, R. Santo, H. R. Schmidt, K. Soderstrom, S. P. Sorensen, K. Steffens, P. Steinhauser, E. Stenlund, D. Stueken, A. Twyhues, A. Vinogradov, and G. R. Young, **Proceedings of Ninth International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions (Quark Mater '91)**, Gatlinburg, TN, November 11-15, 1991, *Nucl. Phys.* **A544** (1992) 543c-546c.

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E. Stenlund, D. Stueken, M. L. Tincknell, and G. R. Young, **Proceedings of The 25th International Conference on High Energy Physics**, Singapore, August 208, 1990, South East Asia Theoretical Physics Association and Physical Society of Japan, 1991.

62. "Transverse and Forward Energy Measurements in Nucleus-Nucleus Collisions at 60 and 200 GeV/Nucleon," S. P. Sorensen, R. Albrecht, T. C. Awes, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, G. Clewing, L. Dragon, A. Eklund, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, J. Idh, P. Jacobs, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Loehner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, F. Plasil, A. M. Poskanzer, M. Purschke, H. G. Ritter, S. Saini, R. Santo, H. R. Schmidt, T. Siemiarczuk, E. Stenlund, M. L. Tincknell, and G. R. Young, **Proceedings of Hadron Structure '91 (Physics and Applications, Vol. 16)**, Stara Lesna, Czechoslovakia, September 16-20, 1991, Slovak Academy of Sciences, Brastislava, Czechoslovakia, 1991.

63. "Nuclear Stopping Power," S. P. Sorensen, R. Albrecht, T. C. Awes, C. Baktash, P. Beckmann, F. Berger, R. Bock, G. Claesson, G. Clewing, L. Dragon, A. Eklund, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, J. Idh, P. Jacobs, K. H. Kampert, B. W. Kolb, P. Kristiansson, I. Y. Lee, H. Loehner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, F. Plasil, A. M. Poskanzer, M. Purschke, H. G. Ritter, S. Saini, R. Santo, H. R. Schmidt, T. Siemiarczuk, E. Stenlund, M. L. Tincknell, and G. R. Young, **Proceedings of The XXI International Symposium on Multiparticle Dynamics**, Wuhan, China, September 23-27, 1991, World, Scientific Publishing, Singapore, 1992.

64. "Lifetimes of the Low Spin States In the Superdeformed Band of ^{192}Hg ," I.Y. Lee, C. Baktash, D. Cullen, J.D. Garrett, N.R. Johnson, F.K. McGowan, D.F. Winchell and C.-H. Yu, **Proceedings of Int. Conf. on Nuclear Structure at High Angular Momentum**, Ottawa, May 1992.

65. "Transition Probabilities up to $I = 36^+$ in ^{160}Yb ," N.R. Johnson, F.K. McGowan, D.F. Winchell, J.C. Wells, C. Baktash, L. Chaturvedi, W.B. Gao, J.D. Garrett, I.Y. Lee, W.C. Ma, S. Pilotte and C.-H. Yu, **Proceedings of Int. Conf. on Nuclear Structure at High Angular Momentum**, Ottawa, May 1992.

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Even-Even Isotopes,” H. Xie, J.D. Garrett, F.K. McGowan, C.-H. Yu, C. Baktash, J.H. Hamilton, N.R. Johnson, I.Y. Lee, J.C. Wells, and R. Wyss, to be submitted to *Nucl. Phys. A*.

IV.A. Abstracts at Meetings

1. “First Results from the Fragment Mass Analyzer at ATLAS,” C. N. Davids, B. B. Back, R. R. Betts, K. Bindra, W. Chung, M. Freer, J. Gehring, D. J. Henderson, W. Kutschera, T. Lauritsen, C. R. Bingham, D. M. Moltz, A. V. Ramayya, J. D. Robertson, K. S. Toth, and W. B. Walters, *Bull. Am. Phys. Soc.* **37** (1992) 1021.
2. “Decay of Mass-Separated ^{199}Bi : Nuclear Structure of ^{199}Pb ,” M. Zhang, C. R. Bingham, J. King, B. E. Zimmerman, H. K. Carter, J. Kormicki, P. Mantica, L. Rayburn, P. Joshi, J. L. Wood, and S. Shastry, *Bull. Am. Phys. Soc.* **37** (1992) 1321.
3. “Alpha Decay Branching Ratios for ^{188}Pb ,” J. D. Richards, C. R. Bingham, B. E. Zimmerman, Y. A. Akovali, K. S. Toth, and H. K. Carter, *Bull. Am. Phys. Soc.* **37** (1992) 1658.
4. “On-Line Nuclear Orientation of Light Sb and I Nuclides,” B. E. Zimmerman, W. B. Walters, P. F. Mantica, Jr., H. K. Carter, M. G. Booth, J. Rikovska, N. J. Stone, C. R. Bingham, and B. D. Kern, *Bull. Am. Phys. Soc.* **37** (1992) 1659.
5. “Photon Measurements and Global Event Characteristics from Nucleus-Nucleus Collisions at 60 and 200 GeV/Nucleon,” F. Plasil, R. Albrecht, T. C. Awes, C. Baktash, P. Beckmann, F. Berger, M. Bloomer, D. Bock, R. Bock, G. Claesson, G. Clewing, L. Dragon, A. Eklund, R. L. Ferguson, A. Franz, S. Garpman, R. Glasow, H. A. Gustafsson, H. H. Gutbrod, M. Hartig, G. Hoelker, J. Idh. P. Jacobs, K. H. Kampert, B. W. Kolb, H. Loehner, I. Lund, F. E. Obenshain, A. Oskarsson, I. Otterlund, T. Peitzmann, S. Persson, A. M. Poskanzer, M. Purschke, H. G. Ritter, B. Roters, S. Saini, R. Santo, H. R. Schmidt, R. Schmidt, T. Siemiarczuk, S. P. Sorensen, K. Steffens, P. Steinhauser, E. Stenlund, D. Stueken, M. L. Tincknell, A. Twyhues, and G. R. Young, abstract of contributed paper of XXVI International Conference on High Energy Physics, Dallas, Texas, August 6-12, 1992.

6. "Signature of Multiple Collisions in Proton-Nucleus Reactions," C. C. Shih, X. C. He, J. Y. Zhang, S. P. Sorensen, and C. Y. Wong, abstract of The Ninth International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions (Quark Matter '91), Gatlinburg, TN, November 11-15, 1991.
7. "Study of the Stopping Power," J.-Y. Zhang, X.-C. He, C. C. Shih, S. P. Sorensen, and C.-Y. Wong, *Bull. Am. Phys. Soc.* **37** (1992) 931.
8. "Search for Berry's Phase Effects in Deformed Nuclei," K. G. Helmer, C. Y. Wu, D. Cline, A. E. Kavka, W. J. Kernan, E. G. Vogt, M. W. Guidry, X. L. Han, R. W. Kincaid, X. T. Liu, H. Schecter, J. O. Rasmussen, A. Shihab-Eldin, M. A. Stoyer, and M. L. Halbert, I. Y. Lee, *Bull. Am. Phys. Soc.* **37** (1992) 871.
9. "Linearity of Nuclear Energies with the P-Factor," D. S. Brenner, R. F. Casten, W.-T. Chou, J.-Y. Zhang, K. Heyde, and N. V. Zamfir, *Bull. Am. Phys. Soc.* **37** (1992) 1321.
10. "A Systematic Analysis of the Energy Signature Splitting in the $\nu i_{13/2}$ Subshell," W. M. Mueller, J. Avakian, H.-Q. Jin, L. L. Riedinger, C.-H. Yu, *Bull. Am. Phys. Soc.* **37** (1992) 979.
11. "Observation of Superdeformation in ^{191}Tl ," C.-H. Yu, S. Pilotte, J. M. Lewis, L. L. Riedinger, I. Bearden, M. P. Carpenter, R. V. F. Janssens, T. L. Khoo, Y. Liang, T. Lauritsen, F. Soramel, *Bull. Am. Phys. Soc.* **37** (1992) 1029.
12. "Rotational Bands in ^{191}Tl ," J. M. Lewis, S. Pilotte, C.-H. Yu, L. L. Riedinger, C. Baktash, J. D. Garrett, N. R. Johnson, I. Y. Lee, F. K. McGowan, *Bull. Am. Phys. Soc.* **37** (1992) 1029.
13. "Six Superdeformed Bands in ^{192}Tl ," Y. Liang, M. P. Carpenter, R. V. F. Janssens, I. Ahmad, R. Henry, T. L. Khoo, T. Lauritsen, F. Soramel, S. Pilotte, J. M. Lewis, L. L. Riedinger, C.-H. Yu, U. Garg, W. Reviol, I. G. Bearden, *Bull. Am. Phys. Soc.* **37** (1992) 1285.
14. "High Spin Studies of ^{181}Au ," C.-H. Yu, H. Q. Jin, J. M. Lewis, W. F. Mueller, L. L. Riedinger, C. Baktash, J. D. Garrett, N. R. Johnson, I. Y. Lee, F. K. McGowan, D. Winchell, *Bull. Am. Phys. Soc.* **37** (1992) 1308.
15. "High-Spin Single-Particle Structure in ^{193}Hg ," J. K. Deng, W. C. Ma, J. H. Hamilton, J. D. Garrett, C. Baktash, N. R. Johnson, I. Y. Lee, F. K. McGowan, S. Pilotte, C. H. Yu, *Bull. Am. Phys. Soc.* **37** (1992) 1285.

16. "Rotational Bands in ^{191}Tl ," J. M. Lewis, S. Pilotte, C.-H. Yu, L. L. Riedinger, C. Baktash, J. D. Garrett, N. R. Johnson, I. Y. Lee, F. K. McGowan, *Bull. Am. Phys. Soc.* **37** (1992) 1659.
17. "A Systematic Analysis of Energy Signature Splitting in the $\nu i_{13/2}$ Subshell," W. F. Mueller, L. L. Riedinger, C.-H. Yu, J.-Y. Zhang, *Bull. Am. Phys. Soc.* **37** (1992) 1660.

IV.B. Invited Talks

C. R. Bingham

"Search for Low-Spin Superdeformed States in Nuclei," Twelfth International Conference on the Application of Accelerators in Research and Industry, Denton, TX, November 2-5, 1992.

M. W. Guidry

"The Fermion Dynamical symmetry Model and Superdeformation," International Conference on Nuclear Structure and Nuclear Reactions, Dubna, Russia, September, 1992.

"A solution of the Shell Model for All Nuclei," First Symposium on Nuclear Physics in the Universe, Oak Ridge, Tennessee, September, 1992.

"An Algebraic Theory of Shape Coexistence," Symposium on Nuclear Physics in Our Times, Sanibel Island, Florida, November, 1992.

L. L. Riedinger

"Tracking Intruder States," International Conference on Nuclear Structure at High Angular Momentum, Ottawa, Canada, May 19-21, 1992.

"Tracking the Effects of Intruder States in Nuclei," Symposium on Nuclear Shapes, American Chemical Society Meeting, Washington, D.C., August 23-28, 1992.

"Intruder States at High Spins," Symposium on Nuclear Physics of Our Times, Sanibel Island, Fl, November 17-21, 1992.

S. P. Sorensen

“Global Aspects of High Energy Nuclear Collisions,” LAMPF Summer School on Nuclear Physics, Los Alamos National Laboratory, NM, August 10-14, 1992.

“Measurements of Transverse and Forward Energy in High Energy Nuclear Collisions,” 2nd International Conference on Physics and Astrophysics of the Quark-Gluon Plasma, Calcutta, India, January 19-23, 1993.

C. L. Wu

“The Composite Particle Representation Approach to the Boson Mapping,” Workshop on the Spurious States in Boson Mapping, Philadelphia, PA, May 1-2, 1992.

“The Optimum Pair Basis in the Nuclear Shell Model,” Symposium in Honor of T. T. S. Kuo, Stony Brook, NY, May, 1992.

“Pauli Effects in Dynamical Symmetries,” Workshop on Algebraic Methods in Quantum Physics, Philadelphia, PA, January, 1993.

IV.C. Colloquia

L. L. Riedinger

“Intruder States—Their Important Role For Normal and Superdeformed Rotational Bands in Nuclei,” University of Kentucky, KY, April 2, 1992.

C. H. Yu

“High Spin Spectroscopy and Nuclear Shapes,” Department of Physics, University of Rochester, Feb., 1992.

J. Y. Zhang

“Identical Bands at Normal Deformation: Challenge to the Traditional Theory,” Brookhaven National Lab, NY, November 15, 1992.

Z. P. Li

“ Q^2 Extension of the DHG Sum Rule,” York University, Canada, May, 1992.

“ Q^2 Extension of the DHG Sum Rule,” Carnegie-Mellon University, Pitts-

burgh, May, 1992.

“Polarized Structure Function of the Nucleon in the Resonance Region,” Oak Ridge National Lab., TN, August, 1992.

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