The Structure of Nuclei Far From Stability

Final Progress Report

E. F. Zganjar

Department of Physics and Astronomy
Louisiana State University
Baton Rouge, Louisiana 70803-4001

For the Grant

DE-FG05-84ER40159

Prepared for the
U. S. Department of Energy
under
Grant No. DE-FG05-84ER40159

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Table of Contents

I.	Introduction and Overview.....	1
II.	Reports	7
	A. Published or in press	7
	B. Submitted.....	10
	C. In preparation.....	10
III.	Scientific Program.....	12
	A. Charged particle spectroscopy	12
	1. Collaborations where LSU personnel served as principal investigators	
	• Search for the β -delayed proton emission of ^{69}Kr at ANL.....	12
	• Search for the α -decay of ^{190}Po at LBNL	14
	• Study of the $^{189\text{m}}\text{Bi}$ α decay at LBNL	16
	• Search for ^{180}Pb at LBNL	19
	2. Collaborations where LSU personnel did not serve as principal investigators	
	• α -decay study of light Pb isotopes at ANL	21
	• Search for heavy proton emitters at ANL.....	22
	• Search for shape coexistence in ^{188}Pb at ANL	23
	B. Nuclear structure	24
	1. A review: electric monopole transitions, shape coexistence, and nuclear structure.....	24
	2. Collaborations where LSU personnel served as principal investigators	
	• Lifetimes of the 0_2^+ states in $^{186,188}\text{Hg}$	32
	• Coexistence effects in ^{187}Au : evidence for nearly identical diabatic intruder structures	33
	• Coexisting band structures in ^{187}Au	36

• Decay of mass-separated ^{189m}Hg and ^{189g}Hg to ^{189}Au	42
• Search for superdeformed States in $^{190,192}\text{Hg}$	47
• The strength of electric monopole transitions and the decay out of the superdeformed bands.	49
• Electric monopole transitions: a review.....	52
3. Collaborations where LSU personnel did not serve as principal investigators.	
• Search for superdeformed states in ^{194}Pb	52
• Nuclear orientation and spectroscopic studies of the decay of ^{187}Pt to ^{187}Ir	53
• Decay chains of ^{202}Fr and ^{204}Fr and α -decay branches.....	54

IV. HRIBF support and Instrumentation

A. RIB development/support

1. RIB in source components	56
2. RIB ion source test components.....	58
• The isotope separator	58
• The 300 KV diagnostic system	58

B. RMS development/support

1. General purpose equipment.....	58
• The moving tape system.....	58
• The DSSD Chamber	63
• The RMS end station	65
2. Specific purpose equipment.....	65
• Picosecond lifetime system	65
• Conversion electron and internal pair spectrometers	67

I. Introduction and Overview

From among a number of important nuclear structure results that have emerged from our research program during the past few years, two stand out as being of extra significance. These are: a) the identification of a diabatic coexisting structure in ^{187}Au which arises solely from differences in proton occupation of adjacent oscillator shells, and b) the realization of a method for estimating E0 strength in nuclei and the resulting prediction that the de-excitation of superdeformed bands may proceed, in some cases, by strong E0 transitions. Both of these were done in collaboration with J. L. Wood (Georgia Tech), with whom the P.I. has had a long-standing collaboration.

While continuing to build upon the base of nuclear structure research carried out at the former UNISOR facility, we began the transition to a research program based on the utilization of radioactive ion beams (RIBs). In addition to modifying the nuclear structure aspects of the program to take advantage of the new opportunities which will be available at the Holifield Radioactive Ion Beam Facility (HRIBF), and elsewhere, we initiated a program in charged particle spectroscopy. With one of the main advantages of RIBs being the ability to reach the proton drip line at high Z , it was felt that this type of spectroscopy was not only important in itself, but also as a precursor to nuclear structure studies on the participating nuclei. To accomplish this, Jon Batchelder from the Cerny/Moltz group at Lawrence Berkeley Laboratory, innovators in charged particle spectroscopy, joined the LSU group as postdoctoral research associate. Jon serves as the LSU group's PI on charged-particle spectroscopy experiments. Since the principal instruments for this type of work at HRIBF will be the HRIBF recoil mass spectrometer (RMS) and double-sided silicon-strip detectors (DSSDs), Jon has conducted several and participated in a number of experiments on the fragment mass analyzer (FMA) at Argonne National Laboratory (ANL). A great deal of appreciation must be extended to ANL and particularly to Cary Davids for assistance in providing all members of the LSU group the opportunity to become familiar with these instruments and the methods relevant to this type of research.

The raw statistics on progress for the past three years include 37 papers/reports either published or submitted. These break-down into 15 journal publications (10 published and 5 submitted), 4 invited papers at international conferences, 6 conference proceedings, 2 Ph.D. theses, and 11 other items (e.g. Bull. Am. Phys. Soc. and progress reports). These are presented in Section II, along with some items that are in preparation.

Since Jon Batchelder joined the group in February, 1994, we have been involved in 7 charged particle studies (experiments or series of experiments), four at Argonne National

Laboratory (ANL) and three at Lawrence Berkeley National Laboratory (LBNL). For 4 of these studies, the LSU group served as principal investigators (3 at LBNL and 1 at ANL). As indicated above, the work at ANL involved a dual purpose: first, to make some important measurements and second, to gain experience in the use of DSSD and RMS systems in preparation for work at HRIBF using radioactive ion beams and the RMS.

Several sets of experiments to search for ground state proton emission from heavy emitters near $Z=82$ were carried out at the ATLAS facility at ANL using the FMA and DSSDs (C. Davids principal investigator). These were extremely productive experiments with ^{165}Ir , $^{165\text{m}}\text{Ir}$, ^{166}Ir , ^{167}Ir , ^{171}Au , and ^{185}Bi being identified, for the first time, as ground-state proton emitters. Another experiment at ANL to probe the proton drip line (J. Batchelder principal investigator) focused on the search for β -delayed proton emission from ^{69}Kr . For nuclei with Z larger than 30, the $T_Z = -3/2$ series of strong β -delayed proton emitters comprises the lightest isotopes observed, all of which were discovered through their β -delayed proton emission. While no β -delayed proton emission from ^{69}Kr was observed, a production cross section of $<100\text{nb}$ was measured. Radioactive ion beams will allow the study of many new β -delayed proton emitters that are exceedingly difficult to reach using stable beam/target combinations. Of particular interest are those nuclei near the proton drip line with $44 \leq Z \leq 49$. The study of the decay properties of these nuclei will provide clues as to the nature of the extended astrophysical r -p and p -processes in this region.

The remaining charged particle studies could actually be classified under nuclear structure, but to facilitate the reader's review of our program, they are included in part A of Section III. In the spherical shell model, the proton $1h_{9/2}$ orbital lies above the $Z=82$ closed shell while the proton $3s_{1/2}$ lies below. Any $1h_{9/2}$ configuration in $Z<82$ nuclei and $3s_{1/2}$ configuration in $Z>82$ nuclei are referred to as proton "intruder" states. As we show in part B of section III, a great deal of recent work has identified the $3s_{1/2}$ and $1h_{9/2}$ intruder configurations in odd-A Bi, Tl, and Au isotopes, and demonstrated a parabolic dependence of their excitation energies with a minimum when the neutron number is midway between major neutron shells. Our work on $^{189\text{m}}\text{Bi}$ α decay clearly indicates that, at least down to neutron number 106, the $3s_{1/2}$ intruder exhibits, in contrast to other reports, the same parabolic shape as the $h_{9/2}$ intruder. Along these same lines, α decay measurements to search for shape coexisting configurations in the even-even nuclei of the $Z=82$ region (arising principally for $h_{9/2}$ proton pair excitations) by searching for excited 0^+ states have been initiated for the case of ^{188}Pb by searching for the fine structure in the α decay of ^{192}Po (C. Bingham principal investigator). As one proceeds further from stability in this region, α -particle spectroscopy provides the only adequate tool for such studies. These ideas will be discussed further in the renewal document to which this progress report is attached.

In addition α particle spectroscopy to search for proton intruder configurations at $Z=82$, experiments to study the magnitude of the $Z=82$ shell gap for nuclei midway between neutron shells took place at ANL and LBNL. If the $Z=82$ shell gap is indeed diminished for $N=104-110$, the reduced α widths (δ^2) would delineate the extent of the stability of the shell gap. These experiments were done on ^{190}Po and ^{180}Pb . While data were obtained on the ^{190}Po decay at LBNL, no evidence for α particles arising from the ^{180}Pb decay were observed. A proposal for a 4-day run at the ANL FMA using DSSD systems to search for ^{180}Pb α decay has been approved by the PAC. All these charged particle experiments are discussed in detail in Section III.A.

Section III.B.1 (A review) is presented in order to provide the reader with a short review of electric monopole transitions and shape coexistence which are the major topics discussed in sections III.B.2 and III.B.3. The first two topics addressed in Section III, “Lifetimes of the $0_2^\pm$ configuration in ^{186}Hg and ^{188}Hg ” and “Coexistence effects in ^{187}Au : evidence for nearly identical diabatic intruder states” were Ph.D. thesis projects of LSU students P. Joshi and D. Rupnik, respectively.

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. Electric monopole transitions result from the penetration of the nucleus by an atomic electron and, thus, unlike the other conversion processes, they carry direct information on the nuclear wavefunction. Changes in the nuclear radius lead to non-vanishing values for the monopole strength function, ρ^2 , which can be determined from the partial half-life of the E0 transition. For many nuclei, such a measurement is quite difficult due to the lifetimes being in the picosecond range and the lack of photons for fast-timing. A picosecond lifetime system, designed to accommodate the cases where nuclear levels decay only by E0 internal conversion, was developed. This enabled us to determine the lifetime of the $0_2^\pm$ levels in $^{186,188}\text{Hg}$. The measured $\rho^2(\text{E0})$ values indicate mixing of the $\pi 2h$ ground state and the $\pi(2p-4h)$ deformed excited configuration $(\pi h_{9/2})^2$ to be 1% and >4% respectively.

Our work on ^{187}Au demonstrated that it is often necessary to go to *completeness* in the spectroscopy in order to extract the relevant physics. Without doubt, that work (D. Rupnik) represents a benchmark in completeness and is one of the most detailed spectroscopic analyses of a radioactive-decay sequence to date. One of the most interesting aspects of the identification of the multiple coexisting structures in ^{187}Au was the identification and location of the bands built on the $h_{9/2}$ and $f_{7/2}$ single-particle orbitals. The intriguing aspect of these data came out of the detailed analysis of the $h_{9/2} \oplus f_{7/2}$ structure. Experimentally, five enhanced E0 transitions that connect only favored $I_1 \rightarrow I_2$ levels ($1/2^-$, $5/2^-$, ...) between the bands were identified. E0 enhancement as not observed between the unfavored $I_1 \rightarrow I_2$ levels ($3/2^-$, $7/2^-$, ...). Analysis

of the favored and unfavored bands within the particle-plus-triaxial-rotor model (PTRM) was able to show that different single particle content in the two configurations (favored and unfavored) is directly responsible for the enhancement and attenuation of the E0 matrix element. These bands in ^{187}Au represent a spectacular example of nuclear coexistence. In spite of rather similar deformation and similar rotational behavior, they can be characterized by different numbers of $N=5$ proton intruders. In contrast to the situation in the neighboring Tl isotopes where the presence of aligned and strongly coupled bands suggest prolate-oblate shape coexistence, the two coexisting structures in ^{187}Au can be associated with near-prolate shapes. This interpretation is consistent with the absence of E0 transitions between unfavored levels. Theoretically, the case of ^{187}Au amplifies the role of the $N=5$ proton intruder occupations in defining *adiabatic* configurations in the Pt-Pb region.

The results of rather complete spectroscopy on the $^{189\text{m,g}}\text{Hg} \rightarrow ^{189}\text{Au}$ decay was also completed as a complement to the ^{187}Au results in that $^{189}\text{Au}/^{187}\text{Au}$ represents the “switchover” point where the Pt core (for $h_{9/2}$ and $f_{7/2}$ proton intruders) changes from a nearly spherical ground state (^{188}Pt) to a deformed ground state (^{186}Pt). Because of this, low energy E0 transitions like those seen in ^{187}Au were not expected in ^{189}Au . The results confirmed this, with only one weak 1268 KeV E0 transition identified, which could, in fact, be the expected $9/2^- \rightarrow 9/2^-$ transition based upon the $0_2^-(\text{deformed}) \rightarrow 0_1^+(\text{spherical})$ transition in ^{188}Pt .

Considerable effort went into searches for population of superdeformed states via β decay. These experiments were performed on $^{190,192}\text{Hg}$ and ^{194}Pb where superdeformed bands at low energy (3-6 MeV) and down to low spin (8^+ in one case) had been observed via in-beam spectroscopy. Specialized equipment was constructed and an active program in internal-pair spectroscopy was initiated in order to facilitate these experiments. The various approaches included: $e^- - \gamma$, $e^- - e^-$, $e^- - e^- - \gamma$, $e^- - e^+$, $e^- - e^+ - \gamma$, $e^- - e^+ - x$, $e^- - e^+ - 511$, $e^- - e^+ - 511 - \gamma$, and $e^- - e^+ - 511 - x$ correlations. The results of all these measurements only allowed us to set upper limits on the extent to which β decay populated these superdeformed states. It is not greatly surprising that such an allowed or first-forbidden β decay would have an additional “shape” hindrance. Had even a slight population been observed in at least one case, however, the results would have not only *located* the superdeformed band in the energy scheme, but would also have shed light on the hindrance associated with the shape transition.

The decay out of superdeformed bands occurs through mixing with weakly deformed states. Using the standard recipes for electromagnetic decay, we were able to make estimates for the decay modes of superdeformed bands. Estimates for E0 decay branches from superdeformed bands suggests that a direct search for such decay is well worthwhile. Experimentally, of course, this should be done via in-beam spectroscopy. Whether the E0 strength will be concentrated in a few transitions or spread over many transitions (possibly

forming a continuum) can only be revealed by experiment. This is discussed further in the proposal document to which this progress report is attached.

A sizable amount of effort has gone into a major review of E0 transitions. This is being done in collaboration with Kris Heyde (Gent) and John Wood (Georgia Tech.). We hope to complete the review in calendar 1996. All these topics are discussed further in Section III.

As indicated above, the major effort of the group during the past three years involved preparation for experiments with radioactive ion beams (RIBs) at HRIBF. In addition to direct planing (e.g. study, PAC proposals, etc.) and expertise building (e.g. experiments at ANL), we have assisted in the design and construction of components for RIB production/analysis and instrumentation for spectroscopy with the RMS (see Section IV). For example, the LSU Department of Physics Machine Shop produced over 200 RIB ion source components out of materials such as tungsten, tantalum, molybdenum, and carbon. Additional components were produced for the isotope separator and the 300 kV diagnostics system, both of which are used to analyze the operation of the RIB ion sources.

A major effort has gone in to the development of a state-of-the-art moving tape system for use at the focal plane of the RMS or DRMS (Daresbury separator - for astrophysics). The unit is designed so that different configurations can be readily assembled to meet the varied requirements at both the RMS as well as at the detector stations. Experimenter designed modules at each of these positions can be easily attached with "standardized" KF-50 *Klamp Flange* vacuum couplings. This unit will become part of the HRIBF facility and available to all users.

The LSU and University of Tennessee groups are collaborating on the design and construction of a DSSD chamber for use with the RMS at HRIBF. The chamber is essentially a rectangular cube with the back plate containing the DSSD and all the electronic and refrigeration components. The remaining 5 plates can be customized as desired by the experimenter, but in the first version, the top and bottom plates contain the calibration source insertion device and the vacuum pump-out port, respectively. This unit will become part of the HRIBF facility and available to all users.

The picosecond lifetime system designed and constructed at LSU, and mentioned above in regard to $\rho^2(E0)$ measurements, is being modified and adapted to the program of research using RIBs. Steve Robinson (Tennessee Tech.) has taken over the lead in these modifications and innovations.

Finally, the major instrumentation for spectroscopy performed by our group has been the internal conversion (IC) spectrometers which we have designed and constructed over the years. As mentioned above in regard to searches for superdeformation, we recently implemented internal-pair (IP) measurements as a spectroscopic tool and designed several systems to carry

out such studies. A dramatic improvement in performance for both IC and IP was obtained by the innovation where the cryogenic, high resolution, wide band, Si(Li) crystals could be “serviced”, both electronically and cryogenically, from “edge-on”. With this arrangement, the Ge γ -ray detectors can be placed directly behind the Si(Li) crystals. In planning for experiments with RIBs, it became obvious, due to the lower beam intensity available with RIBs, that even greater efficiencies would be required. A high efficiency system for both IC and IP spectroscopy, containing 3 Si(Li) crystals that reside on the same side of the moving tape and also serviced “edge-on”, is under development. This is discussed further in the renewal document to which this progress report is attached.

II. Reports

Listed below are the reports, that have emerged during the period of this award (1993 - 1995) under U. S. Department of Energy grant DE-FG05-84ER40159. Entries are numbered as DOE/ER/40159-190 through DOE/ER/40159-228.

A. Published or in press

Journals

- 190 "Search for Population of Superdeformed States in ^{194}Pb Using ^{194}Bi β^+ Decay," M.A. Stoyer, E.A. Henry, Y.A. Akovali, J.A. Becker, C.R. Bingham, J. Breitenbach, H.K. Carter, R.W. Hoff, M. Jarrio, P. Joshi, J. Kormicki, A. Kuhnert, P.F. Mantica, T.F. Wang, J.L. Wood, and M. Zhang, Phys. Rev. C47, 76 (1993).
- 196 "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, Jr., and J. Kormicki, Nucl. Inst. Meth. in Phys. Res., B79, 309 (1993).
- 197 "Lifetimes of the 0_1^+ Configuration in ^{186}Hg and ^{188}Hg ," P.K. Joshi, E.F. Zganjar, D. Rupnik, S.J. Robinson, P.F. Mantica, H.K. Carter, R.L. Gill, W.B. Walters, C.R. Bingham, J. Kormicki, A.V. Ramayya, W.C. Ma, and J.H. Hamilton, Intl. J. Mod. Phys., 3E (June, 1994).
- 198 "Picosecond Lifetime Measurement Systems for Levels populated by Electron Capture and for Levels Decaying by $E0$ Transitions," P.K. Joshi, E.F. Zganjar, S.J. Robinson, and P.F. Mantica, to Nucl. Inst. Meth. in Phys. Res. A335, 461 (1993).
- 203 "Nuclear Orientation and Spectroscopic Studies of the Decay of ^{187}Pt to ^{187}Ir ," M. A. Gummin, K. S. Krane, Y. Xu, T. Lam, E. F. Zganjar, J. B. Breitenbach, B. E. Zimmerman, H. K. Carter, and P. F. Mantica, Phys. Rev. C (in press).
- 207 "Target Selection for the HRIBF Project", J. Dellwo, G.D. Alton, J.C. Batchelder, J. Breitenbach, H.K. Carter, J.A. Chediak, G. di Bartolo, S. Ichikawa, K. Jentoff-Nilsen, and J. Kormicki, Nucl. Instr. Meth. Phys. Res. B99, 335 (1995).
- 208 "Coexistence Effects in ^{187}Au : Evidence for Nearly Identical Diabatic Intruder Structures," D. Rupnik, E.F. Zganjar, J.L. Wood, P.B. Semmes, and W. Nazarewicz, Phys. Rev. C51, R2867 (1995).
- 212 "Excitation Energy of the $\pi s_{1/2}$ Intruder State in ^{189}Bi ", J.C. Batchelder, K.S. Toth, D.M. Moltz, T.J. Ognibene, M.W. Rowe, C.R. Bingham, E.F. Zganjar and B.E. Zimmerman, Phys. Rev. C52, 1807 (1995).
- 225 "Decay of Mass-Separated $^{189\text{m}}\text{Hg}$ (8.7 min) and $^{189\text{g}}\text{Hg}$ (7.7 min) to ^{189}Au ", J.L. Wood, M.O. Kortelahti, E.F. Zganjar, and P.B. Semmes, Nucl. Phys. A, in press.

- 226 "The Strength of Electric Monopole Transitions and the Decay Out of Superdeformed Bands", J.L. Wood, E.F. Zganjar, and K. Heyde, Z. Phys. A, in press.

Invited papers

- 200 "Internal Pair Formation as a High Resolution Spectroscopic Tool", E. F. Zganjar, American Chemical Society, Chicago, IL, August 25-27, 1993.
- 201 "UNISOR", E. F. Zganjar, Proceedings of the Symposium on Reflections and Directions in Low Energy Heavy Ion Physics, J. H. Hamilton et al. eds, World Scientific, New Jersey, 1993, p 8.
- 213 "Electric Monopole Transitions: What They Can Tell Us About Nuclear Structure", E.F. Zganjar and J.L. Wood, International Conference on Exotic Nuclei and Atomic Masses, Arles, France, June 19-23, 1995.
- 227 "Electric Monopole Transitions and Nuclear Structure", E. F. Zganjar, INT-95-3, Nuclear Structure under Extreme Conditions Oct. 2 - Dec. 15, 1995 Seattle Washington, paper presented December 5, 1995.

Conference proceedings

- 214 "Alpha-decay Studies of the Isomer ^{189m}Bi ", J.C. Batchelder, K.S. Toth, D.M. Moltz, T.J. Ognibene, M.W. Rowe, C.R. Bingham, E.F. Zganjar and B.E. Zimmerman, Proceedings of the Intl. Conf. on Exotic Nuclei and Atomic Masses, Arles, France June 19-23, 1995 (in press).
- 215 "The Alpha-Decay Properties of ^{181}Pb Studies", K.S. Toth, J.C. Batchelder, L.F. Conticchio, W.B. Walters, C.R. Bingham, J.D. Richards, B.E. Zimmerman, C.N. Davids, H.Penttillä, Proceedings of the Intl. Conf. on Exotic Nuclei and Atomic Masses, Arles, France June 19-23, 1995 (in press).
- 216 "Electric Monopole Transitions: What They Can Tell Us About Nuclear Structure", E.F. Zganjar and J.L. Wood, Proceedings of the Intl. Conf. on Exotic Nuclei and Atomic Masses, Arles, France, June 19-23, 1995 (in press).
- 217 "Decay Chains of ^{202}Fr and ^{204}Fr and α Decay Branches", C.R. Bingham, J.D. Richards, B.E. Zimmerman, Y.A. Akevali, W.B. Walters, J. Rikowska, P. Joshi, M. Lindroos, O. Tengblad, P. Van Duppen, and the ISOLDE Collaboration, Proceedings Intl. Conf. on Exotic Nuclei and Atomic Masses, Arles, France, June 19-23, 1995 (in press).
- 218 "The Diffusion Properties of Ion Implanted Species in Selected Target Materials", G.D. Alton, J. Dellwo, H. K. Carter, J.Kormicki, G. di Bartolo, J.C. Batchelder, J. Breitenbach, J.A. Chediak, K. Jentoff-Nilsen, and S. Ichikawa. Proceedings of the Conference on Neutrons and their Applications, Crete Greece, June 12-18, 1994, Society of Photo-Optical Instrumentation Engineers Proceedings Series 339, 335 (1995).

- 224 "New Research Opportunities with a Recoil Mass Spectrometer and Radioactive Ion Beams", J.H. Hamilton, A.V. Ramayya, T. Ginter, P.A. Mantica, J.J. Das, J.D. Cole, and E.F. Zganjar, Proc. 2nd Intl. Symp. on Heavy Ion Physics and its Applications, Lanchou, China, Aug., 1995, World Scientific, Singapore (in press).

Ph.D. theses

- 209 "Complete Spectroscopy in the ^{187m}gHg Decay: The Structure of ^{187}Au ", D. Rupnik, Ph.D. Thesis, Louisiana State University, May, 1994.
- 210 Study of Shape Coexistence in Even-Even Neutron Deficient Hg Isotopes", P. Joshi, Ph.D. Thesis, Louisiana State University, December, 1994.

Other publications

- 202 "Structure of Odd-Odd ^{72}As : Theory and Experiment, A. Petrovici, K. W. Schmid, Amand Faessler, D. Pantelica, A. Pantelica, F. Negoita, J. H. Hamilton, A. V. Ramayya, J. Kormicki, N. R. Johnson, I. Y. Lee, C. Baktash, F. K. McGowan, J. D. Cole, E. F. Zganjar, T. M. Cormier, Bull. Am. Phys. Soc. 38, 2170 (1993).
- 205 "New Proton Radioactivity ^{167}Ir ", C.N. Davids, D.J. Blumenthal, D.J. Henderson, H.T. Penttilä, A.H. Wuosmaa, P.J. Woods, R.D. Page, J.C. Batchelder, C.R. Bingham, B.E. Zimmerman, B.C. Busses, L.F. Conticchio, L.T. Brown, A.V. Ramayya, and K.S. Toth, Report to Users of ATLAS, Argonne National Laboratory, ANL-ATLAS-94-2, p.4.
- 206 "Coexisting Near-Prolate Triaxial Structures in ^{187}Au ," D. Rupnik, E.F. Zganjar, J.L. Wood, P.B. Semmes, and W. Nazarewicz, Bull. Am. Phys. Soc. 39, 1419 (1994).
- 219 "New Heavy Proton Radioactivities $^{165,166,167}\text{Ir}$, ^{171}Au , and ^{185}Bi ", C.N. Davids, B.B. Back, D.J. Blumenthal, D.J. Henderson, C.L. Jiang, H.T. Penttilä, D.J. Seweryniak, A.H. Wuosmaa, P.J. Woods, T. Davinson, R.J. Irvine, R.D. Page, J.C. Batchelder, P.K. Joshi, C.R. Bingham, J.D. Richards, B.E. Zimmerman, L.T. Brown, A.V. Ramayya, B.C. Busse, L.F. Conticchio, W.B. Walters, S.J. Freeman, M. Freer and K.S. Toth, Bull. Am. Phys. Soc. 40, 1630 (1995).
- 220 "Excitation Energy of the $\pi s_{1/2}$ Intruder State in ^{189}Bi ", J.C. Batchelder, E.F. Zganjar, K.S. Toth, D.M. Moltz, T.J. Ognibene, M.W. Rowe, C.R. Bingham, and B.E. Zimmerman, Bull. Am. Phys. Soc. 40, 1631 (1995).
- 221 "Alpha-Decay of new Pt Isotopes", (invited paper), C.R. Bingham, K.S. Toth, C.N. Davids, P.J. Woods, H. Penttilä, J.C. Batchelder, D.J. Blumenthal, L.T. Brown, B.C. Busse, L.F. Conticchio, T. Davinson, D.J. Henderson, R.J. Irvine, D. Seweryniak, W.B. Walters, and B.E. Zimmerman, Bull. Am. Phys. Soc. 40, 2072 (1995).
- 222 "Electric Monopole Transition Strength and the Draining of Superdeformed Bands", J.L. Wood, E.F. Zganjar and K. Heyde, Bull. Am. Phys. Soc. 40, 1623 (1995).

- 223 "New Research Opportunities with Recoil Mass Spectrometers and Radioactive Ion Beams", J.H. Hamilton, A.V. Ramayya, P.A. Mantica, and E.F. Zganjar, International Workshop on Physics with Recoil Separators and Detector Arrays, January 30 - February 2, 1995, Nuclear Science Center, New Delhi, INDIA.
- 204 "Progress Report", E. F. Zganjar, report on research under DEFG05-84ER-40159 for the period May 15, 1993 to May 14, 1994.
- 211 "Progress Report", E.F. Zganjar, report on research under DOE grant DE-FG05-84ER-40159 for the period May 15, 1994 to May 14, 1995.
- 228 "Progress Report", E.F. Zganjar, report on research under DOE grant DE-FG05-84ER-40159 for the period May 15, 1993 to May 14, 1996.

B. Submitted

- "Search For ^{180}Tl α Decay in ^{39}K Bombardments of ^{144}Sm ", K.S. Toth, D.M. Moltz, J.C. Batchelder, T.J. Ognibene, M.W. Rowe, R.J. Tighe, J.D. Robertson, and P.F. Mantica, submitted to Phys. Rev. C.
- "Proton Decay of an Intruder State in ^{185}Bi ", C.N. Davids, P.J. Woods, H. Penttillä, J.C. Batchelder, C.R. Bingham, D.J. Blumenthal, L.T. Brown, B.C. Busse, L.F. Conticchio, T. Davinson, D.J. Henderson, R.J. Irvine, D. Seweryniak, K.S. Toth, W.B. Walters, and B.E. Zimmerman, submitted to Phys. Rev. Lett.
- "Nuclear Orientation and Spectroscopic Studies of the Decay of ^{187}Pt to ^{187}Ir ", M.A. Gummin, K.S. Krane, Y. Xu, T. Lam, E.F. Zganjar, J.B. Breitenbach, B.E. Zimmerman, H.K. Carter, and P.F. Mantica, submitted to Phys. Rev. C.
- "Determination of the ^{190}Po α Reduced Width", J.C. Batchelder, K.S. Toth, E.F. Zganjar, D.M. Moltz, T.J. Ognibene, J.D. Powell, M.W. Rowe, C.R. Bingham, and B.E. Zimmerman, submitted to Phys. Rev. C, Brief Repts.
- "Alpha Decay Properties of ^{181}Pb ", K.S. Toth, J.C. Batchelder, L.F. Conticchio, W.B. Walters, C.R. Bingham, J.D. Richards, B.E. Zimmerman, C.N. Davids, and H. Penttillä to be submitted to Phys. Rev. C.

C. In preparation

- Discovery of $^{166,167}\text{Pt}$, and the half-life of ^{168}Pt ", C.R. Bingham, K.S. Toth, C.N. Davids, P.J. Woods, H. Penttillä, J.C. Batchelder, D.J. Blumenthal, L.T. Brown, B.C. Busse, L.F. Conticchio, T. Davinson, D.J. Henderson, R.J. Irvine, D. Seweryniak, W.B. Walters, and B.E. Zimmerman, to be submitted to Phys. Rev. C.

- "Coexisting Band Structures in ^{187}Au ", D. Rupnik, E.F. Zganjar, M.O. Kortelahti, J.L. Wood, P.B. Semmes, H.K. Carter, P.M. Mantica, J. Kormicki, S. Zhu and C.R. Bingham, to be submitted to Phys. Rev. C.
- "Nuclear Orientation and Spectroscopic Studies of the Decay of ^{187}Pt to ^{187}Ir ," M. A. Gummin, K. S. Krane, Y. Xu, T. Lam, E. F. Zganjar, J. B. Breitenbach, B. F. Zimmerman and P. F. Mantica, to be submitted to Phys. Rev. C.
- "The Structure of ^{191}Au ", D. Rupnik, E. F. Zganjar, J. L. Wood, P. Mantica, and H. K. Carter, to be submitted to Phys. Rev. C.

III. Scientific Program

A. Charged particle spectroscopy

1. Experiments where LSU personal were the principal investigator

- Search for the β -delayed proton emission of ^{69}Kr at ANL

Many light, proton-rich nuclei near the drip line have been identified through their β -delayed proton emission. Perhaps the best known is the $T_z = -3/2$, $A = 4n+1$ series. All of the known nuclei in this series (from ^9C to ^{65}Se and ^{73}Sr) are particularly favored by strong β -delayed proton branches ranging from 11 to 100% [1-4]. Beta transitions in the heavier nuclei of this series are dominated by the decay to the isobaric analog state (IAS) in the β daughter (referred to as the emitter for the rest of this report) with $\log ft$ values of ~ 3.3 . A species exhibiting this decay is defined as a strong β -delayed proton emitter. As the branching ratio to this level is large ($\geq 50\%$), the transition from the IAS dominates the proton spectra; for ^{61}Ge [3], ^{65}Se [1] and ^{73}Sr [2] this has been the only transition seen. Observation of this transition readily permits an estimate of the mass of the parent through the use of a formula for the Coulomb displacement energy [5] to determine the difference in energy of the IAS and the parent ground state. Combining this with the proton energy and the ground-state mass of the daughter gives the ground-state mass of the parent.

Figure 1 shows the region of interest of the chart of the nuclides and indicates those nuclei that have been observed to be strong and weak β -delayed proton emitters along with those predicted to be strong emitters. For nuclei with Z larger than 30, the $T_z = -3/2$ series of strong β -delayed proton emitters comprises the lightest isotopes observed, all of which were discovered through their β -delayed proton emission. Also included on the chart are the lightest isotopes of these elements observed with projectile fragmentation [6,7], as well as the lightest isotope predicted to be particle stable [8].

This experiment was performed at the ATLAS facility at Argonne National Laboratory during the month of September 1994. We attempted to produce ^{69}Kr through the $^{40}\text{Ca}(^{32}\text{S}, 3n)$ reaction, with beam energies of 130 and 140 MeV. Recoils exiting the target were mass separated in the Fragment Mass Analyzer (FMA), and imbedded in a 300 μm thick double-sided silicon strip detector (DSSD). This detector is divided into 48 strips in both the x- and y- directions to create 2304 effective pixels over the face of the detector. This type of detector is very insensitive to β particles while having an efficiency for heavy charged particles of nearly unity (the solid angle

Fig. 1. Chart of the nuclides from $Z=31$ to 41 showing those nuclei that have been predicted or observed to decay by β -delayed proton and β -delayed two-proton emission. The lightest masses observed by particle fragmentation are shown if not equal to the lightest observed by β -delayed particle emission. Those nuclei observed to be strong and weak β -delayed proton emitters, and those predicted to be strong emitters are noted.

drops this to an overall efficiency of $\sim 50\%$). A parallel-plate avalanche gas counter (PPAC) was positioned in the focal plane of the FMA to permit mass identification of the reaction recoils that are imbedded in the DSSD; so for each decay event, time-of-flight, mass, and decay energy were recorded.

On-line there were no peaks arising from ^{69}Kr observed. Subsequent analysis of this data has also revealed no evidence of protons arising from the β -delayed proton decay of ^{69}Kr . Assuming an overall efficiency of 10%, and a branching ratio of 50%, this corresponds to a production cross-section for this reaction of less than 100 nb.

This experiment was performed in collaboration with the Bingham (UT) Davids (ANL) Toth (ORNL) and Walters (U of Maryland) Groups.

1. J. C. Batchelder *et al.*, Phys. Rev. **C47**, 2038 (1993).
2. J. C. Batchelder *et al.*, Phys. Rev. **C48**, 2593 (1994).
3. M. A. C. Hotchkis *et al.*, Phys. Rev. **C35**, 315 (1987).
4. J. Cerny and J. C. Hardy, Ann. Rev. Nucl. Sci. **27**, 333 (1977).
5. M. S. Antony *et al.*, At. Data Nucl. Data Tables **34**, 279 (1986).
6. M. F. Mohar *et al.*, Phys. Rev. Lett. **66**, 1571 (1991).
7. S. J. Yennello *et al.*, Phys. Rev. **C 46**, 2620 (1992).
8. P. E. Haustein, At. Data Nucl. Data Tables **39**, 186 (1988).

- Search for the α -decay of ^{190}Po at LBNL

The α decays of very neutron-deficient even-even Po nuclei has been of interest as the experimentally determined reduced α widths (δ^2) can delineate the extent of stability of the $Z = 82$ magic shell [1]. The lightest member of this series for which reliable data are available is ^{192}Po [1, 2]. Quint *et al.* [3] reported evidence for the α decay of ^{190}Po in 1988, when they observed two events with $E_\alpha = 7482 \pm 20$ keV and a half-life of $9.6^{+47}_{-4.4}$ ms. On the basis of α -decay energy systematics they attributed these events to ^{190}Po . However, the δ^2 value for ^{190}Po calculated with the formalism developed by Rasmussen [4] and using the energy and half-life data from ref. [3] seems to be much too small when compared to those of neighboring nuclei, indicating that probably the 9.6 ms half-life is too long since the E_α of 7482 keV fits the energy systematics [5]. This anomalously low value for ^{190}Po is shown in Fig. 2 where a plot of δ^2 [4] for even-even Po, Rn, Ra, Th, and U isotopes versus neutron number is presented.

Fig. 2. The reduced α width δ^2 for even-even Po, Rn, Ra, Th, and U isotopes as a function of the neutron number.

Referring to Fig. 2, the Po δ^2 values seem to reach a saturation and start to decrease at neutron number 110 (^{194}Po). As discussed in Refs. [1,6], this is believed to be due to shape differences between the ground state (2p) and low-lying 0^+ (4p-2h) intruder state in the Pb daughter, resulting in substantial mixing of the two states. As the α decay to the intruder state is strongly hindered, this reduces the total α decay strength resulting in lower δ^2 values. We recently performed an experiment to produce ^{190}Po via the $^{144}\text{Sm}(^{48}\text{Ti}, 2n)$ reaction at a ^{48}Ti beam energy of 210 MeV to test this hypothesis by seeing if the saturation effect extends to ^{190}Po .

Two sets of experiments were performed at the 88 Inch Cyclotron Facility at Lawrence Berkeley National Laboratory using a rapidly rotating recoil catcher wheel system. Briefly, the system works as follows: recoils are stopped in 300- $\mu\text{g}/\text{cm}^2$ Al catcher foils on the edge of a spinning wheel. Because of this motion, the recoil products are rotated between two arrays (above and below) of 6 Si detectors. Half-life information can then be determined by the difference in counts between the detectors. The speed of the wheel can be varied to maximize the efficiency for the half-life of interest and to minimize it for longer-lived species.

In the first set of experiments, the maximum wheel speed was limited to 500 rpm, and as such, we observed no evidence of α emission arising from ^{190}Po . We believe that this was because the half-life of ^{190}Po was too short to be observed with the wheel speeds available. However, we were able to observe an α line arising from the decay of $^{189\text{m}}\text{Bi}$ (see next section).

In the follow-up set of experiments (9/95), we were able to improve the setup so that a wheel speed of 1500 rpm was possible. Data were taken at wheel speeds of 1000 and 1500 rpm. Preliminary analysis indicates alphas arising from the decay of ^{190}Po at an energy of 7.48 MeV, from both wheel speeds, and with a half-life < 2 ms.

This experiment was performed in collaboration with the Bingham (UT) Cerny (LBNL) and Toth (ORNL) Groups

1. J. Wauters *et al.*, Phys. Rev. **C47**, 1447 (1993).
2. M. E. Leino *et al.*, Phys. Rev. **C24**, 2370 (1981).
3. A. B. Quint *et al.*, GSI Report 88-1.
4. J. O. Rasmussen Phys. Rev. **113**, 1593, (1959).
5. C. Borcea *et al.*, Nucl. Phys. **A565**, 158 (1993).
6. J. Wauters *et al.*, Phys. Rev. Lett. **72**, 1329 (1994).
7. J. E. Reiff *et al.*, Nucl. Instr. Methods **A276**, 228 (1989).
8. E. Coenen *et al.*, Phys. Rev. Lett. **54**, 1783 (1985).
9. A. N. Andreyev *et al.*, Nucl. Instr. Meth. **A330**, 125 (1993).
10. H. Geiger and J. M. Nuttall, Philos. Mag. **22**, 613 (1911).

- Study of the $^{189\text{m}}\text{Bi}$ α decay at LBNL

In the spherical shell model, the proton $1h_{9/2}$ orbital lies above the $Z = 82$ closed shell while the proton $3s_{1/2}$ lies below. Any $1h_{9/2}$ configurations in $Z < 82$ nuclei and $3s_{1/2}$ configurations in $Z > 82$ nuclei are referred to as proton "intruder" states. A great deal of recent work has clearly identified the $1h_{9/2}$ intruder configurations in odd-A Tl and Au isotopes, and demonstrated a parabolic dependence of their excitation energy with a minimum when the neutron number is midway between the major neutron shell closures of $N = 82$ and $N = 126$ [1]. In the case of Tl isotopes, data are sufficient to establish that for $N < 110$ the $1h_{9/2}$ excitation energy indeed rises again, following a parabolic trajectory. Figure 3 shows a plot of the level energies of the intruder states in

Fig. 3. Level energies of the proton $h_{9/2}$ and $s_{1/2}$ intruder states in odd-A Tl and Bi nuclei as a function of neutron number.

odd-A Tl and Bi nuclei versus neutron number. Similar behavior is shown in odd-A Au and even-even Pb, Hg and Pt for the $(\pi h_{9/2})^2$ configurations [2,3].

While the picture presented above for the $1h_{9/2}$ intruder in $Z < 82$ nuclei is convincing, it was actually the odd-mass Bi isotopes that provided the first evidence for intruder states in the $Z = 82$ region [4]. The parabolic energy dependence of the $1/2^+$ isomer in the odd-A Bi isotopes came into question, however, with the value reported by Coenen *et al.* [5] of 92 ± 10 keV for the ^{189m}Bi energy that shows a continued drop for $N < 108$ for the $\pi s_{1/2}$ intruder state (this value is based on a decay energy of 7.206 ± 0.015 MeV from Ref. [6]). However, results from a recent investigation by Andreyev *et al.* of 7.34 ± 0.03 MeV for the α decay from this state [7] disagree with the previous data of Schneider [6]. In the present study, we re-investigated the α decay of ^{189m}Bi since the energy of this isomeric level is largely determined by the Q_α value for the α transition connecting it with the ^{185}Tl ground state.

^{189m}Bi was produced in the $^{144}\text{Sm}(^{48}\text{Ti}, p2n)$ reaction utilizing ^{48}Ti beams of 215, 220, and 230 MeV from the Lawrence Berkeley Laboratory 88-Inch Cyclotron. Its α decay was observed by using the rapidly rotating recoil catcher wheel system described above. Figure 4 shows the α spectra observed in the first three detectors at a beam energy of 225 MeV with a wheel speed of 240 rpm. One sees in Fig. 4, α transitions arising from the $(\pi s_{1/2})$ isomer of ^{189}Bi to the $(\pi s_{1/2})$ ^{185}Tl ground state, the $(\pi h_{9/2})$ ground state of ^{189}Bi to the $(\pi h_{9/2})$ isomer of ^{185}Tl , as well as α particles from ^{186}Pb and heavier lead isotopes. The ^{189}Bi isomer was also observed at the faster wheel speed of 500 rpm. On the basis of on these data, a half-life of 7 ± 2 ms for ^{189m}Bi was determined.

Figure 5 shows the α decay scheme of ^{189}Bi and ^{189m}Bi . One sees that our Q_α of 7.46 ± 0.04 MeV for ^{189m}Bi , combined with that of the previously known ^{189}Bi Q_α establishes the excitation energy of ^{189m}Bi as 190 ± 40 keV. This energy is significantly higher than the 92 ± 15 keV value deduced by Coenen *et al.* [5]. However, their excitation energy is based on ^{189m}Bi data [6] with extremely low statistics, wherein the alleged 7.206-MeV peak consists of two counts in one channel located in the midst of a background that is generally one count high. We should add that the ^{189m}Bi Q_α of Andreyev *et al.* [7] results in an excitation energy of 230 ± 30 keV for ^{189m}Bi , in agreement with this work.

Fig. 4. The α spectra in the first three (a,b,c, respectively) of the six upper detectors observed during the bombardment of 225 MeV ^{48}Ti on a 1.5 mg/cm^2 ^{144}Sm target at a wheel speed of 240 rpm.

Fig. 5. The ^{189}Bi and $^{189\text{m}}\text{Bi}$ α -decay scheme.

Refer again to Fig. 3, which shows a plot of the level energies of the intruder states in odd-A Tl and Bi nuclei versus neutron number. The Tl $\pi h_{9/2}$ levels fall on a parabola-shaped curve with a minimum at $N \approx 110$, which suggests that the interpretation of it as a $3s_{1/2}$ intruder state is correct. However, the value deduced by Coenen *et al.* of 92 ± 15 keV for the ^{189m}Bi energy shows a continued drop for $N < 108$ for the $\pi s_{1/2}$ intruder state. On the other hand, our ^{189m}Bi energy and that of Ref. [7] indicate that the $s_{1/2}$ level energies, at least down to $N=106$, exhibit the same behavior as the other $h_{9/2}$ states indicated in Fig. 3.

1. K. Heyde *et al.*, Phys. Rep. **102**, 291 (1983).
2. J. L. Wood, K. Heyde, W. Nazarewicz, M. Huyse and P. Van Duppen, Phys Repts. **215**, 101 (1992).
3. M. Huyse *et al.*, Proceedings of the 5th International Conference on Nuclei Far from Stability, Roseau Lake, Ontario Canada, edited by Ian S. Towner (AIP Conference proceedings No. 164), (1988) p.305.
4. M. Alpsten and G. Astven, Nucl. Phys. **A134**, 407 (1969).
5. E. Coenen *et al.*, Phys. Rev. Lett. **54**, 1783 (1985).
6. J. Schneider, Gesellschaft für Schwerionenforschung, Darmstadt, Thesis Report No. GSI-84-3, 1984 (unpublished).
7. A. N. Andreyev *et al.*, Nuc. Instr. Meth. in Phys Res. **A330**, 125 (1993).

- Search for ^{180}Pb at LBNL

A search for the α decay of ^{180}Pb was conducted at Lawrence Berkeley National Laboratory in an effort to study the magnitude of the $Z = 82$ shell gap for nuclei midway between $N = 82$ and $N = 126$. Some years ago a new set of reduced widths was reported by Toth *et al.* [1]. Contrary to results obtained by the ISOLDE collaboration [2], the widths that were observed were found to have a dependence on N similar to that observed for neighboring elements, i.e., they decreased in value as the $N = 126$ shell was approached.

Figure 6 shows the reduced widths for ground-state-to-ground-state (s-wave) α transitions of even-even Z from 78 to 100. One sees the regularity of these widths as a function of N with the sharp break at $N = 126$. Note that while the δ^2 values for $N < 130$ decreases as Z decreases from 90 towards 82, those of $^{186,188,190,192}\text{Pb}$, contrary to the similarly expected shell effect at $Z = 82$, are larger than neighboring Hg widths. This result could be related to a predicted [3] disappearance of the $Z = 82$ gap midway between $N = 82$ and 126. Global calculations [4,5] of α -decay half-lives indicate at best a weak presence of the $Z = 82$ gap in the light Pb mass region and a theoretical

Fig. 6. Reduced widths for s-wave α transitions of even-even nuclei for $78 \leq Z \leq 100$.

examination [6] of the ground states of even-even neutron deficient Pt, Hg, and Pb isotopes show that some Pb nuclides do not behave as good magic nuclei.

In the 1993 atomic mass evaluation, Borcea *et al.* [7] show plots of Q_α values as a function of N . The difference in Q_α between Po and Pb isotones, which is ~ 5 MeV at $N = 126, 128$, steadily diminishes, as the neutron number decrease, to only 1.5 MeV between ^{190}Po and ^{188}Pb . This last difference is not much larger than the characteristic ΔQ_α values of ~ 1 MeV between other even-even isotones in this mass region. Thus, from systematics, the magnitude of the $Z = 82$ shell gap is unclear. If the $Z = 82$ gap is indeed severely diminished for $N \sim 104-110$, then the widths for Pb nuclides with $A > 192$ and $A < 186$ should fall closer to, and then, for larger and smaller mass numbers, respectively, fall below Hg values.

The experiment was performed at the 88 Inch Cyclotron Facility at Lawrence Berkeley National Laboratory using the rapidly rotating recoil catcher wheel system described above. On-line there was no evidence of α particles arising from the decay of ^{180}Pb . Subsequent analysis of the data indicates that the cross-section for this reaction is significantly lower than the $100\mu\text{b}$ predicted by PACE. (The other explanation, that the half-life is actually less than ~ 3 ms, is considered much less likely.) Further analysis on this data is ongoing. In addition, we have PAC approval to do this experiment using the FMA and DSSD system at Argonne National Laboratory.

1. K. S. Toth *et al.*, Phys Rev Lett. **53**, 1623 (1984).
2. P. Hornshøj *et al.*, Nucl. Phys. **A230**, 365 (1974).
3. R. A. Sorenson, Nucl. Phys. **A420**, 221 (1984).
4. B. Buck *et al.*, Phys. Rev. C **45**, 2247 (1992).
5. B. A. Brown Phys Rev. C **46**, 2247 (1992).
6. S. Yoshida *et al.*, Phys Rev. C **50**, 1398 (1994).
7. C. Borcea *et al.*, Nuc. Phys. **A565**, 158 (1993).

2. Collaborations where LSU personal were not the principal investigator

- Alpha decay study of light Pb isotopes at ANL

J. Batchelder participated in an investigation of the α -decay of $^{181,182}\text{Pb}$ at the Argonne National Laboratory ATLAS accelerator facility as part of a survey experiment in which a 1-pnA beam of 400 MeV ^{92}Mo was used to irradiate targets of $^{90,92,94}\text{Zr}$ to examine yields for one and two-nucleon evaporation products from symmetric cold-fusion reactions. Recoiling nuclei of interest were passed through the fragment mass analyzer [3] and implanted in a double-sided silicon strip detector for α -particle assay.

The α -decay energy of ^{181}Pb has been measured as 7211 ± 10 [1] and 7044 ± 15 keV [2]. In the first study the isotope was produced in ^{90}Zr bombardments of ^{94}Mo and, after traversing a velocity filter, implanted in a position-sensitive Si detector. No half-life for ^{181}Pb was reported in Ref. [1]. In the second investigation the isotope was produced in ^{40}Ca bombardments of ^{144}Sm and transported to a position in front of a Si(Au) surface barrier detector with a fast He-gas-jet capillary system. An estimate of 50 ms was determined [2] for the ^{181}Pb half-life. With the ^{90}Zr target (via the 1n exit channel) we observed an α group at 7065 ± 20 keV which was correlated both with $A = 181$ recoils, and alphas from the ^{177}Hg daughter. This peak had a half-life of 45 ± 20 ms. Our new results for ^{181}Pb are therefore in agreement with those reported in Ref. [2]. We should add that there was no indication in the $^{90}\text{Zr} + ^{92}\text{Mo}$ data of the 7211 ± 10 keV α particles seen by Keller *et al.* [1]. In this experiment no evidence for α -particles arising from the decay of ^{180}Pb were observed. Using the $^{92}\text{Zr}(^{92}\text{Mo}, 2n)$ reaction, 6 counts of alphas from the decay of ^{182}Pb were identified.

This experiment was performed in collaboration with the Bingham (UT) Davids (ANL) Toth (ORNL) and Walters (U of Maryland) Groups

1. J. G. Keller *et al.*, Nucl. Phys. **A452**, 173 (1986).
2. K.S. Toth, D.M. Moltz, and J.D. Robertson, Phys. Rev. C **39**, 1150 (1989)
3. C.N. Davids and J.D. Larson, Nucl. Instr. Meth **B40/41**, 1224 (1989).
4. G. Audi, A.H. Wapstra, and M. Dedieu, Nucl. Phys. **A565**, 193 (1993).

- Search for heavy proton emitters at ANL

Several sets of experiments to search for proton emission from heavy emitters near $Z=82$ were performed at the ATLAS facility at Argonne National Laboratory using the FMA and DSSD (see above for more details on the setup). In the first set of experiments, the collaboration (J. Batchelder for LSU) attempted to produce $^{170,171}\text{Au}$ via the $^{96}\text{Ru}(^{78}\text{Kr}, \text{pxn})$ reactions. Utilizing a ^{78}Kr beam energy of 370 MeV, a new α transition was observed on-line arising from ^{171}Au . In addition, off-line analysis of this data revealed a proton transition arising from this nuclide at a level of $\sim 5\%$ of the α branch with a half-life of 1.7 ± 0.5 ms. A bombarding energy of 410 MeV was used in an attempt to produce ^{170}Au . During this run, a proton line was observed at ~ 1 MeV. Subsequent off-line analysis has shown that these protons arise from the decay of ^{167}Ir formed via the $^{96}\text{Ru}(^{78}\text{Kr}, \alpha p 2n)$ reaction. The half life for this nuclide was determined to be 33 ± 2 ms. There was also some evidence (2 counts) for the ground state proton decay of ^{166}Ir . No proton events were observed that could be attributed to proton decay of ^{170}Au .

In a second set of experiments, a beam of ^{78}Kr bombarded a ^{92}Mo target to produce light Ir isotopes via pxn exit channels. Analysis of the data produced a total of three new proton transitions, (in addition to confirming ^{167}Ir): ^{166}Ir ($T_{1/2} = 8.8^{+2.6}_{-1.9}$ ms), ^{165}Ir ($T_{1/2} = 374^{+83}_{-64}$ μs), and the proton decay of the isomer of ^{165}Ir . Analysis on both the Au and Ir isotopes is continuing.

The third set of experiments involved a search for proton emission from light Bi isotopes through the $^{95}\text{Mo}(^{92}\text{Mo}, \text{pxn})$ reaction. Proton emission from Bi would represent the first proton decay from a nuclide with $Z > 82$. In the light Bi isotopes, the $s_{1/2}$ intruder state is expected to be only two to three hundred keV above the ground state (see previous section). A total of twelve proton events were observed at an energy of 1.585 ± 0.009 MeV with a half-life of 42 ± 14 μs . Four of these events were followed by alphas arising from the decay of ^{184}Pb , indicating that the proton transition in question arises from the proton emission of ^{185}Bi . The short half-life of the proton transition indicates that it must be a $\ell=0$ transition. However, the ground state of ^{185}Bi is expected to be $9/2^-$ (as are all the heavier odd-A Bi isotopes up to 193), making a proton decay from the ground state equal to a $\ell=4$ transition. Placing the proton transition as arising from the $s_{1/2}$ intruder state solves this problem, so it has been concluded that the observed proton transition arises from the isomeric $s_{1/2}$ intruder state in ^{185}Bi .

Future experiments will involve a search for proton decay from the neighboring odd-Z elements At and Fr. As was true for Bi, there is strong competition from α decay that effectively pushes further from stability the point at which proton decay becomes the dominant mode.

These experiments were performed in collaboration with the Bingham (UT), Davids (ANL), Freeman (Manchester), Ramayya (Vanderbilt), Toth (ORNL), Walters (U of Maryland), and Woods (Edinburgh) Groups. C. N. Davids was the principal investigator.

- Search for shape coexistence in ^{188}Pb at ANL

The interaction between coexisting shapes in nuclei near closed shells has been of great interest in the past decade. Excited 0^+ states at low energy can often be identified as the bandheads of structures with differing shapes built on those states. These structures have been identified in $^{190-198}\text{Pb}$ via β decay and α -decay fine structure studies [1, 2]. Coexistence of different shapes in Pb nuclei was predicted by Nilsson-Strutinsky calculations in which both the oblate and prolate minima were predicted [2] to have excitation energies near 1 MeV. The goal of this experiment was to continue the systematic study of the Pb nuclides by searching for excited 0^+ states in ^{188}Pb by observing the fine structure in the α -decay of ^{192}Po .

The experiment was performed at the ATLAS facility at Argonne National Laboratory using the Fragment Mass Analyzer as part of a collaboration headed by the University of Tennessee group. The ^{192}Po was produced via the bombardment of 176 MeV ^{36}Ar on a ^{160}Dy target. This experiment used the same detection system as described in the section "Search for the β -delayed proton emission of ^{69}Kr ", which was led by the LSU group (J. Batchelder). About 600 events were observed for the ^{192}Po ground state α decay to the ground state of ^{188}Pb . However, no peaks arising from the decay to the first excited 0^+ state of ^{188}Pb were observed. In these type of experiments, it is necessary to be able to reject all other alphas as one is searching for a small peak several hundred keV in energy below the main ground-state to ground-state transition. The ^{188}Pb has a small (22 %) α -decay branch, therefore this experiment was hindered by not being able to use parent-daughter correlations to clean-up the α background.

These experiments were performed in collaboration with the Bingham (UT), Davids (ANL), Toth (ORNL), and Walters (U. of Maryland) groups.

1. J. L. Wood *et al.*, Phys. Rep. **215**, 103 (1992).
2. P. van Duppen *et al.*, Phys. Rev. Lett. **52**, 1974 (1984).

B. Nuclear Structure

1. Electric monopole transitions, shape coexistence, and nuclear structure: a review

There are many interesting and important aspects of nuclear structure associated with the electric monopole transition (E0). The mixing of configurations with different mean-square radii gives rise to E0 transitions that can serve as signatures for the occurrence of shape coexistence [1]. It has also been suggested [2] that the draining of superdeformed bands, which mix (even slightly) with other configurations, proceeds via enhanced E0 transitions. There is recent indirect evidence for this [3]. The E0 transition can also provide information on the nature of excitations in terms of their particle-hole structure. Among other things, E0 transitions are associated with isotope and isomer shifts, compressibility of nuclear matter, monopole degrees of freedom, and radial density oscillations.

The E0 strength parameter for a transition from state $|i\rangle$ to state $|f\rangle$, ρ_{if} , is defined by

$$\rho_{if} = \langle f | \sum e_j r_j^2 | i \rangle / eR^2 \equiv \langle f | m(E0) | i \rangle / eR^2 \equiv M_{if}(E0) / eR^2$$

where e_j is the effective monopole charge of the j^{th} nucleon located at r_j , e is the unit of electric charge, and $R = 1.2A^{1/3} \text{ fm}$ is the nuclear radius. If states $|1\rangle$ and $|2\rangle$ with different $\langle r^2 \rangle$ mix, then $|i\rangle = \alpha|1\rangle + \beta|2\rangle$, $|f\rangle = -\beta|1\rangle + \alpha|2\rangle$ and

$$M_{if}(E0) \approx \alpha\beta \Delta \langle r^2 \rangle.$$

Thus, $M_{if}(E0)$ is proportional to the mixing of the configurations and the difference in their mean-square radii. This is a general result, not dependent on a specific nuclear model. $M_{if}(E0)$ will be large whenever the initial and final states involve mixed configurations with very different $\langle r^2 \rangle$, as occurs when shape coexistence is present. $M_{if}(E0)$ is more sensitive to $\Delta \langle r^2 \rangle$ than to the amount of mixing. For example: for maximum mixing $\alpha\beta=0.5$, for 10% mixing $\alpha\beta=0.3$ and for 1% mixing $\alpha\beta=0.1$. Mixing is essential to the generation of E0 strength however, and the decay of the superdeformed band at 2558 keV in ^{238}U provides an excellent example [4]. The E0

transition between the 225 ns 0^+ fission isomer at 2558 keV and the 0^+ ground state in ^{238}U is the slowest E0 transition known ($\rho^2=1\times 10^{-9}$).

Electric monopole transition rates are given by

$$\frac{1}{\tau(\text{E0})} = \rho_{\text{if}}^2 \sum_k \Omega_k(Z, E)$$

where $\tau(\text{E0})$ is the lifetime for E0 decay and $\Omega_k(Z, E)$ is the electronic factor which depends upon the nuclear charge, Z , and the transition energy, E . The index k spans the various processes by which the E0 transition can proceed (K , L_1 , L_2 ... shell internal conversion or internal pair formation). The E0 strength parameter is conventionally quoted in units of $\rho^2 \times 10^3$.

One of the earliest clear-cut examples of shape coexistence was provided by the neutron deficient even-even Hg isotopes [5], several of which are depicted in fig. 7. The ground-state band of these isotopes is based on a proton 2h configuration, while the deformed excited band is based on a proton 2p-4h configuration which arises from the excitation of a proton-pair into the intruder $h_{9/2}$ orbital.

Fig. 7. Weakly deformed (0_1^+) and strongly deformed (0_2^+) bands in several even-even Hg isotopes (see ref. 5 for complete details). The ρ^2 values (units $\rho^2 \times 10^3$) are taken from ref. 6.

In addition to the electric monopole transitions between the 0^+ states in these nuclei, the E0 strength is enhanced for the $\Delta I=0, I \neq 0$ transitions between the shape coexisting configurations. This is a common feature identified with shape coexistence. The lifetimes of the 0_2^+ states in these isotopes are difficult to measure because they fall in the pico-second range and have no γ -ray branching to the 2_1^+ state. However, as discussed in the next section, our recent measurements [6] have yielded half-lives of 204^{+147}_{-45} ps and ≤ 72 ps which correspond to $\rho^2(E0) \times 10^3$ values of $7.7^{+2.2}_{-3.2}$ and ≥ 32 for ^{188}Hg and ^{186}Hg , respectively. Additionally, the mixing of the bands in ^{188}Hg (1%), when computed using the experimental [6] $\rho^2(E0)$ and a deformation of $\beta=0.25$ for the 0_2^+ band, is consistent with the mixing obtained using the experimental [6] $\rho^2(E0)$ and an experimental value [7] for $\Delta\langle r^2 \rangle$.

The tin and cadmium isotopes also provide a dramatic illustration of shape coexistence. In the Sn isotopes, bands of states connected by low-energy transitions with relative $B(E2)$ s that support excited deformed bands are shown in Fig. 8.

Fig. 8. Electromagnetic decay data for $^{114-120}\text{Sn}$. E0 strengths are in units of $\rho^2 \times 10^3$. The numbers in circles are in-band/out-of-band $B(E2)$ ratios. The ratios in circles are the relative E0 branches. The data are taken from ref. 5 and Nuclear Data Sheets.

Fig. 9. Electric monopole transitions in ^{114}Cd . Values of $\rho^2 \times 10^3$ are shown boxed. The data are taken from ref. 5 and Nuclear Data Sheets.

Exceptionally strong E0 strength from the excited deformed structures is observed. The $B(E2)$ values for transitions between low-lying states in ^{114}Cd indicate vibrational and triaxial-deformed structures. The pattern of E0 transitions shown in Fig. 9, weak on the left and strong on the right, clearly indicate which transitions involve the greatest $\Delta\langle r^2 \rangle$.

Fig. 10 shows that in the Pd and Ru isotopes, the E0 strength is quite small between vibrational excitations, but increases to larger values in the $^{98-100}\text{Mo}$ isotopes and to a very large value in ^{102}Mo where a shape coexisting configuration (0_2^+) is known. In this same region, extending down from ^{100}Mo through the $N=58$ isotones to ^{96}Sr , shown in Fig. 11, one observes the strongest E0 strength ($\rho^2 \times 10^3 = 185 \pm 50$) known above ^{56}Ni .

The conventional view of E0 strength in deformed nuclei is that it is associated with β vibrations and is quite strong. The information on ρ^2 values in deformed nuclei is shown in Figs. 12 and 13. Figure 12 shows the information for strongly-deformed nuclei. The nuclei shown in Fig. 13 all have $N=90$ and are usually termed *transitional*. Evidently, the incidence of E0 strength in strongly-deformed nuclei (Fig. 12) does not reveal a definite pattern; and indicates that even the concept of β

Fig. 10. E0 transition strength ($\rho^2 \times 10^3$) in even-even isotopes of Pd, Ru, and Mo. The data are taken from Nuclear Data Sheets.

Fig. 11. E0 transition strength and B(E2) values in the N=58 isotones. The $\rho^2 \times 10^3$ values are given within the shaded arrows, B(E2) values in the boxes (in W.u.), and B(E2) ratios in the circles. The $0_3^+ \rightarrow 0_2^+$ E0 strength in ^{96}Sr is the strongest known above ^{56}Ni . The data are taken from Nuclear Data Sheets.

vibrations is poorly-defined in strongly-deformed nuclei. The lowest excited 0^+ bands in the $N=90$ nuclei (Fig. 13) conform to the standard view of β vibrations. However, the second excited 0^+ bands indicate that the structure of these nuclei is more complicated (see ref. 5, p. 183).

Coexisting shapes based on a proton $2p-6h$ ($\pi h_{9/2}$)² intruder configuration and a proton $4h$ configuration in $^{178-186}\text{Pt}$ has been known [5] for some time. These configurations are shown in Fig. 14 for ^{184}Pt as g and g' respectively. Recent results [9] on ^{184}Pt , however, have added to that picture: Not only is E0 enhancement observed for all $I^\pi \rightarrow I^\pi$ transitions between g and g' , but one also observes [9] two $K=2$ bands, labeled γ and γ' in Fig. 14. The pattern of E0 strength between all these bands is shown in Fig. 14. The $3_2^+ \rightarrow 3_1^+$ transition between γ' and γ is unprecedented in that it is a pure E0, $I^\pi \rightarrow I^\pi$ ($I \neq 0$) transition. No γ -ray intensity is observed [9]. A similar structure is found [10] in ^{186}Pt as well.

Fig. 12. E0 transition strength in several strongly deformed nuclei. The $\rho^2 \times 10^3$ values are given within the transition arrow. The rotational parameter for each band is given in the boxes. The data are taken from Nuclear Data Sheets.

Fig. 13. E0 transitions between bands for several $N=90$ isotones. The $\rho^2 \times 10^3$ values are given within the arrows. The data are taken from ref. 8 and Nuclear Data Sheets.

Fig. 14. The $\Delta I=0$ transitions in ^{184}Pt . The $2_3 \rightarrow 2_1$ and $2_4 \rightarrow 2_2$ transitions are $>20\%$ E0, but the $3_2^+ \rightarrow 3_1^+$ transition between the $\gamma'\gamma$ bands is pure E0. This is unprecedented for $I^\pi \rightarrow I^\pi$, $I \neq 0$ transitions. The data are taken from ref. 9.

The ^{186}Pt nucleus serves as a core for proton-particle configurations in odd-proton ^{187}Au . Spectroscopy of ^{187}Au has revealed two bands based on $h_{9/2}$ proton particle excitations with identical spin sequence, nearly identical relative energies, and E0 transitions which connect only the favored members of the two bands [11] as shown in Fig. 15. These bands in ^{187}Au , shown on the right side of Fig. 15, represent a unique example of nuclear coexistence. In spite of rather similar deformation (both associated with near-prolate shapes) and similar rotational behavior, they can be characterized by different numbers of $N=5$ proton intruders. Calculations [11] indicate that the odd proton in ^{187}Au occupies the $h_{9/2}$ orbital in the favored band for both shapes. On the other hand, the odd proton mainly occupies the $f_{7/2}$ orbital for the lowest unfavored band and mainly the $h_{9/2}$ orbital for the excited unfavored band. The small overlap between the wave functions of the odd proton in the unfavored bands hinders the E0 transitions. This is illustrated in Fig. 15 where the $h_{9/2} \oplus f_{7/2}$ bands are obtained by coupling the unpaired intruder $N=5$ proton to effective ^{186}Pt cores $|A\rangle$ and $|B\rangle$.

Fig. 15. A schematic illustration of the proposed coupling scheme between the unpaired proton in ^{187}Au and effective ^{186}Pt cores. The underlying core configurations contain 0 or 2 protons in the $N=5$ intruder orbitals, and the effective cores $|A\rangle$ and $|B\rangle$ are linear combinations of these. The dotted line indicates the adiabatic PES constructed from the quasiparticle vacuum state at each deformation, and the solid lines indicate diabatic configurations obtained by removing the interaction between the vacuum and two-quasiparticle states involving $h_{9/2}$ proton states. The figure is taken from ref. 11.

1. J. Kantele, in Heavy Ions and Nuclear Structure, Proceedings of the XIV Summer School, Mikolajki, Poland, 1984, eds. B. Sikora and Z. Wilhelmi (Harwood Academic, New York, 1984), p. 391; K. Heyde and R. A. Meyer, Phys. Rev. C **37** (1988) 2170.
2. E. F. Zganjar and J. L. Wood, Nucl. Phys. A **520** (1990) 427c.
3. M. Palacz *et al.*, Nucl. Phys. A **578** (1994) 225; J. X. Saladin *et al.*, preprint, 1995.
4. J. Kantele *et al.*, Phys. Rev. Lett. **51** (1983) 91.
5. J. L. Wood *et al.*, Phys. Repts. **215** (1992) 101.
6. P. K. Joshi *et al.*, Intl. J. Mod. Phys. E **3** (1994) 757.
7. G. Ulm *et al.*, Z. Phys. A **325** (1986) 247.
8. H. Mach *et al.*, Phys. Rev. C **46** (1992) 1849.
9. Y. Xu *et al.*, Phys. Rev. Lett. **68** (1992) 3853.
10. J. McEver *et al.*, Bull. Am. Phys. Soc. **38** (1993) 1819.
11. D. Rupnik *et al.*, Phys. Rev. C **51**, R2876 (1995).

2. Collaborations where LSU personnel served as principal investigators.

- Lifetimes of the 0_2^+ configuration in ^{186}Hg and ^{188}Hg

Coexisting bands of quite different deformation 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.

Fig. 16. Schematic of the picosecond timing technique developed for cases involving pure E0 transitions. The triple coincidence is achieved between the positron (e^+) feeding the level under study, the E0 conversion electron (e^-) resulting from the decay of the level, and the x-ray which results from the internal conversion process. The fast timing coincidence is achieved between the positron detected by the plastic scintillator and the X-ray detected by the BaF_2 scintillator. The detection of the specific conversion electron by a high resolution $\text{Si}(\text{Li})$ system was used, via the triple coincidence requirement, to select the decay sequence of interest.

As pointed out above, 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]. Electric monopole transitions result from the penetration of the nucleus by an atomic electron and, thus, unlike the other conversion processes, they carry direct information on the nuclear wavefunction. Changes in the nuclear radius lead to nonvanishing values for the monopole strength function.

A picosecond lifetime system similar in approach to that pioneered at TRISTAN [6] was developed at UNISOR [7] and is shown schematically in fig. [16]. This system is designed to accommodate the case when nuclear levels are populated by the electron capture process or when the levels decay only by internal conversion. These new systems, described in ref. [7], were used to determine the lifetimes of the 0_2^+ and 2_2^+ levels in $^{186,188}\text{Hg}$. The half-life values were measured to be 204 ± 45 ps in ^{188}Hg and ≤ 52 ps in ^{186}Hg . The corresponding values of $\rho^2(\text{E}0) \times 10^3$, obtained from the partial half-lives, were $7.7_{-3.2}^{+2.2}$ and ≥ 32 , respectively. These are shown in fig. 7. Additionally, the half-lives of the 2_2^+ levels were determined to be 141 ± 31 ps in ^{188}Hg and 48 ± 27 ps in ^{186}Hg . The mixing of the coexisting configurations, shown in Fig. 7 for $^{182-190}\text{Hg}$, was determined to be 1% and $> 4\%$ for ^{188}Hg and ^{186}Hg , respectively.

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. Lett. **B48**, 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. **C37**, 2170 (1988).
6. H. Mach, R.L. Gill and M. Moszynski, Nucl. Inst. Meth. **A280**, 49 (1989).
7. P. K. Joshi *et al.*, Nucl. Inst. Meth. in Phys. Res. **A335**, 461 (1993).

- Coexistence effects in ^{187}Au : evidence for nearly identical diabatic intruder structures.

The expected rich structure of the ^{187}Au nucleus, on the basis of its transitional character (the $h_{9/2}$ intruder is very near the ground state), provided the motivation to do complete spectroscopy on the $^{187\text{m}}\text{Hg}$ and $^{187\text{g}}\text{Hg}$ decay. One of the more interesting aspects of the identification of the multiple coexisting structures in ^{187}Au (see the next section for more details) was to locate the bands built on the $h_{9/2}$ and $f_{7/2}$ single-particle orbitals.

It has been established in ^{185}Au that the $h_{9/2}$ and $f_{7/2}$ single particle orbitals lead to separate band structures [1]. Analysis of the experimental data for the ^{187}Au nucleus

established one structure with the $h_{9/2}$ and $f_{7/2}$ bands mixed [2]. Theoretical calculations performed on this mixed configuration in the framework of the particle plus triaxial rotor model, PTRM, where a multi-j quasiparticle is coupled to an axially asymmetric rotor, confirmed this interpretation [2].

The mixed $h_{9/2} \oplus f_{7/2}$ structure in ^{187}Au has two negative-parity, $9/2^-$ bands built on the ^{186}Pt 0_1^+ and 0_2^+ configurations. As shown in Fig. 17, these bands have identical spins and nearly identical relative energies. The high degree of similarity between the experimental structures implies that there is very little difference in the deformation of the coexisting bands and, in this case, is consistent with prolate-prolate mixing in the ^{186}Pt core.

Fig. 17. The bands built on the $9/2^-$ and $9/2^-$ in ^{187}Au . The levels are drawn so that the centroids (calculated for both bands using energies of 8 levels, from $9/2^-$ to $17/2^-$) are at the same energy. The centroid separation energy is 334.4 keV. The levels depopulating by E0 transitions are denoted by •.

The most interesting aspect of the ^{187}Au data came out of a detailed analysis of the $h_{9/2} \oplus f_{7/2}$ structure. Experimentally, five enhanced E0 transitions that connected only favored $I \rightarrow I$ levels between the bands were identified. E0 enhancement was not observed between the unfavored $I \rightarrow I$ levels (see Fig. 18). Analysis of the PTRM orbitals, in a spherical basis, for the favored and unfavored bands provides the insight

to explain this heretofore unobserved phenomenon. The single particle content of the favored bands is mostly $h_{9/2}$, while the single particle content of the unfavored bands is $f_{7/2}$ in the more deformed and $h_{9/2}$ in the less deformed band. This different single particle content is directly responsible for the enhancement and attenuation of the E0 matrix element and gives rise to the hindrance of the E0 transitions between the unfavored levels of the two bands. This effect is shown in Fig. 15.

The diabaticity of nuclear motion is one of the most important and intriguing issues of the nuclear many-body problem. It appears naturally in the context of medium and large-amplitude collective motion which embraces such phenomena as anharmonic vibrations, coexistence, exotic decays, fission, fusion, and heavy-ion collisions. All those phenomena involve dynamical interaction between various stable mean fields characterized by different intrinsic symmetries and corresponding strong intrinsic quantum numbers that can isolate nuclear configurations in the phase space. The transition from one stable mean field to another goes through one or several level

Fig. 18. The same levels shown in fig. 17 but with the actual energy scale and with the favored (solid lines) and unfavored (open lines) separated. E0 transitions are observed only between the favored levels. This is an unprecedented observation.

crossings around which the original symmetry of the system is broken and the "effective" quantum numbers disappear [3-5]. Even at high excitation energies there exist well-ordered diabatic states that can be beautifully described by stable mean fields. Examples of these are superdeformed states or high-spin isomers.

The stringent test of the theories of large amplitude collective motion is provided by measurements of near-lying excited states built upon different intrinsic configurations. This kind of experimental information tells us about a mixing between stable minima and the dependence of this mixing on excitation energy, i.e., it addresses explicitly the issue of diabaticity.

The negative-parity bands in ^{187}Au represent a spectacular example of nuclear coexistence. In spite of rather similar deformations and similar rotational behavior, they can be characterized by different numbers of the $N=5$ proton intruders. In contrast to the situation in the neighboring Tl isotopes where the presence of aligned and strongly coupled bands suggest prolate-oblate shape coexistence, the two coexisting structures in ^{187}Au can be associated with near-prolate shapes. This interpretation explains the absence of E0 transitions between unfavored bands and gives additional evidence for the prolate $f_{7/2}$ configurations in this mass region [6,7]. Theoretically, the case of ^{187}Au once again amplifies the role of the $N=5$ proton intruder occupations in defining diabatic configurations in the Pt-Pb mass region.

1. A. J. Larabee *et al.*, Phys. Lett. **169B**, 21 (1986).
2. D. Rupnik *et al.*, Phys. Rev. C **51**, R2867 (1995).
3. A. Bulgac and D. Kusnezov, Nucl. Phys. **A545**, 549c (1992).
4. W. Nazarewicz, Nucl. Phys. **A557**, 489c (1993).
5. K. Iwasawa, F. Sakata, W. Nazarewicz, T. Marumori, and J. Terasaki, Phys. Lett. B **339**, 1 (1994).
6. G. J. Lane *et al.*, Phys. Lett. B **324**, 14 (1994); G. J. Lane, G. D. Dracoulis, A. P. Byrne, P. M. Walker, A. M. Baxter, J. A. Sheikh, and W. Nazarewicz, Nucl. Phys. **A586**, 316 (1995).
7. A. J. Larabee, M. P. Carpenter, L. L. Riedinger, L. H. Courtney, J. C. Waddington, V. P. Janzen, W. Nazarewicz, J.-Y. Zhang, R. Bengtsson, and G. a. Leander, Phys. Lett. **169B**, 21 (1986).

- Coexisting band structures in ^{187}Au

Levels in ^{187}Au have been studied by the radioactive decay of $^{187\text{m}}\text{Hg}$ ($J^\pi=13/2^+$) and $^{187\text{g}}\text{Hg}$ ($J^\pi=3/2^-$) using mass-separated sources. Multiscaled spectra of γ rays, X rays, and conversion electrons, as well as $\gamma\gamma$ t, γXt , γet , and eXt coincidences were obtained. Decay schemes have been constructed incorporating >99% of the intensity assigned to the high-spin and low-spin decays. The γ -ray gated conversion-electron spectra permitted determination of 367 conversion coefficients. A variety of coexisting band structures were established in ^{187}Au . Some of these have nearly identical analogs in the heavier odd-mass Au isotopes. The remaining bands reveal new degrees of

freedom at low excitation energy and a number of electric monopole (E0) transitions are observed to de-excite members of these new bands. These observations are discussed in terms of particles and holes coupled to the neighboring doubly-even Pt and Hg *cores*. The work represents a benchmark in *complete* spectroscopy following radioactive decay. The ^{187}Au nucleus is located in a region of rapidly changing ground-state behavior. Between ^{187}Au and ^{186}Au a very large isotope shift, comparable to that between ^{186}Hg and ^{185}Hg [1], has been observed [2]. These are the largest isotope shifts identified in this region and are interpreted [1,2] as due to sudden changes in ground-state deformation.

A systematic study [3] of the excited states of $^{185,187,189}\text{Au}$ reveals that the band structure that exists in ^{189}Au and the heavier odd-mass Au isotopes [4] persists in ^{187}Au . However, the ^{187}Au nucleus is at the "critical" point in that its core nucleus for proton-particle excitations, ^{186}Pt , has a deformed ground state while the ground state of ^{188}Pt (the corresponding core nucleus for ^{189}Au) is nearly spherical. Moreover, in ^{187}Au there are additional low-lying excited states that are observed [5] to decay by electric monopole (E0) transitions. These additional states and their decay by E0 transitions indicate [5] the presence of shape coexistence in ^{187}Au .

The shape coexistence in ^{187}Au is attributed [5] to the unusual intruder state structure and collective core structure in this region. In the neutron-deficient Au isotopes, the $\pi^{+1}h_{9/2}$ and $\pi^{+1}i_{13/2}$ intruder states are observed [6,7] to lie at very low excitation energy. The recognition of the $\pi^{+1}f_{7/2}$ intruder, presented as such in the in-beam data on ^{185}Au [8] and ^{187}Au [9] (in both cases only for the high spin parts of the band), provides little help in identifying separate $h_{9/2}$ and $f_{7/2}$ structures. Our data, however, show that in ^{187}Au , the $h_{9/2}$ and $f_{7/2}$ form a mixed configuration.

The present work was undertaken to provide as detailed a level scheme of ^{187}Au as possible in order to form a basis for a detailed discussion of the structure of ^{187}Au . The work demonstrates that it is necessary to go to *completeness* in the spectroscopy in order to extract the relevant *physics*. The single-particle orbitals that lie close to the Fermi energy and participate in the low-energy excitations are good candidates for the theoretical description of shape coexistence in a nucleus. In the ^{187}Au nucleus, such orbitals, below the Fermi energy, are the positive-parity single-particle states $s_{1/2}$, $d_{3/2}$, and $d_{5/2}$, and the negative-parity $h_{11/2}$ single-particle state. These orbitals, as proton-hole states in a core-particle picture, couple to the $^{188}_{80}\text{Hg}$ nucleus as the core. ^{188}Hg has a ground state configuration (0_1^+) that is weakly deformed with axial asymmetry [6,10] and an excited band (0_2^+) that is moderately prolate deformed with strong axial asymmetry [6,10].

structure, with the exception of a missing level with spin 1/2 and one extra experimental level with spin 3/2.

The structure of the $h_{11/2}$ configuration in ^{187}Au , shown in figure 20, was calculated in the same manner as the structure of $s_{1/2} \oplus d_{3/2} \oplus d_{5/2}$. Overall, there is a very good agreement between the experimental and calculated energy spectra, and every calculated state up to $\sim 1\text{MeV}$ above the $11/2^-$ bandhead has an experimental counterpart.

Systematics of the $\pi^{+1}(h_{9/2} \oplus f_{7/2})$ and $\pi^{+1}i_{13/2}$ states in the ^{185}Au , ^{187}Au , and ^{189}Au isotopes is shown in Fig. 21. The most important feature of the systematics is the exchange of the character (or nature) of the $(h_{9/2} \oplus f_{7/2})$ and $(h_{9/2} \oplus f_{7/2})'$ bands between the isotopes ^{187}Au and ^{189}Au . In ^{187}Au the $h_{9/2} \oplus f_{7/2}$ band has the intruder character, while the $h_{9/2} \oplus f_{7/2}$ band in ^{189}Au is the "normal" band. The analog of this

Fig. 20. the $h_{11/2}$ and $(h_{11/2})'$ (denoted as "intruders") family of negative-parity states in ^{187}Au (separated by a dotted line). The left part of the figure shows the results of the PTRM calculation, while on the right are experimental data. Level energies are given in keV relative to the basic state. The band head energy for the calculated intruder band is adjusted to be the same as the experimental band head. For λ , Δ , and $E2^+$ definitions see also Fig. 19. Levels depopulated with the $E0$ transitions are denoted by a *.

$h_{9/2} \oplus f_{7/2}$ normal band in ^{187}Au is the $(h_{9/2} \oplus f_{7/2})'$ band. The explanation underlying these observations comes from the systematics of the even-Pt isotopes which serve as cores for these odd-Au isotopes. For the ^{184}Pt and ^{186}Pt isotopes the intruder 0^+ state is the ground state, while for ^{188}Pt the ground state 0^+ is the "normal" state. The intruder 0^+ state is about 0.8 MeV above the ground state in ^{188}Pt . That is also why the intruder $h'_{9/2}$ band in ^{189}Au should lie much higher than the $h_{9/2}$, and is not observed [12] (see also next section). A comparison between the PTRM calculations and the experimental levels for the coupling of the $h_{9/2} \oplus f_{7/2}$ and $i_{13/2}$ to the ground state of ^{186}Pt as a core are shown in Fig. 22.

Fig. 21. The structure of the $\pi^{+1}(h_{9/2} \oplus f_{7/2})$ states in the ^{185}Au , ^{187}Au , and ^{189}Au isotopes. The levels are drawn so that the first "normal" $9/2^-$ levels are at the same height.

In order to extract the relevant physics, it became obvious that a new level of spectroscopic sensitivity and completeness would be required. Without doubt, this work represents a benchmark in completeness and is one of the most detailed spectroscopic analyses of a radioactive decay sequence to date. Newly developed

spectroscopic instruments and spectroscopic techniques were used to accomplish that task.

Fig. 22. The negative-parity states $h_{9/2} \oplus f_{7/2}$ and $(h_{9/2} \oplus f_{7/2})'$ (separated by dashed lines), and the $i_{13/2}$ family of positive parity states (boxed in by the dotted lines) in ^{187}Au . The results of the PTRM calculation are shown on left and the experimental data on the right. Level energies are given in keV relative to the basic state. The $i_{13/2}$ band head is drawn at 1135 keV (PTRM) and 1001 keV (exp.) above the $h_{9/2} \oplus f_{7/2}$ band head, but denoted as "0" to show that it is another band. The band head energy for the calculated intruder band ($h_{9/2} \approx f_{7/2}$)' is adjusted to be the same as the experimental band head. Levels with depopulating E0 transitions are denoted by a •.

1. G. Ulm *et al.*, Phys. A325, 247 (1986).
2. K. Wallmeroth *et al.*, Phys. Rev. Lett. 58, 1516 (1987) and K. Wallmeroth *et al.*, Nucl. Phys. A493, 224 (1989).
3. M. O. Kortelahti, E. F. Zganjar, H. K. Carter, C. D. Papanicolopoulos, M. A. Grimm, and J. L. Wood, J. Phys. G14, 1361 (1988).
4. E. F. Zganjar *et al.*, Phys. Lett. 58B, 159 (1975).

5. C. D. Papanicolaopolous, M. A. Grimm, J. L. Wood, E. F. Zganjar, M. O. Kortelahti, J. D. Cole, and H. K. Carter, *Z. Phys.* **A330**, 371 (1988).
6. K. Heyde, P. Van Isacker, M. Waroquier, J. L. Wood, R. A. Meyer, *Phys. Repts.* **102**, 291 (1983).
7. J. H. Hamilton, P. G. Hansen, and E. F. Zganjar, *Rept. Prog. Phys.* **48**, 631 (1985).
8. A. J. Larabee, M. P. Carpenter, L. L. Riedinger, L. H. Courtney, J. C. Waddington, V. P. Janzen, W. Nazarewicz, Y.-Y. Zhang, R. Bengtsson, and G. A. Leander, *Phys. Lett.* **169B**, 21 (1986).
9. C. Bourgeois, M. G. Porquet, N. Perrin, H. Sergolle, F. Hannachi, G. Bastin, and F. Beck, *Z. Phys.* **A333**, 5 (1989).
10. R. Bengtsson, T. Bengtsson, J. Dudek, G. Leander, W. Nazarewicz, and Jing-ye Zhang, *Phys. Lett.* **183B**, 1 (1987).
11. P. B. Semmes, private communication.
12. J. L. Wood, M. O. Kortelahti, E. F. Zganjar, and P. B. Semmes, *Nucl. Phys. A*, in press.

- Decay of mass-separated ^{189m}Hg and ^{189g}Hg to ^{189}Au

As discussed above, the focal point of investigations of the odd mass gold isotopes has been the low-lying intruder states [1] which are observed in the neutron-deficient Au isotopes. In $^{186,185}\text{Au}$ the intruder state becomes the ground state and a very large isotope shift is observed between ^{187}Au and ^{186}Au [2]. In addition, low-lying excited states are observed [3] to decay by electric monopole transitions in $^{187,185}\text{Au}$: this is unique [4] to this mass region. The nucleus ^{189}Au is the lightest isotope of gold with a low-energy structure that is apparently [5,6,7] free of these unique features, and closely resembles [8] the heavier odd-mass Au isotopes.

This study is part of a systematic investigation of the decays of the neutron-deficient mercury isotopes to provide a detailed picture of low-spin states in the odd-mass Au isotopes. The decays of 8.7 min ^{189m}Hg and 7.7 min ^{189g}Hg to ^{189}Au have been studied previously by Berg *et al.* [5] and Wood *et al.* [6]. In-beam studies [7] of ^{189}Au have provided information on high-spin states.

The present study had two main objectives. First, ^{189}Au is crucially located between the stability line and the far from stability regions. The latter regions rely heavily on systematics [9] for the detailed characterization of excited states. It was therefore vital that the excited states of ^{189}Au be characterized as thoroughly as possible. Second, ^{189}Au is on the border of a major change in nuclear structure. The more neutron-deficient odd-mass Au isotopes show a steep drop of a number of different intruder states [3] between ^{187}Au and ^{185}Au . Not all of these states were known to have counterparts in ^{189}Au . This work was aimed at extending the systematics of the new intruder states from $^{185,187}\text{Au}$ into ^{189}Au .

The earlier study [5] assigned 108 transitions to the $^{189m}\text{Hg} \rightarrow ^{189}\text{Au}$ decay scheme and determined multipolarities for 64 transitions. In the present work 316 transitions

were assigned and 164 multipolarities are determined. A comparison of the present results for ^{189}gHg with the work of Berg *et al.* [5] is more difficult. They did not extract separate feeding intensities for levels populated in each of the decays. For the lines which we see only in the ^{189}gHg decay, we have assigned 109 to the $^{189}\text{gHg} \rightarrow ^{189}\text{Au}$ decay scheme. Berg *et al.*, assigned only 6.

The most distinctive feature of the states of ^{189}Au is the very close resemblance that they bear to states in $^{191}, ^{193}, ^{195}\text{Au}$. This is especially pronounced for the low-lying positive parity states (fig. 23), and for the negative parity states associated with the $11/2^-$ isomeric state (fig. 24). The negative parity states associated with the $9/2^-$

Fig. 23. The systematics of the bands built on the positive-parity proton-hole configurations ($s_{1/2}$, $d_{3/2}$, $d_{5/2}$) in $^{185}\text{--}^{195}\text{Au}$. The bars with arrows indicate energies above which low-spin levels have been omitted.

state at 325 keV form a band which shows bigger differences with ^{191}Au , and where comparison can be made, with $^{193}, ^{195}\text{Au}$ (fig. 25); but the basic pattern is still similar.

We have shown [10] that the systematic features of $^{195-189}\text{Au}$ persist into $^{187,185}\text{Au}$. The data for $^{185,187}\text{Au}$ are included in figs. 23-25. Besides the smooth continuation of the $^{195-189}\text{Au}$ systematics into $^{187,185}\text{Au}$, additional states appear at low excitation energy in $^{187,185}\text{Au}$. The lowest of these are shown in figs. 23-25: notably, the 322, 371, and 712 keV states in ^{185}Au and the 443 and 881 keV states in ^{187}Au . These have been discussed in detail elsewhere [3, 4, 11]. They are interpreted as resulting from core intruder configurations [12] in $^{184,186}\text{Pt}$, $^{186,188}\text{Hg}$. These core intruder configurations are expected [12] at higher excitation in ^{189}Au . Their signature is expected to be E0 de-excitation strength. A careful search for E0 transitions was made in the present study, with no strong evidence found. The E0 decay of the 443 and 881 keV excited states in ^{187}Au corresponds [3] to 0_2^+ states in ^{186}Pt and ^{188}Hg at 472 and 825 keV, respectively. The 0_2^+ states in ^{188}Pt and ^{190}Hg

Fig. 24. The systematics of the bands built on the $h_{11/2}$ proton-hole configuration in $^{185-195}\text{Au}$. Medium-spin levels have been omitted above the bars with arrows.

lie [12] at 798 and 1279 keV, respectively. We deduce that the states in ^{189}Au corresponding to these core excitations are displaced upwards in energy to an

excitation where the present scheme is incomplete and where population is very weak. We estimate this to be above 1300 keV excitation for the ^{190}Hg core excited state and above 1135 keV excitation for the ^{188}Pt core excited state.

In order to help characterize the low-lying states and test the completeness of the experimental scheme, calculations have been performed with the particle + triaxial rotor model (PTRM) based on the formalism of ref. [13]. The Woods-Saxon potential was used to describe the deformed mean field, and the same potential has been used to describe the neighboring even-even Pt and Hg nuclei [14] as well as single-proton bandheads in this region [15]. For each set of calculations, the core is assumed to have a single fixed shape, and β_2 and β_4 deformation parameters are taken from the bandhead predictions [15] or the ^{188}Pt core [14]. The γ deformation was fitted to the experimental data, and the core 2^+ energy is obtained from Grodzins' rule and the γ value. Pairing is treated within the BCS method, so that the Fermi level (λ) and pairing gap (Δ) are derived and are not input parameters. The PTRM Hamiltonian was diagonalized within the space of low-lying one-quasiparticle states, and magnetic

Fig. 25. The systematics of the bands built on the $h_{9/2}$ proton-particle configuration in $^{185-195}\text{Au}$. Second and third excited states of a given spin-parity are omitted above the bars with arrows.

dipole matrix elements were calculated with the spin g-factor of the odd proton (g_s) taken as 70% of the free value, and the core g-factor (g_R) was estimated as Z/A .

The theoretical description using the particle + triaxial rotor model illustrates the usefulness of this approach in spite of its simplicity and the strong restriction to a fixed core shape. With minimal freedom in the parameters, a good description of all the low energy spectroscopic data (especially magnetic dipole and electric quadrupole moments and transitions) is achieved. For each of the three families of collective states (identified as the positive parity states, $h_{11/2}$ states, and " $h_{9/2} + f_{7/2}$ " states), every calculated level within ~ 900 keV of the corresponding bandhead has an experimental counterpart, and thus strongly supports the completeness of the experimental scheme.

1. K. Heyde, P. van Isacker, M. Waroquier, J. L. Wood, and R. A. Meyer, Phys. Repts. 102 (1983) 291.
2. K. Wallmeroth, G. Bollen, A. Dohn, P. Egelhof, J. Grüner, F. Lindenlauf, U. Krönert, J. Campos, A. Rodriguez Yunta, M. J. G. Borge, A. Venugopalan, J. L. Wood, R. B. Moore, and H.-J. Kluge, Phys. Rev. Lett. 58 (1987) 1516; Nucl. Phys. A493 (1989) 224; G. Savard, J. E. Crawford, J. K. P. Lee, G. Thekkadath, H. T. Duong, J. Pinard, S. Liberman, F. LeBlanc, P. Kilcher, J. Obert, J. Oms, J. C. Putaux, B. Roussière, J. Sauvage, and the ISOCELE Collaboration, Nucl. Phys. A512, 241 (1990).
3. C. D. Papanicolopoulos, M. A. Grimm, J. L. Wood, E. F. Zganjar, M. Kortelahti, J. D. Cole, and H. K. Carter, Z. Phys. A330 (1988) 371; C. D. Papanicolopoulos, Ph.D. thesis, Georgia Tech, 1987; D. Rupnik, Ph.D. thesis, Louisiana State University, 1994.
4. E. F. Zganjar, M. O. Kortelahti, J. L. Wood, and C. D. Papanicolopoulos, in Proc: 5th Int. Conf. on Nuclei Far From Stability, Rosseau Lake, Ontario, Canada, 1987, ed. I. S. Towner, AIP Conference Proceedings 164 (American Institute of Physics, New York 1988), p. 313.
5. V. Berg, R. Foucher, and Å. Höglund, Nucl. Phys. A244 (1975) 462.
6. J. L. Wood, R. W. Fink, E. F. Zganjar, and J. Meyer ter Vehn, Phys. Rev. C14 (1976) 682.
7. Y. Gono, R. M. Lieder, M. Müller-Veggian, A. Neskakis, and C. Mayer-Böricke, Nucl. Phys. A327 (1979) 269; Ts. Venkova, G. V. Marti, R. M. Lieder, W. Gast, A. Georgiev, D. Kutchin, H. Schnare, K. Strähle, T. Rzaca-Urban, J. Heese, and K. H. Maier, Z. Phys. A344 (1992) 231; C. Bourgeois, A. Korichi, N. Perrin, D. G. Popescu, F. Azaiez, D. Hojman, H. Sergolle, and G. Bastin, *ibid.* A343 (1992) 243.
8. E. F. Zganjar, J. L. Wood, R. W. Fink, L. L. Riedinger, C. R. Bingham, B. D. Kern, J. L. Weil, J. H. Hamilton, A. V. Ramayya, E. H. Spejewski, R. L. Mlekodaj, H. K. Carter, and W. D. Schmidt-Ott, Phys. Lett. 58B (1975) 159.
9. J. L. Wood, in Future Directions in Studies of Nuclei Far From Stability, eds. J. H. Hamilton *et al.* (North-Holland, Amsterdam, 1980) p. 37.
10. M. O. Kortelahti, E. F. Zganjar, H. K. Carter, C. D. Papanicolopoulos, M. A. Grimm, and J. L. Wood, J. Phys. G14 (1988) 1361.
11. D. Rupnik, E. F. Zganjar, J. L. Wood, P. B. Semmes, and W. Nazarewicz, Phys. Rev. C51 (1995) R2867.
12. J. L. Wood, K. Heyde, W. Nazarewicz, M. Huyse and P. Van Duppen, Phys. Repts. 215 (1992) 101.
13. S. E. Larsson, G. A. Leander and I. Ragnarsson, Nucl. Phys. A307 (1978) 189.
14. R. Bengtsson, T. Bengtsson, J. Dudek, G. Leander, W. Nazarewicz and J.-y. Zhang, Phys. Lett., 183B (1987) 1.
15. W. Nazarewicz, M. A. Riley and J. D. Garrett, Nucl. Phys. A512 (1990) 61.

- Search for superdeformed states in $^{190,192}\text{Hg}$

An Introduction

Many superdeformed (SD) bands have been discovered in the Hg-Tl-Pb region. Population of SD bands has been accomplished for the most part with heavy-ion, fusion-neutron evaporation (HI,xn) reactions and typically involves excitation energies of ~ 50 MeV and grazing angular momenta $>30\hbar$. With the relatively large excitation energy and angular momentum involved, the reactions populate states high-up in the SD bands. Depopulation of these states typically occurs via E2 transitions within the band until competing transitions decaying out of band dominate. Fission isomers in the actinide region have been populated in other reactions, including light-ion reactions (d,p), (α ,2n), etc. [1]. Thus, other methods which attempt to directly populate the lower end of the SD band are open for study.

One possible alternative method of populating SD states is through β decay. Because of the dissimilar parent ground state and daughter SD state, β -decay population of the SD states is expected to be highly hindered. Nevertheless, studies [2,3] of the β^+ decay of $^{232,234}\text{Am}$ to $^{232,234}\text{Pu}$ have revealed a weak delayed-fission branch ($\sim 6 \times 10^{-5}$ for ^{234}Am and $\sim 7 \times 10^{-4}$ for ^{232}Am), indicating that the fission isomer in $^{232,234}\text{Pu}$ might be populated. Other earlier work on β -delayed fission is found in refs. [4,5]. However, because the calculated excitation energies of the second minimum in the Hg-Tl-Pb region are ~ 3 -8 MeV, Q_β must be rather large in order to populate the SD band through β^+ decay. Additionally, allowed β -decay transitions ($\Delta I = \pm 1, 0$ and no parity change, $\Delta\pi = \text{no}$), first-forbidden β -decay transitions ($\Delta I = \pm 1, 0$ and $\Delta\pi = \text{yes}$), and first-forbidden unique β -decay transitions ($\Delta I = \pm 2$ and $\Delta\pi = \text{yes}$) restrict the spin of the decaying state to spins near that of the known SD states.

By e^- - γ , e^- - e^- correlations.

Superdeformed bands had been identified in ^{192}Hg [6,7] and in ^{190}Hg [8] but had not been placed in the energy scale. Theoretically, the band head was predicted to be around 3 to 5 MeV [9,10,11]. The of out-of-band transitions are enhanced around spin value 10 and therefore the levels with low spins and the band head are very weakly populated. In the case of radioactive decay of ^{192}Tl (ground state and isomeric state spin values of 7^+ and 2^- , respectively), the probability of feeding the superdeformed band at states 8^+ , 6^+ 2^+ , and 0^+ is possible. As shown in other sections, shape coexisting bands are observed to decay by E0 transitions and, since no γ rays have been

observed as the depopulating transitions from these SD band, it was thought that E0 transitions might provide a decay path.

Experiments were conducted in an attempt to observe E0 decay out of the superdeformed bands in $^{190,192}\text{Hg}$ by looking at high-energy/low-energy electron-electron correlations, and electron- γ correlations. In order to accomplish this, four Ge and two Si(Li) detectors were arranged around the two detecting stations on the UNISOR beam line, as shown in Fig. 37 (ahead). The ^{192}Tl isotope has a 7^+ isomer ($T_{1/2} = 10.8$ min) and a 2^- ground state ($T_{1/2} = 9.6$ min). The production of the ^{192}Tl ground state with spin 2^- was achieved through the $^{182}\text{W}(^{16}\text{O}, 6n)^{192}\text{Pb}$ reaction. To produce the ^{192}Tl 7^+ isomer, the reaction $^{181}\text{Ta}(^{16}\text{O}, 5n)^{192}\text{Tl}$, was employed. The ^{192}Tl reaction products were deposited on a tape which was then moved to the two detecting stations shown in Fig. 37 (ahead). At the first station, the tape was twisted by an angle of 45° , so that it would shine on the two Si(Li) detectors (one horizontal one vertical) and allow the conversion electrons to reach the detectors without having to pass through the tape.

In a similar manner an attempt was made to locate the superdeformed band of ^{190}Hg using the reaction $^{185}\text{Re}(^{16}\text{O}, 11n)^{190}\text{Bi}$ and the resulting β -decay path $^{190}\text{Bi} \rightarrow ^{190}\text{Pb} \rightarrow ^{190}\text{Tl}$ to produce the low-spin (2^-) ^{190}Tl ground state. No evidence for superdeformed band population was found in any of these experiments.

By internal pair formation

The results from the experiments described above suggested that possible E0 transitions from the superdeformed bands in $^{190,192}\text{Hg}$ are weaker than the sensitivity of the detection systems employed. For E0 transitions, internal pair formation process become a competing mode of depopulation when the transition energy involved is greater than 2 MeV in $Z=80$ nuclei. In order to study pair production events, a new beam line detector station was constructed. This was necessary because one requires two Si(Li) detectors in close proximity (facing each other is satisfactory if they are very close), as well as two Ge detectors facing each other to detect the 511-keV γ -ray photons that result from the e^+ annihilation. Finally, another Ge system is required to function as an X-ray detector. The new beam line module designed to accommodate these five existing detectors is shown in Fig. 38 (ahead). In this configuration only one Si(Li) can directly view the activity on the tape. The other Si(Li) detector can only receive electrons after they have passed through the tape ($\approx 0.001''$ mylar). Since one

is now only interested in high-energy electrons (> 2 MeV), this is not a serious problem.

The two Si(Li) detectors had energy resolutions of 1.85 keV (in front of the tape) and 4.95 keV (behind the tape) at 500 keV electron energy. The detector behind the tape had an intrinsic energy resolution of 1.90 keV. Reactions similar to those described above were used to produce $^{190,192}\text{Tl}$.

In the analysis of the data, a two-dimensional matrix of electron-electron correlations was generated. This matrix was then analyzed in such a way that all e^- , e^+ , 511γ , 511γ , γ , X correlations could be extracted and related to $E_{e^+} + E_{e^-} + 1.022$ MeV (the E0 transition energy). The $e^- + e^-$ correlations from internal conversion between levels in $^{190,192}\text{Hg}$ (e.g. $4^+ \rightarrow 2^+ \rightarrow 0^+$) were used to test this system. It performed precisely as expected. However, no E0 internal pairs were detected. The limitation on the population of the SD bands was determined to be 2×10^{-3} and 2×10^{-4} per 100 decays at 2 MeV and 3 MeV, respectively, in ^{192}Hg ; and 3×10^{-3} and 5×10^{-4} per 100 decays at 2 MeV and 3 MeV, respectively, in ^{190}Hg .

1. V. Metag, D. Habs, and H. J. Specht, Phys. Rep. **65**, 1 (1980).
2. H. L. Hall *et al.*, Phys. Rev. C **42**, 1480 (1990).
3. H. L. Hall *et al.*, Phys. Rev. C **41**, 618 (1990).
4. V. I. Kuznetson, N. K. Skobelev, and G. N. Flerov, Yad. Fiz. **5**, 271 (1967).
5. Yu. P. Gangriskii *et al.*, Yad. Fiz. **27**, 894 (1978).
6. J. A. Becker, N. Roy, E. A. Henry, M. A. Deleplanque, C. W. Beausang, R. M. Diamond, J. E. Draper, F. S. Stephens, J. A. Cizewski and M. J. Brinkman Phys. Rev. C **41** (1990) R13.
7. D. Ye, R. V. F. Janssens, M. P. Carpenter, E. F. Moore, R. R. Chasman, I. Ahmad, K. B. Beard, Ph. Benet, M. W. Drigert, P. B. Fernandez, U. Garg, T. L. Khoo, S. L. Ridley and F. L. H. Wolfs Phys. Rev. C **41** (1990) R13.
8. M. W. Drigert, *et al.*, Nucl. Phys. A **530** (1991) 452.
9. M. Girod, J. P. Delaroche, J. Libert and I. Deloncle Phys. Rev. C **45** (1992) R1420.
10. W. Satula, S. Cwiok, W. Nazarewicz, R. Wyss and A. Johnson Nucl. Phys. A **529** (1991) 289.
11. P. Bonche, J. Dobaczewski, H. Flocard, P. H. Heenen, S. J. Kriger, J. Meyer and M. S. Weiss Nucl. Phys. A **519** (1990) 509.

- The strength of electric monopole transitions and the decay out of the superdeformed bands

There is emerging evidence that E0 transitions can be associated with shape coexistence in heavy nuclei (see, e.g., [1, 2]). An essential ingredient in this association is the mixing (see, e.g., [3]) of configurations with different equilibrium deformations. In certain cases, pure E0 transitions are seen [4] even when M1 and E2 decay is possible. With detailed spectroscopic information [1] becoming available in regions of shape coexistence, it becomes possible to quantitatively relate E0 transition strengths, $\rho^2(\text{E0})$, to differences in mean-square charge radii, $\Delta\langle r^2 \rangle$, or to differences

in quadrupole deformation, $\Delta\langle\beta^2\rangle$. Thus, it becomes possible to make realistic estimates of $\rho^2(E0)$ for decay out of superdeformed bands. We show that it is possible for the E0 decay to be the dominant mode. Searches for draining transitions have not been very successful, with only a few examples established [5]. A study of K X-ray yields, which would be large for E0 transitions because they are strongly converted in the K shell, have resulted in an unclear picture [6, 7]. A direct search for E0 decay of superdeformed bands using discrete-line conversion-electron spectroscopy has not yet been made to our knowledge.

The strength of E0 transitions can be expressed (see, e.g., [8]) as

$$\rho^2(E0) = \left(\frac{3Z}{4\pi}\right)^2 a^2 b^2 (\Delta\langle\beta^2\rangle)^2 \quad (1)$$

or as

$$\rho^2(E0) = \frac{Z^2}{R^4} a^2 b^2 (\Delta\langle r^2\rangle)^2, \quad (2)$$

where a and b ($=\sqrt{1-a^2}$) are the mixing amplitudes of the coexisting configurations and R ($= 1.2 A^{1/3}$ fm) is the nuclear radius. The strongest known $\rho^2(E0)$ in heavy nuclei ($A>56$) is in ^{96}Sr [9] which has $\rho^2(E0; 0_2^+ \rightarrow 0_1^+) = 0.185^{50}$. From the Sr isotope shift data [10], we deduce $\Delta\langle r^2\rangle = 0.6 \text{ fm}^2$ for the shape coexisting configurations in ^{96}Sr [2, 9], whence from eq. 2 we estimate a maximum $\rho^2(E0)$ in Sr ($Z = 38$) of 0.14. Recently, $\rho^2(E0)$ data have become available for the decay of the shape coexisting states in $^{186,188}\text{Hg}$ [11]. From the ^{185}Hg isomer shift data [12], the $\rho^2(E0)$ values of 0.0077 (^{188}Hg) and >0.032 (^{188}Hg) [11] require a^2 values of 0.012 and >0.04 , respectively. This is consistent with mixing amplitudes in $^{180,182,184}\text{Hg}$ deduced from α -decay widths [13]. (An effective monopole charge of 1.0 is assumed in all cases considered here.)

The decay out of superdeformed bands occurs through mixing with weakly deformed states. Typical values of β for superdeformed and weakly deformed configurations are 0.5 and 0.1 (see, e.g., [14]), respectively. Thus, $\Delta\langle\beta^2\rangle = 0.24$ and we estimate a maximum $\rho^2(E0)$ of 4.3 ($Z = 60$) and 7.7 ($Z = 80$) (cf. eq. 1). Using the standard recipes (see, e.g., [15, 16]) for electromagnetic decay, estimates can be made for the decay modes of superdeformed bands. We present some estimates in fig. 26.

The present estimates of E0 decay branches from superdeformed bands suggests that a direct search for such decay is well worthwhile. This search should be at low energy, as is evident from fig. 1. Whether the E0 strength will be concentrated in a few transitions or be spread over many transitions (possibly forming a continuum) can only

be revealed by experiment. To our knowledge, no such search has been carried out. Circumstantial evidence [7, 19] suggests that, at least in certain cases, the search might be successful.

Fig. 26. Electromagnetic decay branches for a "typical" superdeformed band in a nucleus with $Z=80$ and hindrances relative to Weisskopf single-particle estimates, H_W , and mixing amplitudes a , as shown. Transition energies are given in keV. The strongly enhanced 100 keV $E2$ transition is in the superdeformed band. Its strength, which corresponds to $B(E2) = 2000$ Wu, is based on observed mean lifetimes in superdeformed bands. The hindered 200 keV transitions represent decay strength arising from mixing between superdeformed and weakly deformed states, with hindrances characteristic of non-collective $E2$ and $M1$ transitions, and a mixing amplitude characteristic of observed values [17] for coexisting states in the Pb isotopes. The very hindered 1-2 MeV transitions are assigned strengths similar to those observed [18] in the electromagnetic decay of the fission isomer in ^{238}U .

1. J. L. Wood *et al.*, Phys. Repts. **215**, 101 (1992).
2. E. F. Zganjar, and J. L. Wood, Nucl. Phys. **A520**, 427c (1990); J. L. Wood, in Proc. Int. Conf. on Nuclear Shapes and Nuclear Structure at Low Excitation Energies, Antibes, France, June 1994, ed. M. Vergnes *et al.* (Editions Frontières, Gif-sur-Yvette, France, 1994), p. 295; E. F. Zganjar, and J. L. Wood, in Proc. Int. Conf. on Exotic Nuclei and Atomic Masses, Arles, France, June 1995, in press; J. L. Wood, E. F. Zganjar, and K. Heyde, work in progress.
3. K. Heyde, and R. A. Meyer, Phys. Rev. **C37**, 2170 (1988).
4. J. Schwarzenberg, J. L. Wood, and E. F. Zganjar, Phys. Rev. **C45**, R896 (1992); Y.-S. Xu *et al.*, Phys. Rev. Lett. **68**, 3853 (1992).
5. A. Atac *et al.*, Phys. Rev. Lett. **70**, 1069 (1993); R. Janssens, private communication, 1995.
6. E. F. Moore *et al.*, Phys. Lett. **258B**, 284 (1991).
7. M. Palacz *et al.*, Nucl. Phys. **A578**, 225 (1994).
8. J. Kantele, in Heavy Ions and Nuclear Structure, Proceedings of the XIV Summer School, Mikolajki, Poland, 1984, eds. B. Sikora and Z. Wilhelmi (Harwood Academic, New York, 1984) p. 391.
9. H. Mach *et al.*, Phys. Rev. **C41**, 350 (1990).
10. F. Buchinger *et al.*, Phys. Rev. **C41**, 2883 (1990).
11. P. Joshi *et al.*, Intl. J. Mod. Phys. **E3**, 757 (1994).
12. G. Ulm *et al.*, Z. Phys. **A325**, 247 (1987).
13. J. Wauters *et al.*, Phys. Rev. **C50**, 2768 (1994).
14. W. Nazarewicz, Phys. Lett. **B305**, 195 (1993).
15. K. S. Krane, Introductory Nuclear Physics, John Wiley and Sons, New York, 1988, p. 332.
16. J. Kantele, Nucl. Instr. Meth. **A271**, 625 (1988).
17. P. Dendooven *et al.*, Phys. Lett. **226B**, 27 (1989).
18. J. Kantele *et al.*, Phys. Rev. Lett. **51**, 91 (1983).
19. J. X. Saladin *et al.*, preprint 1995; and J. X. Saladin., private comm., 1995.

- Electric monopole transitions: A review

Section B.1 above provides a brief review of some aspects of E0 transitions that comes from a general review that is on-going between E. F. Zganjar (LSU), J. L. Wood (Georgia Tech.), and K. Heyde (Gent). This review will identify every excited 0^+ state in all even-even nuclei, every known E0 transition in all nuclei, and report all measured ρ^2 values (or compute them from reported lifetimes). The review will discuss the role of E0 transitions in the elucidation of nuclear structure and the correlations between experimental measurements and predictions of various nuclear models. We expect to complete it sometime during 1996.

3. Collaborations where LSU personnel were not the principal investigators.

- Search for superdeformed states in ^{194}Pb .

It was thought [1] that the population of superdeformed (SD) states in ^{194}Pb following the β^+ decay of ^{194}Bi provided a better case than that of $^{190,192}\text{Hg}$. The LANL group used the same detector systems which we designed for the $^{190,192}\text{Hg}$ experiments and performed the experiment at UNISOR. The β decay of ^{194}Bi , with its large Q_β value and high spins of the decaying isomeric state, provides a favorable

opportunity to search for population of known SD states in the daughter nucleus, ^{194}Pb . Both γ rays and conversion electrons were measured in singles and coincidence; however, no evidence for the population of SD states was observed. Upper limits for the population of certain SD states range from 0.0 to 2.05 per 100 decays, but, within error, all consistent with 0.0.

This work was done in collaboration with the LLNL (Henry), ORNL (Akovali) Tennessee (Bingham), Georgia Tech (Wood), UNISOR (Mantica) groups. M. A. Stoyer (LLNL) was the principal investigator. P. Joshi represented the LSU group.

1. M. A. Stoyer *et al.*, Phys. Rev. C **47**, 76 (1993).

- Nuclear orientation and spectroscopic studies of the decay of ^{187}Pt to ^{187}Ir .

The nuclear structure of odd-proton ^{187}Ir was studied following the radioactive decay of mass-separated ^{187}Pt . Two experiments were done: a spectroscopy study in which γ -ray and electron singles and γ - γ and γ -e coincidences were observed, and a nuclear orientation study in which γ -ray angular distributions were measured from ^{187}Pt oriented at low temperatures in an iron host.

The isotopes of Ir-Pt-Au-Hg around $A=187$ lie near a closed proton shell at $Z=82$ and a half-filled neutron shell at $N=104$. This is a transitional region in which the nuclear shape changes with increasing mass from prolate to oblate. Nuclei in this region have a very rich structure, with rotational bands built upon oblate, prolate, or triaxial intrinsic shapes, as well as excitations due to β and γ vibrations. Many transitional nuclei are also known to display shape coexistence (see the review by Hamilton *et al.*[1]), in which the low-lying structure of the nucleus can be based on bands having different shapes, such as prolate and oblate. This widely manifested phenomenon is illustrated by the existence of bands with different deformations, in which strong in-band $B(E2)$ values indicate the stable deformation of the bands.

The investigation of ^{187}Ir was part of a study of the systematics of the odd Ir isotopes from $A=185$ to 193 using the method of low-temperature nuclear orientation to elicit the low-lying structure. An interesting question concerning the structure of ^{187}Ir is whether the nucleus should be described as a rigid triaxial or a γ -soft axial rotor. Potential energy surface calculations of the even-even cores of ^{187}Ir by Bengtsson *et al.* [2] indicate that ^{186}Os should have a single, prolate minimum (with a deformation of 0.2 to 0.25), while ^{188}Pt should have a γ -soft potential energy surface. In the absence of strong polarization effects, single-particle levels built upon those configurations

should reflect one of the two core structures. Unfortunately, it is difficult experimentally to distinguish between a weakly-deformed triaxial and a γ -soft nucleus.

A detail level scheme, accounting for approximately 92% of the γ -ray intensity and including transitions up to 2.4 MeV has been established. The E2/M1 multipole mixing ratios of a number of transitions in ^{187}Ir were determined from the conversion coefficients and angular distribution anisotropies. A particle-plus-triaxial-rotor model was used to interpret the data, and mixing ratios calculated in that model agree very well with experimental values for transitions among the positive-parity bands.

1. J. H. Hamilton *et al.*, Rept. Prog. Phys., 48, 631 (1985).
2. R. Bengtsson *et al.*, Phys. Lett. 183B, 1 (1987).

- Decay chains of ^{202}Fr and ^{204}Fr and α decay branches

The decay chains of ^{202}Fr and ^{204}Fr were observed at the ISOLDE facility with Si α and Ge γ detectors. The activities were made by the bombardment of a ThC target with a pulsed 1-GeV proton beam, ionized with a positive surface ionization source, and directed from the general purpose separator along the low-mass beam line. The separations were rapid resulting in a pulsed Fr beam at the collection station, in response to the pulsed proton beam. For the shorter activities, decay between beam pulses was followed using detectors located right at the collection spot. The production rates were sufficiently high to get quite good statistics for the principal decay modes.

^{204}Fr is known to have three isomers, 3^+ , 7^+ and 10^- from earlier work [1]. In the present work, in addition to α transitions from each isomeric state, we measured the isomeric transition from the 10^- state to the 7^+ state, and obtained a good estimate of the ec/β^+ decay rate of ^{204}Fr isomers to ^{202}Rn from the observation of known γ -rays in ^{202}Rn . The population and de-population of the three different isomers in ^{200}At was used to confirm branching ratios measured in earlier work [1].

Only two isomers, 10^- and 3^+ , were known in ^{202}Fr . No isomeric transition was observed in its γ -ray decay spectrum. After α decay of each isomer to the equivalent isomer in ^{198}At , the decay chain was further traced by measurement of the alphas emitted by the daughters and granddaughters. The number of α decays away from each isomer in ^{198}At is about equal to the number of decays into each isomer, indicating that the α -decay branch of each isomer is essentially 100%. However, a few α -decays of ^{198}Po indicate that a small fraction, $\approx 2\%$ of the ^{198}At produced, actually decays via

ec/ β^+ to Po. This permits the placement of a very large lower limit on the α -decay branch for each of the two isomers populated in ^{198}At ; the α branch is $\geq 97\%$ for the 3^+ isomer and $\geq 94\%$ for the 10^- isomer.

This work was done in conjunction with the Tennessee (Bingham), ORNL (Akovoli), Maryland (Walters) Oxford (Rikowska), ISOLDE groups. C. Bingham (Tennessee) was the principal investigator. P. Joshi represented the LSU group.

1. M. Huyse *et al.*, Phys. Rev. C **46**, 1209 (1992).

IV. HRIBF Support and Instrumentation

A. RIB development/support

1. RIB ion source components

The LSU Nuclear Spectroscopy Group and the LSU Department of Physics and Astronomy Machine Shop assisted the ion-source development effort at the Holifield Radioactive Ion Beam Facility (HRIBF) by producing components for the HRIBF negative surface ionization and electron-beam plasma ion sources with the following objectives:

- a)* To determine the feasibility of the LSU Department of Physics and Astronomy machine shop to produce such components and then to determine the appropriate scope of involvement should the concept prove feasible.
- b)* To assist in the development of working ion sources by providing additional flexibility and a more rapid response in the production and re-design of ion source components.

The LSU Department of Physics and Astronomy Machine Shop produced over 200 ion source parts from "difficult to machine" materials such as tungsten, tantalum, molybdenum, and carbon (graphite). In terms of complete ion-sources, that would amount to approximately 2.5 units. A sketch of the electron beam plasma ion source is presented in Fig. 27. There was no cost to HRIBF associated with the manufacture of these components. All materials acquisition, electron-beam welding costs (performed in a commercial shop), and coordination efforts were borne by the LSU Nuclear Spectroscopy Group. All machine shop time was borne by the LSU Department of Physics and Astronomy. The machine shop time was quite extensive since numerous "jigs" and other devices had also to be constructed in anticipation of possibly making multiple copies (see objective *a* above). Materials acquisition costs alone exceed \$15,000. Electron-beam welding charges amounted to \$1,800.

While the components produced were deemed (by HRIBF personnel) to be as good as could be produced in any commercial shop, and although HRIBF was interested in pursuing objective *a* above, the Department of Physics and Astronomy was reluctant to enter into a "contractual" arrangement to guarantee delivery of ion sources on a fixed schedule. Since the Machine Shop serves all experimental programs in the department, the departmental administration felt that it could not afford to lose the flexibility required

to serve those programs. So, while the "test" was successful (LSU could indeed manufacture such ion sources), the test also showed that the effort would reduce the

Fig. 27. A schematic of the HRIBF electron beam plasma ion source. Components for approximately 2.5 ion sources were fabricated at LSU. The scale is approximately 1/2 size.

"flexibility" of the shop to concentrate on the department's most "pressing" projects (always determined on an *ad hoc* basis).

The LSU Nuclear Spectroscopy Group and the LSU Department of Physics Machine Shop will, however, continue to fulfill objective *b* above. This has quite recently involved the production of a number of the larger components (outer disk and cylinder, see Fig. 27) out of graphite.

2. RIB ion source test components

- The isotope separator

During the years of UNISOR operations, the LSU Nuclear Spectroscopy Group and the LSU Department of Physics and Astronomy Machine Shop manufactured most components associated with the UNISOR isotope separator, particularly those for the "ion-source end" of the device. Although the isotope separator is now used solely as a test facility for the development of HRIBF RIB ion sources, we have continued to provide that service. Apart from a large chamber (wonder box) which connects the beamline to either the isotope separator or to the HRIBF ion source (which is much larger than the isotope separator ion source), most of the components were individual and provided on an "as needed" basis. This type of activity will continue since ion-source development at HRIBF will require a continual effort.

- The 300 KV diagnostics system

A specialized tape transport system which comprises the heart of the system to analyze the radioactive ion beam emanating from the 300 KV platform was constructed at LSU. The radioactive ions are deposited on a quarter-inch wide tape and transported to a detecting station. A Ge detector at the detecting station is used to collect the gamma spectra. The data are collected using a PC based data acquisition system. A completely new software package was developed (by HRIBF) to calculate the rate of production of the radioactive ions in the beam. Since rates can be calculated on-line, this system will help the operators to tune and direct the radioactive ion beam to the secondary target with greater speed and efficiency. The system is configured so that it can easily be withdrawn from the beamline during experiments.

B. RMS development/support

1. General purpose equipment

- The moving tape system

The LSU Nuclear Spectroscopy Group is providing, at no cost to HRIBF, the moving tape system which will be used in association with the RMS and the DRMS. The system, shown schematically in Fig. 28, uses 1.3 inch (35 mm) tape which can be made out of different materials and with different thicknesses. The thickness is important in terms of having control over the location of the stopped reaction products in the tape (apart from using degraders). This is important for charged particle

spectroscopy where a minimum of degradation due to "source" thickness (i.e. buried in the tape) can be tolerated.

Fig. 28. Overview of the tape transport system in two of its possible configurations. The dimensions X, Y, and Z can be chosen at will. RMS stands for recoil mass spectrometer.

The drive unit contains the tape in a cassette arrangement where it is "stuffed" (not wound) into the cassette on one side and "pulled" out on the other. This arrangement makes it much easier to customize the system for each experiment as shown below. The unit will be mounted on wheels (*wheels up* leveling screws when being used), so that it can be easily installed and removed. The "piping" to the RMS and to the detectors is made entirely out of NW 50 *Klamp-Flange* stainless steel pipe and flanges as shown in Fig. 29. That pipe has an I.D of 1.88 inches. The design is such that

Fig. 29. The "tinker toy" arrangement which provides the flexibility inherent in the tape transport system. All vacuum connections use standard KF-50, *Quick Connect* flanges and clamps (see also Fig. 30.)

different configurations can be readily assembled to meet the varied requirements at both the RMS and at the detector station. Experimenter designed modules at each of these positions can be easily attached with the *Klamp-Flange*, sometimes called *Quick Connect*, which is a "standardized" vacuum product. An example is shown in Fig. 30 for astrophysics measurements (half-life by positron decay).

Fig. 30. A possible "customized" detector station. The left figure shows the standard "adjustable" vacuum system in which the tape moves and a phallus end which could be placed at the center of a gamma-ray detector array. The right figure shows an application desired by the astrophysics group for positron decay measurements where only a small modification of the system is required.

The system will consist of a number of "modules". These will include ones for simply removing one mass/charge and carrying it to the detectors as shown in Fig. 31, to ones to allow gamma and charged particle spectroscopy right at the focal plane where the tape is used to get a "clean" spot every so often (depending upon half-lives etc.) as shown in Fig. 32. At the detector end there will be ones

Fig. 31. A possible configuration employing a pair spectrometer.

which are a simple "turn around" in a thin-wall aluminum phallus as shown in Fig. 29. Later improvements will include the ability to collect three charge states of one mass. This will be especially important for RIB experiments.

The drive unit contains a standard stepping motor. It will have an on-board computer so that tests can be made without requiring the data acquisition computer. The system consists of four components; a PC interface, a controller, a translator/driver, and a motor. With windows based software the control program can be generated and edited on the PC and downloaded to the motor controller via RS232c. The controller has the capability to run open or closed loop and has programmable speed and ramping. There are also 8 inputs and 8 outputs for user definable functions. The translator/driver can be run in either full or microstep mode. By executing microsteps of 1/10 of a full step these drivers increase step resolution, reduce amplitude of resonance, and achieve more stable torques. The motor is a 6.0 A/phase, 300 oz-in double shaft two phase model with 1.8 degree step angle. All operations can be programmed and tested prior to connection to the data acquisition system. The 8 inputs can be set-up to accommodate CAMAC.

Fig. 32. A possible configuration for short half-life measurements (< 0.5 sec). In this arrangement, the tape serves only to periodically remove the long-lived daughter products from the detector position.

Fig. 33. Schematic of a configuration employing a gamma-ray detector array. The insert shows a possible enhancement of the system to include charged particle detectors within the array.

- The DSSD chamber

The use of double-sided silicon strip detectors (DSSD) at the focal plane of an RMS is a powerful tool for charged particle spectroscopy. A DSSD consists of an ion implanted Si Substrate that is divided into horizontal strips on one side and vertical strips on the other. A charged particle will leave a signal in one front strip and one back strip (relative to the ion beam direction). This effectively results in N^2 *pixels* (N being the number of strips on each side). The reason for making these pixels small is the difference in range between electrons and heavier charged particles. By keeping the pixels small and thin, the electrons will not leave enough energy in one pixel to be observed, but heavier charged particles will.

Fig. 34. Schematic of the prototype DSSD chamber. The design is for flexibility in that the "cover plates" can be customized. Only the plate containing the DSSD with its electronics and refrigeration is sketched.

In addition to being transparent to electrons, correlations between parents and daughters can be made to establish a heavy-charged particle (α or proton) decay chain. Correlations between the PSAC (position sensitive avalanche counter) and the DSSD will also give information on the mass number (A) of the parent in addition to its half life. The DSSD detectors that will be used at HRIBF are 40 strips by 40 strips (1600 pixels). They must be large detectors (4 cm²) because of the great dispersion afforded

The LSU group (Jon Batchelder) has designed and the LSU and University of Tennessee Machine Shops have constructed a prototype DSSD chamber which is schematically depicted in Fig. 34. The chamber is essentially a rectangular cube with the back plate containing the DSSD. Only the rear stainless steel cover plate, which contains all the electronic and refrigeration components, is shown. Other plates can be customized (or left blank) as desired by the experimenter. The top and bottom plates contain the source insertion device and vacuum port, respectively. The rear plate has a Be window to allow for external X-ray spectroscopy.

Architectural floor plan of a rectangular room, labeled "23'" at the top. The plan shows a central open area, a long dark rectangular feature (possibly a stage or screen) at the top, and two smaller dark rectangular features on the left and right sides. The room is divided into sections by walls and doors. Dimensions are provided for the overall size and internal divisions.

Overall dimensions: 23' (width) x 10' (depth).

Internal dimensions and divisions:

- Top section: 3.75' (width) x 2.875' (depth).
- Left section: 2.875' (width) x 2.875' (depth).
- Right section: 2.875' (width) x 2.875' (depth).
- Bottom section: 2.875' (width) x 2.875' (depth).

The plan also includes a detailed view of the top section, showing a long dark rectangular feature with a series of small rectangular elements (possibly seats or equipment) along its length. The bottom section shows a similar dark rectangular feature. The central area is a large open space with a few small rectangular features (possibly tables or equipment) and a central doorway.

64

- The RMS end station

Jon Batchelder assisted HRIBF in the design work on the RMS parallel plate avalanche counter (PSAC). To show the size of this detector, a schematic which he prepared is given in Fig. 35. The LSU nuclear spectroscopy group and the LSU Physics Department Machine Shop constructed a large *end-plate* (same size as the PSAC shown above) for the RMS which will provide an exit-port for various on-line experiments at the RMS focal plane (behind the PSAC), such as work with DSSD detectors, tape drives, etc. This was done at no cost to HRIBF.

2. Specific purpose equipment

- Picosecond lifetime system

Measurements using the picosecond lifetime system and a schematic describing one application of the technique were given in section III.B.2 and Fig. 16, respectively. The measurement of nuclear level lifetimes that lie in the range of 10^{-10} to 10^{-12} seconds can be accomplished with the delayed-coincidence method, provided the timing resolution of the fast coincidence circuit is good enough to allow the distinction between the delayed- and prompt-timing spectra. For sensitivity in the picosecond regime, a full-width at half-maximum (FWHM) for the prompt timing spectrum on the order of a few hundred picoseconds is required. This is not attainable by using standard semiconductor detectors owing to their inherently slow charge collection times.

A system to measure nuclear level lifetimes in the picosecond range had been developed [1] at the TRISTAN on-line separator facility, which was able to achieve adequate timing resolution with the implementation of BaF₂ scintillators for the detection of γ radiation. This system was based on the measurement of a fast coincidence between a β^- ray, detected in a thin plastic scintillator, and a γ ray observed in a BaF₂ crystal. Since the energy resolution of a BaF₂ detector is rather poor (typically 9% for the 662-keV transition in ¹³⁷Cs) when compared with the resolution attainable with a standard semiconductor detector, a slow coincidence circuit that uses a Ge γ -ray detector to isolate the γ cascade of interest was employed. The resulting highly selective $\beta^- - \gamma - \gamma$ fast/slow triple coincidence timing circuit allowed the measurement of nuclear lifetimes to better than 10 ps [1].

One limitation of the above system, however, was the requirement of a cascade of γ radiations and the use of a Ge detector as the transition-selective element. This requirement precluded the measurement of lifetimes for certain nuclear levels,

particularly those that decay solely by electric monopole (E0) transitions, such as in $^{182-188}\text{Hg}$. Since an E0 transition results in the emission of a conversion electron (e^-) with no corresponding γ ray, these transitions would be missed in the system described above.

Another limitation of the picosecond lifetime system is its reliance on the β^- decay process to trigger the fast coincidence system. For nuclei that lie on the neutron deficient side of the valley of β stability, the electron capture process can compete favorably with positron (β^+) decay, especially in cases where the decay energies are low and Z is large. When β^+ decay is the dominant process, a fast timing system that is essentially the same as the TRISTAN [1] system can be used; however, in the situation where the process of electron capture dominates, there is no emission of a β ray and therefore no trigger for the fast timing circuit.

Fig. 36. Setup of the detectors used to measure picosecond lifetimes. The vertically placed plastic and BaF_2 detectors were used to extract the timing information, whereas the horizontally placed Ge and Si(Li) detectors were used for energy selection. On the bottom-left side of the figure, the tape used for transporting the radioactive source to the detecting stations can be seen. The upper BaF_2 crystal can be replaced with plastic for β^- or β^+ detection.

We made significant modifications to the design of the TRISTAN picosecond lifetime system with the implementation of BaF₂ crystals as X-ray detectors, and the replacement of the Ge γ detector with a Si(Li) e⁻ detector. The use of either a BaF₂ crystal to detect the resulting X-rays from the K-conversion process, or the plastic crystal to detect the β^+ , provides additional flexibility. Such a system allows the lifetime measurement of a level that decays solely by an E0 transition. A schematic of the system as it was employed on one of the UNISOR beam-line modules is shown in Fig. 36.

Development of this system was done in conjunction with S. J. Robinson and P. M. Mantica.

- [1] H. Mach *et al.*, Nucl. Inst. Meth. **A280**, 49 (1989).
- [2] P. K. Joshi *et al.*, Nucl. Inst. Meth. **A335**, 465 (1993).

- Conversion electron and internal pair spectrometers.

Some of that which is presented here goes back further than three years, but several new "configurations" of older instruments for conversion electron spectroscopy were used to perform several of the experiments described in this progress report. Additionally, the discussion will show the evolution of systems designed for conversion-electron and internal-pair spectroscopy to those which are designed for research with RIBs at HRIBF.

Figure 37 shows a detector station employing two low-temperature, high resolution Si(Li) detectors for conversion-electron spectroscopy, three Ge detectors for gamma and X-ray spectroscopy, and a moving tape system. The Si(Li) system in the horizontal arrangement with the bellows is the type designed and constructed at LSU and used for a decade at UNISOR. The vertical system (without a bellows) was developed and added to the system in order to do high-resolution, wide-band, electron-electron-gamma correlations (the tape was twisted to 45 degrees so that both Si(Li) crystals could view the "activity" unimpeded by the tape). This system not only is capable of electron-electron-gamma correlations, but also has the ability (albeit with modest efficiency) to detect internal pairs (e⁺ and e⁻) resulting from internal-pair formation of high energy transitions - particularly E0 transitions. Its use is described in section III.B.2 (Search for superdeformed states).

In order to improve the efficiency and to add the 511-511 keV annihilation as another "gate" (180 degree correlation), the system depicted in Fig. 38 was assembled. In this system, two of the bellows Si(Li) electron systems were placed facing each

other horizontally, and two Ge detectors (principally for the 511 keV annihilation gate, but also active for any gamma ray) were placed facing each other vertically. It was absolutely imperative to have another photon detector (capable also of detecting low energy X-rays) in the system. This was placed at the back of the beam line by moving the tape collector to a 45 degree position, as shown in Fig. 38. This system provided greater efficiency and sensitivity for the internal-pair formation experiments. Its use is described in section III.B.2 (Search for superdeformed states).

Fig. 37. Sketch of the right beam line with two detecting stations and the tape drive which moves the tape inside the beam line to transport the nuclei under study, from the collection point, where the radioactive nuclei are deposited on the tape, to the detecting stations. This set-up of detectors was used in the experiment to search for population of the superdeformed bands in $^{190,192}\text{Hg}$ by $e^-e^+\gamma$ (internal pair) correlations. In this arrangement, the high resolution, wide band Si(Li) electron detectors are at 90° with respect to each other and the tape is twisted to 45° so that both Si(Li) crystals can view the "activity" unimpeded by the tape.

Fig. 38. The beam line module used in the search for superdeformed bands in $^{190,192}\text{Hg}$ using the internal-pair process. The two Si(Li) detectors were placed horizontal and the two Ge detectors were placed vertical. Another Ge detector which functioned as an X-ray detector was placed horizontal at the far end of the beamline. Tape drive and calibration source ports were connected at 45° to the beamline. The Si(Li) detectors were placed in extremely close geometry because of the small opening angle between the e^+ and e^- pairs resulting from internal-pair formation.

Fig. 39. Arrangement to "service" the Si(Li) detectors from "edge-on" and simultaneously enable the placement of Ge γ -ray detectors directly behind the Si(Li) crystals. See text for more information.

A dramatic improvement in performance of the above system for internal-pair spectroscopy was obtained by the innovation shown in Fig. 39 where the cryogenic, high resolution, wide band Si(Li) crystals could be "serviced" both electrically and cryogenically from "edge-on". This was accomplished as shown in the right two panels of Fig. 39. With this arrangement, the Ge detectors could be placed directly behind the Si(Li) crystals (as shown in the left panel), thus greatly improving the geometry (and concomitantly the efficiency) of the system. This system was finished subsequent to the shutdown of HHIRF so it has not been fully implemented, but off-line tests agree with its design specifications. This system provided the highest conversion electron resolution yet obtained for such thick Si(Li) crystals, better than 1.80 keV FWHM at 975 keV electron energy.

Fig. 40. The new Si(Li) arrangement for high resolution, wide band, conversion-electron and internal-pair spectroscopy using RIBs at HIRBF.

In planning for experiments with radioactive ion beams (RIBs), it became obvious, due to the lower beam intensity, that even greater efficiencies would be required. One of the goals of the LSU Nuclear Spectroscopy Group involves the elucidation of multi-particle multi-hole states along $N=Z$ which one can "reach" with RIBs. In this application, as is discussed in the proposal document to which this progress report is attached, internal-pair formation spectroscopy will be a principal tool. Thus, the system depicted in Fig. 40 is being developed for work at HRIBF. In this arrangement, the Si(Li) detectors are also serviced "edge-on", but here they all reside on the same side of the tape. Although this systems is designed principally for internal pair-spectroscopy, each of the Si(Li) detectors can be used as individual conversion-electron spectrometers and used for electron-electron correlations at the same time that

the internal-pair spectroscopy is on-going. This configuration is designed to replace a single Ge detector in a Ge gamma-ray array, or to be simply sandwiched between two Ge detectors.

Correlated

Summed

Fig. 41. Methods of detecting the e^+ , e^- pairs using the detector system shown in Fig. 40. See text for more details.

Figure 41 shows the ways the new system is used in internal-pair spectroscopy. The variable θ represents the opening angle between the electron-positron pair. There are two ways to detect the internal pair events: first, as correlated events where one "adds up" the energy deposited in two Si(Li) detectors (plus 1.022 keV to give the transition energy), or one receives the pairs already "summed" in one crystal. The two complement each other. This system is described further in the proposal document to which this progress report is attached.