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Nuclear Structure Research

Annual Progress Report

U. S. Department of Energy

Grant DE-FG05-87ER40330

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October 31, 1993

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1. Introductory Overview

The most significant development this year has been the successful elucidation of the low-energy systematics of the very neutron-deficient Pr, Nd, Pm, and Sm isotopes. This includes an extensive set of Nilsson bandheads in ^{133}Nd . Previous information in this region was very meager and our work revealed some serious errors in earlier decay scheme work. The results require some significant reassessments of mean-field calculations in this region. (This is now being pursued in collaboration with Prof. P. B. Semmes, Tennessee Tech.) This work was part of the thesis work of J. Breitenbach who received his Ph.D. in April 1993.

Part of our program continues to focus on shape coexistence and electric monopole (E0) transitions in nuclei. Following our discovery of coexisting "gamma" bands connected by E0 transitions in ^{184}Pt (Phys. Rev. Lett. 68, 3853 (1992)), we have now established a similar behavior in ^{186}Pt from ^{186}Au decay data. This includes a pure E0 transition between states with $J^\pi = 3^+$, just as was seen in ^{184}Pt .

Progress has been made in elucidating the low-energy systematics of the neutron-deficient Ir isotopes. This information is from the decays of Pt isotopes. Besides providing reliable low-energy systematics, these data should reveal whether or not prolate and oblate shapes (predicted in mean-field calculations) coexist at low energy in the Ir isotopes.

A search for the population of the superdeformed band in ^{194}Pb in the decay of ^{194}Bi was unsuccessful. A paper was published in Physical Review C.

An extensive program of systematics for nuclei at and near $N = Z$ has been initiated as preparation for the planned nuclear structure research program using the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge.

Theoretical investigations have continued in collaboration with Prof. K. Heyde, Institute of Nuclear Physics, Gent, Belgium and with Prof. D. J. Rowe,

University of Toronto; and have been initiated with P. B. Semmes. A paper on electromagnetic decay patterns from intruder states in the Cd isotopes has been published in Physical Review C. A paper on intruder analog states and $4p-4h$ configurations in the lead isotopes has been submitted.

This year the contract has supported, besides the principal investigator (two months, full time), four graduate students (one for twelve months, half time; one for six months, half time; and two for three months half time).

2.0 UNISOR Research

UNISOR research has involved data analysis, level scheme construction, and comparison of level schemes with theory. All or part of three students' theses depend(ed) on this. There are also on-going collaborations with Prof. E. F. Zganjar (LSU), Prof. K. S. Krane (Oregon State Univ.), Dr. B. E. Gnade (Texas Instr. Corp., Dallas), Dr. R. A. Braga (Sch. of Chemistry, Georgia Tech). The data sets relate to two areas of nuclear structure: the onset of deformation in the extremely neutron-deficient Pr, Nd, Pm, and Sm isotopes; and shape coexistence in the neutron-deficient Ir, Pt, Au, and Hg isotopes.

2.1 Onset of Deformation in the Extremely Neutron-Deficient Pr, Nd, Pm, and Sm Isotopes

Work has proceeded on the decays

(Extensive γ and conversion-electron multiscaling and γ - γ , γ -x, e- γ , and e-x coincidence data sets were obtained using a high-temperature thermal ion source. The construction of this ion source constituted part of the doctoral thesis work of J. Breitenbach.) Based on part of this program, J. Breitenbach was awarded his Ph.D. by Georgia Tech in April 1993. The analyses of the $^{133}\text{Pm} \rightarrow ^{133}\text{Nd}$ and $^{133}\text{Nd} \rightarrow ^{133}\text{Pr}$ decay schemes are completed and manuscripts are in preparation. The analysis of the A = 135 and 137 decay schemes continues.

A major development in this program is the elucidation of the low-energy systematics of the Pr and Pm isotopes and the N = 73 and 75 isotones. Part of the N = 73 systematics are shown in Figure 1. The keys to these have been our level schemes for ^{133}Pr and ^{133}Nd . The ^{133}Pr level scheme is based on decays

Figure 1. Systematics of the $7/2^+$ [404] and $9/2^+$ [514] bands and the $1/2^+$ [411] state in the $N = 73$ isotones. Data are taken from A. P. Byrne et al., Nucl. Phys. A548, 131 (1992) -- ^{129}Ba ; M. Placz et al., Z. Phys. A338, 467 (1991) and Nuclear Data Sheets -- ^{131}Ce ; this work and S. Lunardi, private communication -- ^{133}Nd ; S. M. Mullins et al., J. Phys. G13, L201 (1987) -- ^{135}Sm .

of ^{133g}Nd ($J^\pi = 7/2^+$) and ^{133m}Nd ($J^\pi = 1/2^+$) and thus includes both medium/high and low-spin states. The ^{133}Nd level scheme is based on the decay of ^{133}Pm and privately communicated information (from an in-beam study made using the 40-detector array GASP located at Legnaro, Italy) provided by Prof. S. Lunardi (Padova). Exchange of the UNISOR and GASP data permitted the identification of five Nilsson bands in ^{133}Nd .. $7/2^+$ [404] (0), $1/2^+$ [411] (128), $9/2^-$ [514] (176), $5/2^+$ [402] (291), $3/2^-$ [532] (354 keV) .. the first such characterization ever made in this deformed region. The GASP data provided the band structures, the UNISOR data provided the relative energies and spin-parities of the band heads (especially the M3 isomeric transition and β decay of the $1/2^+$ [411] band head). Our $^{133m}\text{Nd} \rightarrow ^{133}\text{Pr}$ and $^{133}\text{Pm} \rightarrow ^{133}\text{Nd}$ decay schemes are completely new: these decay schemes were previously unknown.

The systematics reveals that major changes are needed in the $^{135}\text{Sm} \rightarrow ^{135}\text{Pm}$ decay scheme of K. S. Vierinen et al. (Nucl. Phys. A499, 1 (1989)) and the $^{137}\text{Sm} \rightarrow ^{137}\text{Pm}$ decay scheme of N. Redon et al. (Z. Phys. A325, 127 (1986)). Our analysis of the $A = 135$ and 137 data sets are well along and show that incorrect spins and parities and missing levels faulted the earlier studies. The extensive set of Nilsson states in ^{133}Nd reveals that changes in the mean field parameters for this region (J.-Y. Zhang et al., Phys. Rev. C39, 714 (1989)) are necessary. This is being pursued in collaboration with P. B. Semmes.

Contributed papers on the ^{133}Nd levels and the $A = 137$ decay chain were presented at the Asilomer APS meeting by J. L. Wood and R. A. Braga, respectively.

2.2 Shape Coexistence in the Neutron-Deficient Ir, Pt, Au, and Hg Isotopes

Work has proceeded on the decays

The analyses of the $^{181}_{\text{Pt}} \rightarrow ^{181}_{\text{Ir}}$, $^{187}_{\text{Hg}} \rightarrow ^{187}_{\text{Au}}$, $^{189}_{\text{Hg}} \rightarrow ^{189}_{\text{Au}}$, and $^{189}_{\text{Tl}} \rightarrow ^{189}_{\text{Hg}}$ are completed. The $^{187,189}_{\text{Au}}$ studies are in collaboration with E. F. Zganjar and $^{187}_{\text{Au}}$ constitutes part of the thesis work of one of his students. The $^{189}_{\text{Hg}}$ study is in collaboration with B. E. Gnade. The $^{181}_{\text{Ir}}$ study constitutes part of the thesis work of K. Jentoft-Nilsen (Georgia Tech). Manuscripts for $^{187}_{\text{Au}}$, $^{189}_{\text{Au}}$ and $^{189}_{\text{Hg}}$ are in preparation and await the completion of particle-core coupling calculations by P. B. Semmes. The analysis of the $^{184\text{m,g}}_{\text{Au}} \rightarrow ^{184}_{\text{Pt}}$ is well along and has revealed a very complicated isomeric decay pattern: this is being elucidated in collaboration with K. S. Krane. The analysis of the $^{186}_{\text{Au}} \rightarrow ^{186}_{\text{Pt}}$ is just beginning, but already reveals the unusual pattern of EO decays observed (at UNISOR) in the $^{184}_{\text{Au}} \rightarrow ^{184}_{\text{Pt}}$ decay (Y. Xu et al., Phys. Rev. Lett. 68, 3853 (1992)): the $^{186}_{\text{Pt}}$ study constitutes part of the thesis work of J. McEver (Georgia Tech).

These studies are part of an extensive program investigating the onset of shape coexistence in the $Z \sim 80$, $N \sim 104$ region. Many of the gross features have been elucidated (J. L. Wood et al., Phys. Repts. 215, 101 (1992)). However, many details remain to be resolved, especially the issue of particle-core coupling, cf. W. Nazarewicz et al., Nucl. Phys. A512, 61 (1990). Particle-core coupling calculations are now in progress for $^{187,189}_{\text{Au}}$, $^{189}_{\text{Hg}}$, as noted above. The next task will be to understand the coexisting

triaxiality in $^{184,186}\text{Pt}$. The E0 transitions between the gamma bands (and the two $K^\pi = 0^+$ bands) indicates that triaxial shapes with different mean-square radii are mixing (K. Heyde and R. A. Meyer, Phys. Rev. C37, 2170 (1988)).

Work will continue next with an analysis of data on the $^{183\text{m},g}\text{Pt}$ (43s, 6.5m) decays to ^{183}Ir which is also part of the thesis work of K. Jentoft-Nilsen.

Contributed papers on the ^{181}Ir and ^{186}Pt schemes were presented at the Asilomar APS meeting by K. Jentoft-Nilsen and J. McEver, respectively.

3.0 Planning of Experiments for HRIBF

A considerable effort has been devoted to planning the nuclear structure physics that will be pursued at HRIBF by the UNISOR consortium. A number of criteria are considered to be important guides to these plans and are outlined below.

The main theme of the experimental program at HRIBF should be to obtain nuclear structure information that cannot be obtained using any other facility or techniques. Thus, a strong case can be made for studying heavy ($40 < A < 100$) nuclei at and near the $N = Z$ line: the information on nuclei with $N \approx Z$ could be roughly doubled. Nuclear structure at and near the $N \approx Z$ line is characterized by isobaric symmetry. This region also has a number of closed shells which gives rise to simple spherical shell model configurations and exotic multi-particle - multi-hole configurations.

Among the directions chosen for HRIBF research are: identification of $J_{\max}$ states in the $f_{7/2}$ shell and $4p - 4h$ and $8p - 8h$ states in ^{56}Ni (similar to the deformed coexisting states in ^{40}Ca , cf. J. L. Wood et al., Phys. Repts. 215, 101 (1992) -- see Figure 3.2). (A number of excited 0^+ states are known in ^{56}Ni from a (p,t) study (H. Nann and W. Benenson, Phys. Rev. C10, 1880 (1974)), but nothing is known of their structure.) The $J_{\max}$ states are very simple (they are "stretched" shell model states) and are sensitive to the residual force acting between nucleons (cf. A. Poves and A. Zucker, Phys. Repts. 70, 235 (1981)). However, the goal is to take the program into a potentially new area of nuclear structure: the collectivity of multi-particle-multi-hole structures with low isospin. A theoretical initiative is underway on this topic in collaboration with K. Heyde (see Section 4.1). One of the issues is whether or not particle-hole excitations break isobaric symmetry: protons, being further apart in a particle-hole excitation should Coulombically repel less strongly.

A compilation, evaluation and systematization of data on excited states in all nuclei bounded by $10 \leq Z \leq 100$, $20 \leq N \leq 100$ on the neutron-deficient side of stability has been initiated.

4.0 Other Experimental Work

A first study of $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ has been made at the 3MV tandem accelerator at the University of North Texas, Denton. This was a γ -ray singles measurement on the 1.020 MeV resonance. It is planned to initiate γ - γ coincidence measurements next year. These will be aimed at observing high-lying low-energy intraband transitions which would signal strongly-deformed (possibly coexisting) bands. This work is in collaboration with B. E. Gnade.

A Letter of Intent has been submitted to the ISOLDE Committee proposing a study of deformation in the very-neutron deficient Ce, Pr, Nd, Pm, Sm, and Eu isotopes by detailed γ -ray and conversion-electron studies pending the development of a laser ion source which would selectively ionize these elements. This is a collaboration between Georgia Tech, LSU, K. U. Leuven, and the Universities of Liverpool and Manchester.

5.0 Theory

Theory has involved development of two themes: modelling of intruder states and a description of coexisting collective structures; modelling of collective structures in heavy even- and odd-mass nuclei based on an SU(3) core description.

5.1 Intruder States and Coexisting Collective Structures

Work has continued on the concept of intruder analog states (K. Heyde et al., Phys. Rev. C46, 541 (1992)) with an application to collective bands in the very neutron-deficient Pb isotopes. A paper has been submitted for publication. Applications to light $N = Z$ region nuclei and $Z = 50$ region nuclei are now underway. In light $N = Z$ region nuclei an exploration of intruder spin combined with isospin is being explored as the basis of an algebraic description of coexisting collective structures in, e.g., ^{56}Ni . (This program is, in part, targeted at potential experiments at HRIBF.)

A paper entitled "Proton 2p-2h Intruder Excitations and the Modified Vibrational Intensity and Selection Rules" has been published in Physical Review C.

This work is in collaboration with K. Heyde with whom the P. I. holds a NATO Travel Grant.

5.2 Description of Collective Bands in Heavy Even- and Odd-Mass Nuclei Based on an SU(3) Core Description

It has long been known that light nuclei can be described by an SU(3) coupling scheme. In heavier nuclei, however, it is expected that strong mixing of irreps will occur due to interactions such as spin-orbit coupling. Nevertheless, we believe that SU(3) models can still provide a context for understanding rotational behavior in heavy deformed nuclei.

Calculations for even-even nuclei are rather straightforward. Using the Coupled Rotor-Vibrator Model, we have found (M. Jarrío, J. L. Wood, and D. J. Rowe, Nucl. Phys. A528, 409 (1991)) that there is, indeed, considerable mixing of SU(3) irreps. However, we find that these mixtures remain rather constant within each particular rotational band. It is thus possible to picture an intrinsic state experiencing adiabatic rotations, and we can describe these nuclei in terms of a "soft" SU(3) structure.

We are currently working towards a similar description of odd-mass nuclei. With the inclusion of an unpaired nucleon, it becomes necessary to investigate the effects of particle-core coupling. We expect a strongly coupled basis to be most appropriate for heavy deformed nuclei, and this has led us to investigate the nature of strongly coupled SU(3) states. Unlike standard rotor models, however, SU(3) does not admit spinor irreps. Hence, due to the odd nucleon's spin, it is not possible in the strongly-coupled system to build true SU(3) representations. Our immediate goal has thus been to obtain an approximate picture in which an SU(3) core, a spinless particle, and a spinor are coupled. With this intent, we have been investigating the structure of Nilsson Model states in the absence of spin. Such states will not possess pure SU(3) symmetry, as the L-squared ("well-flattening") term will split the degeneracy of states within a given irrep. Nevertheless, we find that SU(3) does provide a dynamical symmetry, and hence there will be no mixing of SU(3) irreps. Thus we can strongly couple the spinless particle and the core in a rather straightforward manner.

The long-term goal of this research is to provide a comprehensive description of heavy deformed nuclei in an SU(3) context. Toward this aim, we hope to build an SU(3) picture of particle-core coupling including spin degrees of freedom, in order to establish a solid description of odd-mass nuclei. With such a model in hand, it will be possible to begin making

comparisions with experimental data. These comparisons will enable us to infer details about the mixtures of $SU(3)$ states which make the intrinsic states of rotational bands.

This work constitutes part of the thesis work of M. Jarrio (Georgia Tech).

This work is in collaboration with D. J. Rowe.

6.0 Overseas Trips

No overseas trips were made at DOE expense or on DOE supported time this year.

7. Personnel

Senior Staff

Dr. J. L. Wood, Professor of Physics, Principal Investigator, Full time,
2 months.

Graduate Students

Mr. Jurgen Breitenbach, Ph.D. thesis work.⁺ Half-time, 3 months.

Mr. Martin Jarrio, Ph.D. thesis work. Half-time, 12 months.

Ms. Kristi Jentoft-Nilsen, Ph.D. thesis work. Half-time, 6 months.

Mr. Jimmie McEver, Ph.D. thesis work. Half-time, 3 months.

⁺Ph.D. awarded April 1993.

8.0 Summary of Publications, Preprints, Abstracts, and a Thesis, 1993

1. "Proton 2p-2h Intruder Excitations and the Modified Vibrational Intensity and Selection Rules", K. Heyde, C. De Coster, J. L. Wood, and J. Jolie, Phys. Rev. C46, 2113 (1992).
2. "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).
3. "Detailed Nuclear Structure Studies Far From Stability", J. L. Wood, J. Schwarzenberg, E. F. Zganjar, and D. Rupnik, Hyp. Int. 75, 51 (1992).
4. "Nuclear Orientation Studies of ^{187}Ir Via On-Line Nuclear Orientation", 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, Jr., Hyp. Int. 75, 447 (1992).
5. "On-Line Nuclear Orientation Study of ^{184}Au ", Y. Xu, K. S. Krane, M. A. Gummin, J. L. Wood, M. M. Jarrio, J. B. Breitenbach, E. F. Zganjar, D. Rupnik, H. K. Carter, P. F. Mantica, Jr., and B. E. Zimmerman, Hyp. Int. 75, 481 (1992).
6. "Deformation Studies in the Extremely Neutron-Deficient Praseodymium, Neodymium, and Promethium Isotopes", J. Breitenbach, R. A. Braga, J. L. Wood, P. B. Semmes, and J. Kormicki, in Nuclei Far From Stability/Atomic Masses and Fundamental Constants 1992, Institute of Physics Conference Series No. 132 (Philadelphia, 1993), p. 575.
7. "Intruder Analog States: A New Classification of Coexisting Particle-Hole Excitations Near Closed Shells", K. Heyde, C. De Coster, J. Jolie, and J. L. Wood, *ibid.*, p. 539.
8. "Spectroscopy Results at UNISOR In the Eighties", J. L. Wood, in Proc. of

the Symposium on Reflections and Directions in Low Energy Heavy Ion

Physics, ed. J. H. Hamilton et al. (World Scientific, Singapore, 1993),
p. 40.

9. "Possible Evidence for Particle-Hole Intruder Analog Multiplets in the Pb Region", K. Heyde, P. Van Isacker, and J. L. Wood, preprint.
10. "Isomerism, Deformation and Bands in ^{133}Nd ", J. Breitenbach, J. L. Wood, R. A. Braga, J. Kormicki, and P. B. Semmes, Bull. Am. Phys. Soc. 38, 1806, AD4 (1993).
11. "Decay of Mass-Separated ^{137}Eu and ^{137}Sm ", R. A. Braga, J. Breitenbach, J. L. Wood, and P. B. Semmes, Bull. Am. Phys. Soc. 38, 1806, AD6 (1993).
12. "The Decay of Mass-Separated ^{181}Pt to ^{181}Ir and Systematics in the Odd-Mass Ir Isotopes", K. Jentoft-Nilsen, J. L. Wood, and J. Schwarzenberg, Bull. Am. Phys. Soc. 38, 1819, BD6 (1993).
13. "Electric Monopole Transitions in Platinum 186", J. McEver, J. L. Wood, M. Jarrio, and J. Schwarzenberg, Bull. Am. Phys. Soc. 38, 1819 BD8 (1993).
14. "Deformation in the Neutron-Deficient Rare Earth Isotope: Radioactive Decay Scheme Studies in the Neodymium, Promethium, and Samarium Isotopes", J. B. Breitenbach, Ph.D. Thesis, Georgia Tech, April 1993.

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