

PROJECT ADMINISTRATION DATA SHEET

Project No. (Q5325-2A0) ☒ ORIGINAL ☐ REVISION NO. _____
G-33-683 (Continuation of G-33-604) XXXX/GIT DATE 4 / 25 / 86
Project Director: Dr. R. W. Fink School/Dept: Chemistry
Sponsor: Department of Energy, Oak Ridge Operations

Type Agreement: Contract Mod. No. A023 to DE-AS05-76ER03346Award Period: From 2/1/86 To 8/31/88 (Performance) 1/31/88 (Reports)

Sponsor Amount:	This Change	Total to Date
Estimated: \$	<u>77,000</u>	\$ <u>77,000</u>
Funded: \$	<u>77,000</u>	\$ <u>77,000*</u>

Cost Sharing Amount: \$ 26,324 Cost Sharing No: G-33,315 (E5325-2A0)Title: Nuclear Chemistry Research & Spectroscopy

ADMINISTRATIVE DATA

OCA Contact Brian J. Lindberg X4820

1) Sponsor Technical Contact:

2) Sponsor Admin/Contractual Matters:

EnLoe RitterMarlena ClarkU. S. Department of EnergyU. S. Department of EnergyDivision of Nuclear PhysicsProcurement and Contracts DivisionOffice of High Energy & Nuclear PhysicsOak Ridge OperationsWashington, DC 20545P. O. Box EOak Ridge, TN 37830Defense Priority Rating: N/AMilitary Security Classification: N/A(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of \$500 or 125% of approved proposal budget category.

Equipment: Title vests with None proposed or anticipated

COMMENTS:

*These funding amounts are in addition to previous mods. Total contract value is now \$1,161,930.

This is a follow-on project to G-33-604.

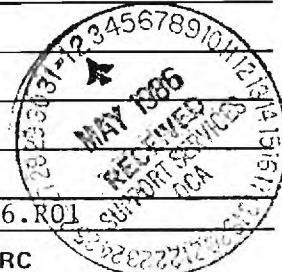
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(Reports)

Grant/Contract Closeout Actions Remaining:

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None

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NUCLEAR CHEMISTRY RESEARCH AND SPECTROSCOPY WITH RADIOACTIVE SOURCES

Twenty-first Annual Progress Report
U. S. Department of Energy
Contract DE-AS05-76ERO-3346

R. W. Fink
Professor of Chemistry & Principal Investigator

August 31, 1985

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF CHEMISTRY
ATLANTA, GEORGIA 30332

1985



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NUCLEAR CHEMISTRY RESEARCH AND SPECTROSCOPY WITH RADIOACTIVE SOURCES

1.0 INTRODUCTION

The nuclear chemistry group in the School of Chemistry continues investigating the radioactive decay of nuclei far from stability under this DOE contract. These nuclei are produced with heavy ions from the Holifield Heavy Ion Research Facility [HHIRF] and studied on-line with the University Isotope Separator at Oak Ridge [UNISOR]. Radioactive decay represents a unique method for the population of low-energy, low-spin structures in nuclei, and new phenomena which do not occur near stability can be explored. Our research encompasses three aspects of nuclear structure: (1) nuclear spectroscopy with detailed $\gamma\gamma$, $e^-\gamma$, $X\gamma$, etc. multi-parameter coincidence spectrometry; (2) on-line laser hyperfine structure [hfs] and isotope shift measurements for the determination of nuclear quadrupole moments, nuclear spins, and changes in mean nuclear charge radii as a means of revealing systematic shape changes in nuclei; and (3) theoretical calculations of predictions of nuclear models for comparison with experimental level structures in nuclei studied at UNISOR.

Such studies of low energy (≤ 2 MeV), low-spin ($\leq 21/2$) structures in nuclei far from stability serve as a unique contribution to the results of the much larger field of in-beam spectroscopy which provides information on the higher energy, high spin states (mostly yrast states). It is essential to have the combined results, in order to test critically the competing applicable theoretical ideas and nuclear models.

We concentrate mostly (but not exclusively) on odd-mass nuclei, in which the odd nucleon probes an even-mass core, to observe such phenomena as the onset of abrupt shape changes, the occurrence of shape coexistence, and shell-model intruder states—information critical for testing concepts fundamental to an understanding of low-energy nuclear structure, such as nuclear deformation, shell models, collective models, and particle-core couplings and uncouplings.

Experimental data have been acquired on the decays of mass chains $A = 201$ (entered at ^{201}At), $A = 197$ and 199 (entered at Po), and $A = 135, 137, 139$ (entered at Eu). These investigations are in active progress as discussed below. Our studies of mass chain $A = 203$ (entered at ^{203}At) have been completed and constitute part of the PhD thesis of Dr. Paul Semmes (completed in July, 1985). A manuscript for publication is in preparation.

Progress with the on-line nuclear laser is current re-directed toward the systematic study of hfs and optical shifts of neutron-deficient Pb isotopes on which UNISOR previously has conducted extensive and detailed nuclear spectroscopy studies. One of our graduate students, Mr. Jeffrey C. Griffin, received an ORAU fellowship and since June, 1985, has been in residence at Oak Ridge for full-time thesis research with the laser facility.

Since April, 1985, UNISOR has been under new management (Dr. Ken Carter, Director) and has received much increased beam time from HHIRF. This has resulted in increased data acquisition and thus a new enthusiasm on the part of the university participants. Ion source developments at UNISOR have been very active this year, resulting a a new miniature high temperature thermal ionization ion source ($>2000^\circ\text{C}$ with less than 400 watts of input power) which gives good yields of Ba, Sm, Pm, and other rare earth isotopes. A new FEBIAD plasma ion source is currently under test. During a long (12 shift) run on ^{185}Hg decay in July, the highest yields ever obtained by far in any UNISOR run and the best $e^- \gamma t$ and $\gamma \gamma t$ coincidence data ever seen at UNISOR were produced from a low-temperature ($\sim 1000^\circ\text{C}$) Nielsen ion source using the $^{176}\text{Hf}(^{16}\text{O}, 7n)^{185}\text{Hg}$ reaction with enriched $^{176}\text{HfO}_2$ targets. The low-temperature suppresses emission of Au and other elements without loss of intensity of volatile Hg activity. Some new techniques of redirecting the heavy ion beam onto the target were also employed.

The use of the powerful Perkin-Elmer on-line computers at HHIRF allows data tapes to be analyzed by one team of people as they come off data acquisition by another team. By the end of a run, therefore, given sufficient manpower, the data are not only acquired, but analyzed. This greatly facilitates UNISOR research and will enable us to keep up with the increased number of runs from UNISOR/HHIRF in the future. (Formerly the data tapes required 6 - 12 months for analysis back at the university campus.) As an example, the results of the long ^{185}Hg run in July could be written as an abstract (whose deadline was also in July) for presentation at a meeting in October. We regard the Perkin-Elmer computer system at HHIRF as a major improvement and breakthrough in our UNISOR research.

Coming in 1986 will be the low-temperature nuclear orientation $^3\text{He}/^4\text{He}$ dilution refrigerator on-line to the mass separator for determination of nuclear spins, g-factors, and nuclear magnetic moments of radioactive nuclides far from stability. Our group will participate fully in the installation and use of this equipment, and one of our graduate students, Mr. C. P. Perez, is interested in it for his PhD thesis research.

Our theoretical calculations with nuclear models, in collaboration with Dr. G. A. Leander of UNISOR, has resulted in several publications by Dr. Paul Semmes and coauthors, and it constitutes the major part of his PhD thesis in chemistry (completed July, 1985). Additional manuscripts based on this thesis are in preparation for publication. Dr. Semmes has accepted a postdoctorate at the Joint Institute for Heavy Ion Research at Oak Ridge to continue theoretical studies with Dr. Leander and other theorists there.

Dr. R. A. Braga received a half-time (6 week) appointment during the summer of 1985 from the Joint Institute for Heavy Ion Research for both technical and scientific work at UNISOR.

All of these new developments at UNISOR/HHIRF lead us to look forward to 1986 and beyond with great enthusiasm and high expectations of exciting research.

2.0 NUCLEAR SPECTROSCOPIC STUDIES

2.1 Decay of 1.5 min ^{201}At

The status of the study of the decay of mass separated 1.5 min ^{201}At remains essentially the same as described last year [ORO-3346-257], since no additional runs were performed this year. To date, only γ -ray time-sequenced and $\gamma\gamma$ coincidence data have been obtained from which a decay scheme consisting of six levels has been constructed.

The level scheme of ^{201}Po , and the odd-mass Po isotopes in general, can be described in terms of a simple particle-core coupling in which either a particle is coupled to the $A-1$ Po core or a hole is coupled to the $A+1$ Po core. The single quasiparticle states available to the odd neutron at low energies are the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ and $i_{13/2}$ orbitals.

More detailed analysis and additional data are required before a more complete discussion is possible. Towards this end, the acquisition of higher quality $\gamma\gamma$ and $e^-\gamma$ coincidence data is planned.

2.2 Decay of Mass Separated $^{195,197}\text{Po}$ to Levels in $^{195,197}\text{Bi}$

As an extension of our studies of the level schemes of the odd-mass bismuth isotopes, we have initiated studies of the decay of $^{195m,g}\text{Po}$ (20 sec, 4.5 sec) and $^{197m,g}\text{Po}$ (26 sec, 56 sec). The impetus of these investigations is a further effort to characterize and systematize the shell-model states present in the odd-mass Bi isotopes arising from the coupling of $h_{9/2}$, $f_{7/2}$, and $i_{13/2}$ odd protons to the even-even Pb cores. In addition, the occurrence at low energy of the $s_{1/2}$ shell-model intruder state, best described as the coupling of a hole to the Po $\pi[2p]$ cores, has been identified in the heavier Bi isotopes from decay studies¹⁾ and recently indirectly in $^{187-195}\text{Bi}$ by observing the alpha decay of the odd-Bi isotopes²⁾. Identification in ^{197}Bi would complete

¹R. A. Braga, et al. Nucl. Phys. A349, 61 (1980)

²E. Coenen, et al. Phys. Rev. Lett. 54, No. 16, 1783 (1985)

the systematics of the $s_{1/2}$ intruder state.

The activities of mass separated $^{195,197}\text{Po}$ were produced by the $(^{19}\text{F},9n)$ reaction on natural Re targets (in the form of a Re-Mo alloy) at 160 MeV at HHIRF/UNISOR. Gamma-ray and alpha-particle time-sequenced spectroscopy were carried out on both isotopes and $\gamma\gamma$ coincidence data were obtained following the decay of ^{197}Po . The data are currently undergoing analysis. The decay of ^{197}Po constitutes part of the PhD thesis research of Mr. C. P. Perez.

2.3 Decay of 9 sec ^{137}Eu , 45 sec ^{137}Sm , and the Search for a New Region of Deformation

During the past year our investigation of the predicted new region of deformation³⁾ in the $Z > 50$, $N < 82$ rare earth nuclei has proceeded to detailed spectroscopic studies of the transitional nuclei ^{137}Sm and ^{137}Pm populated from the decay of 9 sec ^{137}Eu and 45 sec ^{137}Sm , respectively.

³G. A. Leander, et al. Phys. Lett. B110, 17 (1982)

The study of the decay of ^{137}Eu is an extension of our initial investigation into this region begun last year with the study of ^{139}Eu decay [see Annual Report, ORO-3346-257].

In the odd-mass Sm isotopes, as the neutron number decreases from $N = 81$, the $1/2^+$ member of the $d_{3/2}$ multiplet, as observed and calculated in $^{139,141}\text{Sm}$, becomes the ground state. Below ^{139}Sm , a drastic change of regime is predicted. Following the phase transition to a rotational regime, it is initially the $7/2^+[404]$ and the $5/2^+[402]$ band head that is calculated to become the ground state band.

To produce the activities of ^{137}Eu and ^{137}Sm , a variety of reactions was utilized as listed in Table 1.

Table 1 - Reactions used to produce ^{137}Eu and ^{137}Sm

Target	Projectile	Compound Nucleus	Energy (MeV)
nat_{Ag}	^{35}Cl	$^{142,144}\text{Gd}$	160
nat_{At}	^{32}S	$^{139,141}\text{Eu}$	165
^{92}Mo	^{48}Ti	^{140}Gd	220
^{92}Mo	^{46}Ti	^{138}Gd	210

The reaction products were mass separated on-line at UNISOR and x-ray and γ -ray time-sequenced spectroscopy were carried out. Also, $\gamma\gamma$ coincidence data were obtained.

The γ -rays associated with the decay chain $^{137}\text{Eu}(\beta^+)^{137}\text{Sm}(\beta^+)^{137}\text{Pm}$ have been identified (see Table 2) and a preliminary decay scheme for ^{137}Pm has been constructed (see Fig. 1).

Table 2 - Gamma-rays associated with $^{137}\text{Eu} \rightarrow ^{137}\text{Sm} \rightarrow ^{137}\text{Pm}$ decay chain

E_{γ} (keV) ^{137}Eu decay	E_{γ} (keV) ^{137}Sm decay
421.5	163.7, 168.4, 188.0
484.0	216.5, 337.9, 380.4
531.4	408.2, 559.4, 761.1

Of particular interest in the level structure of ^{137}Pm is the position of the $11/2^-$ state observed in the heavier odd-mass Pm isotopes (Fig. 2). This $h_{11/2}$ odd-proton state comes lower in energy as one moves toward the more neutron-deficient nuclei. If this trend continues, the $11/2^-$ state should eventually become the ground state, as has recently been shown to occur in the odd-mass Eu isotopes at ^{139}Eu ⁴⁾. However, the lack of spin information makes

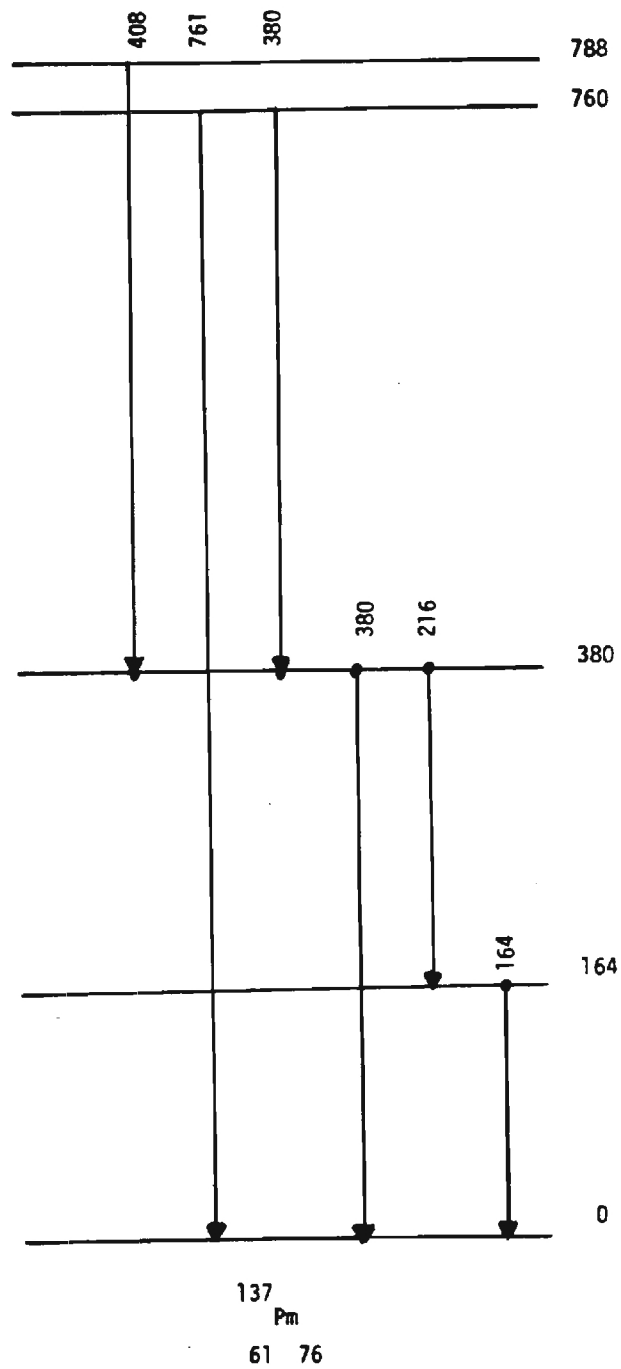


Fig. 1 - Preliminary decay scheme of 45 sec ^{137}Sm to levels in ^{137}Pm

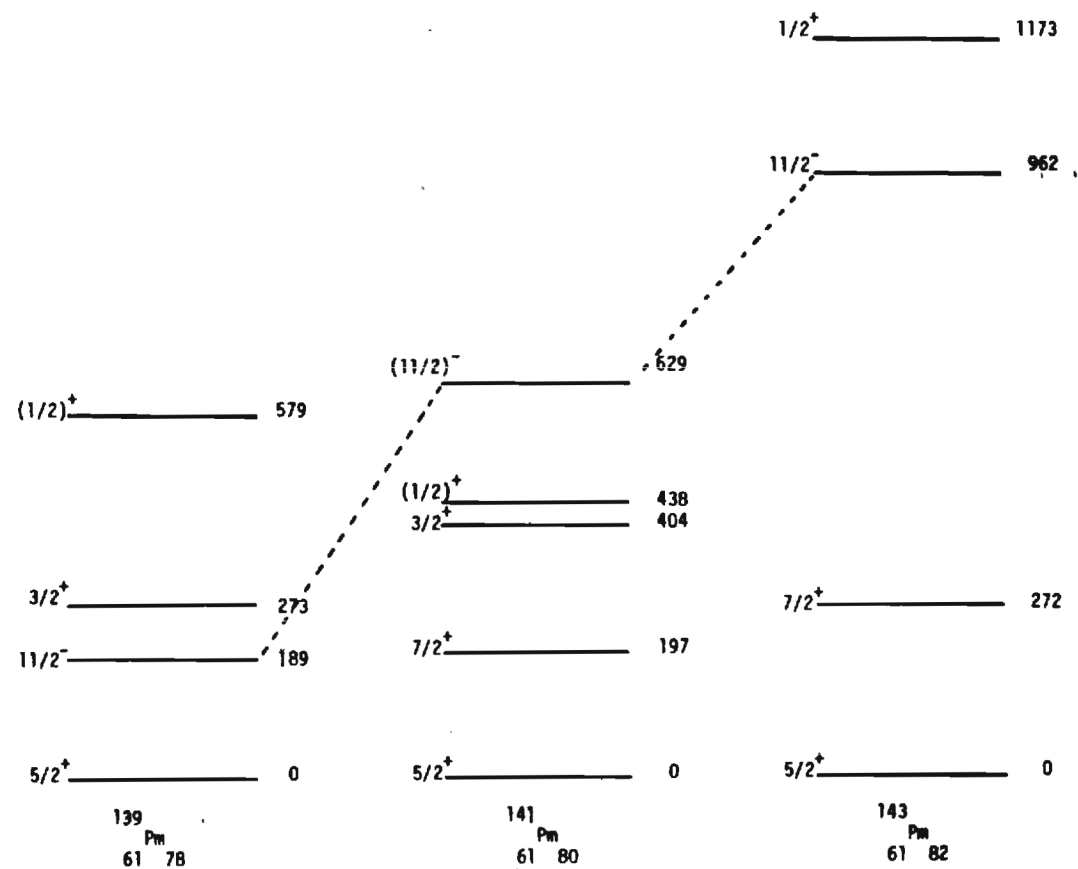


Fig. 2 - Systematics of Odd-Mass Pm Isotopes

further discussion of the structure of ^{137}Pm impossible. Therefore, an additional experiment is scheduled for early fall, 1985, to perform conversion electron spectrometry on mass separated sources of ^{137}Sm from which multipole mixing ratios can be obtained and spins deduced.

⁴S. Lunardi, et al. Z. Physik A321, 177 (1985)

2.4 Decay of mass separated 7.4 min ^{203}At to levels in ^{203}Po

In the past year, the study of the decay of 7.4 min $^{203}\text{At} \rightarrow ^{203}\text{Po}$ has been completed. The decay scheme for $^{203}\text{At} \rightarrow ^{203}\text{Po}$ was built almost entirely from the $\gamma\gamma$ and $e^-\gamma$ coincidence data and is presented in Figs. 3 and 4. In all, 30 excited states have been identified and 45 transitions have placed in the decay scheme, incorporating approximately 90% of the total intensity assigned to this decay. Prior to this work, only three excited states in ^{203}Po were known⁵, at 62 keV(3/2-), 133 keV(1/2-), and 641.4 keV(13/2+). Of these, the first and last are confirmed in this work, but the 1/2- state has not been observed and is expected to be populated only weakly in the decay of ^{203}At ($J\pi = 9/2-$ based on systematics). Spin-parity assignments for the excited states are based on the transition multipolarities deduced from observed internal conversion coefficients and decay patterns and lead to the following unique spin assignments for the negative-parity states: 62.6 keV(3/2-), 531.9 (5/2-), 639.5 (7/2-), 719.0 (7/2-), and 803.2 (9/2-). The 639.5 keV level was reported recently as a 9/2- state⁶, although the details of the spin-parity assignment are not given. Their placement of the 639.5 keV level is based on an in-beam experiment in which the 639 keV γ -ray is observed to decay with the same halflife (45 sec) as the 641 keV isomeric transition. This observation

⁶

B. Fant, et al. AFI Biannual Report 1982-83; pp. 104

implies that there must exist a 2.0 keV transition connecting the two states,

⁵B. Jonson, et al., Nucl. Phys. A174, 225 (1971)

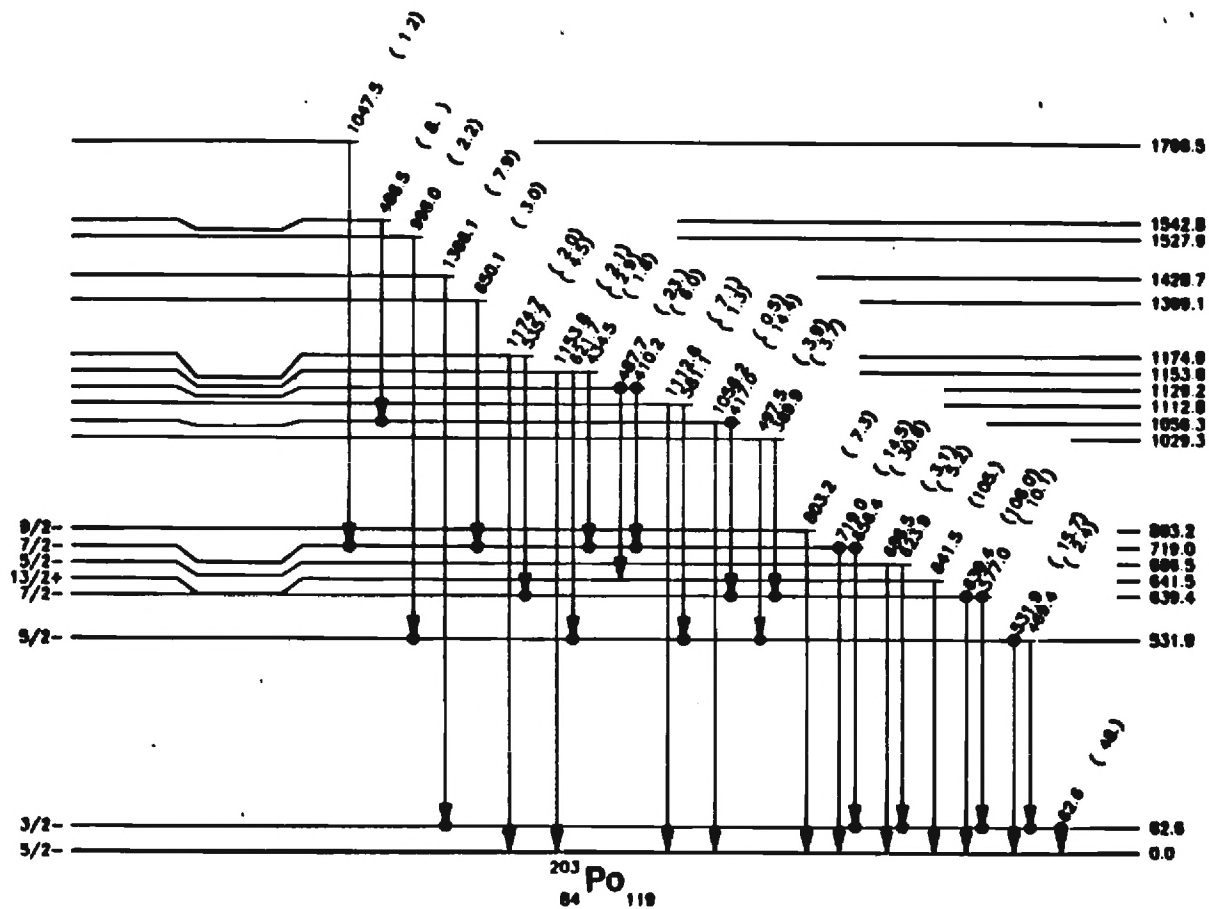


Fig. 3 - Negative-parity states and decay scheme for ^{203}At (7.4 min) \rightarrow ^{203}Po

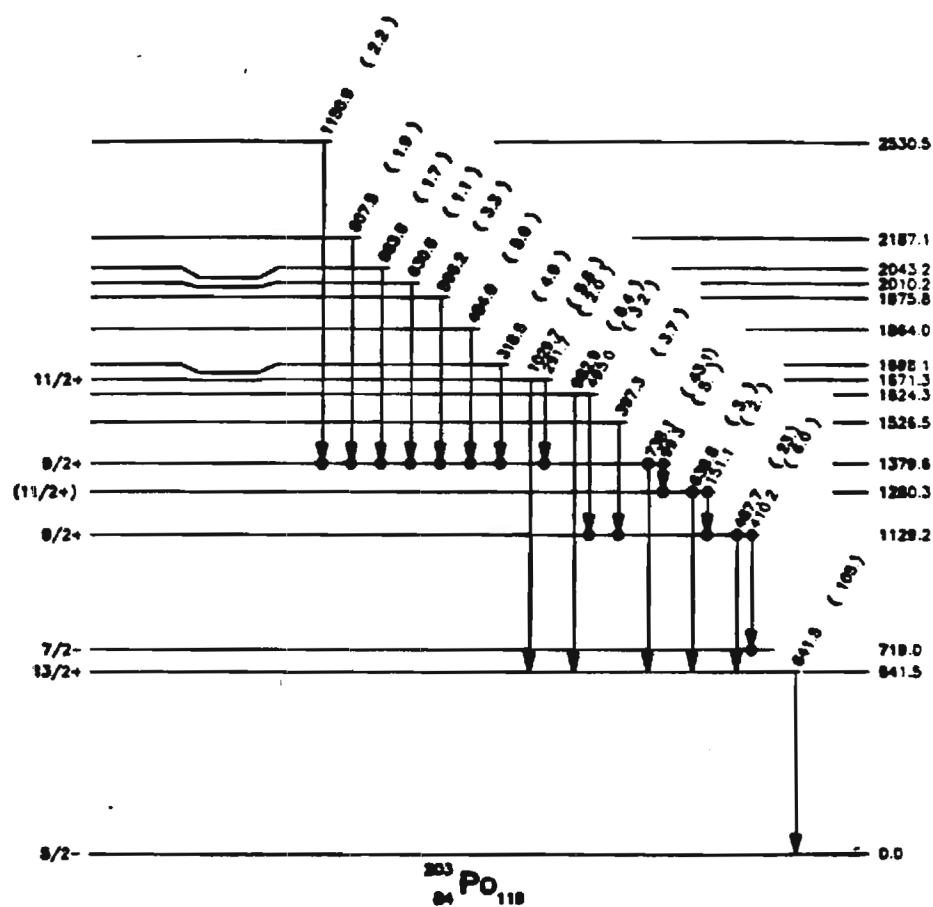


Fig. 4 Decay scheme for $^{203}\text{At} \rightarrow ^{203}\text{Po}$: Positive-parity states.

and this transition has been assigned a multipolarity of M2 (ref. 6) giving their $9/2^-$ spin-parity assignment for the 639 keV level. However, their data also suggest that the branching ratio for the 2.0 keV transition is approximately 33% (compatible with an upper limit of approximately 50% from the present work), which implies that the $B(M2)$ value is $\sim 4 \times 10^{-6}$ Weisskopf units, some 200 times smaller than those found in other odd-N nuclei in this region^{7,8}.

⁷M.R. Schmorak, Nuclear Data Sheets 23, 287 (1978)

⁸M. R. Schmorak, Nuclear Data Sheets 43, 383 (1984)

This discrepancy suggests that a multipolarity assignment of M2 to the 2.0 keV transition is unlikely. Furthermore, in the present study, a 577.0 keV E2 transition was observed that connects the 639.5 keV level to the 62.6 keV ($3/2^-$) level in addition to the transition to the $5/2^-$ ground state. These facts require a spin-parity assignment of $7/2^-$ for the 639.5 keV level.

The positive-parity states, shown in Fig. 4, generally show strong coincident transitions only among themselves. The lone E1 transition to the negative parity states is the 410.2 keV transition between the 1129.2 ($9/2^+$) and 719.0 ($7/2^-$) keV levels. The spin-parity assignment of the 641.5 keV isomeric state has been reported previously⁹ and is confirmed here. The $9/2^+$

⁹B. Jonson, et al. Nucl. Phys. A174, 225 (1971)

assignment to the 1379.6 keV level is based on the strong 738.1 keV E2 transition to the $13/2^+$ isomer. This transition is essentially pure E2 (within experimental error) and therefore strongly suggests $\Delta J\pi = 2, \text{ no}$, since M1 radiation is generally strong in odd-mass nuclei when not forbidden by angular momentum selection rules. Thus, we have made the following unique spin-parity assignments: 641.5 keV ($13/2^+$), 1129.2 ($9/2^+$), 1379.6 ($9/2^+$), and 1671.3 ($11/2^+$). Also,

the 1280.3 keV level has been assigned tentatively $11/2^+$, based on systematics.

Finally, the ratio of electron K-capture to β^+ decay depends very strongly on the decay energy and therefore can be used to measure the decay energy Q_{EC} . The K/β^+ ratio has been determined in this work by gating on a suitable γ -ray and comparing the number of coincident K x rays to 511 keV annihilation photons. For instance, the K/β^+ ratio for the 1113 keV level was determined to be 3.0 ± 0.8 by gating on the 1113 keV γ -ray to the ground state. This K/β^+ ratio corresponds to a β^+ endpoint energy of 2.90 ± 0.30 MeV¹⁰⁾ to the 1113 keV level and thus to a value of $Q_{EC} = 5.03 \pm 0.30$ MeV for the decay $^{203}\text{At} \rightarrow ^{303}\text{Po}$, which agrees very well with an estimate of 5.04 MeV from the 1983 mass tables¹¹⁾. Also, the K/β^+ ratio to the 1671 keV

¹⁰ C. M. Lederer, et al., Table of the Isotopes, 7th Ed (John Wiley & Sons, Inc. New York, 1978)

¹¹ K. Bos, et al. Nucl. Phys. A432, 140 (1985)

was determined to be 5.7 ± 1.3 by gating on the 1030 keV γ -ray to the isomeric level at 641 keV. This ratio corresponds to a β^+ endpoint of 2.40 ± 0.20 MeV and $Q_{EC} = 5.09 \pm 0.20$ MeV, in good agreement with the above result. The latter measurement provides an important confirmation that the 1030 keV γ -ray and its associated band of states do indeed belong above the isomeric level.

The low-energy structure of odd-A nuclei is largely determined by the structure of the neighboring doubly-even cores, and in ^{203}Po , for example, a weak coupling description should be appropriate. Weak coupling implies that the states observed in the odd-A nucleus can be well described as the odd particle coupling to a single core state. For ^{203}Po , the shell model orbitals accessible to the odd neutron at low energy are the $f_{5/2}$, $p_{3/2}$, $p_{1/2}$ and $i_{13/2}$. The levels in ^{203}Po at 0, 63, 130, and 642 keV have been identified previously as the corresponding one-quasiparticle states (coupled to the core 0^+ ground

state⁹⁾. For the negative-parity levels, a multiplet of states is expected at about 700 keV due to the odd neutron in $f_{5/2}$, $p_{3/2}$, or $p_{1/2}$ orbital coupling to the core $2+$ state. The allowed couplings lead to one state with spin-parity $9/2-$, two with $7/2-$, and three each with $5/2-$, $3/2-$, and $1/2-$. Similar considerations suggest that a large number of states should be found near 1200 keV (coupling to the core $4+$ state), 1600 keV (coupling to the core $6+$, $8+$), and so on. States with the same spin and parity can mix and split, of course, but mixing between states in different multiplets is assumed to be small in the weak coupling approximation. Of all these states, only those with spin near that of the parent ($9/2-$ for ^{203}At) are expected to be strongly populated in radioactive decay. The observed negative-parity states in ^{203}Po (Fig. 5) fit the expected pattern quite well. Groups of states are clearly evident near 650 and 1100 keV, including one $9/2-$, two $7/2-$ and $5/2-$ states in the first groups. All states below 1 MeV have unique spin and parity assignments, and these follow the systematic trend (fig. 5) well. There is, however, one obvious difference between the states found in ^{203}Po and those in $^{205,207}\text{Po}$. In the latter, the transition from the $9/2-$ state to the ground state is the strongest in the spectrum, while in ^{203}Po , it is much weaker. This apparent discrepancy is due to the changing position of the $i_{13/2}$ isomeric state; in $^{205,207}\text{Po}$ the $9/2-$ state is fed almost entirely by an M2 transition from the isomer, while in ^{203}Po , the isomeric state lies below the $9/2-$ state, and thus no such feeding is possible.

The positive-parity states can be described in essentially the same way, ie, as an odd neutron in the $i_{13/2}$ orbital coupling to the core states. Thus, at about 700 keV above the isomeric state, there should be one state each with spin-parity $9/2+$, $11/2+$, $13/2+$, $15/2+$, and $17/2+$, and at higher energy there should be more states with a wider spin range. Also, the $9/2+$ and $11/2+$ states are expected to be the most strongly populated in the radioactive decay of ^{203}At .

The observed positive-parity states in ^{203}Po and their systematic features are shown in Figs 4 and 6, respectively. In all these nuclei, the first $9/2+$ level strongly populates the isomeric state and also deexcites by an $E1$ transition to a $7/2-$ state. Also, feeding to the isomer is found in all these nuclei from a group of levels about 1100 keV above the isomeric state, and the state at 1210 keV (639 keV above the isomer) in ^{203}Po is tentatively identified as the $11/2+$ state observed in the heavier isotopes. The second $9/2+$ state at 1380 keV (738 keV above the isomer) in ^{203}Po is a puzzle; it has no known analog at such low energy in the heavier isotopes, and its feeding pattern is unusual in that virtually no other transitions are found involving these levels. The detailed nature of this state remains an open question.

This work constitutes part of the PhD thesis of Paul Semmes (July, 1985), and a manuscript on the decay of 7.4 min ^{203}At is in preparation for publication.

2.5 Preparation of the $\text{ThB}[^{212}\text{Pb}]$ thoron active deposit as a conversion electron and alpha-particle standard

The need at UNISOR of a short-lived conversion electron and alpha-particle standard for energy and relative intensity calibrations has prompted us to prepare such a source which is kept at UNISOR and prepared on demand whenever needed. The source, consisting of 10.6 hour $\text{ThB}[^{212}\text{Pb}]$ in equilibrium with its 60.5 min $\text{ThC}[^{212}\text{Bi}]$ and 3.1 min $\text{ThC}''[^{208}\text{Tl}]$ daughters, produces a host of conversion electron lines suitable for energy and relative intensity calibrations, as well as a number of alpha-particle groups, including long-range alphas up to 11 MeV. The short half-lives of ThB and its daughters prevent any permanent contamination inside the vacuum of the tape transport systems at UNISOR. The number of electron lines, from 24.510 to 2526.29 keV, from this source covers the whole range of energies required at UNISOR. In

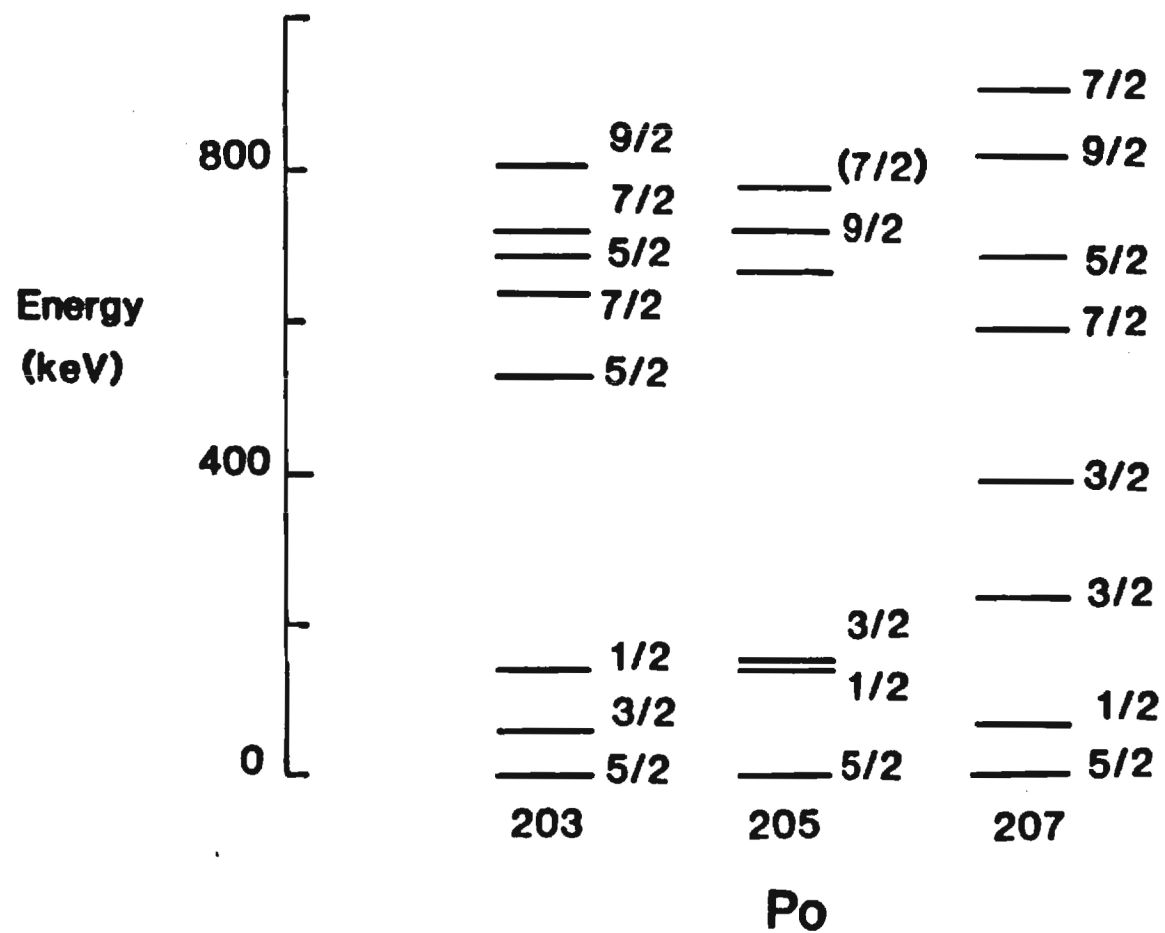


Fig. 5 . Negative-parity systematics of the odd-mass Po isotopes, $203 \leq A \leq 207$.

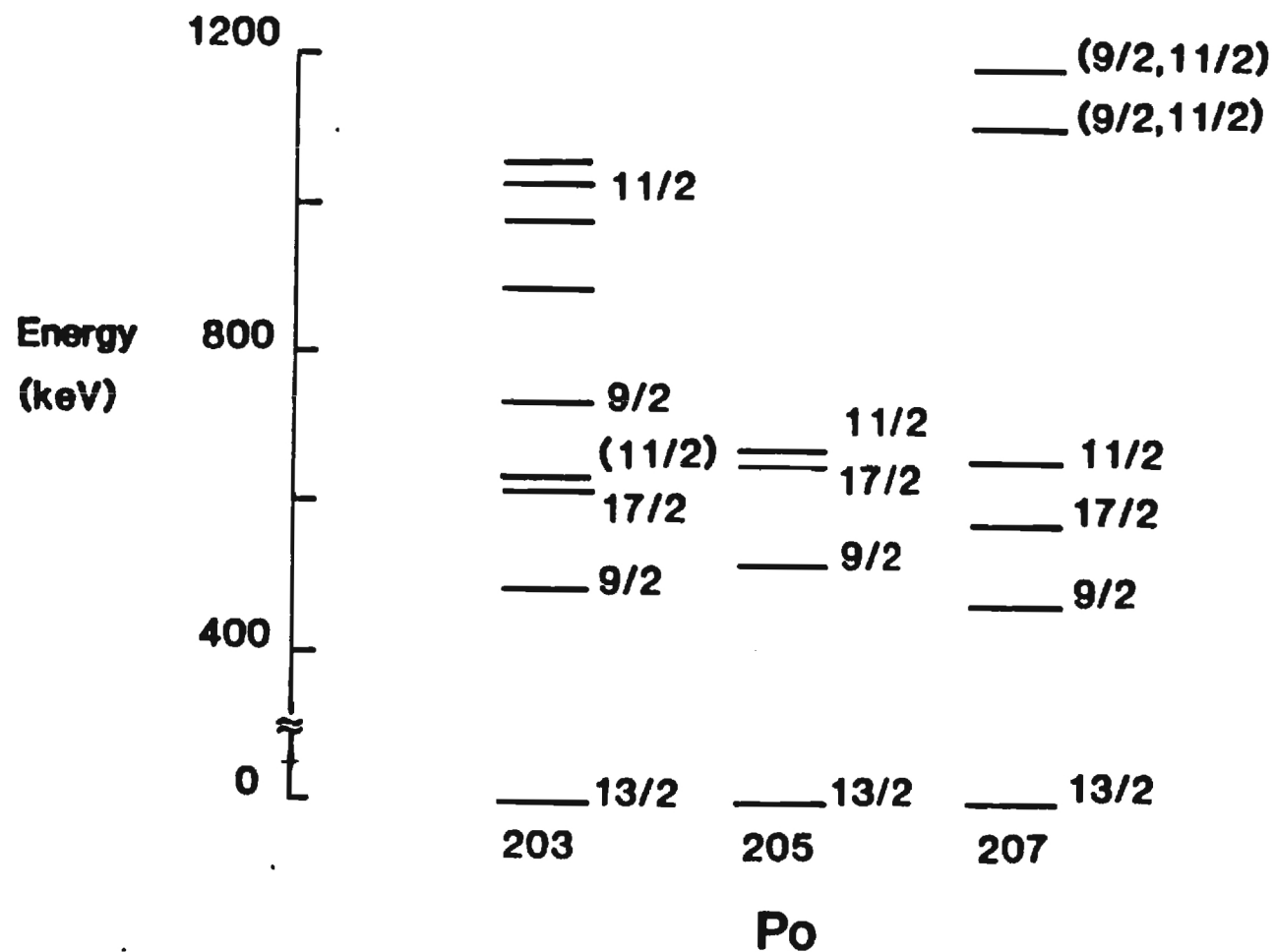


Fig. 6 . Positive-parity systematics of the odd-mass Po isotopes, $203 \leq A \leq 207$.

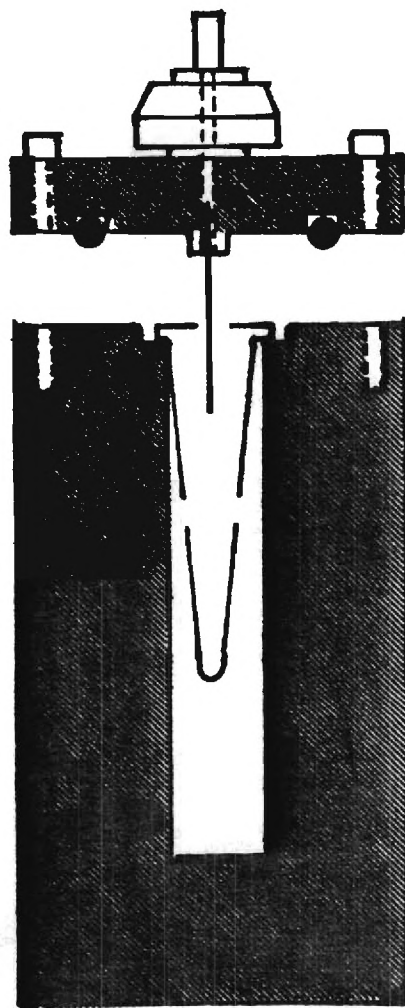
addition, the abundance of low energy lines below 500 keV provides calibration lines not otherwise available for such electron sources as ^{137}Cs and ^{207}Bi .

The ThB source is obtained as the thoron active deposit from 55 sec $\text{Tn}[^{220}\text{Rn}]$ on a metal planchet (or for stronger sources, on the tip of a wire held at a negative voltage of 500 to 1000 volts). The source of the thoron gas is the decay of 70 year ^{232}U in secular equilibrium with its daughter, 1.9 year $\text{RdTh}[^{228}\text{Th}]$. The carrier-free activity of ^{232}U (500 μCi) was deposited in the well of a specially designed stainless steel container. A conical glass sieve is inserted into the well to permit only the thoron gas to reach the planchet or wire while also providing a positioning base for the metal planchets. For the preparation of wire-deposited sources, a top for the generator was constructed having a ceramic high voltage feedthrough, as shown in the figure (page 17).

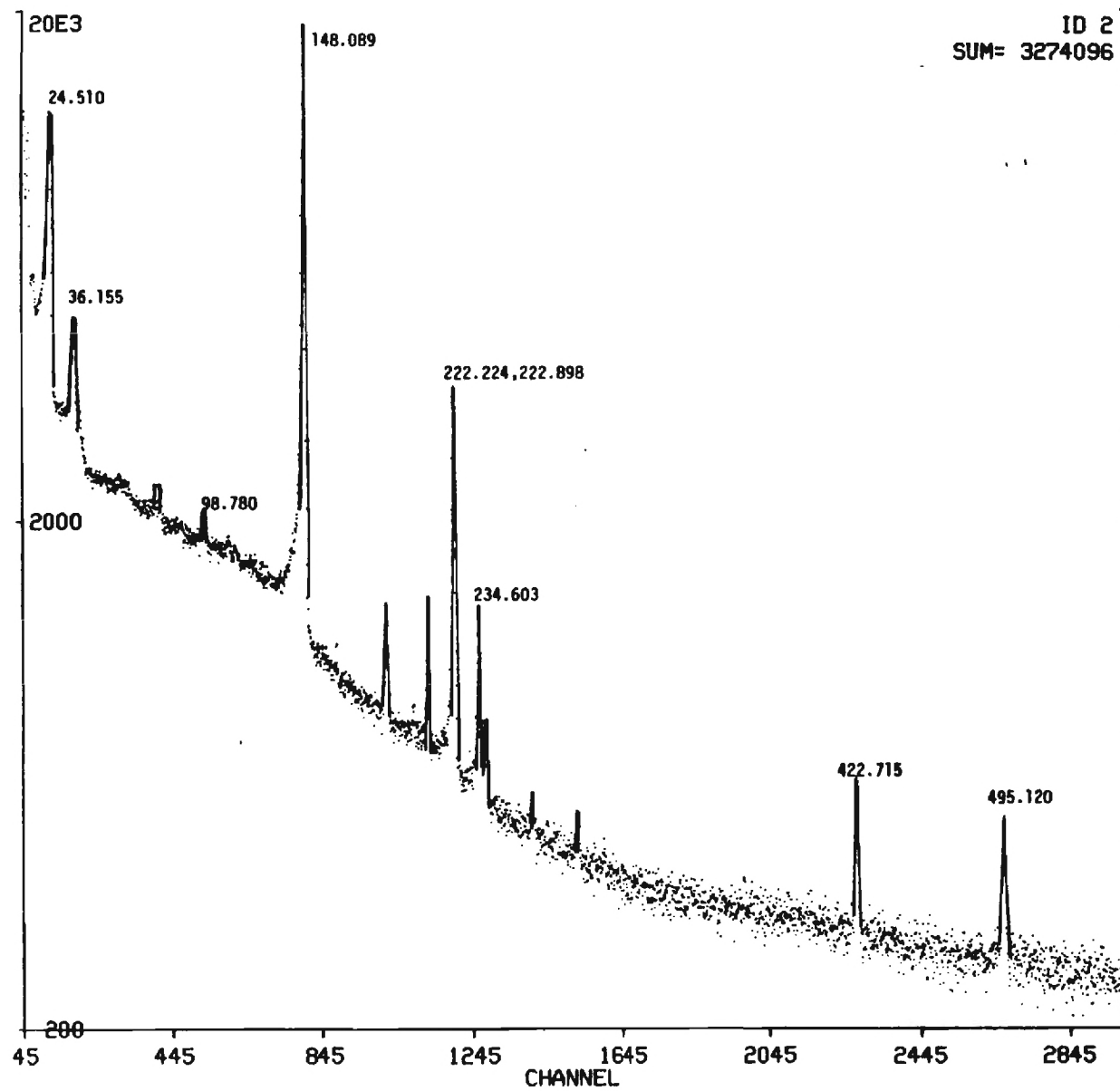
The conversion electron spectrum obtained from this thoron active deposit is shown in the figure on page 18. In addition, this source can also serve as an alpha-particle energy calibration standard. The alpha-particle spectrum obtained with a Si detector is shown in the figure on page 19. The peaks at 6050+6090 and 8784 keV are from the decays of 60.5 min $\text{ThC}[^{212}\text{Bi}]$ and 0.3 μsec $\text{ThC}'[^{212}\text{Po}]$, respectively.

2.6 Nuclear Laser Spectroscopy on Kr and Pb Isotopes

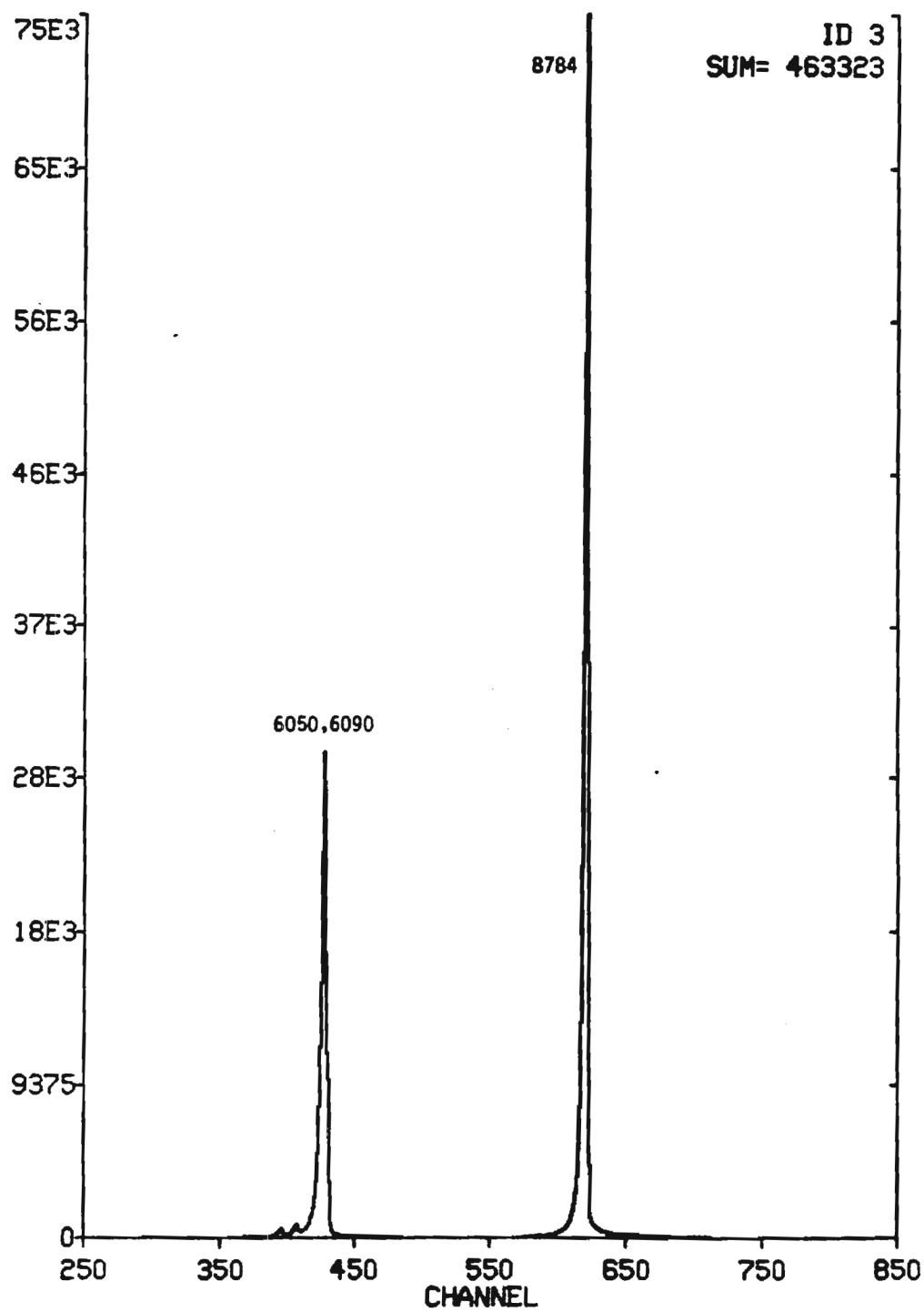
Determination of the nuclear magnetic dipole and spectroscopic quadrupole moments (μ_I , Q_S) from measurements of the electronic hyperfine structure [hfs] and of changes in the root-mean-square nuclear charge radii ($\delta\langle r^2 \rangle$) from isotope shift (IS) measurements are being carried out with a tunable ring dye laser in a collinear laser-ion beam geometry coupled to the UNISOR isotope separator. These quantities provide fundamental and important tests of applicable nuclear models. Our current experiments on Kr and Pb isotopes, performed in collaboration with Dr. H. K. Carter of UNISOR, will constitute part of the PhD thesis of Mr. Jeffrey Griffin, who is on ORAU fellowship at



Thoron gas radionuclide generator: 70 year $^{232}\text{U} \rightarrow 1.9 \text{ year } ^{228}\text{Th} \rightarrow ^{212}\text{Pb}[\text{ThBCC'C}']$ (10.6 hour active deposit). A negative 500 to 1000 volts may be applied to the wire, or a planchet (Cu) laid over the glass sieve without any applied voltage. The long-lived parent material is deposited on the bottom of the stainless steel vessel. Only 54 min $^{220}\text{Rn}[\text{Tn}]$ gas is in contact with the wire or planchet, leaving a 10.6 hour active deposit useful for conversion electron and alpha-particle energy and relative intensity calibration standards (see text).



Conversion electron spectrum from thoron active deposit, 10.6 hour ThB
 ^{212}Pb - ^{212}Bi - ^{212}Po / ^{208}Tl equilibrium mixture as observed with a Si detector



Alpha-particle spectrum observed with a Si detector from thoron active deposit, ThB[^{212}Pb - ^{212}Bi - ^{212}Po - ^{208}Tl].

Oak Ridge.

Our current experiments with Kr isotopes are aimed at completely developing the non-optical detection method of Resonance Ionization Spectroscopy [RIS]¹²⁾

¹²⁾ S. Hurst, M. G. Payne, S. D. Kramer, and J.P. Young, Revs. Modern Phys. 51 767 (1979)

as an alternative to the optical resonance fluorescence technique. Analysis of data obtained from our initial resonance fluorescence experiments on stable Kr isotopes indicated the presence of a high background combined with a low overall efficiency, definitely precluding the use of this technique on the much smaller beams of radioactive Kr isotopes. Thus, for experiments with radioactive Kr, development of the RIS technique is a necessity.

RIS differs from resonance fluorescence in that it depends on particle detection rather than photon detection. In the collinear laser-fast beam experiment using RIS, the atoms are selectively excited by the absorption of a photon from the collinear dye laser and subsequently ionized by a second laser, which is also collinear with the ion(atom) beam. Detection of Kr ions as a function of the scanning dye laser frequency substitutes for the detection of the resonance photons from the deexcitation of the excited states in the resonance fluorescence technique. For the application of the RIS technique to Kr studies, we are using the 5145Å line of the Ar⁺ pump laser as the second (ionizing) transition.

We have installed and tested the RIS system with stable Kr beams. In these tests we obtained very high background rates with the channeltron particle detector. Subsequent calculations indicate that this background is due to non-selective collisional ionization of the ion(atom) beams by residual gas atoms in the vacuum chamber. To overcome this background problem, we have designed and are building a new super high vacuum chamber that will enable us to lower our

pressure from the current 10^{-6} Torr to 10^{-9} Torr for RIS experiments. This should lower the background by a factor of 10^3 , making IS and hfs measurements possible. Complete development of the RIS technique will also allow its application to measurements on Xe isotopes.

In addition to the ongoing work with Kr isotopes, we also have initiated laser studies on a series of Pb isotopes. These investigations should be interesting, particularly in light of recently published experimental results using γ -ray spectroscopy to study the neutron-deficient $^{192-198}\text{Pb}$ isotopes¹³⁾.

¹³

P. van Duppen, E. Coenen, K. Deneffe, et al. Phys. Rev. Lett. 52, 1974 (1984)

These results offer the first observation of low-lying deformed states in neutron-deficient even-even Pb isotopes. These states appear to be similar to the well-deformed bands which are found at low energies in the light Hg isotopes ($A \leq 188$)¹⁴⁾. As with the Hg isotopes, the states in Pb are observed

¹⁴

A. F. Barfield, et al. Z. Physik A311, 205 (1983)

to drop in energy with decreasing atomic number. In fact, the 0_2^+ state is found to be the first excited state in $^{192,194}\text{Pb}$. If the 0_2^+ state continues to drop in energy towards more neutron-deficient isotopes, then mixing between the deformed and ground state band heads will increase and isotope shift measurements on the very light Pb isotopes will be crucial in determining the character of the ground state.

Laser spectroscopic measurements of hfs and IS in the Pb isotopes can be completed using conventional resonance fluorescence spectroscopy. We have obtained and installed the dye laser optics and dye for the 7230\AA transition in Pb. This involved quite a lot of work, as this is a new wavelength region for the UNISOR laser system. This work is completed and we are currently making measurements on stable and neutron-rich Pb isotopes in order to develop the system and to determine an accurate efficiency. Subsequently, we will

extend the measurements to the neutron-deficient Pb isotopes produced with heavy ion beams from the HHIRF tandem accelerator and/or ORIC.

This work constitutes the PhD thesis research in nuclear chemistry for Mr. Jeffrey Griffin, who has received an ORAU fellowship (June 15, 1985) and is now in residence in Oak Ridge.

3.0 NUCLEAR STRUCTURE CALCULATIONS WITH NUCLEAR MODELS

In the past year, our theoretical work based on the Core-Quasiparticle Coupling Model [CQCM]¹⁾ for odd-mass nuclei has been completed. This work

¹F. Döna and S. Frauendorf, Phys. Lett. 71B, 263 (1977)

centered on two areas: (1) A study of Pauli exchange effects for the odd particle in the Interacting Boson-Fermion Model [IBFM] by a numerical comparison with the CQCM (which is based on dynamical field theory and the BCS method), and (2) testing Interacting Boson Model [IBM] descriptions for the even-even Hg isotopes with CQCM calculations for the neighboring odd-mass nuclei. These two topics are discussed separately below.

3.1 An Investigation of Exchange Effects in the IBFM

As discussed in last years Annual Report, ORO-3346-257, the IBFM and the CQCM are two particle-core coupling models with a number of similarities. In both models, a major part of the particle-to-core coupling is achieved through a $q \cdot Q$ term, ie, through an interaction with the quadrupole field of the core. The generality of this coupling prescription, together with the inherent flexibility of the core descriptions in these two models, has led to broad applicability for both, ie both models can be applied to spherical, deformed, and transitional odd-mass nuclei. There is, however, an essential difference between these two models in the way Pauli exchange effects are treated. In the IBFM, there is an explicit exchange term which can be visualized as describing a process in which the odd particle exchanges with one of the constituent fermions in a boson. This exchange term carries an overall strength parameter Λ_0 and also depends on v^2 , the occupancy of the j -shell. In the CQCM, exchange effects arise from the BCS treatment of the residual pairing interaction. This treatment also requires the specification of two parameters, the Fermi energy λ (which controls the j -shell occupancy),

and the pairing gap energy Δ (which is related to the strength of the residual pairing interaction).

A series of energy calculations have been performed with the two models in which the only difference is in the handling of the Pauli exchange effects. These calculations, which were discussed in last year's annual report, ORO-3346-257, coupled an odd particle in a partly-filled $j = 9/2$ shell to a set of cores exhibiting the IBA dynamical symmetries $SU(5)$, $O(6)$, and $SU(3)$. The resulting spectra for a given j -shell occupancy obtained in the IBFM as a function of Λ_0 were compared to those obtained in the CQCM as a function of Δ . The greatest differences between the IBFM and CQCM were observed for $v^2 = 0.8$ and an $SU(3)$ core, which corresponds to the coupling of a hole to a prolate rotor in the geometric picture. The low-lying states found in the calculation correspond to rotational bands built upon $K = 9/2$ and $K = 7/2$ band heads. These rotational bands were found to be much less compressed in the IBFM than in the CQCM, which suggests that the IBFM may be able to attenuate the Coriolis interaction, ie, that the mixing of the K bands which arises from the core Hamiltonian may be attenuated by the exchange term. The most direct way to study this mixing is to examine the interband collective E2 transition rates, since these vanish between pure K bands in the geometric picture²⁾, and this

²A. Bohr and B. Mottelson, Nuclear Structure, Vol. 2 (Benjamin, Reading, Mass. 1975)

analysis of the Coriolis matrix elements has been completed this year.

In the geometric picture, interband transitions occur solely due to Coriolis

mixing, and thus the transition rates are directly related to these interaction matrix elements. Furthermore, the E2 operator has the same form in both the CQCM and the IBFM, namely

$$T(E2) = e_c Q + e_f q \quad (3-1)$$

where e_c and e_f are the effective electric quadrupole charges for the core and the odd fermion and Q and q are the core and particle quadrupole operators. By choosing the fermion effective charge equal to zero and using the same effective core charge in the two models, the differences in calculated E2 transition rates can be related easily to the effective Coriolis mixing matrix elements. The simplest way to extract the mixing matrix elements is to consider two band mixing only and to approximate the SU(3) core quadrupole matrix elements with those of a rigid axial rotor, i.e.

$$\langle R' \| Q \| R \rangle = Q_0 \sqrt{(2R+1)} \langle R020 | R'0 \rangle \quad (3-2)$$

where Q_0 is chosen to reproduce the diagonal SU(3) matrix elements. This results in collective E2 transition rates between the mixed bands given by

$$B(E2; I \rightarrow I') = e_c^2 Q_0^2 [\sum_k A_k B_k \langle IK20 | I'-K \rangle]^2 \quad (3-3)$$

where e_c is the effective charge and the amplitudes A_k and B_k are determined from the two band mixing calculation. For $K =$

9/2, 7/2 mixing, the $I = 9/2 \rightarrow I' = 9/2$ transition is quite simple because the AB product is given by

$$(A_K B_K)^2 = V^2 / (\Delta E)^2 \quad (3-4)$$

where ΔE is the energy difference of the two $I = 9/2$ states after mixing and V is the mixing matrix element. Therefore, from the calculated E2 rate for the $I = 9/2 \rightarrow I' = 9/2$ transition, the magnitude of the effective mixing matrix element V can be extracted using equations (3-2) to (3-4). The use of the rigid rotor approximation to obtain equation (3-2) is well justified since, for $I = j$, the odd particle couples to the lowest members of the core ground state band, where the difference between the SU(3) and rigid rotor quadrupole matrix elements is a few percent or less.

Furthermore, the additional implicit assumptions of the rigid rotor, namely that the core ground state band has an $R(R+1)$ energy dependence and that the odd particle couples only to the ground state band, are exactly satisfied for the SU(3) core. The former requirement is the origin of the Coriolis mixing, and the latter requirement is met since the core quadrupole operator cannot connect different bands in the SU(3) core, and so the ground state band is decoupled from the others. This procedure for extracting the mixing matrix element can be checked directly for the CQCM due to the two-step diagonalization procedure used there. In all cases studied, the extracted matrix elements agrees to within 2% of the values used by the CQCM computer code from the projection of the core energies.

The effective Coriolis matrix elements obtained from the IBFM $(9/2)_2 \rightarrow (9/2)_1$ E2 transition rate for an SU(3) core and $v^2 = 0.8$ are shown in Fig. 7 as a function of Λ_0 . As Λ_0 varies from 0.50 to 2.50 MeV, the energy difference between the two $I = 9/2$ states ranges from 1370 to 140 keV, and the extracted matrix element varies from 127 to 35 keV. A linear extrapolation gives an intercept of 153 keV for the unattenuated Coriolis matrix element, in very good agreement with the single-particle plus rigid rotor value of 150 keV. The dashed line on Fig. 7 shows the result of the CQCM calculation for $\Delta = 1.0$ MeV and a j-shell occupancy of 0.8. The attenuation relative to 150 keV is due to the BCS pairing factor $u_1u_2 + v_1v_2$. This result is not very sensitive to the placement of the Fermi energy, i.e., moving the Fermi energy so that the energy difference between the two $I = 9/2$ states ranges from 600 to 180 keV changes the effective Coriolis matrix element by only 2 keV. This is because the Fermi energy is approximately midway between the two adiabatic $I = 9/2$ states and so small changes in the Fermi level affect the BCS pairing factor $u_1u_2 + v_1v_2$ very little.

The effective Coriolis matrix element also varies with v^2 in the IBFM due to the $v^2(1-v^2)$ factor in the exchange term. For example, allowing v^2 to vary from 0.80 to 0.74 with Λ_0 kept fixed at 1.25 MeV produces a range in energy differences between the two $I = 9/2$ states of 650 to 170 keV; the corresponding variation in the extracted matrix element is from 94 to 83 keV, i.e., significantly smaller than that obtained with Λ_0 . This suggests that in a practical IBFM calculation, Λ_0 can be chosen to reproduce the observed Coriolis

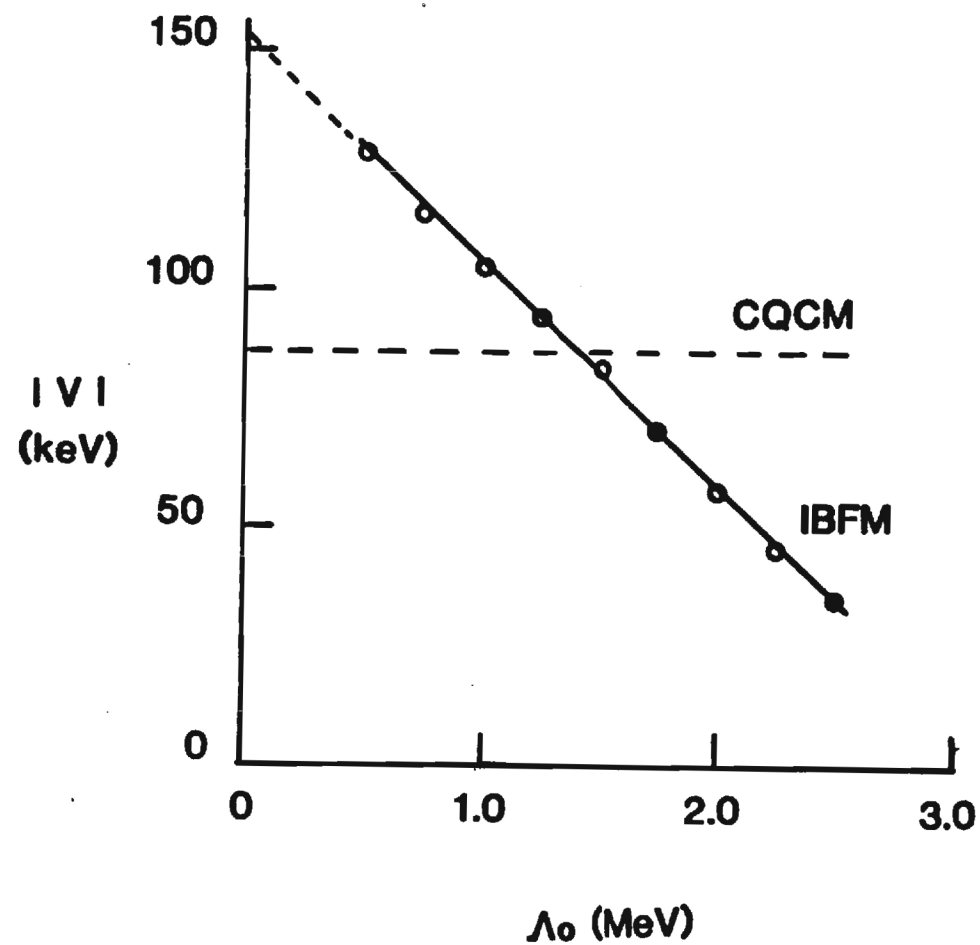


Fig. 7 - The effective Coriolis matrix element for an SU(3) core plus an odd particle in a partly filled $j = 9/2$ shell.

mixing, while v^2 is used to reproduce the energies of the Nilsson bandheads. However, this apparent flexibility may be severely restricted when additional requirements are considered, such as that v^2 must give a reasonable estimate of the j-shell occupancy for the nucleus or nuclei under consideration. This work has been completed and a manuscript prepared for publication in Phys. Rev. C.

3.2 Testing IBA Descriptions of the Even-Mass Hg Isotopes

The even-mass Hg isotopes display at least two unusual features, ie, (1) the low-energy structure of the heavier isotopes apparently changes very little, as evidenced by the remarkable constancy in energy of the low-lying states for $A = 192$ to 200 , and (2) an extra band of states, interpreted as a rotational band built upon a coexisting shape, has been observed for $A \leq 190$. A quantitative interpretation of these phenomena has been provided in the framework of the proton-neutron version of the Interacting Boson Model [IBM-2] in ref. 3. In that work, the extra band of states (intruder band) is

³A. Barfield, et al. Z. Physik A311, 205 (1983) and private communication

interpreted as due to a proton pair excitation across the $Z = 82$ shell gap. This leads to an increase in the number of valence proton pairs (bosons) from 1 boson (hole pair) in the regular configuration to 3 bosons (2 hole pairs + 1 particle pair) for the intruder configuration. The regular and intruder configurations are treated separately in standard IBM-2 calculations and are then allowed to mix. These calculations gave good agreement with the observed energy spectra in both the heavy and light isotopes, but one surprising result was the predicted shape change (oblate to prolate) in the ground state band.

The results of these even-mass calculations are used directly as input for the CQCM odd-mass calculations, which can then be used to test the even-mass core description or to provide insight into the structure of the odd-mass nuclei.

In the previous annual report (ORO-3346-257), the results of such energy calculations for the $\nu 1_{13/2}$ bands in the odd-mass Hg isotopes from 197 to 187 were presented. In those calculations, the $q \cdot Q$ coupling parameter (κ) was chosen to reproduce the energy of the $17/2^+ (j+2)$ state in ^{197}Hg , and then held fixed for all other calculations. The pairing energy gap Δ was obtained from odd-even mass differences, and the Fermi energy λ was chosen to reproduce the energy of the $11/2^+ (j-1)$ state in each nucleus, as suggested in ref. 4. For each nucleus, the $A+1\text{Hg}$ core was used, and thus the effects of

⁴ J. Meyer-ter-Vehn, Nucl. Phys. A249, 111 (1975)

the predicted changing core quadrupole field are included. The resulting calculated energy spectra for the $\nu 1_{13/2}$ bands in odd-mass Hg isotopes from 189 to 197 agreed reasonably well with the experimental data. This agreement suggests, but does not prove, that the core quadrupole field is changing in the ground state band of the heavier Hg isotopes, as suggested in ref. 1. The effect of the changing quadrupole core field can be tested by using a single Hg core for the odd-mass calculations. The ^{198}Hg core was chosen for this purpose, because the experimental quadrupole moment is known for the first 2^+ state and agrees well with the calculated value. The odd-mass calculations were then performed for $^{197-189}\text{Hg}$ with both κ and Δ fixed at their $A = 197$ values; only the Fermi energy was varied for each nucleus, and was again adjusted to reproduce the energy of the $11/2^+ (j-1)$ state. (Note: using a constant value for Δ instead of that obtained for each nucleus from odd-even mass differences had a negligible effect on the calculated spectra.) The results of these calculations can be summarized as follows: The agreement with the data was as good as with the changing cores, and in fact the two sets could not be easily distinguished. Clearly, these calculations have not been sensitive enough to determine whether the quadrupole field of the even-mass Hg isotopes changes as described. An interesting question at this point is whether this insensitivity

is due to imprecision in locating the Fermi energy in a single j -shell calculation, or whether the odd particle itself is not a sufficiently sensitive probe when the Fermi energy penetrates the j -shell. This question is not answered in the present work, but the Hg cores are tested more stringently in the Au and Tl calculations.

3.3 Odd-Mass Au and Tl Calculations

The experimental systematics⁵⁾ of the $h_{9/2}$ bands in $^{197-191}\text{Tl}$ and the $h_{11/2}$ bands in $^{195-189}\text{Au}$ are shown in Fig. 8. The $h_{9/2}$ and $h_{11/2}$ proton configurations are expected to be nearly pure particle and pure hole, respectively, and thus for the odd-mass calculations it is sufficient to use only a single core, namely the appropriate Hg core. The quadrupole coupling parameter κ was taken to be 2.7 MeV, as in the odd-Hg calculations. The pairing energy Δ was fixed at 0.7 MeV for all the odd proton calculations, as in ref. 4; insufficient information in ref. 6 precluded the use of odd-even mass differences. For calculations in the Tl isotopes, the Fermi energy was varied

⁵E. F. Zganjar, in Future Directions in Studies of Nuclei far from Stability, edited by J. H. Hamilton, et al (North-Holland, 1980).

⁶A. H. Wapstra and K. Bos, At. Data and Nucl. Data Tables 19, 177 (1977)

to give a best fit to the level energies in ^{197}Tl , and this resulted in a particle number of 1.0 in the (nearly empty) $h_{9/2}$ subshell. In all subsequent Tl calculations, the Fermi energy was kept fixed at the corresponding value (-2.0 MeV). The same procedure was used for the Au isotopes, with the Fermi energy fitted for ^{195}Au , giving 10.0 particles in the (nearly filled) $h_{11/2}$ subshell. The corresponding Fermi energy, found to be 1.5 MeV, was then kept fixed for the remaining Au calculations. In this way, the remaining calculations for Tl ($A = 191$ to 195) and Au ($A = 189$ to 193) directly test the effect of the changing quadrupole field, since the core energies remain essentially constant.

The results of these calculations are summarized in Fig. 9. The strongly-coupled band pattern found experimentally in the Tl isotopes is well

reproduced for ^{197}Tl (^{196}Hg core), but the agreement steadily worsens with decreasing A , where a transition to a decoupled band pattern is predicted by the calculations. In ^{191}Tl , for example, the first $13/2^-$ state lies lower in energy than the first $11/2^-$ state in these calculations, in disagreement with experiment. This result was not sensitive to the placement of the Fermi energy, and in fact allowing even a half-filled j -shell does not produce the observed ordering for the $11/2$ and $13/2$ states. The results for the Au isotopes are similar. The decoupled band pattern found experimentally is well reproduced for ^{195}Au (^{196}Hg core), but again the agreement steadily worsens with decreasing A . For example, the first $9/2^-$ state drops in energy with decreasing A and is predicted to become the first excited state in the $h_{11/2}$ band at ^{189}Au . Experimentally, the $9/2^-$ state changes very little in energy and actually rises slightly with decreasing A .

The consistent failures in these particle-core calculations for the Au and Tl isotopes clearly show that the quadrupole fields of the even-mass Hg isotopes are not properly described in ref. 3. In particular, the ground state band does not appear to undergo the oblate to prolate shape change predicted in that work, but instead must retain a weakly oblate structure similar to that found in $^{196,198}\text{Hg}$. Therefore, an alternative description of the even-mass Hg isotopes within the framework of ref. 3 is needed.

This work constitutes part of the PhD thesis of Paul Semmes (July, 1985) in nuclear chemistry. A manuscript has been prepared on this subject for publication in Phys. Rev. C.

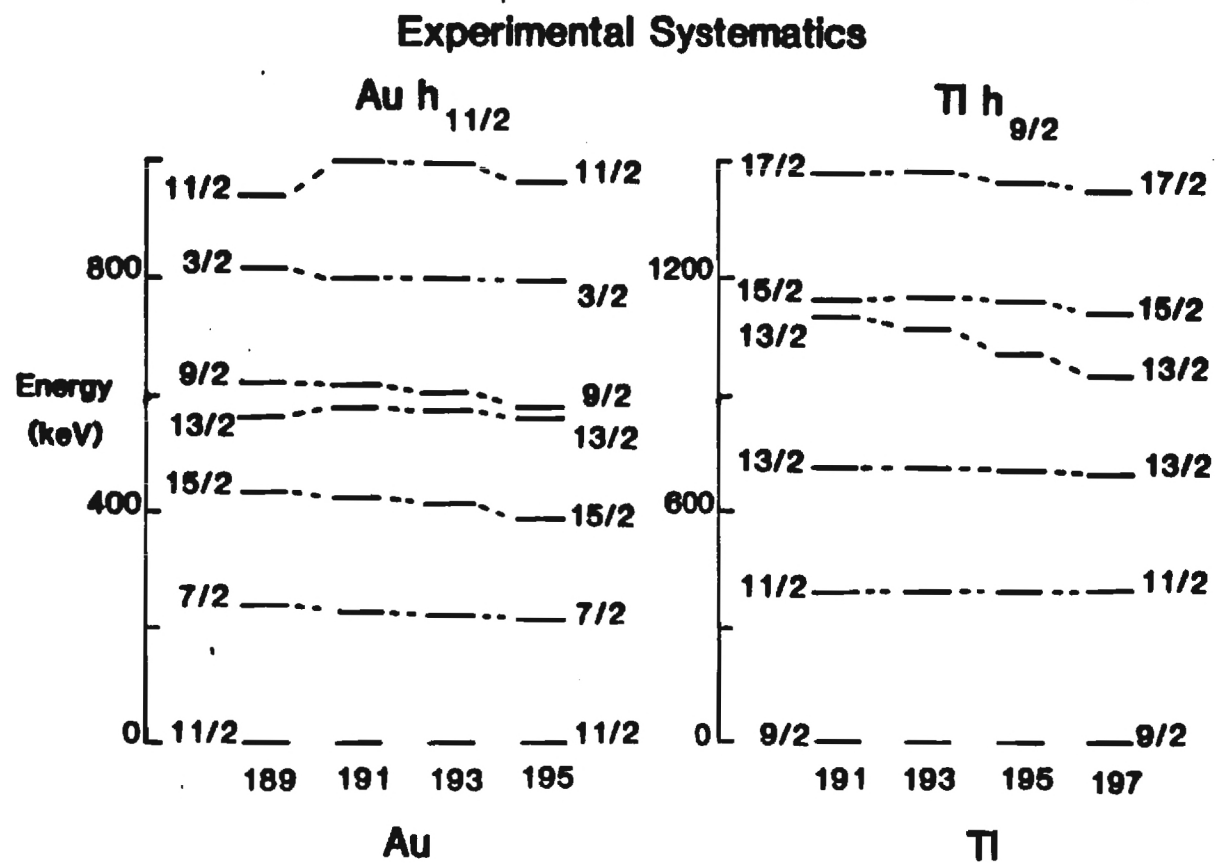


Fig. 8 - Experimental systematics of negative parity states in odd-mass Au isotopes ($h_{11/2}$ band, $A = 189$ to 195) and odd-mass Tl isotopes ($h_{9/2}$ band, $A = 191$ to 197)

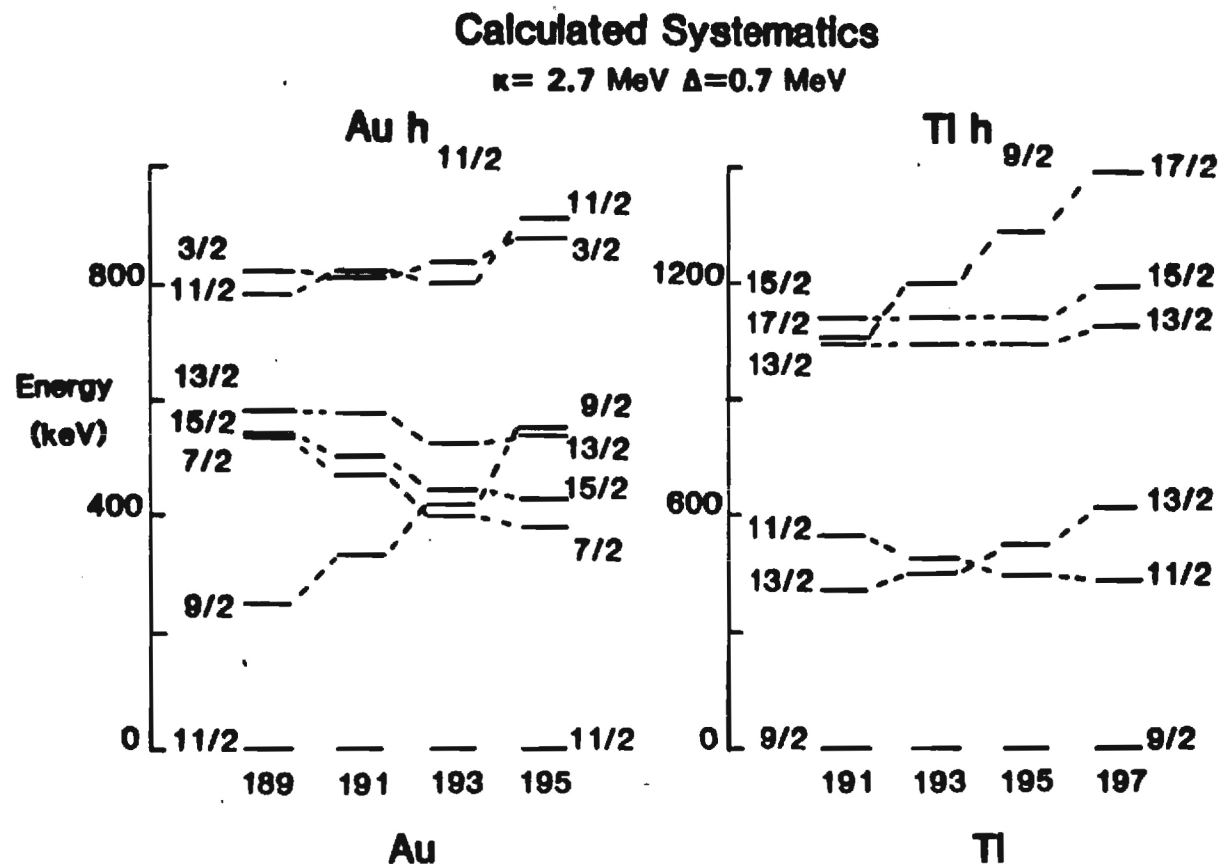


Fig. 9 - Calculated systematics of negative-parity states in odd-mass Au isotopes ($h_{11/2}$ band, $A = 189$ to 195) and odd-mass Tl isotopes ($h_{9/2}$ band, $A = 191$ to 197).

4.0 TECHNICAL SUPPORT

4.1 Computer Operations

With the increased utilization of the HHIRF Perkin-Elmer 3230 mainframe computers for UNISOR data acquisition and analysis, we have modified existing codes used for data analysis on the Georgia Tech CDC Cyber 760 mainframe computer to handle HHIRF magnetic tape format.

4.2 Equipment Added

During the past year we have purchased assorted optics for use at the UNISOR laser facility and a channeltron for the 30°R beam line at UNISOR. In addition, a beam port cup for mounting the channeltron was manufactured in the Georgia Tech Chemistry machine shop, as was a stainless steel vessel for the radiothoron gas generator. For use in this radionuclide generator, 500 μCi of an equilibrium 70 year ^{232}U -1.9 year $^{228}\text{Th}[\text{RdTh}]$ was purchased.

To augment the graphics capabilities of our recently acquired computer terminal, we have ordered an Epsom FX-80 dot-matrix printer for the Nuclear Chemistry Laboratory at Georgia Tech.

4.3 Technical Work at UNISOR

Dr. R. A. Braga received a 1/2 time summer appointment (equivalent to 6 weeks full-time) at the Joint Institute for Heavy Ion Research at Oak Ridge for research and technical work at UNISOR, June 15 - Sept. 15, 1985, and remained 1/2 time on this DOE contract. Dr. R. W. Fink spent approximately 3 1/2 weeks full-time in Oak Ridge during summer, 1985, performing technical work (isotope separator operations) at UNISOR.

5.0 PERSONNEL

Senior Staff

Dr. R. W. Fink, Professor of Chemistry & Principal Investigator
(1/4 time, 12 months equivalent to full-time summer)

Dr. R. A. Braga, Research Scientist
(1/2 time DOE, summer, 1985 + full-time Fall, 1985)

Graduate students

Paul Semmes (Completed PhD, July, 1985, Nuclear Chemistry)
(Presently: Postdoctoral fellow at Joint Institute for Heavy
Ion Research, Oak Ridge, Tennessee)

Jeffrey C. Griffin (Chemistry). Continuing PhD thesis research.
(In residence at Oak Ridge/UNISOR, supported by ORAU fellowship)

Cesar P. Perez (Chemistry). Continuing PhD thesis research.
(Supported in part at Georgia Tech Reactor, 1984 - July 31, 1985,
by DOE contract August 1 - Sept. 15, 1985, and by teaching
Sept. 15, 1985 - present time)

Mr. John Shannon, Senior Undergraduate Research Participant in
nuclear chemistry, 1984/85. Graduated June, 1985.

Marlon Walker (Chemistry). Supported by teaching and transferred
to physical chemistry, April, 1985.

New Graduate Students

We expect the arrival September 24, 1985 of two new students as follows:

Mark Harvison (Chemistry) B.S. Augusta College 1985.

Larry Pittman (Chemistry) B.S. Augusta College, 1985

6.0 LIST OF PUBLICATIONS, MEETINGS, SEMINARS, AND TALKS PRESENTED

- "Decay of ^{138}Eu and Deformation in the Light Sm Region," R. L. Mlekodaj, G. A. Leander (UNISOR), R. A. Braga (Chemistry, Georgia Tech), and other UNISOR coauthors, Abstr. #68, Division of Nuclear Chem. & Technol., Am. Chem. Soc. (Chicago, Illinois, Sept. 8 - 13, 1985)
- "Decays of $^{117}\text{Xe} \rightarrow ^{117}\text{I} \rightarrow ^{117}\text{Te}$," R.S. Lee, J.H. Hamilton, A. C. Xenoulis, R. W. Fink, and other UNISOR coauthors, Phys. Rev. C32, 277 - 287(1985) [ORO-3346-239]
- "Decay of Mass Separated $^{201,203}\text{At}$," R. A. Braga, P. B. Semmes, and R. W. Fink, Abst. Division of Nuclear Chem. & Technol., Am. Chem. Soc. (St. Louis, Mo., April, 1984)
- "Decay of Mass Separated $^{201m,g}\text{Po}$ Isomers to Levels in ^{201}Bi ," R. A. Braga and R. W. Fink, Nucl. Phys. A (1985) [ORO-3346-256]
- "Decay of ^{188}Tl and the Observed Shape Coexistence in the Bands of ^{188}Hg ," J.D. Cole, J. H. Hamilton, A. V. Ramayya, J. L. Wood, R. W. Fink, and other UNISOR coauthors, Phys. Rev. C30, 1267 - 1275 (1984)
- "Reaction of Benzenediazonium-2-carboxylate with Reactor-Produced, No-Carried-Added ^{18}F -fluoride. A Novel Synthesis of 2- ^{18}F -fluorobenzoic Acid," A. D. Stroupbauer, C. L. Liotta, and R. W. Fink, Int. J. Appl. Radiat. Isotopes 35, 787 - 791 (1984) and Invited Paper, Div. of Nuclear Chem. & Technol., Am. Chem. Soc. (St. Louis, Mo, April, 1984)
- "Preparation of a Thoron Gas Radionuclide Generator for $^{212}\text{Pb}[\text{ThB}]$ Conversion Electron and Alpha-particle Calibration Sources," R. W. Fink, UNISOR Workshop, Oak Ridge, Tennessee (June 26, 1985)
- "Particle-Core Coupling Calculations for the Positive-Parity States in Odd-Mass Hg Isotopes: A Test of IBA Core Descriptions," P. B. Semmes, G. A. Leander, and J. L. Wood, in Interacting Boson-Boson and Boson-Fermion Systems, edited by O. Scholten (World Scientific Publishing Co. Ltd., Singapore, 1984); pp. 208 - 213
- "Unpaired Nucleons as Probes of Core Collective Fields," G. A. Leander, P. B. Semmes, and F. Dönau, in Interacting Boson-Boson and Boson-Fermion Systems, edited by O. Scholten (World Scientific Publishing Co., Ltd., Singapore, 1984); pp. 167 - 180
- PhD Thesis: Paul Barksdale Semmes, "I. Core-Quasiparticle Coupling Model Calculations as a Test of Interacting Boson Approximation Core Descriptions of the Even Mass Mercury Isotopes. II. Decay of Mass Separated ^{203}At ." Completed July, 1985.
- "Decay of ^{137}Sm and Deformation in the Light Pm Region," R. A. Braga, R. W. Fink, and other UNISOR coauthors, Bull. Am. Phys. Soc. 30 (1985) [Asilomar, California, October, 1985] [ORO-3346-261]
Presented at UNISOR Workshop, June 26, 1985, Oak Ridge, Tennessee

- "Coexisting Collective Structure in ^{185}Hg " (from Decay of $^{185\text{m},g}\text{Hg}$), E. F. Zganjar, J. L. Wood, R. A. Braga, R. W. Fink, and other UNISOR coauthors, Bull. Am. Phys. Soc. 30, (1985) [ORO-3346-262]
(Asilomar, California, October, 1985)
- "An Investigation of Exchange Effects in the Interacting Boson-Fermion Model," P. B. Semmes, G. A. Leander, O. Lewellen, and F. Dönau, Phys. Rev. C (submitted, 1985)
- "Testing IBM Cores through Particle-Core Coupling: Negative Parity States in the Odd-Mass Tl and Au Isotopes," P. B. Semmes, A. F. Barfield, B. R. Barrett, and J. L. Wood, Phys. Rev. C. (submitted, 1985)
and talk presented to the Holifield Theory Users Meeting, Oak Ridge, Tennessee (May 10-11, 1984)
- "Decay of Mass Separated 7.4 min ^{203}At ," P. B. Semmes, R. A. Braga, R. W. Fink, J. L. Wood, and J. D. Cole, Nucl. Phys. A (in preparation, 1985)
[ORO-3346-265]

NUCLEAR CHEMISTRY RESEARCH AND SPECTROSCOPY
WITH RADIOACTIVE SOURCES

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NUCLEAR CHEMISTRY RESEARCH AND SPECTROSCOPY WITH RADIOACTIVE SOURCES

1.0 INTRODUCTION

The nuclear chemistry group in the School of Chemistry continues investigations of radioactive decay of nuclei far from stability under this DOE contract. These nuclei are produced with heavy ions from the Holifield Heavy Ion Research Facility [HHIRF] and studied on-line with the University Isotope Separator at Oak Ridge [UNISOR]. Radioactive decay represents a unique method for the population of low-energy, low-spin structures in nuclei, and new phenomena which do not occur near stability can be explored. Our research interest encompasses three aspects of nuclear structure: (1) nuclear spectroscopy with detailed $\gamma\gamma$, $e^-\gamma$, $X\gamma$, $\alpha\gamma$ multiparameter coincidence spectrometry; (2) measurements of singles γ -ray angular distributions and magnetic moments of mass separated low-temperature oriented nuclei, using the helium dilution refrigerator "ORIENT" being installed on-line to the isotope separator; and (3) on-line laser hyperfine structure (hfs) and isotope shift measurements for determination of nuclear quadrupole moments, nuclear spins, and changes in mean nuclear charge radii as a means of revealing systematic shape changes in nuclei.

These studies of low energy (≤ 2 MeV), low-spin ($\leq 21/2$) structures in nuclei far from stability serve as a unique contribution to the results of the much larger field of in-beam spectroscopy which provides information on the higher energy, high-spin (mostly yrast) states. It is essential to have the combined results, in order to test critically the competing applicable theoretical ideas and nuclear models.

We concentrate mostly (but not exclusively) on odd-mass nuclei, in which the odd-nucleon probes an even-A core, in order to observe such phenomena as the onset of abrupt shape changes, shape coexistence, and shell-model intruder states. This information is critical for testing concepts fundamental to an understanding of low-energy nuclear structure, such as nuclear deformation, shell models, collective models, and particle-core couplings and uncouplings.

Our efforts this year have concentrated on the predicted new region of nuclear deformation ($Z \geq 60$, $N \leq 76$) in the neutron-deficient rare earths, as well as transitional nuclei between this deformed region and the closed shells at $Z = 50$, $N = 82$. Experimental data have been acquired on mass chains $A = 136$, 138, and 140 (entered at Eu) and $A = 137$ and 139 (studied from the Sm decays). [See Sect. 2.1].

In addition, we have collaborated in experiments on decays of mass separated $^{185m,g}\text{Hg}$ and $^{189m,g}\text{Hg}$, in which data were acquired, both for $\gamma\gamma$ and $e^-\gamma$ coincidences, of statistical quality higher than any previously obtained. Such high statistical quality was required to resolve some crucial remaining nuclear structure questions (see Sect. 2.5).

Progress with the on-line UNISOR laser facility is directed toward a systematic study of hfs and optical shifts of neutron-deficient Pb and Tl isotopes on the decays of which UNISOR previously completed extensive detailed nuclear structure studies. One of our graduate students (J.C. Griffin) continues in residence at Oak Ridge on ORAU fellowship to devote full-time to his PhD thesis research with the laser (see Sect. 2.6).

During this year we have utilized various shops at Georgia Tech to fabricate high temperature FEBIAD ion source parts and quartz items for the laser and for growing paramagnetic host crystals for use in the nuclear orientation facility (see Sect. 4.0).

Owing to inadequate funds arising not only from lower-than-promised DOE support (\$18K less than promised for the current three-year renewal period), but also to additional cuts due to GRH (\$3K) and increased costs (salary increases, fringe benefit and overhead charges), we were unable to maintain our personnel longer than about 7 months of this contract year, even with no summer support for graduate students otherwise on teaching assistantships; our full-time research scientist, R. A. Braga, had to be terminated August 31, 1986.

The present research effort is being drastically curtailed and the present level of participation in UNISOR/HHIRF cannot be maintained without a sufficient increase in DOE support in 1987 (see Renewal Proposal Budget).

2.0 NUCLEAR SPECTROSCOPIC STUDIES

2.1 Decay of Mass Separated Rare Earth Nuclides and Deformation in the Light Rare Earth Region

Leander and Moeller¹⁾ have predicted the existence of reasonably strong deformation in neutron-deficient Sm and Pm isotopes at masses which are close enough to the line of stability that there is the possibility of producing and studying their structures. In continuing our investigation of this region of deformation in the $Z > 50$, $N < 82$ rare earth nuclei, a series of experiments were carried out this past year.

The first set of experiments consisted of detailed $\text{ce-}\gamma\text{t}$ coincidence spectrometry on sources of mass separated ^{137}Sm (45 sec) and γt coincidence spectrometry of mass separated sources of $^{139\text{m},8}\text{Sm}$ (9.5 sec, 3.0 min). In both cases the activities were produced by bombarding stacked foils of $^{\text{nat}}\text{Mo}$ with ^{48}Ti beams from the 25 MV folded tandem accelerator at HHIRF with on-line mass separation at UNISOR. The preliminary decay schemes for $^{137,139}\text{Sm}$ are shown in Fig. 1.

Of particular interest in the level structure of ^{137}Pm is the position of the $11/2^-$ state observed in the heavier odd-mass Pm isotopes. This $11/2^-$ odd-proton state comes lower in energy as one moves toward the more neutron-deficient nuclei. Recent in-beam spectroscopy²⁾ indicates that the $11/2^-$ state becomes the ground state in ^{137}Pm . Whereas in the heavier odd-mass Pm isotopes, E3 transitions between the $11/2^-$ excited state and $5/2^+$ ground state are observed, in ^{137}Pm a $5/2^+ \rightarrow 11/2^-$ transition of E3 multipolarity is expected. However, no transition of E3 multipolarity could be identified in the conversion electron experiment.

¹⁾G. Leander and P. Moeller, Phys. Lett. 110B, 17 (1982)

²⁾C. W. Beausang, et al., Bull. Am. Phys. Soc. 30, 1264 (1985)

Two possible explanations exist: 1) The E3 transition has an energy of less than 30 keV, so that it could not be converted in the K-shell and the energies of outer-shell conversion electrons are below the 25 keV lower limit cutoff of the Si(Li) detector used; (2) Similar to other $N = 76$ isotones, a decoupled band structure exists with the $11/2^-$ and $7/2^-$ members coming low enough in energy to be both below the $5/2^+$ state. The deexcitation would then proceed via a $5/2^+ \xrightarrow{\text{E1}} 7/2^- \xrightarrow{\text{E2}} 11/2^-$ sequence. Currently, there is no resolution of this problem.

A clue to the existence of the possible decoupled- band structure in ^{137}Pm may exist in ^{139}Pm . For this reason, a detailed spectroscopic study of the decay of ^{139}Sm was initiated recently; analysis is incomplete at the time of this report (August, 1986).

In addition to these studies on specific isotopes, a series of experiments using the He-jet transport system was undertaken. The impetus for these studies was twofold: 1) Even with the high temperature thermal ion source, the activities of mass separated rare earth nuclides are low. The He-jet system was used, in order to enhance the yields. (2) Since no mass separation is performed, the activities from a number of species are observed; this provided an opportunity to conduct a survey of the neutron-deficient rare earth nuclei in the region of $Z > 50$, $N < 82$. The activities were produced by bombarding ^{112}Sn foils with ^{28}Si ion beams at energies ranging from 170 to 210 MeV. A number of species were observed and identified as discussed below.

The decay schemes for the new isotope 3.9 sec ^{136}Eu [Bull. Am. Phys. Soc. 31, 836 (1986)], as well as for 12 sec ^{138}Eu and 1.5 sec ^{140}Eu are shown in Fig. 2. Prior to this study, no observation of the decay of ^{136}Eu had been accomplished. However, the task of identification was aided by knowledge of the energies of the γ -rays emitted in the 12-10-8-6-4-2-0+ yrast cascade in ^{136}Sm reported by Lister, et al.³⁾. In this mass chain, the EC decay of ^{136}Sm was reported⁴⁾; a γ -ray of 114.5 keV energy and a 42 ± 4 sec half-life were observed and attributed to the decay of ^{136}Sm . Eighteen additional γ -rays, not organized into a decay scheme, were attributed also to this decay; not all of them have been observed in the current experiments. The decay of ^{136}Sm to ^{136}Pm is shown in Fig. 3.

³C. J. Lister, et al., Phys. Rev. Lett. 55, 810 (1985)

⁴G. D. Alkhazov, et al., Z. Physik A305, 185 (1982)

⁵D. D. Bogdanov, et al., Nucl. Phys. A275, 229 (1977)

⁶A Charvet, et al., Z. Physik A321, 697 (1985)

In the $A = 138$ mass chain, ^{138}Eu has been reported to decay with isomeric half-lives of 35 and 1.5 sec⁵⁾. In the current study, the 8-6-4-2-0+ γ -rays of the yrast cascade were found to decay with a half-life of 12 ± 1 sec; this result is in agreement with the report of Charvet, et al.⁶⁾. No isomeric half-life was observed. At $A = 140$, little was previously known about the EC decay of ^{140}Eu . A high-spin producing reaction was reported to give a ^{140}Eu isomer which decayed with a 20 sec half-life⁷⁾. A low-spin producing reaction produced an isomer which decayed to the 2+ level with a half-life of 1.5 sec^{8,9)}. Earlier UNISOR experiments

⁷D. Habs, et al., Z. Physik 250, 179 (1972)

⁸L. Westgaard [ISOLDE], Bull. Am. Phys. Soc. 17, 907 (1972)

⁹L. Westgaard, et al., Proc. Int. Conf. Nuclear Physics, Munich, Vol. 1 (1973); p.696

with mass separated sources failed to detect the 20 sec halflife. In the present study, again there is no indication of a high-spin 20 sec isomer. The 530.7 keV γ -ray from the ^{140}Sm first-excited state is observed to decay with a 1.3 ± 0.3 sec halflife.

A number of other activities were observed and identified in these He-jet experiments. Of these, the decay schemes for 24 sec ^{134}Pm , 7 sec (?) ^{130}Pr , and 1.6 min ^{132}Pr are shown in Figs. 4 and 5.

A summary of the experiments are listed in Table 1. (R. A. Braga)

Table 1				
Target	Projectile	(Energy)	Mass Separated Activity	Experiment
nat_{Mo}	^{48}Ti	(225 MeV)	^{137}Sm	ce- γ t
nat_{Mo}	^{48}Ti	(230 MeV)	^{139}Sm	$\gamma\gamma\text{t}$
^{112}Sn	^{28}Si	(170, 190, 210 MeV)	He-jet	$\gamma\gamma\text{t}$

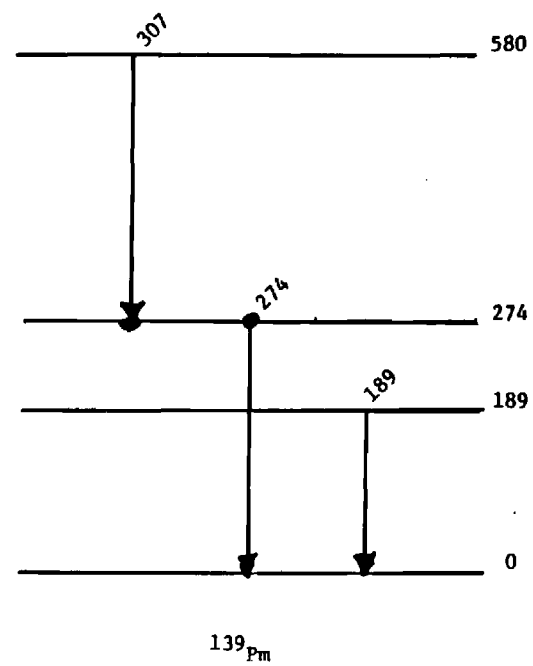
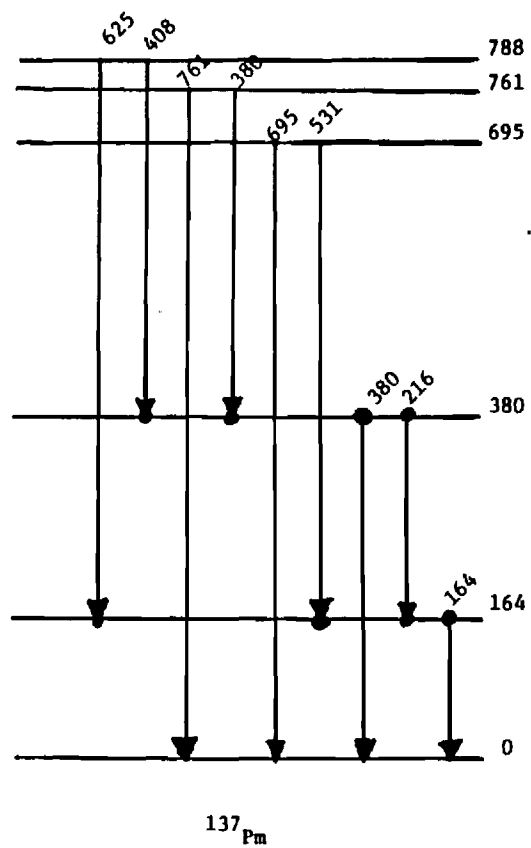


Fig. 1

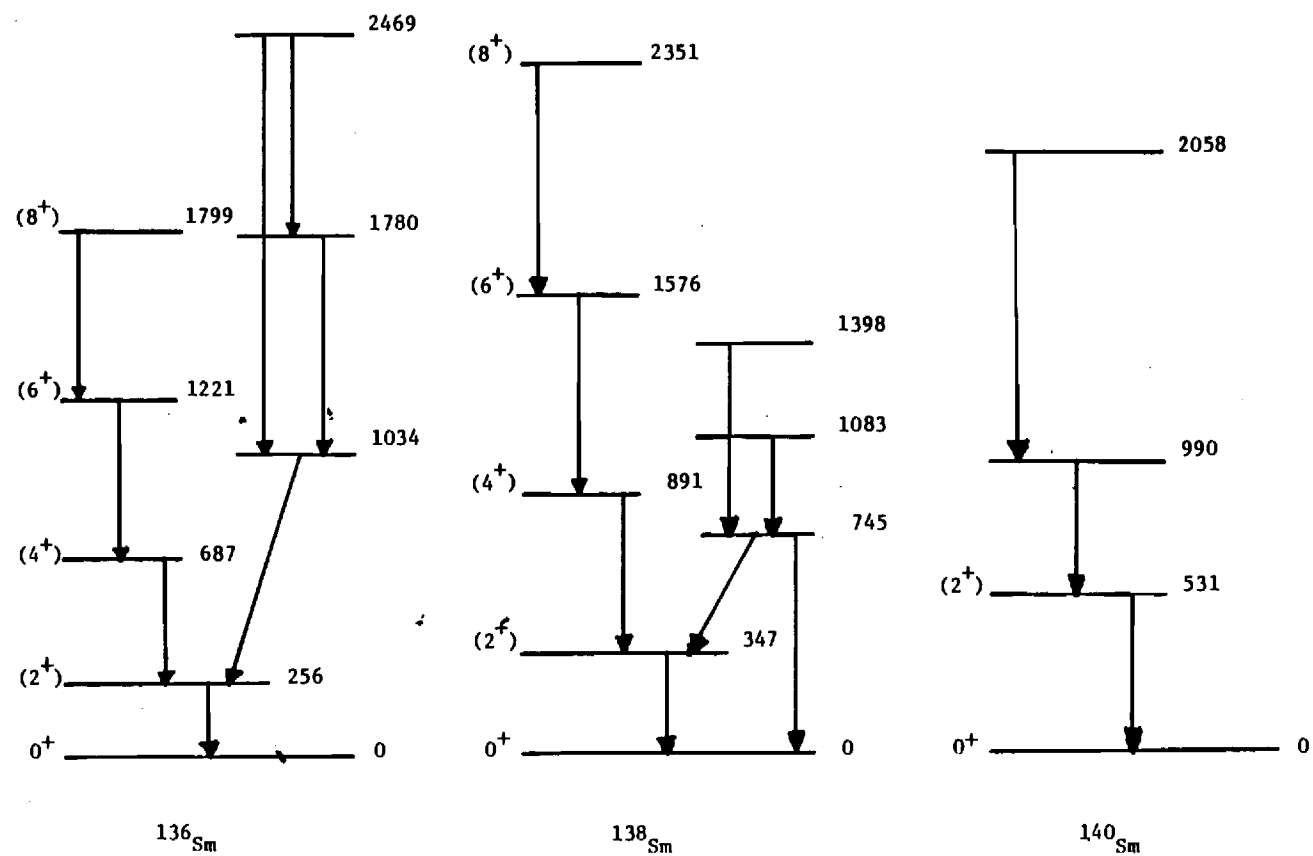
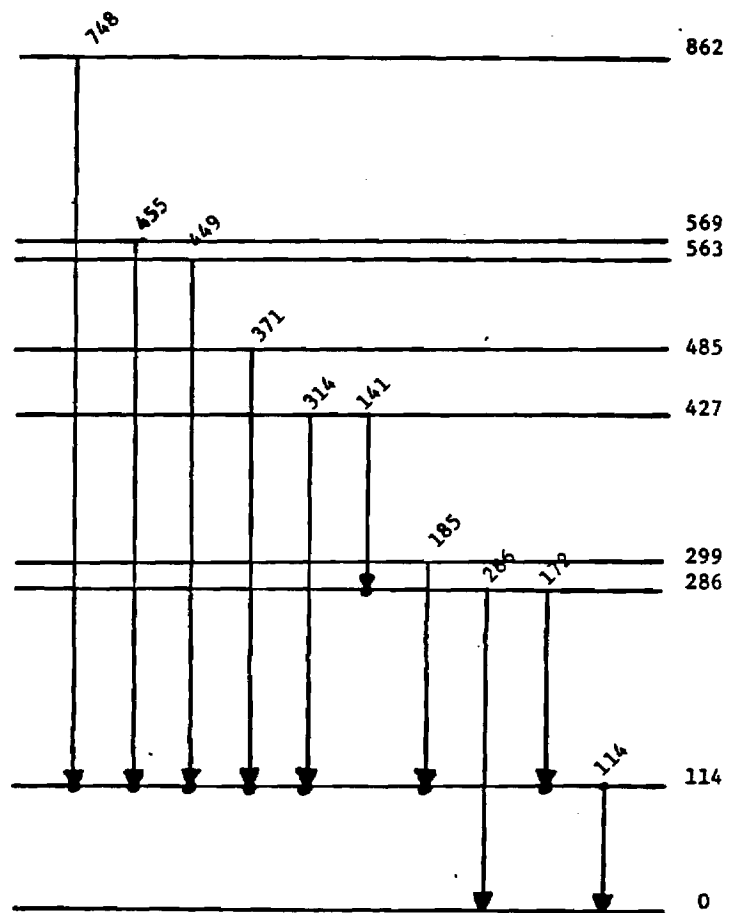


Fig. 2



136_{Pm}

Fig. 3

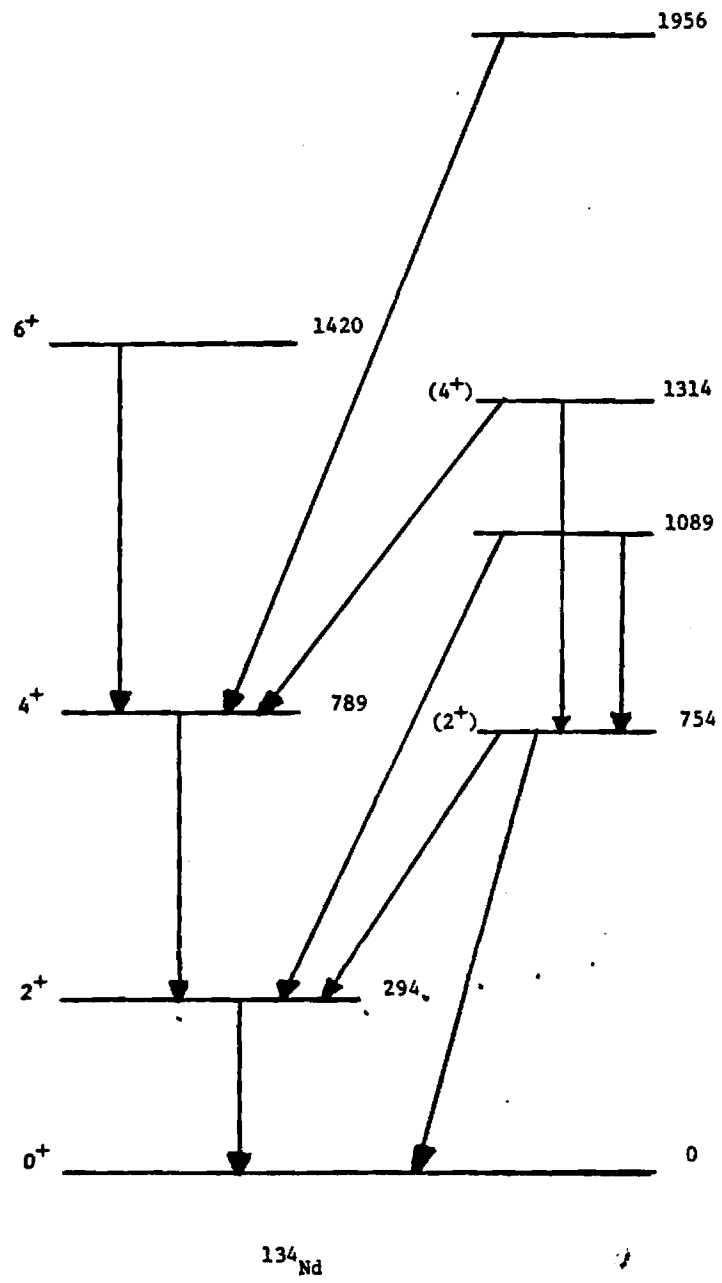


Fig. 4

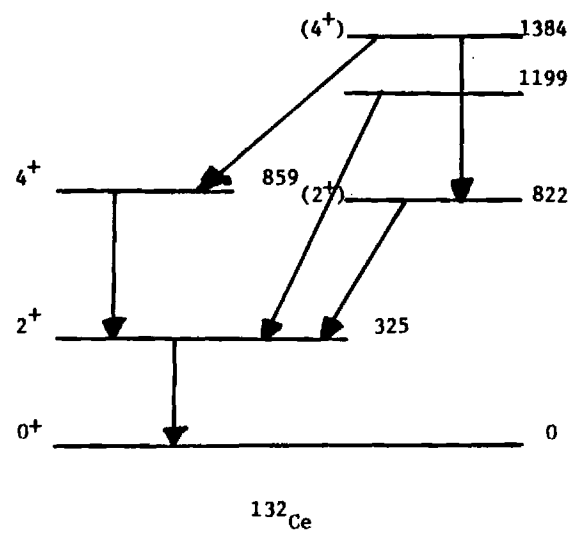
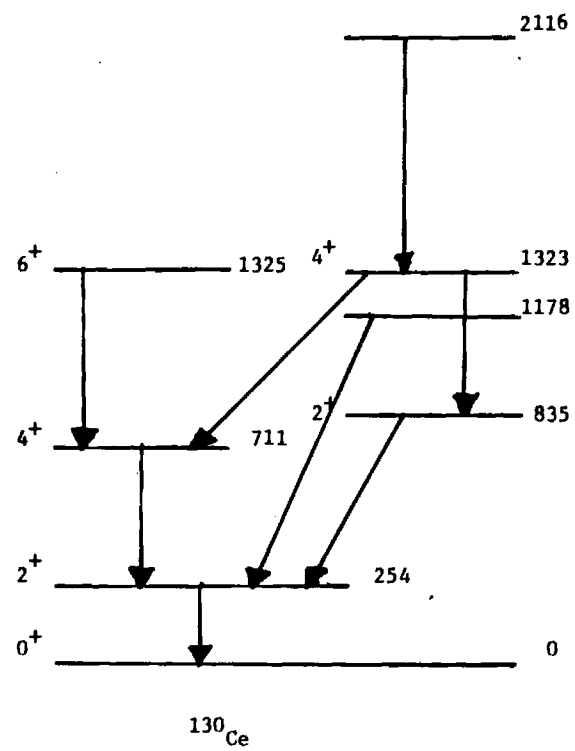


Fig. 5

2.2 Decay of Mass Separated A = 201 Isobars

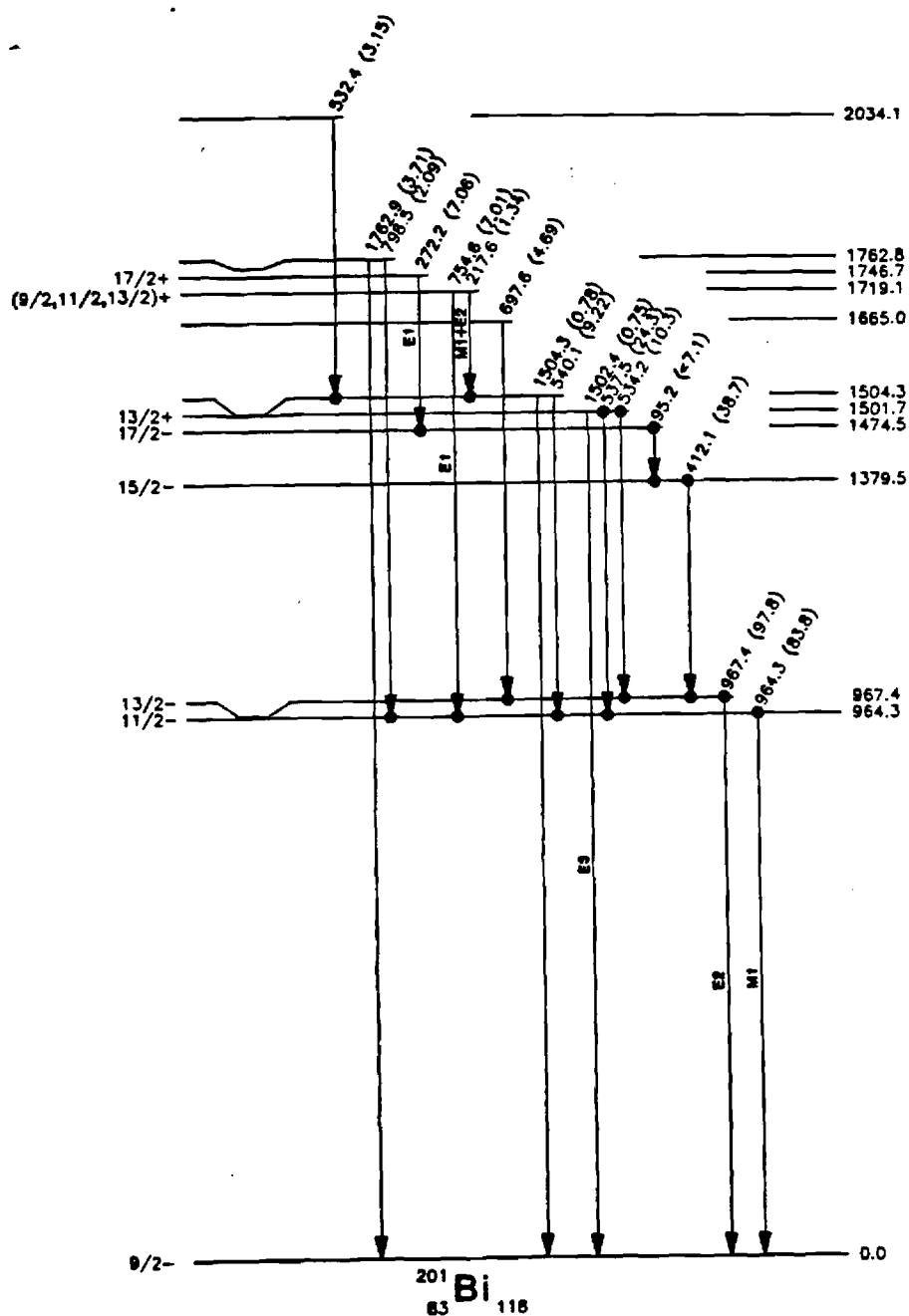
The decay of 9.0 min $^{201m}\text{Po}(13/2^+)$ and 15.3 min $^{201g}\text{Po}(3/2^-)$ isomers has been studied with mass separated sources via the $^{193}\text{Ir}(^{14}\text{N},6n)^{201m,g}\text{Po}$ reaction at 116 MeV, using the UNISOR facility. Time-sequenced spectra of X-rays, γ -rays, and conversion electrons, as well as $\gamma\gamma$ t and $X\gamma$ t coincidence spectra, were obtained. A decay scheme has been constructed (see figures) that incorporates 93% of the decay intensity assigned to levels in ^{201}Bi . Levels resulting from the $h_{9/2}$, $f_{7/2}$, and $i_{13/2}$ particle states have been observed. A full paper has been accepted for publication in Nuclear Phys. A (1986) by R.A. Braga, P.B. Semmes, W. R. Western, and R. W. Fink.

Studies of the β^+/EC decay of 1.5 min ^{201}At to levels in ^{201}Po and of the α -decay to $^{197g}\text{Bi}(9/2^-)$ and the subsequent decay of the latter to levels in ^{197}Pb have reached a point where a rapid communication [Phys.Rev.C] is in preparation. No previous knowledge exists of the level structures in ^{201}Po or ^{197}Pb from the radioactive decay of the $^{201}\text{At}(9/2^-)$ and $^{197g}\text{Bi}(9/2^-)$ parents, respectively.

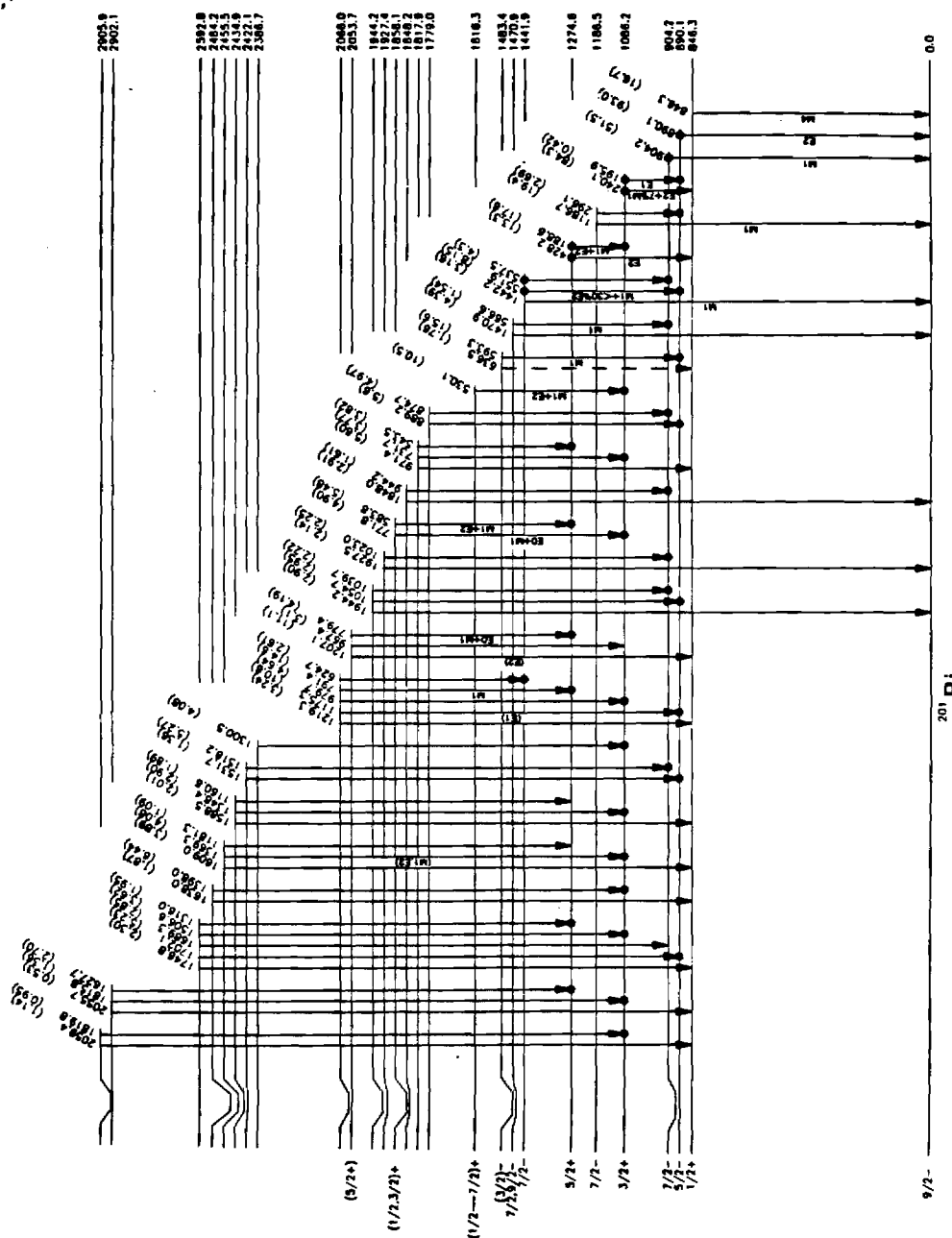
(R.A. Braga, C. P. Perez, & R. W. Fink)

2.3 Decay of Mass Separated 7.4 min ^{203}At

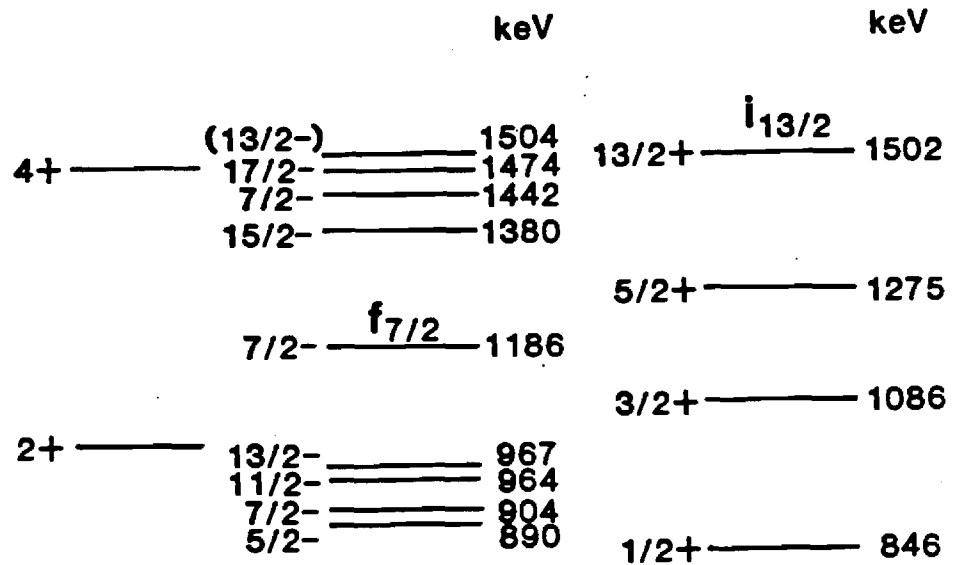
The radioactive decay of 7.4 min ^{203}At to levels in ^{203}Po has been studied via the $^{nat}\text{Ir}(^{16}\text{O},4-6n)^{203}\text{At}$ reactions at 125 MeV, using the UNISOR facility. Time-sequenced spectra of X-rays, γ -rays, and conversion electrons were obtained, together with $\gamma\gamma$ t, $e^-\gamma$ t, and Xe^-t coincidence spectra. A decay scheme has been constructed that incorporates 90% of the decay intensity assigned to ^{203}At . The decay scheme and details were given in last year's annual report, ORO-3346-260 (1985). All excited states below 1 MeV have been assigned unique spin-parity values, and the observed level scheme can be qualitatively understood in terms of a particle-core weak coupling description. The ground-state decay energy has been deduced to be $Q_{\text{EC}} = 5.06 \pm 0.20$ MeV from γ -ray-gated EC/β^+ ratios. A full paper is in preparation for publication by P. B. Semmes, R. A. Braga, R. W. Fink, J.L. Wood, and J.D. Cole for Nuclear Phys. A (1986/87).



Levels in ^{201}Bi observed in the decay of 9.0 min $^{201\text{m}}\text{Po}$ (13/2+) isomer. The total transition intensities are given in parenthesis after the transition energies.



Levels in ^{201}Bi observed in the decay of 15.3min ^{201}Po ($3/2^-$) isomer. The total transition intensities are given in parentheses after the transition energies.



$0^+ \text{ } ^{200}\text{Pb}$
 $9/2^- \text{ } h_{9/2}^{+1}$
 0

$s_{1/2}^{-1}$

Level structure in ^{201}Bi . Low-lying negative-parity states are shown on the left side along with the ^{200}Pb core. On the right side, the positive-parity band built on the $s_{1/2}$ intruder state, along with the $i_{13/2}$ particle state is shown.

2.4 Decay of Mass Separated $^{195,197}\text{Po}$ Isotopes

We have attempted to extend our studies of the level schemes of the odd-mass bismuth isotopes to ^{195}Bi and ^{197}Bi by following the β^+/EC decay of $^{195\text{m},g}\text{Po}$ (20 sec, 4.5 sec) and $^{197\text{m},g}\text{Po}$ (26 sec, 56 sec), produced by bombarding natural Re targets (in the form of Re-Mo alloy) with 160 MeV ^{19}F ions from HHIRF and studied on-line at UNISOR. Gamma-ray and alpha-particle time-sequenced spectroscopy was carried out on both mass chains, and $\gamma\gamma$ coincidence data were obtained following the mass 197 decays.

These investigations are part of an effort to characterize and systematize the shell-model states present in the odd-mass bismuth isotopes which arise from the coupling of $h_{9/2}$, $f_{7/2}$, and $i_{13/2}$ odd proton states to the even-even Pb cores. Recent in-beam studies^{10,11)} have identified the high-spin levels in $^{195,197}\text{Bi}$.

¹⁰T. Lönroth, et al., Phys. Rev. C33, 1641 (1986)

¹¹T. Chapman, et al., Phys. Rev. C33, 130 (1986)

Of the states arising from the coupling of the odd-proton to the cores, only the $i_{13/2}$ states (at 888 and 1196 keV in ^{195}Bi and ^{197}Bi , respectively) and the 11/2- and 13/2- members resulting from the $\pi h_{9/2} \otimes 2+$ coupling (at 1009 and 1001 keV in ^{197}Bi) are observed.

In addition, the occurrence at low energy of the $s_{1/2}$ shell-model intruder state has been identified in the heavier Bi isotopes from the decay studies^{12,13)} and indirectly in $^{187-195}\text{Bi}$ by observing the alpha decay of the odd Bi isotopes¹⁴⁾.

¹²R. A. Braga, et al., Nucl. Phys. A349, 61 (1980)

¹³R. E. Stone, et al., Phys. Rev. C31, 582 (1985)

¹⁴E. Coenen, et al., Phys. Rev. Lett. 54, 1783 (1985)

Analysis of the data revealed that while activities of both ^{197}Po and to a lesser extent, ^{195}Po , were produced, the alpha-decay branches ($\sim 85\%$ for ^{197}Po and $\sim 95\%$ for ^{195}Po) dominate the decays. The result is that, although activities associated with the decay of other members of the $A = 197$ and 195 mass chains are observed, no γ -rays associated with the β^+/EC decays of ^{197}Po or ^{195}Po to levels in bismuth were observed. This inability to populate states in $^{197,195}\text{Bi}$ by decays of $^{197,195}\text{Po}$ isotopes requires that these investigations be set aside.

(C. P. Perez and R. A. Braga)

2.5 Band and Coexisting Collective Structures in ^{189}Au and ^{185}Au

Excited states in ^{189}Au were studied by γ -ray and ce^- spectrometry following EC, β^+ decay of 8.6 min $^{189\text{m}}\text{Hg}(13/2+)$ and 7.6 min $^{189\text{g}}\text{Hg}(3/2-)$. These activities were produced via the enriched $^{180}\text{Hf}(^{16}_0, 7\text{n})^{189\text{m}}\text{Hg}$ and $^{181}\text{Ta}(^{16}_0, 8\text{n})^{189}\text{Tl}(\text{EC}, \beta^+)^{189\text{g}}\text{Hg}$ reactions. The decay of the low-spin $(3/2-)$ ^{189}Hg ground state and the high-spin $(13/2+)$ isomer populated states in ^{189}Au from $J = 1/2$ to $17/2$. The UNISOR on-line isotope separator at HHIRF was used to isolate the $A = 189$ mass chain. Data of high statistical quality were obtained (72 million $\gamma\gamma$ and 25 million $\text{ce}^-\gamma$ coincidence events). Virtually complete band structures for the $s_{1/2}$, $d_{3/2}$, $h_{9/2}$, and $h_{11/2}$ bands were determined below about 1.2 MeV excitation. Spin(6) symmetry from the study of the positive parity bands is implied. This work was part of a collaboration with M. Kortelahti and E. F. Zganjar (LSU), J. L. Wood (Physics, Georgia Tech), H. K. Carter and R. L. Mlekodaj (UNISOR) and a preliminary report was presented [Bull. Am. Phys. Soc. 31, 874 (1986)]. (R. W. Fink & R. A. Braga)

The EC, β^+ decays of 28 sec $^{185\text{m}}\text{Hg}(13/2+)$ and 55 sec $^{185\text{g}}\text{Hg}(1/2-)$ to excited states of ^{185}Au were studied by γ -ray and ce^- singles and coincidence spectrometry. The ^{185}Hg sources were produced at HHIRF with the reaction $^{176}\text{Hf}(^{16}_0, 7\text{n})$ by 140 MeV $^{16}_0$ beams and studied on-line with the UNISOR isotope separator. Transitions with strong E0 components were observed to feed the $h_{9/2}$ and $h_{11/2}$ bands. These are interpreted to result from the coupling of the $h_{9/2}$ and $h_{11/2}$ single-proton configurations to excited 0^+ configurations in the ^{184}Pt and ^{186}Hg cores, respectively. This study was a collaboration with other UNISOR coworkers E. F. Zganjar (LSU), C. Papanicolopoulos and J. L. Wood (Physics, Georgia Tech), A.J. Larabee, M. Carpenter, D. Love, C.R. Bingham, and L. L. Riedinger (Univ. of Tennessee), and J. C. Waddington (McMaster Univ, Canada). A short report was presented [Bull. Am. Phys. Soc. 30, 1275 (1985)], and a somewhat longer report appears in the ORNL Physics Division Report for 1985, and a more extensive paper will appear in the Proc. Am. Chem. Soc. Symposium on Recent Advances in the Study of Nuclei Off the Line of Stability, Chicago, Illinois (Sept., 1985). (R. W. Fink and R. A. Braga)

2.6 Nuclear Laser Spectroscopy

Measurements of the hyperfine structures (hfs) and isotope shifts (IS) of atomic levels for a series of isotopes provide model-independent determinations of nuclear magnetic dipole moments, spectroscopic quadrupole moments, and changes in the root-mean-square nuclear charge radii of the isotopes. Systematic determination of these properties provides a crucial test for applicable nuclear models. The measurement of isotope shifts, in particular, is extremely valuable in defining regions of deformation.

During the past year we were able to use the collinear laser--fast ion(atom) beam technique¹⁾ at the UNISOR laser facility (shown schematically in the figure) to measure the IS for ¹⁹⁶Pb, the first of a series of neutron-deficient Pb isotopes ¹⁹⁶⁻¹⁹⁰Pb to be studied. These studies should be particularly interesting in view of recent nuclear spectroscopy results²⁾ revealing the observation of low-lying deformed states in neutron-deficient even-even Pb nuclei. These states imply shape coexistence at low energy. This was not predicted for the lead isotopes, but has been observed experimentally via laser spectroscopy in the neighboring isotopic chains of thallium³⁾, mercury⁴⁾, and gold⁵⁾.

¹S. L. Kaufman, Opt. Comm. 17, 309 (1976); W. H. Wing, et al., Phys. Rev. Lett. 41, 1488 (1976)

²P. Van Duppen, et al. Phys. Rev. Lett. 52, 1974 (1984); Phys. Lett. 154B, 354 (1985)

³J. A. Bounds, et al. Phys. Rev. Lett. 55, 2269 (1985)

⁴P. Dabkiewicz, et al., Phys. Lett. 82B, 199 (1979); T. Kuhl, et al., Phys. Rev. Lett. 39, 180 (1977)

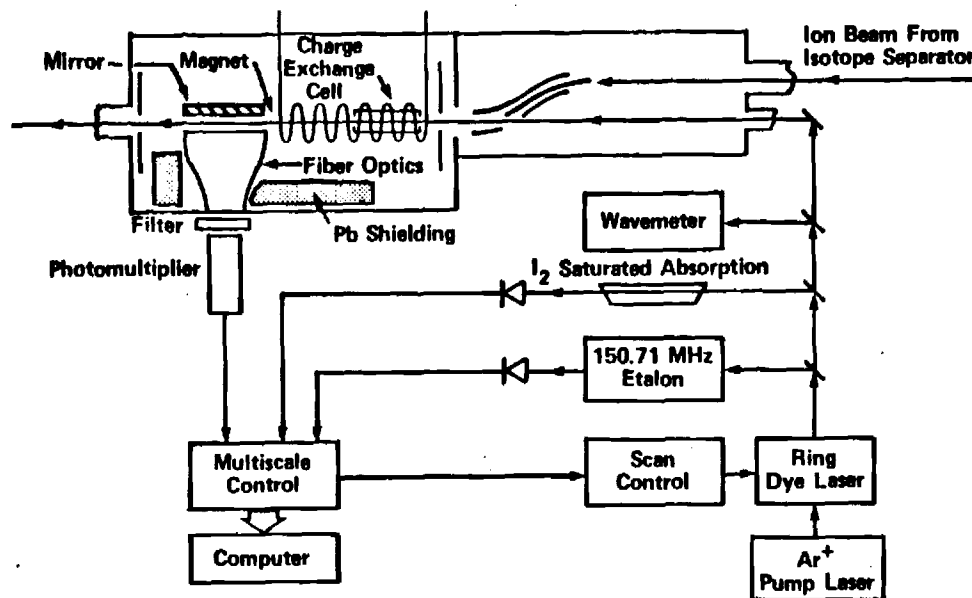
⁵K. Wallnesoth, private comm (1986)

⁶R. Kirchner, et al., Nucl. Instr. Meth. 133, 187 (1976); 139, 295 (1976)

⁷R. Kirchner, et al., Nucl. Instr. Meth. A247, 265 (1986)

One of the first problems faced in preparing for on-line laser experiments of this type is to determine the beam production necessary from the ion source of the isotope separator. Since production rates are highly dependent on the ion source and its parameters (as well as on the target--projectile combination), we have spent a great deal of time developing the recently acquired UNISOR version of the GSI FEBIAD-F ion source⁶⁾. Using a ¹⁶O beam on a natural tungsten stacked foil target, we found that the FEBIAD-F offers the necessary production for laser experiments (8×10^4 atoms/sec) of ¹⁹⁶⁻¹⁹²Pb. We are currently working to improve and extend the range of adequate production to ^{191,190}Pb isotopes.

ORAU 84108.2



One technique that we have tried in order to improve the production of Pb isotopes with the FEBIAD-F is that of "bunched beam release"⁷⁾. As originally developed by Kirchner, et al⁷⁾, this technique (also called "pulsing") involves creating a cool pocket, containing the target and catcher foils, within the ion source. This externally-cooled pocket stores the reaction products until cooling is removed. At this time the products are promptly released for ionization. The advantage of this technique is a very high signal-to-noise ratio due to the very rapid release of a large number of product atoms. Our tests with the UNISOR FEBIAD-F revealed that it is unsuitable for pulsing, primarily due to its small volume. UNISOR has, however, just completed construction of the large-volume FEBIAD-B2, like one used at GSI. We are just beginning the development of the hardware needed to implement pulsing with this ion source.

We have also been working on the development of two frequency reference systems to replace the standard I₂ (iodine) saturated-absorption system used for previous UNISOR laser experiments. The standard I₂ system, with the I₂ cell at room temperature, cannot be used because I₂ exhibits almost no absorption at the 723 nm Pb wavelength. The first of the replacement systems is an I₂ saturated-absorption system modified so that the I₂ cell can be heated to approximately 300°C. At this temperature there is sufficient population of high states in the I₂ gas to allow absorption at the very red wavelength used for Pb. A further improvement was the acquisition of a larger I₂ cell. This gives a longer interaction distance with the laser beam and therefore a stronger absorption signal. This work was carried out in collaboration with Bill Fairbank of Colorado State University.

The second frequency reference standard that we have worked with is an optogalvanic spectroscopy system⁸⁾ with an uranium hollow-cathode lamp.

⁸ R. B. Green, et al., Appl. Phys. Lett. 29, 727 (1976)

⁹ B. A. Palmer, et al., Los Alamos National Lab. Report LA-8251-MS (July, 1980)

This system involves recording the change in voltage across the hollow-cathode discharge caused by the laser frequency scanning through an optical transition frequency of uranium. The voltage changes then appear as peaks at characteristic uranium atomic wavelengths. Many of these peaks have been tabulated by Palmer⁹⁾. This system is very easy to set up and operate, but it has the major disadvantage of offering very few uranium peaks in the region of interest. Our recent on-line experiments have used optogalvanic spectroscopy as the frequency reference, but we are currently favoring the modified I₂ saturated-absorption system for future measurements, because it offers more peaks and narrower peak widths.

In September, 1985, we submitted a request for 16 shifts of tandem accelerator time to the HHIRF (PAC-6). All 16 shifts were approved with the first few coming in April, 1986. After overcoming some early, unexpected difficulties, we were able to determine the isotope shift of ^{196}Pb in early June, 1986. After a HHIRF accelerator shutdown for scheduled maintenance in midsummer, we are proceeding with our experiments on the neutron-deficient isotopes of Pb down to about $A = 192$. These experiments, performed in collaboration with Dr. H. K. Carter of UNISOR, will comprise part of the PhD thesis of Jeffrey C. Griffin.

Jeff Griffin also collaborated on the hfs and IS measurements of neutron-deficient Tl isotopes [Bull. Am. Phys. Soc. 31, 874 (1986)] in which collinear fast atom beams were used to excite the 535 nm transitions between the $6^2\text{P}_{3/2}$ and the $7^2\text{S}_{1/2}$ hyperfine structures of $^{194\text{m}}\text{Tl}$ isomer. From the $\text{S}_{1/2}$ doublet, a hyperfine constant $A_{1/2} = 285$ MHz is obtained from which a magnetic moment of $0.531 \mu_N$ is deduced, which compares with values of 0.495 and 0.518 for $^{190\text{m}}\text{Tl}$ and $^{192\text{m}}\text{Tl}$, respectively, obtained in earlier measurements. The hyperfine constants obtained from the $\text{P}_{3/2}$ quartet were $A_{3/2} = 5.7$ MHz and $B_{3/2} = 700$ MHz. The latter value implies a spectroscopic quadrupole moment of 0.62 eb. The isotope shift measured relative to ^{205}Tl is 9.50 ± 0.05 GHz which is not consistent with the value of 10.37 ± 0.12 GHz reported in the literature¹⁰⁾. The UNISOR results will be compared with the systematic trends of data from ^{189}Tl to ^{207}Tl .

¹⁰⁾ D. Goorvitch, et al., Phys. Rev. 188, 1897 (1969)

2.7 L-Subshell X-ray and Coster-Kronig Yields at Z = 70, 60, and 54

We are completing the analysis of K and L x-ray coincidence measurements of radioactive 1.9 year ^{171}Tm , 17.7 year ^{145}Pm , and 9.9 day ^{131}Cs to Yb, Nd, and Xe at $Z = 70, 60, \text{ and } 54$, respectively. These experiments were carried out at Georgia Tech in 1980 when Dr. M. Tan held a postdoctoral appointment in nuclear chemistry. Detailed corrections for peak tailing and other effects are required using the multiple gate method developed by us earlier^{1,2)}.

¹⁾ B.E. Gnade, R.A. Braga, J.L. Wood, and R.W. Fink, Nucl. Instr.Meth. 164, 163 (1979)

²⁾ B.E. Gnade, R.A. Braga, and R. W. Fink, Phys.Rev. C23, 580 (1983); C21, 2025 (1980)

Values for the L_2 - L_3 Coster-Kronig transition probability f_{23} for $Z = 70$, 60, and 54 are being obtained, together with the L_2 and L_3 subshell x-ray fluorescence yields at $Z = 70$ and 60, and possibly also the L_1 - L_2 and L_1 - L_3 Coster-Kronig transition probabilities and the L_1 subshell x-ray fluorescence yields at $Z = 70$ and 60. This work is a collaborative effort with M. Tan (Erzurum University, Turkey), P. V. Rao (Emory University), R. A. Braga, and R. W. Fink (Georgia Tech). The results are being prepared for publication.

3.0 NUCLEAR STRUCTURE CALCULATIONS WITH NUCLEAR MODELS

3.1 Investigation of Exchange Effects in the Interacting Boson-Fermion Model

A study of Pauli exchange effects for the odd particle in the Interacting Boson-Fermion Model (IBFM) has been completed by a comparison with a Core-Quasiparticle Coupling Model (CQCM) based on dynamical field theory and the BCS method. Spectra for a partly filled j -shell coupled to Interacting Boson Model cores are calculated in both models. Values of the IBFM exchange parameter Λ_0 are found which lead to about the same spectra as in the CQBM. Variations of Λ_0 around this value can alter the energy spectra and the Coriolis mixing between bands much more than variations of the corresponding BCS parameter Δ . However, variations of Λ_0 also effectively alter the position of the Fermi level, which should set constraints on phenomenological applications of the IBFM. An extensive preliminary report of this work was presented in last year's Annual Report, ORO-3346-260 (August, 1985), and the results are now published [Phys. Rev. C33, 1476 (1986)] as a collaboration with G. A. Leander, D. Lewellen, and F. Dönau. This study was based on the PhD thesis of P. B. Semmes in nuclear chemistry (August, 1985).

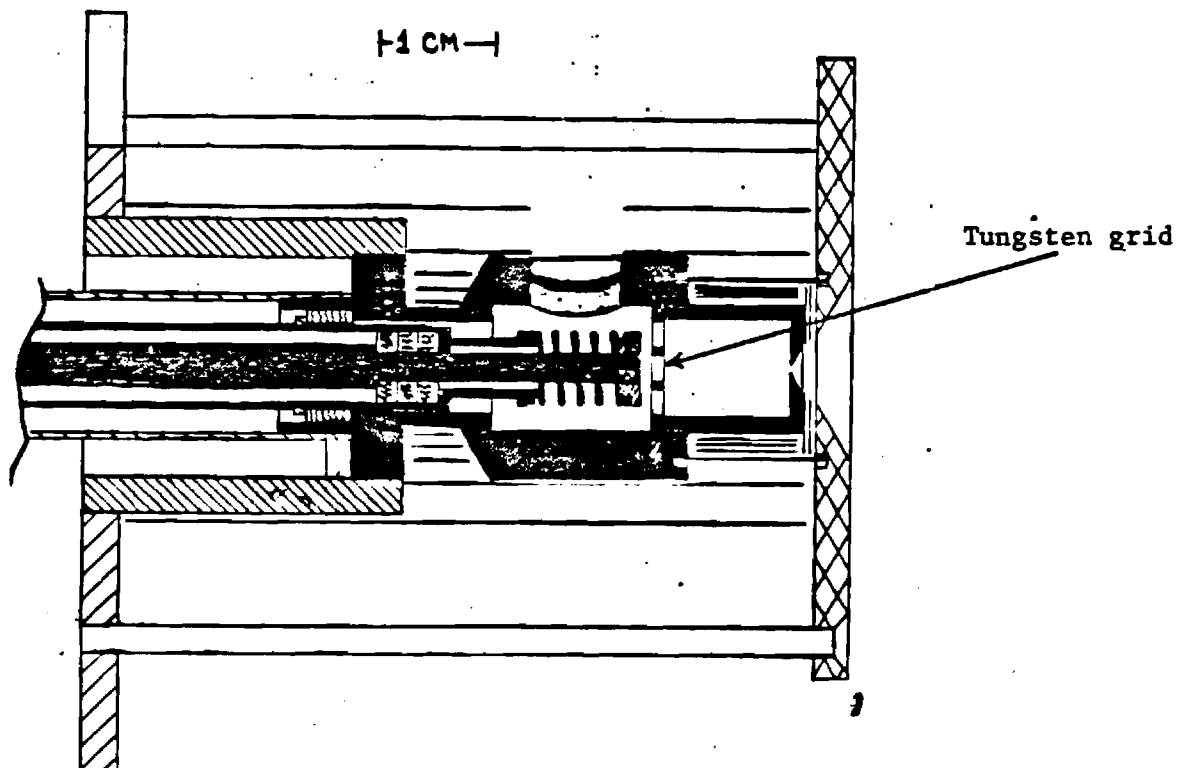
3.2 Testing IBM Cores Through Particle-Core Coupling: Negative Parity States in the Odd-Mass Tl and Au Isotopes

Particle-Core coupling calculations have been completed for the $h_{9/2}$ bands in the odd-Tl isotopes ($A = 191$ to 197) and the $h_{11/2}$ bands in the odd-Au isotopes ($A = 189 - 195$). The even-mass Hg core descriptions were taken from previous proton-neutron Interacting Boson Model (IBM-2) calculations, and thus a comparison between the experimental and calculated level schemes for the Tl and Au isotopes can be interpreted as a test of the core description. A predicted transition from positive $Q(2+)$ near $A = 195$ to negative $Q(2+)$ near $A = 191$ is not borne out by the odd-A data. These, results, combined with new IBM-2 calculations, indicate that the Hg isotopes are more U(5) than O(6) in character. This work is based on the PhD thesis in nuclear chemistry of P. B. Semmes (August, 1985). A more extensive report was given in last year's annual report, ORO-3346-260 (August, 1985) and a full paper, in collaboration with A. F. Barfield, B. R. Barrett, and J. L. Wood, is to appear shortly in Phys. Rev. C (1986).

4.0 TECHNICAL CONTRIBUTIONS TO UNISOR

4.1 Fabrication of FEBIAD ion sources for UNISOR

Parts for two complete FEBIAD ion sources and five tungsten extraction grids have been fabricated at Georgia Tech. Very high temperature materials are required, since the ion source reaches temperatures of 3000°K , so the parts are made of tantalum, molybdenum, boron nitride, and the most vulnerable part, the extraction grid electrode, should be made of pure tungsten. Initially the first FEBIAD ion sources had tantalum grids (m.p. 2996°C) whose small extraction holes melted shut after some hours of operation, but the machine shops at ORNL and in the chemistry and physics departments at Georgia Tech could not machine pure tungsten. However, tungsten grids were finally manufactured at Georgia Tech in the main GTRI machine shop using their special Electrode-Discharge cutting machine, for which special graphite cutting tools had to be custom fabricated. Five such pure tungsten grids were produced (m.p. $3410 \pm 20^{\circ}\text{C}$). These should enable the new FEBIAD ion sources to operate with very long lifetimes. A drawing of the FEBIAD ion source is shown below.



4.2 Computer Operations

We completed the modification of codes used for data analysis on the Georgia Tech CDC Cyber 990 mainframe computer to handle HHIRF magnetic tape format. In addition, we have obtained data analysis codes written at HHIRF for the Perkin-Elmer 3230 mainframe computer and modified by W. T. Milner of the HHIRF staff for use on VAX computer systems. We are implementing these "VAX PACK" codes on the Georgia Tech Chemistry VAX-780 computer.

4.3 Equipment Added, Purchased, and Fabricated

This past year a number of items were fabricated by the Georgia Tech Chemistry Glass Laboratory for use at UNISOR. These included (1) a glass gas-drying trap and a cylindrical quartz sublimation pistol with sample "boats" for use in the preparation of paramagnetic host crystals for the nuclear orientation facility at UNISOR, and (2) a large quartz saturation cell for the UNISOR laser facility.

In addition, a tweeter assembly and associated optics and dyes were purchased for the laser facility, in order to obtain the wavelength capabilities required to do the Pb studies (Sect. 2.6).

5.0 PERSONNEL

Senior Staff

Dr. R. W. Fink, Professor of Chemistry & Principal Investigator
(38% time, including full-time summer)

Dr. R. A. Braga, Research Scientist
(Full-time to August 31, 1986)

Graduate Students

Jeffrey C. Griffin (Chemistry). Continuing PhD thesis research.
(In residence at Oak Ridge/UNISOR/on ORAU Fellowship)

Cesar P. Perez (Chemistry). Continuing PhD thesis research.
(Supported by teaching assistantship, 12 months)

6.0 LIST OF PUBLICATIONS, MEETINGS, AND TALKS PRESENTED

- "Decay of Mass Separated 7.4 min ^{203}At ," P. B. Semmes, R. A. Braga, R. W. Fink, J. L. Wood, and J. D. Cole, Nucl. Phys. A (1986)
[ORO-3346-265]
- "Decay of Mass Separated $^{201\text{m}}\text{Po}$ and $^{201\text{g}}\text{Po}$," R. A. Braga, P. B. Semmes, W. R. Western, and R. W. Fink, Nucl. Phys. A (in press) (1986)
[ORO-3346-256]
- "Am and Cm Chemistry and Technology," (Book Review), R. W. Fink, J. Am. Chem. Soc. (1986)
- "Decay of ^{137}Sm and Deformation in the Light Pm Region," R. A. Braga, R. W. Fink, and other UNISOR coauthors, Bull. Am. Phys. Soc. 30, 1264 (1985)
[Asilomar, California, October, 1985]
- "Coexisting Collective Structure in ^{185}Au from Decay of $^{185\text{m,g}}\text{Hg}$," E. F. Zganjar, J. L. Wood, R. A. Braga, R. W. Fink, and other UNISOR coauthors, Bull. Am. Phys. Soc. 30, 1275 (1985) [Asilomar, Calif., October, 1985]
- "An Investigation of Exchange Effects in the Interacting Boson-Fermion Model," P. B. Semmes, G. A. Leander, O. Lewellen, and F. Dönau, Phys. Rev. C33, 1476 (1986)
- "Testing IBM Cores through Particle-Core Coupling: Negative Parity States in the Odd-Mass Tl and Au Isotopes," P. B. Semmes, A. F. Barfield, B. R. Barrett, and J. L. Wood, Phys. Rev. C (1986)
[ORO-3346-269]
- "Band Structures in ^{189}Au from $^{189\text{m,g}}\text{Hg}$ Decay," M. Kortelahti, E. F. Zganjar, J. L. Wood, R. A. Braga, R. W. Fink, H. K. Carter, and R. L. Mlekodaj, Bull. Am. Phys. Soc. 31, 874 (1986)
[Washington, D. C., April, 1986]
- "Decay of the New Isotope ^{136}Eu ," R. L. Mlekodaj, R. A. Braga, C. P. Perez, and other UNISOR coauthors, Bull. Am. Phys. Soc. 31, 836 (1986)
[Washington, D. C., April, 1986]
- "Decay of ^{138}Eu , ^{136}Eu , and Deformation in the Light Pm Region," R. L. Mlekodaj, R. A. Braga, and other UNISOR coauthors, Proc. Am. Chem. Soc. Symposium on Nuclei far from Stability, (Chicago, 1985)
- "Shape Coexistence in ^{185}Au from Decay of $^{185\text{m,g}}\text{Hg}$," E. F. Zganjar, R. A. Braga, R. W. Fink, and other UNISOR coauthors, Proc. Am. Chem. Soc. Symposium on Nuclei far from Stability, (Chicago, 1985)
- "Hyperfine Structure and Isotope Shift of $^{194\text{m}}\text{Tl}$," J. A. Bounds, J. C. Griffin, and other UNISOR coauthors, Bull. Am. Phys. Soc. 31, 874 (1986)
[Washington, D. C., April, 1986]
- "New Developments at UNISOR and Current Studies of Short-Lived, Neutron-Deficient Rare Earth Nuclides," R. W. Fink and R. A. Braga, Seminar, School of Nuclear Engineering, Georgia Tech, April 17, 1986.
- "Beta Decay of Light Eu and Sm Isotopes with A = 136, 138, and 140," R. L. Mlekodaj, G. A. Leander, B. D. Kern, A. Kortelahti, and R. A. Braga, (manuscript in preparation for publication, 1986)

NUCLEAR CHEMISTRY RESEARCH AND SPECTROSCOPY WITH RADIOACTIVE NUCLEI

**23rd Annual Progress Report
U.S. Department of Energy
Contract DE-AS05-76ERO-3346**

**R. W. Fink
Professor of Chemistry & Principal Investigator**

August 31, 1987

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NUCLEAR CHEMISTRY RESEARCH AND SPECTROSCOPY WITH RADIOACTIVE NUCLEI

Twenty-third Annual Progress Report
U.S. Department of Energy
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1987

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1.0 INTRODUCTION

Research supported in part by this contract has become totally devoted to the study of far-from-stable radioactive nuclei with the UNISOR facility [University Isotope Separator at Oak Ridge] on-line with HHIRF [Holifield Heavy Ion Research Facility]. The purpose of these UNISOR studies is to investigate the low-spin ($< 21/2$), low-energy (< 3 MeV) nuclear structures and stability, most of which are not generally accessible by in-beam spectroscopic methods. The UNISOR facility is one of the few in the world where an isotope separator provides the mass selection needed for detailed nuclear spectroscopy following radioactive decay. The results, when combined with those from available in-beam spectroscopy, enables one to test critically the competing theoretical concepts and calculations from nuclear models.

The UNISOR studies are centered on cases where an odd valence nucleon or valence pair of nucleons act as probes of the characteristics of the core. This leads to observations of abrupt shape changes, shape coexistence, and shell-model intruder states in the region of low nuclear excitation energy. Detailed singles and $\gamma\gamma$ t, $e^-\gamma$ t, $X\gamma$ t, and $\alpha\gamma$ t multiparameter coincidence measurements are carried out, and soon measurements of singles γ -ray angular distributions and magnetic moments of mass-separated, low-temperature oriented nuclei will begin using the helium dilution refrigerator on-line to the isotope separator.

All of these investigations are carried out in collaboration with several other UNISOR member groups, each of which, like ours, would alone be too small to meet the requirements of large-scale experiments for operating manpower and the diversity of expertise needed to deal with the complexity of this research. The advantage of this collaboration is that such expertise is thus available through UNISOR for the benefit of all.

The UNISOR investigations reported below are those carried out in collaboration with other UNISOR coworkers, but for which our group carries the primary responsibility. In particular, what is reported below centers on two neutron-deficient regions of interest, one around the $Z = 82$ closed shell (from $Z = 77$ to 85) and the other in the rare earths around the new region of deformation at $N < 76$ and $Z > 56$.

One of our graduate students (J.C. Griffin) completed his PhD thesis in nuclear chemistry at UNISOR in 1987 and is currently employed at Savannah River Laboratory, Aiken, S.C. Two more students are actively pursuing PhD degrees in nuclear chemistry via UNISOR, and a third is expected to join the program

in the coming year. Dr. R. A. Braga continues to participate in UNISOR research part-time, although he is now mostly employed by the School of Chemistry as Advanced Laboratory Manager; he devotes some 8 - 16% time to this DOE contract.

2.0 NUCLEAR SPECTROSCOPIC STUDIES

2.1 Decay of Mass Separated Rare Earth Nuclides and Nuclear Structure in the Neutron-Deficient Region

2.1.1 Decay of Mass Separated 45 sec ^{137}Sm

Large nuclear deformations are expected in neutron-deficient nuclei with $N < 82$ and $Z > 50$. Leander and Moeller¹⁾ have predicted that this region of deformation is close enough to the line of stability in the neutron-deficient Sm and Pm isotopes that the possibility of producing and studying their structures exists. Macroscopic calculations by Ragnarsson, et al.²⁾ around the neutron-deficient Sm, Gd nuclei have predicted stable prolate shapes except for the $N = 76$ isotones where the γ -degree of freedom is expected to give major effects. Recently, the nucleus ^{138}Sm was found³⁾ to have not only a small prolate-oblate energy difference, but also a triaxial equilibrium shape.

Our current excursion into this region of deformation centers on the study of the decay of 45 sec ^{137}Sm to levels in ^{137}Pm (an $N = 76$ isotone, where the γ -degree of freedom is expected to come into play). The activities of ^{137}Sm were produced by bombarding stacked foils of natural molybdenum targets with ^{48}Ti beams from the 25 MV folded tandem accelerator at HHIRF with on-line mass separation at UNISOR. The experiments consisted of $\gamma\gamma$ and $\text{ce}^-\gamma$ coincidence, as well as γ -ray singles and ce^- singles, spectrometry. The decay scheme for ^{137}Sm is shown in Fig. 1.

¹G. Leander and P. Moeller, Phys. Lett. 110B, 17 (1982)

²I. Ragnarsson, et al. Nucl. Phys. A233, 329 (1974)

³B.D. Kern, R.A. Braga, R. W. Fink, C.P. Perez, and other UNISOR coauthors, Phys. Rev. C (1987) (submitted)

⁴N. Redon, et al. Z. Physik A325, 127 (1986)

This level scheme is in essential agreement with that of Redon, et al.⁴⁾ with the exception of the spin-parity assignments, which in their case were based solely on systematics. Whereas in the heavier odd-mass Pm isotopes, the $11/2^-$ state is observed to be an excited state, in ^{137}Pm , this odd-proton state drops in energy to become the ground state. Recent in-beam spectroscopy⁵⁾

⁵C. W. Beausang, et al., Bull. Am. Phys. Soc. 30, 1264 (1985)

confirms this assignment of $11/2^-$ as the ground state. The $7/2^+$ assignment of Redon, et al.⁴⁾ for the 163.4 keV level is not consistent with our measurement of the conversion coefficient for the 163.4 keV transition. The α_K value of 0.264, along with L/K and L/M conversion electron ratios of 2.0 and 2.9, respectively, result in the establishment of E2 multipolarity for the 163.4 keV transition and therefore a spin assignment of $7/2^-$ for the 163.4 keV level. Our measured conversion coefficients also indicate that the 216.7 and 380.5 keV transitions deexciting the 380.5 keV level are both M1 in nature. This leads to a tentative assignment of $9/2^-$ to the 380.5 keV level. The 408.5 keV transition in ^{137}Pm populating the 380.5 keV level is also M1 in character. However, due to the tentative assignment of $9/2^-$ to the 380.5 keV level, no spin assignment is made for the 789.0 keV level.

The $11/2^-$ assignment for the ground state of ^{137}Pm is of particular interest in relation to the heavier odd-mass Pm isotopes. In the heavier odd-A Pm isotopes, E3 transitions are observed between the $11/2^-$ excited state and the $5/2^+$ ground state. In ^{137}Pm , however, no transition with E3 multipolarity is established. The lack of this observation reinforces our conclusion that, as with other $N = 76$ isotones, a decoupled band structure exists with both the $11/2^-$ and $7/2^-$ members coming low enough in energy to both be below the $5/2^+$ state. The deexcitation would then proceed via a $5/2^+ \rightarrow \text{E1} \rightarrow 7/2^- \rightarrow \text{E2} \rightarrow 11/2^-$ sequence. The level at 344.1 keV is a possible candidate for the $5/2^+$ state, although the conversion coefficient for the 180.4 keV transition deexciting this level is inconclusive. The decoupled band systematics for the $N = 76$ isotones is shown in Fig. 2, relative to the $11/2^-$ state. (R.A. Braga)

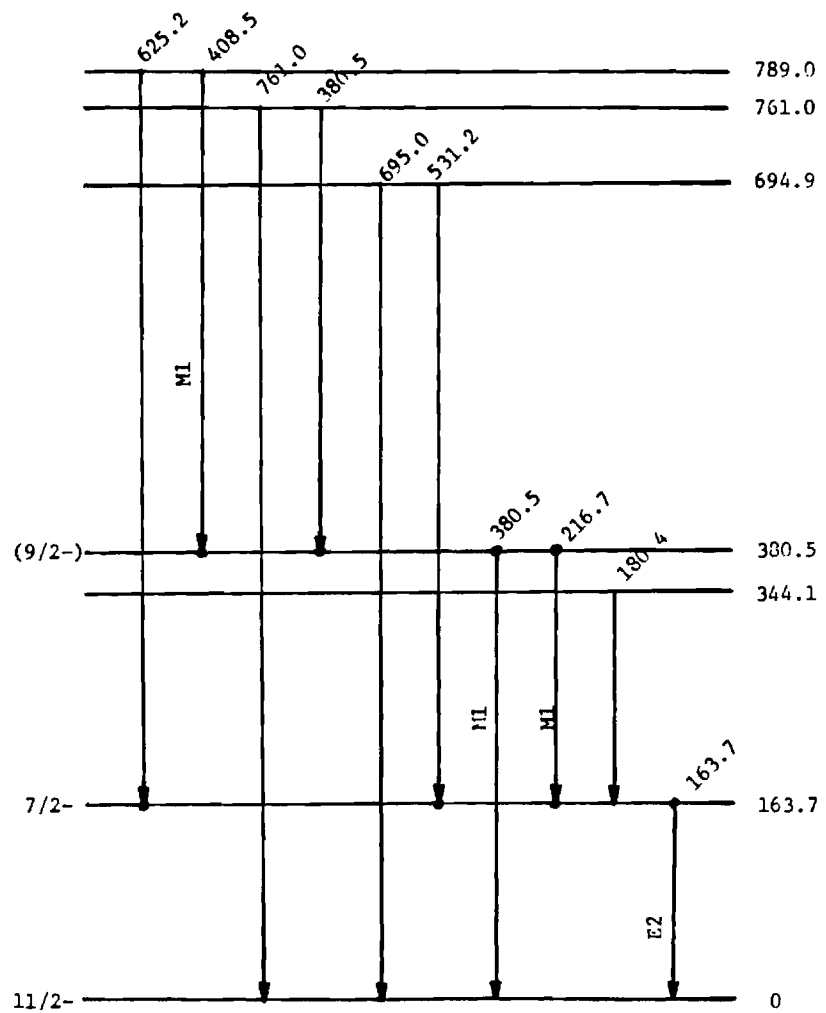
2.1.2 Transition through Triaxial Shapes of the Light Sm Isotopes and the Decay of $^{136,138,140}\text{Eu}$ Isotopes

A transition from spherical to deformed shape in Sm isotopes with $N < 82$ has long been predicted on the basis of elementary shell structure considerations⁶⁾, and was borne out by recent measurements⁷⁾ of yrast level

⁶⁾ R. K. Sheline, Revs. Modern Phys. 32, 1 (1960)

⁷⁾ C. J. Lister, et al., Phys. Rev. Lett. 55, 810 (1985)

energies down to $N = 72$. The detailed nature of this shape transition is of interest in nuclear structure for comparison with the analogous shape transition



^{137}Pm

Fig. 1

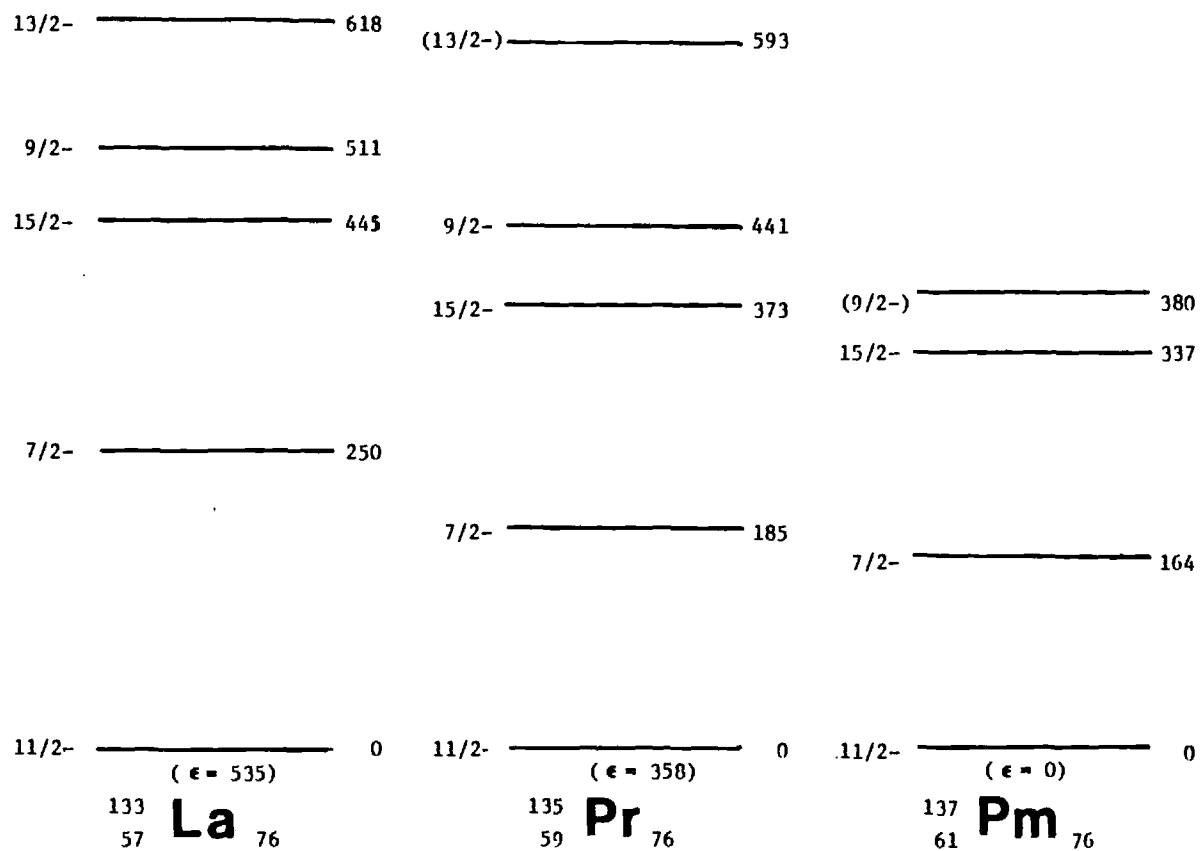


Fig. 2

at $N > 82$. A paper on the transition through triaxial shapes of the light Sm isotopes has been submitted for publication to Phys. Rev. C [Preprint ORO-3346-276].

In this study we make the following contributions to the experimental and theoretical understanding of the $N < 82$ transitional Sm isotopes:

(i) Level schemes for the $N = 74, 76$, and 78 isotopes of Sm are constructed from the γ -rays following β^+ , EC decay of $^{136,138,140}\text{Eu}$ parents. Members of the gamma band were observed in all three daughter nuclei. A half-life of 3.9 ± 0.5 sec was obtained for the decay of ^{136}Eu .

(ii) Spectroscopic calculations were performed using the triaxial rotor model, with all parameters derived microscopically from a Woods-Saxon deformed shell model.

(iii) The experimental gamma bands are also compared with predictions of the interacting boson model obtained from previously existing parameter sets.

(iv) Comparison with the data supports the characterization of the $^{138,138,140}\text{Sm}$ nuclei in terms of a triaxial intrinsic shape. Furthermore, the large change in the 2^+ energy between ^{134}Sm and ^{140}Sm can be understood within the framework of the deformed shell model by taking into account triaxial rotation of the heavier isotopes, which tends to increase the 2^+ energy.

(R. A. Braga, R. W. Fink, C.P. Perez, and other UNISOR coworkers)

2.2 Decay of Neutron-Deficient Rare Earth Nuclei Observed Using the He-jet Transport System

In continuing our investigation of the region of deformation in the $Z > 56, N < 82$ rare earth nuclei, a series of experiments was carried out using the He-jet transport system on-line to HHIRF. While the He-jet system has the advantage of enhancing the yields of rare earth activities, it is at the sacrifice of mass identification. Therefore, the aim of these experiments was to establish coincidence relationships and construct decay schemes as an aid to further studies utilizing mass separation for isotopic identification.

Our interest in this region involves the systematic study of the change from spherical, through transitional, to deformed nuclei as the proton drip line is approached. In addition, the rotational gamma-bands in many of the even-even nuclei have yet to be identified.

The activities were produced by bombarding an enriched ^{92}Mo foil target with 250 MeV $^{46}\text{Ti}^{+12}$ ion beams. Collection/counting intervals of 7 sec, 35 sec, and 175 sec were utilized. The data consisted of $\gamma\gamma$ coincidence and

and time-sequenced γ -ray spectra, with typical counting rates of 12,000 and 40,000 counts/sec, respectively.

A number of activities, in addition to those reported in last year's progress report, have been observed. These are shown in Figs. 1 and 2, with the coincidence relationships listed in Table 1. These level schemes were constructed solely on the basis of coincidence relationships and previously reported transitions. X-ray coincidence data were utilized in establishing Z identification. (C.P. Perez, R. A. Braga, R. W. Fink, and other UNISOR coworkers)

TABLE 1 - Coincidence Relationships Observed in He-Jet Experiments

Gamma-rays observed from the decay of $^{131}\text{Pr} \rightarrow ^{131}\text{Ce}$

E_{γ} (keV)	Coincident γ -rays (keV)
136	147, 430
140	147, 213
147	136, 140, 194, 566
194	147
213	140, 147
430	136, 147
566	147

Gamma-rays observed from the decay of $^{135}\text{Pm} \rightarrow ^{135}\text{Nd}$

199	363, 366, 464, 514, 628, 978, 1016
363	199
464	713
978	199
1016	199

Gamma-rays observed from the decay of $^{129}\text{Nd} \rightarrow ^{129}\text{Pr}$

87	164, 174, 363
164	87
174	87
363	87

Gamma-rays observed from the decay of $^{133}\text{Nd} \rightarrow ^{133}\text{Pr}$

61	164, 197, 250, 414, 476
164	64, 197, 250, 476, 637

Gamma-rays observed in the decay of $^{133}\text{Nd} \rightarrow ^{133}\text{Pr}$, continued...

E_γ (keV)	Coincident γ -rays (keV)
197	61, 164
250	61, 164
414	61, 164, 625
625	61, 164, 476
637	61, 164

Gamma-rays observed from the decay of $^{137}\text{Nd} \rightarrow ^{137}\text{Pr}$

98	308, 342, 464
129	177, 250, 270, 342, 409, 464
177	129, 342, 464
190	208, 250
208	98, 190, 342, 440, 464, 471
250	129, 190, 208, 270, 464
270	129, 250, 464
306	342, 464
342	98, 129, 177, 208, 306, 464
409	129
440	208, 464
464	98, 129, 177, 208, 306, 464
471	208

Gamma-rays observed from the decay of Unidentified Europium activity

255	Eu K_α , 777
777	Eu K_α , 255

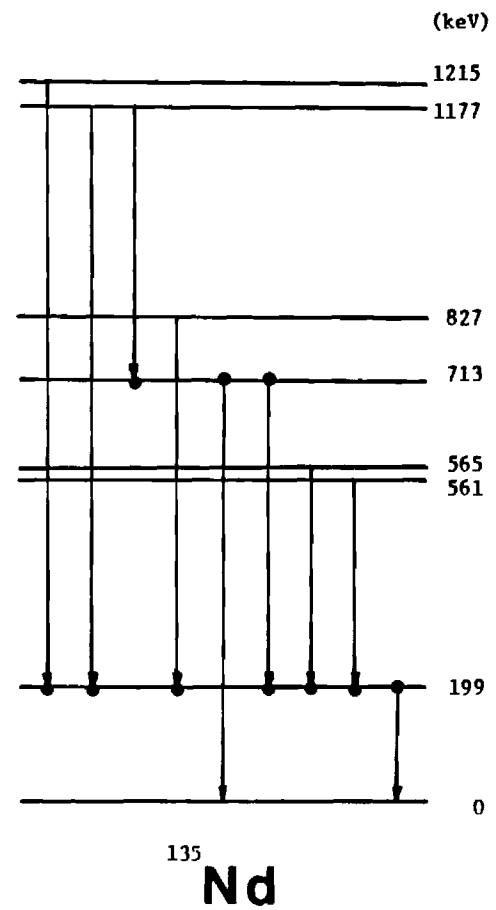
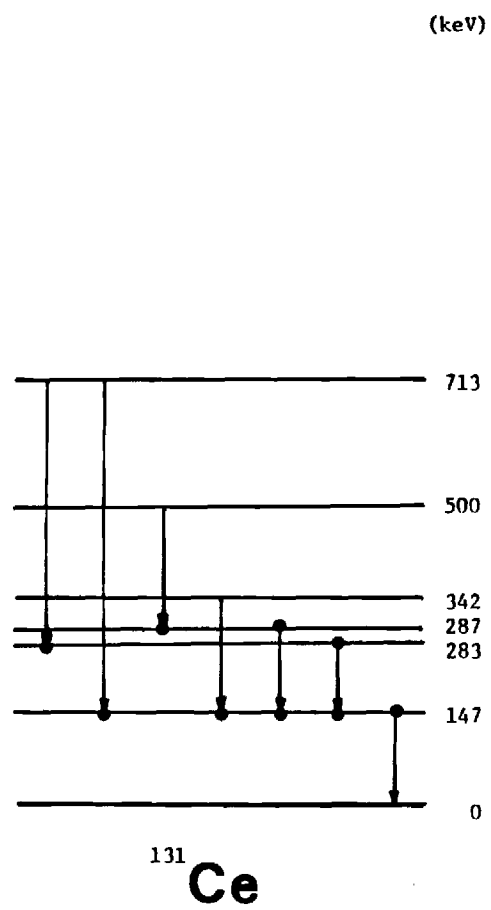


Fig. 1

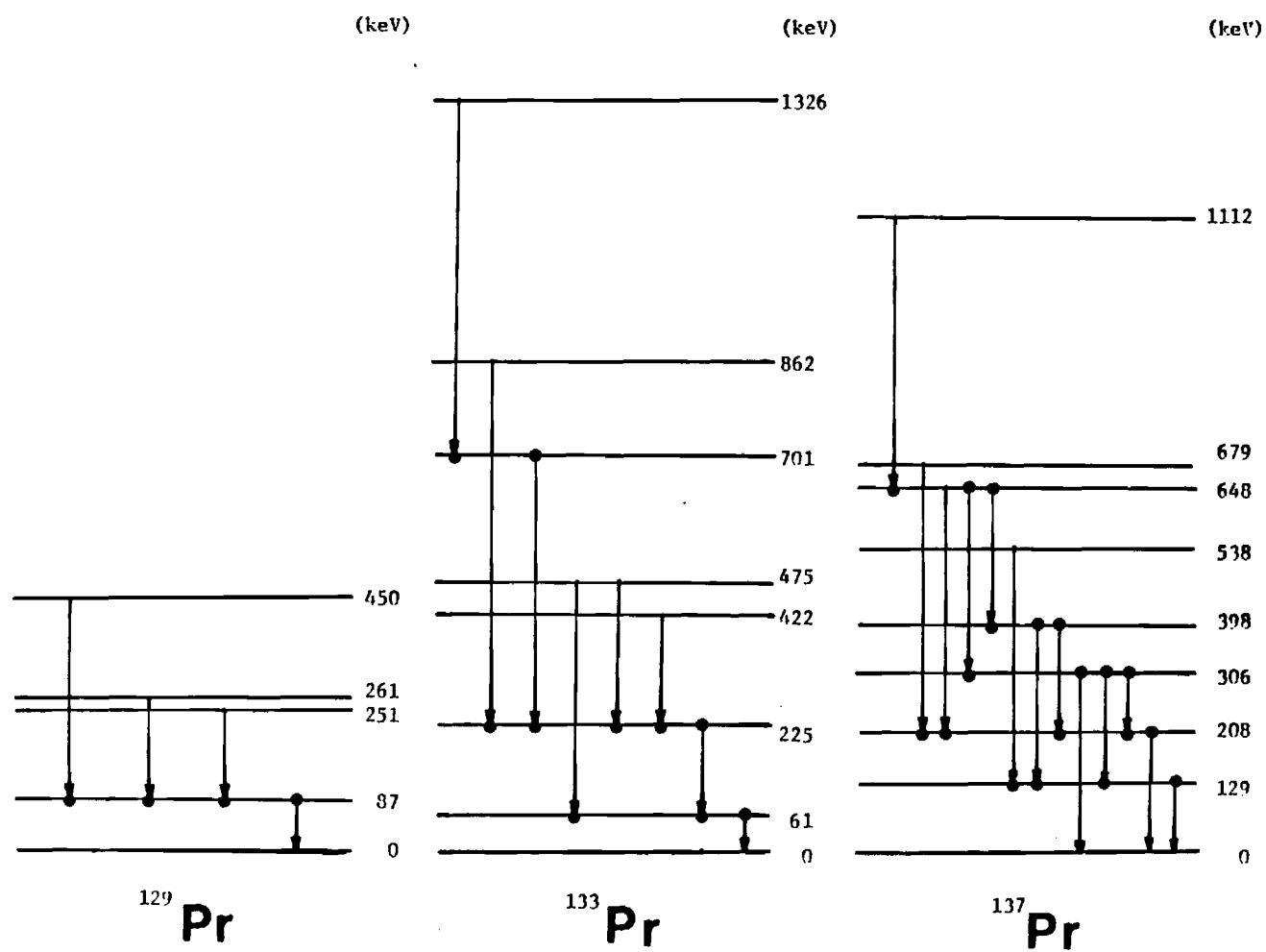


Fig. 2

2.3 Decay of Mass Separated 180 sec ^{195}Bi to levels in ^{195}Pb

Recently, additional low-lying states have been found in neutron-deficient even-even Pb isotopes other than the virtually pure single-particle states¹⁾. These new states, found in $^{190-198}\text{Pb}$, are excited 0+ levels that

¹P. Van Duppen, et al., Phys.Rev.Lett. 52, 1974 (1984); Phys. Lett. 154B, 354 (1985)

descend in energy with decreasing neutron number, becoming the first excited state in ^{194}Pb . In ^{196}Pb , the associated 2+ and 4+ states have also been found^{1,2)} in a

²J. Penninga, et al. in Nuclei Off the Line of Stability, Am. Chem. Soc. Symp. Series 324 (1986)

³K. Heyde, et al. Phys. Repts. 102, 291 (1983); Nucl. Phys. A466, 189 (1987)

⁴A. Baklin et al., Nucl. Phys. A351, 490 (1981)

⁵N. G. Jonson, et al., Nucl. Phys. A371, 333 (1981)

pattern that appears more rotational than vibrational. These states and their associated band structure have been interpreted as deformed bands¹⁾ resulting from proton-pair excitations across the $Z = 82$ closed shell. These deformed bands are called shell-model intruder states³⁾, and their presence in the even-even Pb nuclei implies shape coexistence similar to that observed in the singly-closed shell even-even Sn nuclei ($Z = 50$)^{4,5)}.

The discovery of these low-lying intruder states in the even-even Pb isotopes introduces the possibility of a new degree of freedom in the description of the low-energy structure of the neighboring odd-A Pb isotopes. Though the presence of low-energy intruder states in the neutron-deficient odd-A Pb nuclei has not been observed previously, the close relationship in structure that exists between adjacent even- and odd-mass nuclei certainly indicates that such states should exist.

A possible signature of this shape coexistence is the presence of transitions with an electric monopole (E0) component. Transitions between nuclear levels of the same spin-parity can always contain an E0 component; for levels with spin-parity other than 0+, the E0 component must compete with higher multipoles. Between 0+ states, only a pure E0 transition is possible which proceeds almost entirely by internal conversion (for low energy transitions). Because E0 transitions occur via Coulomb coupling between the protons and the atomic electrons, these transitions are especially sensitive to the details of the nuclear wavefunction. The E0 matrix element is determined entirely by the wave functions of the 0+ states, so

that studies of E0 transitions provide information on the nature of these states. The ground-state E0 transitions from low-lying 0^+ states were used to establish the presence of shape coexistence in the even-A $^{190-198}\text{Pb}$ isotopes¹⁾. In the neighboring odd-A Pb nuclei, one expects transitions with an E0 component between single-particle states coupled to two differently shaped cores (spherical and deformed). The presence of such transitions in the neutron-deficient, odd-A Pb nuclei would constitute strong evidence for shape coexistence.

The lightest odd-A Pb isotope for which detailed experimental data are available on the single-particle states is ^{197}Pb ⁶⁾. The reported experimental data on ^{195}Pb are primarily limited to high-spin results from in-beam reaction studies^{7,8,9)}. The information on low-energy states in ^{195}Pb is restricted to the placement of the $13/2^+$ level at approximately 200 keV, based on alpha-decay studies of $^{199\text{m},g}\text{Po}$ ¹⁰⁾. The assignment of $3/2^-$ as the ground-state spin-parity is based on analogy with ^{197}Pb .

⁶⁾J. L. Wood, private communication (1986)

⁷⁾H. Helppi, et al., Phys. Lett. 67B, 279 (1977)

⁸⁾H. Richel, et al., Z. Physik A284, 425 (1978)

⁹⁾M. Pautrat, et al., Phys. Ser. 34, 378 (1986); J. Phys. (London) G12, 1285 (1986)

¹⁰⁾R.E. Stone, et al., Phys. Rev. C31, 582 (1985)

The present study of the decay of 180 sec ^{195g}Bi to excited states in ^{195}Pb was therefore undertaken to (1) map out the systematics of the single-particle states and (2) search for evidence of shape coexistence in ^{195}Pb . This would be the first observation of shape coexistence in a singly-closed shell odd-A nucleus. Radioactive decay is the only way to study low-spin, low-energy states in nuclei far from stability. This work constituted part of the PhD thesis of Jeffrey C. Griffin [Nuclear Chemistry, June, 1987] and a manuscript for publication is being prepared. What follows below is a summary of the results.

The 180 sec ^{195g}Bi sources were produced via the $\text{natRe}(^{16}\text{O}, \text{xn})^{195g}\text{Bi}$ reaction using 140 MeV ^{16}O ions from the HHIRF tandem accelerator, the energy being chosen to optimize the cross section which was estimated from calculation with the ALICE code¹¹⁾. The ^{16}O beam intensity was 150 - 300 particle-namps. The natural Re target consisted of a stack of thin, self-supporting Re-Mo alloy foils, with total thickness 19.2 mg/cm^2 , mounted inside the UNISOR version of the FEBIAD-F ion source, in which the target also serves as catcher. The reaction

¹¹⁾M. Blann, Rept. COO-3494-29 (1975) (unpublished)

products diffuse out of the target foils into the ion source where they are ionized and extracted into the UNISOR isotope separator. The separated isotope is directed down the beam line onto an aluminized Mylar tape, which constitutes part of the tape transport system¹²⁾. The tape transports the radioactivity to various detector stations for analysis. All data in the present experiment were acquired with a collection/counting time of 350 sec (approx. 2.3 halflives).

¹²⁾R. L. Mlekodaj, et al. Nucl. Instr. Meth. 186, 299 (1981)

Time-sequenced singles γ -ray, ce^- spectra and $\gamma\gamma$ t, $X\gamma$ t, and $ce^-\gamma$ t coincidence data were acquired at two counting stations.

Our decay scheme for the decay of 180 sec ^{195g}Bi to levels in ^{195}Pb is shown in Figs. 1 and 2, and the results of data analysis on γ -ray energies, intensities, in Table 1; on internal conversion coefficients, in Table 2; on $\gamma\gamma$ coincidences, in Table 3; and on γce^- coincidences, in Table 4. The decay scheme is based primarily on the coincidence data and energy sums and differences, along with intensity balances. Strong γ -rays having no coincident transitions are assumed to go to the ground state or to the low-lying isomeric level (13/2+) in ^{195}Pb . In all, 26 excited states have been located and 34 transitions have been assigned. There is no prior work on the low-energy, low-spin levels in ^{195}Pb .

The ground-state spin-parity (3/2-) was assigned from systematics⁶⁾ of the heavier odd-A Pb isotopes and from a study of the alpha-decay of $^{199m,g}\text{Po}$. We have assigned the 134.6 keV transition, the most intense low-energy γ -ray, as the 5/2- \rightarrow 3/2- ground-state transition. The 5/2- spin-parity assignment for the 134.6 keV level is again based on systematics and agrees with the assigned M1+E2 multipolarity of the 134.6 keV transition. Spin-parity assignments for the excited states of ^{195}Pb are based on assigned multipolarities of the transitions populating and depopulating each level deduced from measured conversion coefficients. For many levels, only the parity and a range of possible spin assignments could be determined and are reported only for those levels where the spin choices can be narrowed to three or fewer.

The second group of transitions observed are those we assign to the positive-parity ($i_{13/2}$) states (Fig. 2). This group actually is four parallel sets of γ -rays with no coincidences found between the different sets. The most intense γ -ray of each set (776.4, 808.0, 890.0, and 894.3 keV) is assigned as the one feeding the 13/2+ isomeric level, which is tentatively placed at 203.9 keV above the ground state. An M4 transition has been observed in other neutron-deficient Pb isotopes between the 13/2+ and 5/2- states ($^{197,199}\text{Pb}$), but no evidence was

found for its presence in ^{195}Pb . We observe another transition, however, which appears to connect the positive- and negative-parity bands. This transition, a 499.4 keV γ -ray placed by coincidence as feeding the 830.3 keV negative-parity level (Fig.1) is assigned E1 multipolarity based on its conversion coefficient.

A particularly interesting aspect of the positive-parity states (Fig. 2) is the presence of two highly-converted transitions at 317.7 and 401.3 keV, the measured conversion coefficients for which indicate that they are highly converted because of either a high multipolarity (E3 or M4) or admixture of $E0+M1+E2$ multipolarities. The 317.7 keV transition has a K-shell conversion coefficient greater than expected for M3 transitions, while that of the 401.3 keV transition is greater than expected for M4 transitions. Since there is no evidence for the presence of high multipolarity transitions at these excitation energies in neutron-deficient odd-A Pb isotopes, we assign the $E0+M1+E2$ multipolarity to both of these transitions.

These transitions at 317.7 and 401.3 keV are assigned, respectively, as transitions between $9/2+(11/2+)$ and $11/2+(9/2+)$ levels (see Fig. 2). The appearance of these transitions with an E0 component is a strong indicator for shape coexistence, suggesting that these are transitions from states arising from the coupling of the $i_{13/2}$ orbital to the deformed-band core states. The presence of transitions with an E0 component among the negative-parity states, indicative of a strongly-deformed negative-parity band, is expected but not observed in the present work.

The higher-energy negative-parity states (Fig. 1) in odd-mass Pb nuclei can also be described in terms of the odd neutron in available orbitals ($p_{3/2}$, $f_{5/2}$, $p_{1/2}$) coupling to the various excited core states. In analogy with the positive-parity states, the coupling of the various negative-parity orbitals to the core 2_1^+ and to the deformed-band core states will result in a large number of negative-parity states at about 1000 - 1300 keV above the ground-state in ^{195}Pb . Again, those states with nearly the same spin as $^{195}\text{g}_{\text{Bi}}$ ($9/2^-$) are expected to be populated most strongly in β^+/EC decay. We do observe a number of levels in this energy region, but we are unable to make unique spin assignments for them. We do not observe any highly converted transitions among the negative-parity states.

In our decay scheme (Figs. 1 and 2) we have located states at 134.6 keV, 329.4 keV, and the ground-state which are candidates for those corresponding to coupling of the odd neutron in the available single-particle orbitals ($f_{5/2}$, $p_{1/2}$, and $p_{3/2}$, respectively) to the even-A core 0^+ ground-state. We have

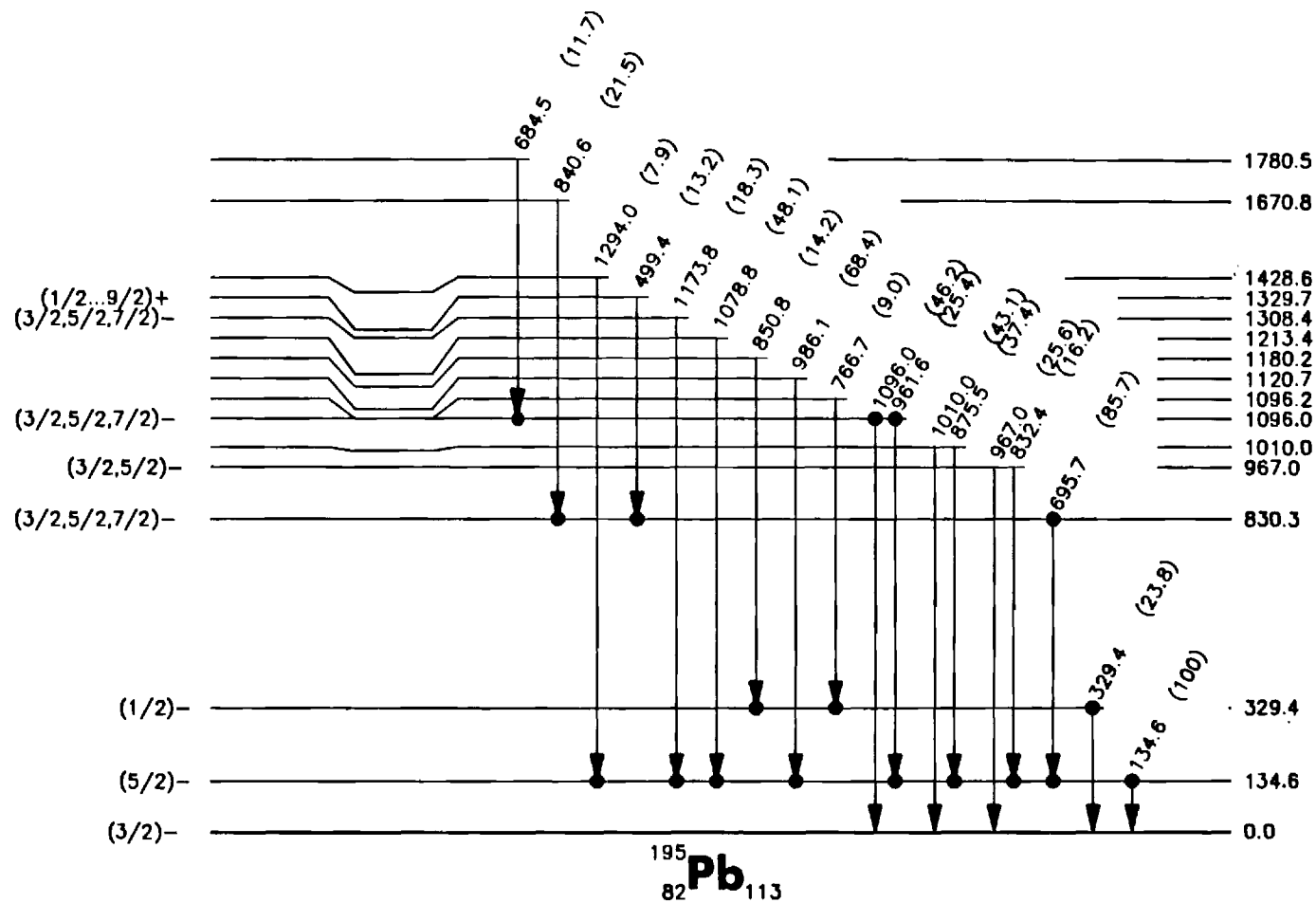
also placed at 203.9 keV above the ground-state the $13/2^+$ isomeric state produced by coupling the odd neutron in the $i_{13/2}$ orbital to the core ground-state. However, the energy of this $13/2^+$ state is very tentative, since it has not been observed to decay to any lower states in ^{195}Pb .

Finally, we determined the Q_{EC} value for the decay of $^{195\text{g}}\text{Bi}$ to $^{195\text{g}}\text{Pb}$. This value was previously estimated to be 5800 ± 450 keV from systematics¹³⁾.

¹³A. H. Wapstra, et al., Nucl. Phys. A432, 1 (1985)

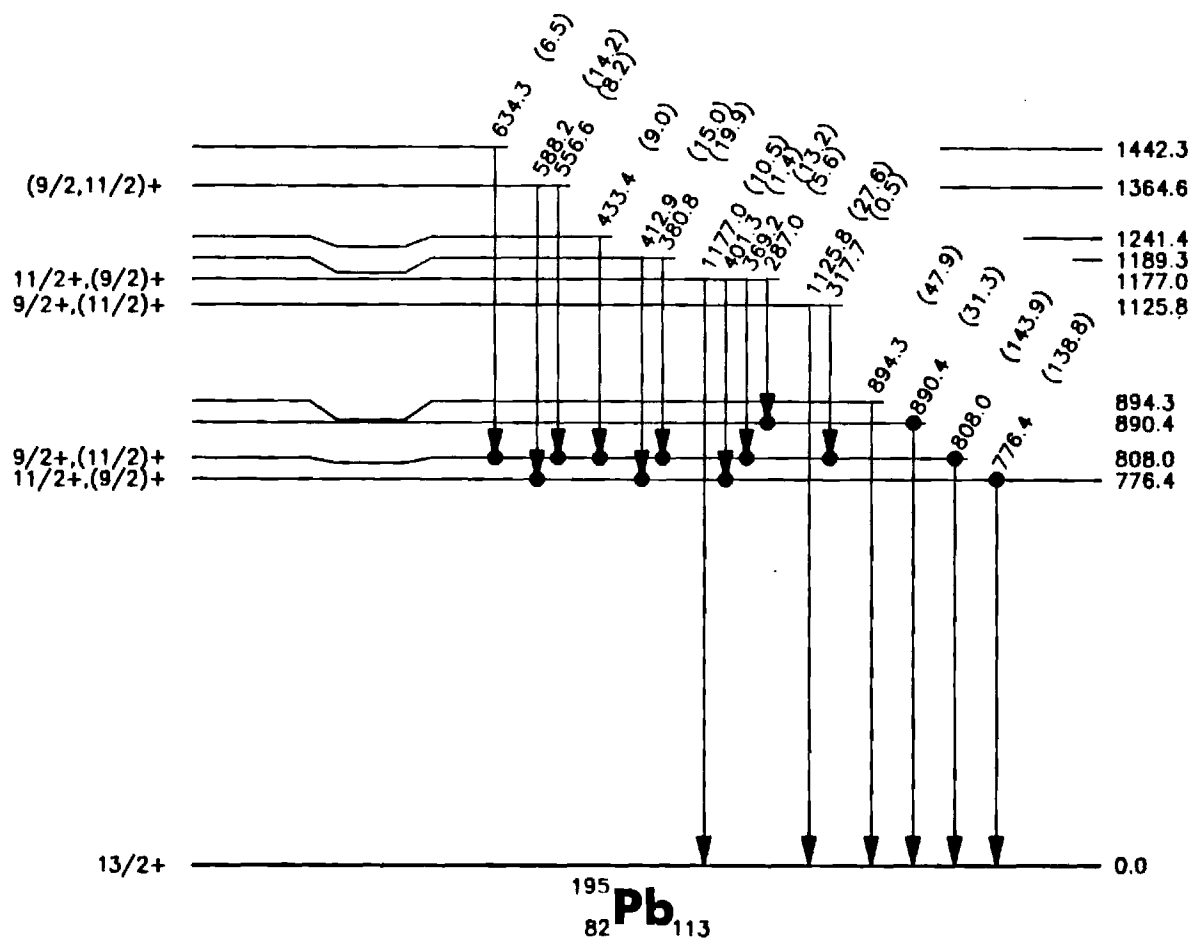
Because the K/β^+ ratio is very sensitive to the value of Q_{EC} , we measured this ratio for the feeding of the 1010.0 keV negative-parity level in ^{195}Pb to be $K/\beta^+ = 2.47_{-1.00}^{+2.98}$, corresponding to a β^+ endpoint of 2950_{-550}^{+650} keV¹⁴⁾ for the feeding of the 1010.0 keV level. This gives $Q_{\text{EC}} = 4980_{-550}^{+650}$ keV for the decay energy of $^{195\text{g}}\text{Bi} \rightarrow ^{195\text{g}}\text{Pb}$, in fair agreement with the systematic value¹³⁾. As a check of this measurement, we made a similar determination using the 1125.7 keV γ -ray that populates the $13/2^+$ isomeric level in $^{195\text{m}}\text{Pb}$. This measurement gives $K/\beta^+ = 6.10_{-4.0}^{+11.4}$ corresponding to a β^+ endpoint of 2200_{-650}^{+800} keV, which yields a value of $Q_{\text{EC}} = 4350_{-650}^{+800}$ keV for the decay of $^{195\text{g}}\text{Bi}$ to $^{195\text{m}}\text{Pb}(13/2^+)$. If the tentative placement of the $13/2^+$ level at 203.9 keV is added to this, the result is $Q_{\text{EC}} = 4550_{-650}^{+800}$ keV to the ^{195}Pb ground-state. Within the rather large error limits, this is in agreement the other determination.

It should be noted that the 180 sec $^{195\text{g}}\text{Bi}$ parent nucleus is an excellent candidate for the nuclear orientation experiments, owing to its large hyperfine field in an iron host and its expected large magnetic moment ($\mu = 4.6$ nm for ^{207}Bi , for example). This experiment is proposed in the accompanying Renewal Proposal. The information obtained in the present work is essential for any nuclear orientation study of excited states in ^{195}Pb . (J. C. Griffin)



Negative-parity states from decay of $180\text{ sec } ^{195}\text{Bi}$. The 499.4 keV transition (E1 assignment) connects to the positive-parity band.

Fig. 1



Positive-parity states from decay of 180 sec ^{195}Bi . The $13/2+$ level is very tentatively assigned at 203.9 keV above the $3/2-$ ground-state. Here all the level energies shown are relative to the $13/2+$ state shown as 0.0 keV. The two $E0+M1+E2$ transitions at 317.7 and 401.3 keV indicate shape coexistence from coupling of the $13/2+$ orbital to the deformed-band core states.

Fig. 2

Table 1. Energies and Relative Intensities of Gamma Rays in the Decay of $^{195}\text{Bi} \rightarrow ^{195}\text{Pb}$

E_γ (keV)	ΔE_γ	I_γ	ΔI_γ	I_{Tot}	E_i	E_f
134.6	0.2	100	7.1	≈ 310	134.6	0.0
287.0	0.2	5.6	0.5	8.3	1177.0*	890.4*
317.7	0.5	0.5	0.3	≈ 3	1125.8*	808.0*
329.4	0.2	23.8	1.7	31.4	329.4	0.0
369.2	0.2	13.2	1.0	15.3	1177.0*	808.0*
380.8	0.6	19.9	6.1		1189.3*	808.0*
401.3	0.4	1.4	0.4	≈ 9.0	1177.0*	776.4*
412.9	0.2	15.0	1.1	15.6	1189.3*	776.4*
433.4	0.2	9.0	0.7	9.3	1241.4*	808.0*
499.4	0.2	13.2	1.0	13.3	1329.7	830.3
533		<1			not placed	
556.6	0.3	8.2	0.8	8.5	1364.6*	808.0*
588.2	0.2	14.2	1.2	14.7	1364.6*	776.4*
634.3	0.2	6.5	0.6		1442.3*	808.0*
684.5	0.25	11.7	1.1	11.9	1780.5	1096.0
695.7	0.2	85.7	6.1	88.6	830.3	134.6
766.7	0.25	9.0	0.7		1096.1	329.4
776.4	0.2	138.8	10.0	139.9	776.4*	ϵ
808.0	0.2	143.9	10.4	145.2	808.0*	ϵ
832.4	0.3	16.1	1.4	16.3	967.0	134.6
840.6	0.2	21.5	6.8		1670.9	830.3
850.8	0.2	14.2	1.2		1180.2	329.4
875.7	0.2	37.4	2.8	37.6	1010.0	134.6
890.4	0.4	31.3	8.1		890.4*	ϵ
894.3	0.2	47.9	3.6	48.1	894.3*	ϵ
961.6	0.2	25.4	1.9	25.6	1096.0	134.6
967.0	0.2	25.6	1.9	25.8	967.0	0.0
986.1	0.2	68.4	4.9	68.7	1120.7	134.6
1010.0	0.2	43.1	3.1	43.3	1010.0	0.0
1078.8	0.2	48.1	3.5	48.3	1213.4	134.6
1096.0	0.2	46.2	3.3	46.4	1096.0	0.0
1125.8	0.2	27.6	2.0	27.7	1125.8*	ϵ
1173.8	0.2	18.3	1.4	18.4	1308.4	134.6
1177.0	0.2	10.5	0.8		1177.0*	ϵ
1294.0	0.2	7.9	0.7		1428.6	134.6

* indicates positive-parity level. Level energy given with respect to $13/2^+$ isomeric level (ϵ). See text for discussion.

Table 2. Internal Conversion Coefficients (α_K) and Adopted Multipolarities

E_γ (keV)	Present work	Theory [Rose et al., 1978]		Assigned Multipolarity
		M1	E2	
134.6	2.1 ± 0.2	3.7	0.37	M1 + E2
287.0	0.48 ± 0.06	0.39	7.0×10^{-2}	M1
317.7	$4.9 \pm 3.2^*$	0.34	5.6×10^{-2}	E0 + M1 + E2
329.4	0.32 ± 0.03	0.28	5.2×10^{-2}	M1
369.2	0.16 ± 0.02	0.21	4.0×10^{-2}	M1 + E2
380.8	obscured a)	0.19	3.7×10^{-2}	—
401.3	$5.4 \pm 2.7^*$	0.17	3.3×10^{-2}	E0 + M1 + E2
412.9	$0.040 \pm 0.008^*$	0.16	3.2×10^{-2}	E2
433.9	$0.034 \pm 0.016^*$	0.14	2.8×10^{-2}	E2 + M1 (E2)
499.4	$0.011 \pm 0.009^*$	(E1: 8.0×10^{-3})		E1
533	obscured a)	7.8×10^{-2}	1.8×10^{-2}	—
556.6	0.037 ± 0.006	7.0×10^{-2}	1.7×10^{-2}	M1 + E2
588.2	0.035 ± 0.005	6.0×10^{-2}	1.5×10^{-2}	M1 + E2
634.3	obscured b)	4.4×10^{-2}	1.2×10^{-2}	—
684.5	0.019 ± 0.003	4.0×10^{-2}	1.1×10^{-2}	E2 + M1
695.7	0.034 ± 0.004	3.8×10^{-2}	1.0×10^{-2}	M1 + E2
766.7	obscured b)	3.0×10^{-2}	8.4×10^{-3}	—

Table 2. (continued)

E_γ (keV)	Present work	Theory [Rose et al., 1978]		Assigned Multipolarity
		M1	E2	
776.4	0.008 ± 0.001	3.0×10^{-2}	8.2×10^{-3}	E2
808.0	0.009 ± 0.002	2.7×10^{-2}	7.6×10^{-3}	E2
832.4	$0.014 \pm 0.004^*$	2.5×10^{-2}	7.2×10^{-3}	M1 + E2
840.6	0.007 ± 0.003	2.4×10^{-2}	7.0×10^{-3}	E2
850.8	obscured a)	2.3×10^{-2}	6.9×10^{-3}	—
875.7	0.006 ± 0.002	2.2×10^{-2}	6.6×10^{-3}	E2
890.4	obscured a)	2.1×10^{-2}	6.4×10^{-3}	—
894.3	0.005 ± 0.002	2.0×10^{-2}	6.4×10^{-3}	E2
961.6	$0.007 \pm 0.002^*$	1.7×10^{-2}	5.6×10^{-3}	E2 + M1 (E2)
967.0	0.008 ± 0.002	1.7×10^{-2}	5.6×10^{-3}	E2 + M1
986.1	0.005 ± 0.001	1.6×10^{-2}	5.4×10^{-3}	E2
1010.0	0.005 ± 0.001	1.5×10^{-2}	5.2×10^{-3}	E2
1078.8	0.004 ± 0.001	1.3×10^{-2}	4.6×10^{-3}	E2
1096.0	0.004 ± 0.001	1.2×10^{-2}	4.5×10^{-3}	E2
1125.8	0.005 ± 0.001	1.1×10^{-2}	4.2×10^{-3}	E2 + M1
1173.8	0.007 ± 0.002	1.0×10^{-2}	3.8×10^{-3}	M1 + E2
1177.0	obscured b)	1.0×10^{-2}	3.8×10^{-3}	—
1294.0	e ⁻ peak too weak	8.0×10^{-3}	3.2×10^{-3}	—

* indicates α_K determined from coincidence gate

a) indicates gamma-ray peak obscured

b) indicates conversion-electron peak obscured

Table 3 Gamma-Gamma Coincidence Relationships Placed
in the $^{195}\text{Bi} \rightarrow ^{195}\text{Pb}$ Decay Scheme

Gate Energy (keV)	Coincidences
134.6	499.5, 511, 695.7, 832.4, 875.7, 961.6 986.1, 1078.8, 1173.8
287.0	890.4
329.4	511, 766.7, 850.8
369.2	511, 808.0
401.3	776.4
412.9	776.4
433.9	808.0
499.5	134.6, 511, 695.7
556.6	808.0
588.2	776.4
684.5	961.6, 1096.0
695.7	134.6, 499.5, 511, 840.6
766.7	329.4, 511
776.4	412.9, 511, 588.2
808.0	369.2, 380.8, 433.9, 511, 556.6, 634.2
832.4	134.6, 511
840.6	134.6, 695.7
850.8	329.4
875.7	134.6
890.4	287.0

Table 3 (continued)

Gate Energy (keV)	Coincidences
894.3	511
961.6	134.6
967.0	134.6
986.1	134.6, 511
1010.0	Nothing
1078.8	134.6, 511
1096.0	684.5
1125.8	Nothing
1173.8	134.6
1177.0	Nothing
1294.0	134.6

Table 3 **Gamma-Gamma Coincidence Relationships Assigned to the Decay ^{195}Bi + ^{195}Pb , But Not Placed in the Decay Scheme**

Gate Energy (keV)	Coincidences
329.4	808.0
533	776.4, 894.3, 1125.8(v.w.)
556.6	776.4(v.w.)
588.2	433.9(v.w.)
695.7	1250
766.7	776.4(v.w.)
776.4	766.7
894.3	533
1078.9	630.9

Table 4 Gamma-Electron Coincidence Relationships Placed
in the $^{195}\text{Bi} \rightarrow ^{195}\text{Pb}$ Decay Scheme

Gate Energy (keV)	Coincidences
134.6	K499.4, K695.7, L695.7, M695.7, K832.4, K875.7 K961.6, K986.1, K1078.8, L1078.8
287.0	K890.4
329.4	K766.7, K850.8
369.2	K808.0
401.3	Nothing
412.9	K776.4
433.9	Nothing
499.4	K134.6, L134.6, M134.6, K695.7, L695.7, M695.7
556.6	Nothing
588.2	Nothing
695.7	K134.6, L134.6, M134.6
766.7	K329.4
776.4	K401.3, L401.3, K412.9, K434, K588.2
808.0	K317.7, K369.2, L369.2, M369.2
832.4	K134.6, L134.6, M134.6
840.6	K134.6, L134.6, K695.7
850.8	K329.4
875.7	K134.6, L134.6, M134.6
890.4	K287.0, L287.0
894.3	Nothing
961.6	K134.6, L134.6, M134.6

Table 4 (continued)

Gate Energy (keV)	Coincidences
967.0	Nothing
986.1	K134.6, L134.6, M134.6
1010.0	Nothing
1078.8	K134.6, L134.6, M134.6
1096.0	Nothing
1123.8	Nothing
1173.8	K134.6, L134.6, M134.6
1177.0	Nothing
1294.0	K134.6, L134.6, M134.6

Table 4 Gamma-Electron Coincidence Relationships Assigned to the Decay $^{195}\text{Bi} \rightarrow ^{195}\text{Pb}$, But Not Placed in the Decay Scheme

Gate Energy (keV)	Coincidences
287.0	K134.6
329.4	K776.4
499.5	K808.0(v.w.)
766.7	K134.6, L134.6
850.8	K134.6, L134.6, K808.0
894.3	K287.0
1096.0	K134.6(v.w.)

Table 4 Electron-Gamma Coincidence Relationships Placed
in the $^{195}\text{Bi} \rightarrow ^{195}\text{Pb}$ Decay Scheme

Gate Energy (keV)	Coincidences
K401.3	776.4
K317.7	808.0

2.4 Decay of the Low-Spin Isomer of ^{195}Pb

By bombarding natural Re targets with 140 MeV ^{16}O ions followed by on-line separation of the mass 195 reaction products at UNISOR, the low-spin isomer of ^{195}Pb was produced. Thus, γ -ray transitions between low-spin states in ^{195}Tl were enhanced relative to those observed in earlier UNISOR ^{195}Pb decay work. Real-time-tagged data of γ -ray and e^- singles, as well as $e^- \gamma$ coincidence events were accumulated. These data will be used to obtain a more complete picture of the low-spin structure in ^{195}Tl and to search for shape coexistence in the low-lying levels of this nucleus. This work was in collaboration with C.R. Bingham and other UNISOR coauthors. A preliminary report appeared as an abstract.

C.R.Bingham, H.V. Carmichael, V. Janzen, L.L. Riedinger, W. Schmitz, R. A. Braga, R. W. Fink, J.L. Wood, M. Kortelahti, E. F. Zganjar, C. Girit, H.K. Carter, and R. L. Mlekodaj, Bull. Am. Phys. Soc. 31, 1236 (1986) [Vancouver, Canada, October, 1986]

2.5 Decay of Mass Separated 1.5 min ^{201}At

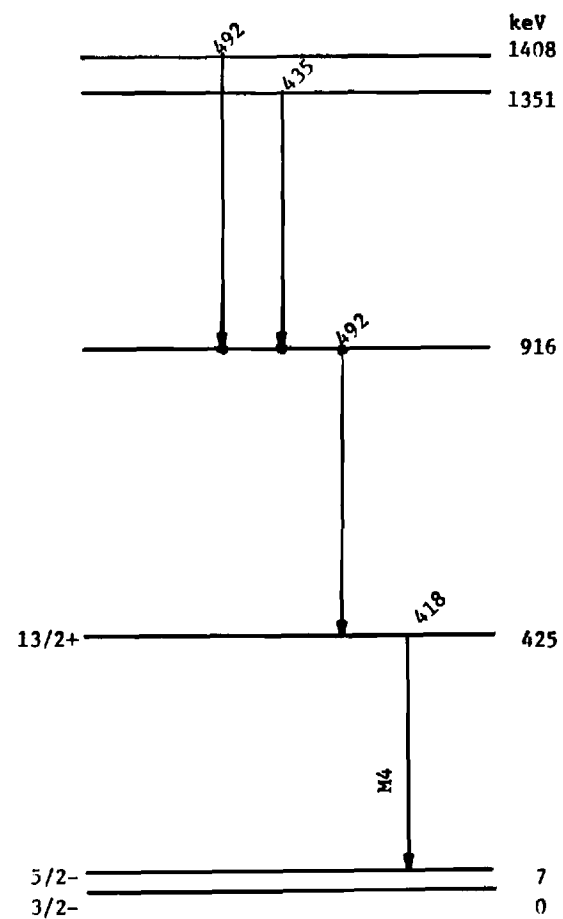
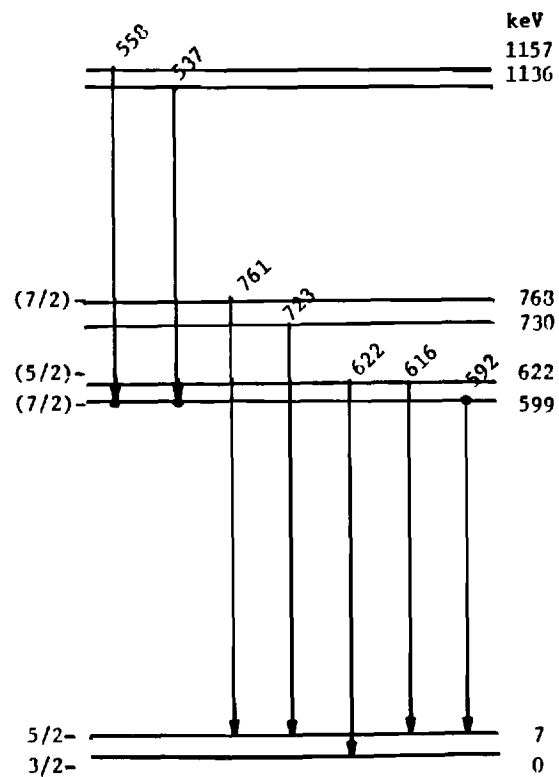
During the past year, no additional experiments were conducted on the β^+ , EC decay of 1.5 min ^{201}At to levels in ^{201}Po and on the α -decay to ^{197g}Bi (9/2-) and the subsequent decay of the latter to levels in ^{197}Pb . However, the recently completed works on the decay of ^{203}At to levels in ^{203}Po ¹⁾ and on the decay of ^{195g}Bi to ^{195}Pb ²⁾, along with additional information on the decay of ^{197}Bi ³⁾, have lead to the construction of preliminary level schemes for both ^{201}Po and ^{197}Pb . These structures are shown in Figs. 1 and 2, respectively.

¹ P. B. Semmes, R. A. Braga, R. W. Fink, J.L. Wood, and J.D. Cole, Nucl. Phys. A464, 381 (1987)

² J. C. Griffin, PhD thesis, School of Chemistry, Georgia Tech (June, 1987); see Sect.2.3 above.

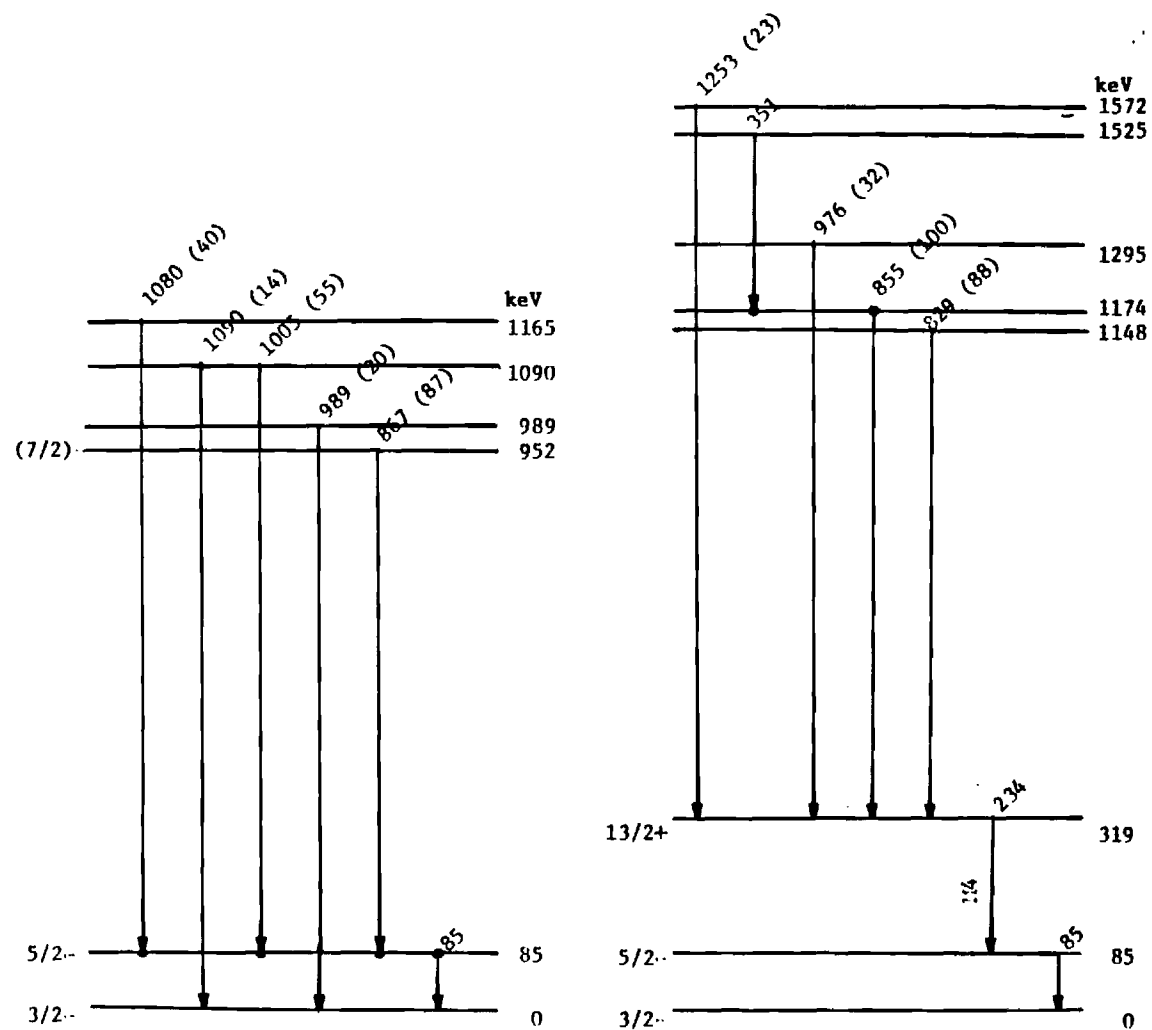
³ P. Van Duppen, private communication

The transitions assigned to the decays of ^{201}At to ^{201}Po and of ^{197g}Bi to ^{197}Pb are found, in both cases, to be divided into two major groups; transitions in each group show coincidences only among themselves, indicating that they belong to a band sequence not connected (or very weakly connected) to the other group.



^{201}Po

Fig. 1



^{197}Pb

Fig. 2

The group of transitions shown on the left side of Figs. 1 and 2 are assigned to negative-parity states, based on coincidence relationships and energy sums. The second group of transitions are assigned to populated the positive-parity ($i_{13/2}$) states in ^{201}Po and ^{197}Pb (right side of Figs. 1 and 2). In both ^{201}Po and ^{197}Pb , the $13/2+$ state is observed to deexcite via an M4 transition to the $5/2-$ first excited state of the respective nucleus.

Prior to this study, the only information on the level structures of ^{201}Po and ^{197}Pb consisted of the $13/2+$ isomeric decays. (R.A. Braga & C. P. Perez)

2.6 Decay of Mass Separated ^{185}Au to levels in ^{185}Pt

Present knowledge about the mass 185 Au isotope suggests the existence of the ground-state and a ($5/2-$) isomeric level with halflives of 6.8 and 4.33 min, respectively, but there is some evidence for this to be wrong. Part of the present investigation is to determine the isomer actually produced in our reaction by means of accurate halflife measurements. The production of the higher spin state ^{185}Au would be favored, but there might be a mixture present.

The decay of ^{185}Au to ^{185}Pt and subsequently to ^{185}Ir has been studied via the $^{181}\text{Ta}(^{12}\text{C},8n)^{185}\text{Au}$ reaction at 140 MeV, using the UNISOR facility. The $\gamma\gamma$ and $\text{ce}^-\gamma$ coincidence as well as the singles spectra were obtained. Comparison of two publications on ^{185}Pt levels^{1,2)} shows inconsistent results, especially in two highly converted transitions of 309 and 542 keV. Our data feature excellent statistics (approximately 500 million coincidence events) and thus make possible a critical reassignment of the levels and transitions in ^{185}Pt , as well as in ^{185}Ir , where our statistics are far superior to previously published data^{3,4)}. As other odd-mass nuclei in this region have already been studied and the proposed study of the decay of ^{183}Au by our group in the near future, this would provide experimental information for a systematic and theoretical study of shape isomers.

Preliminary results in the ^{185}Au to ^{185}Pt decay show strong disagreement in the assignment of the 542 keV transition which had been published as highly converted. Fig. 1 shows the coincident γ -rays of a gate placed on the 542 keV γ -ray peak. Some strong lines crucial to the correct assignment of this transition had not been reported. The construction of the decay scheme is currently in progress. Fig. 2 shows the coincidence spectrum of a 98 keV γ -ray gate, and Fig. 3 shows the partial decay scheme obtained so far. The

high quality of the assigned lines due to the good statistics is apparent.

Studies of the decay to the granddaughter ^{185}Ir are also currently being investigated. The superior amount of data obtained, compared to previous publications, provides many new transitions, in addition to the enhanced population of low-spin levels. A decay scheme is being constructed.

This work is part of the PhD thesis of J. Schwarzenberg and is being carried out with other UNISOR coworkers, including J. L. Wood of the School of Physics.
(J. Schwarzenberg)

¹B. Roussiere, et al., Nucl. Phys. A438, 93 (1985)

²E. Van Walle, thesis, Univ. of Leuven, Belgium

³C. Schüick, et al., Nucl. Phys. A325, 421 (1979)

⁴S. Andre, et al., Nucl. Phys. A325, 445 (1979)

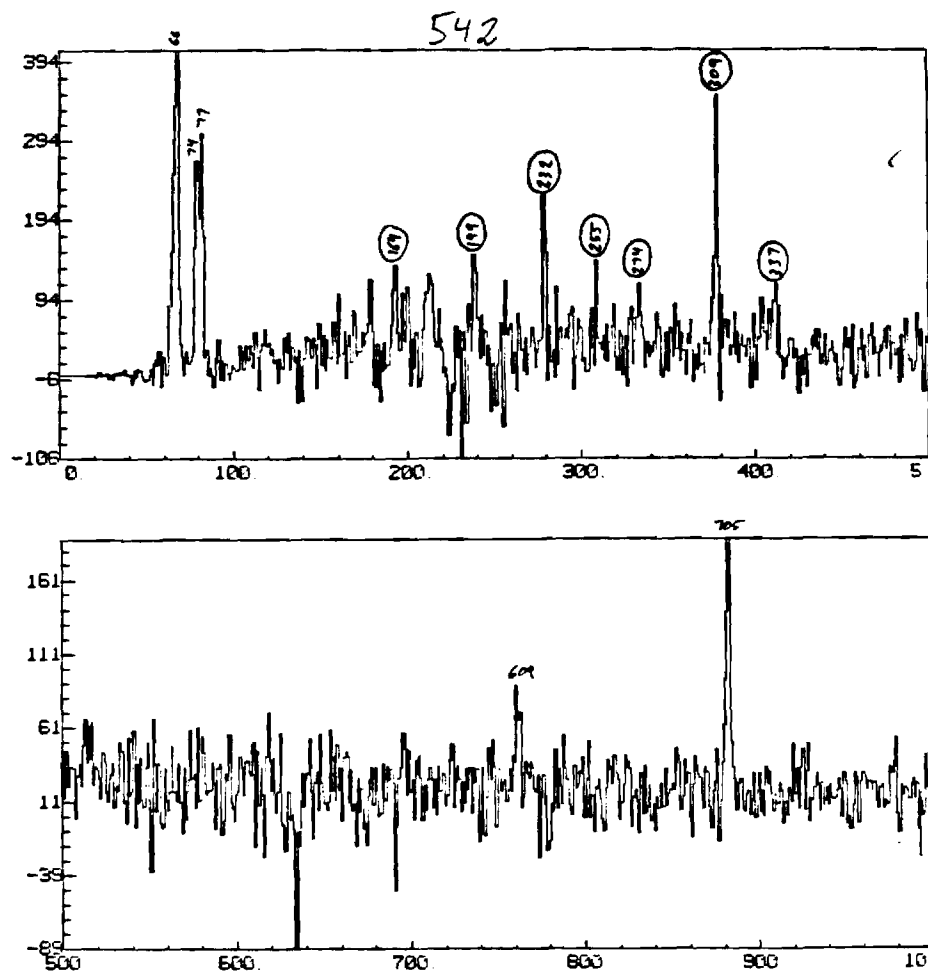
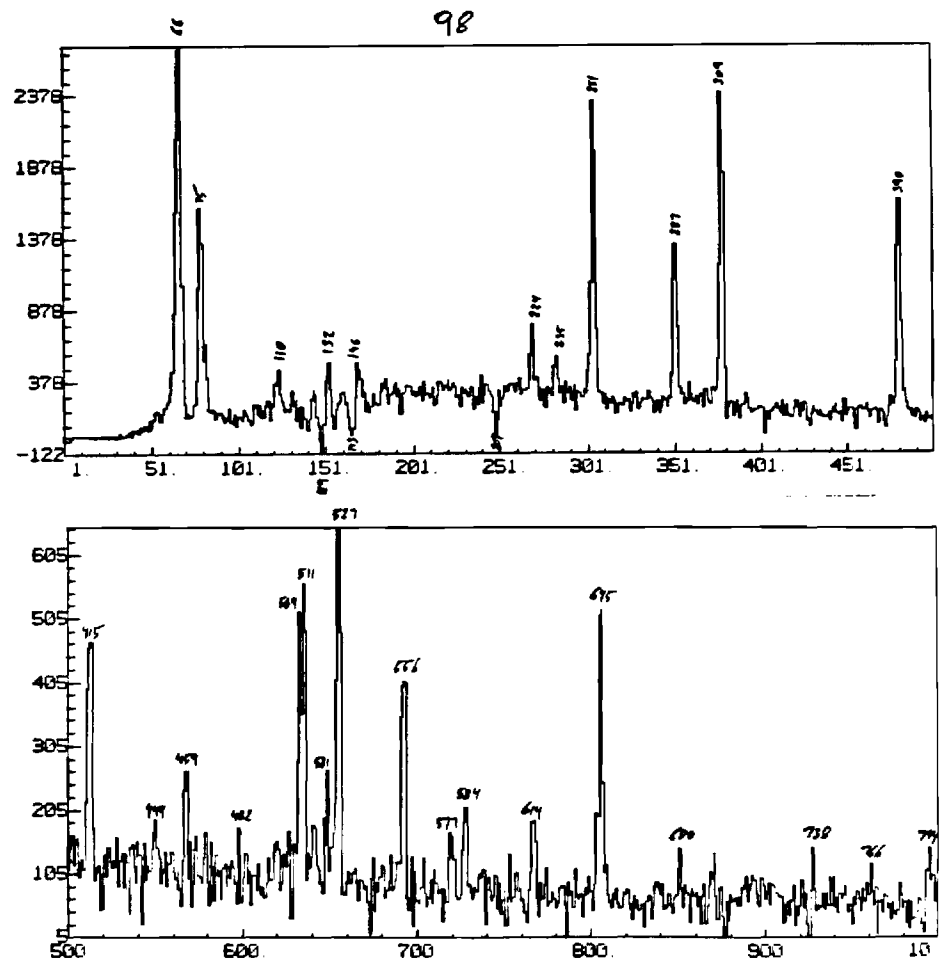


Fig. 1 Decay of ^{185}Au to ^{185}Pt

Coincidence spectrum of a gate on the 542 keV gamma-ray

A circle is drawn around the energies, which have not been reported to be in coincidence.

(all energies in keV)



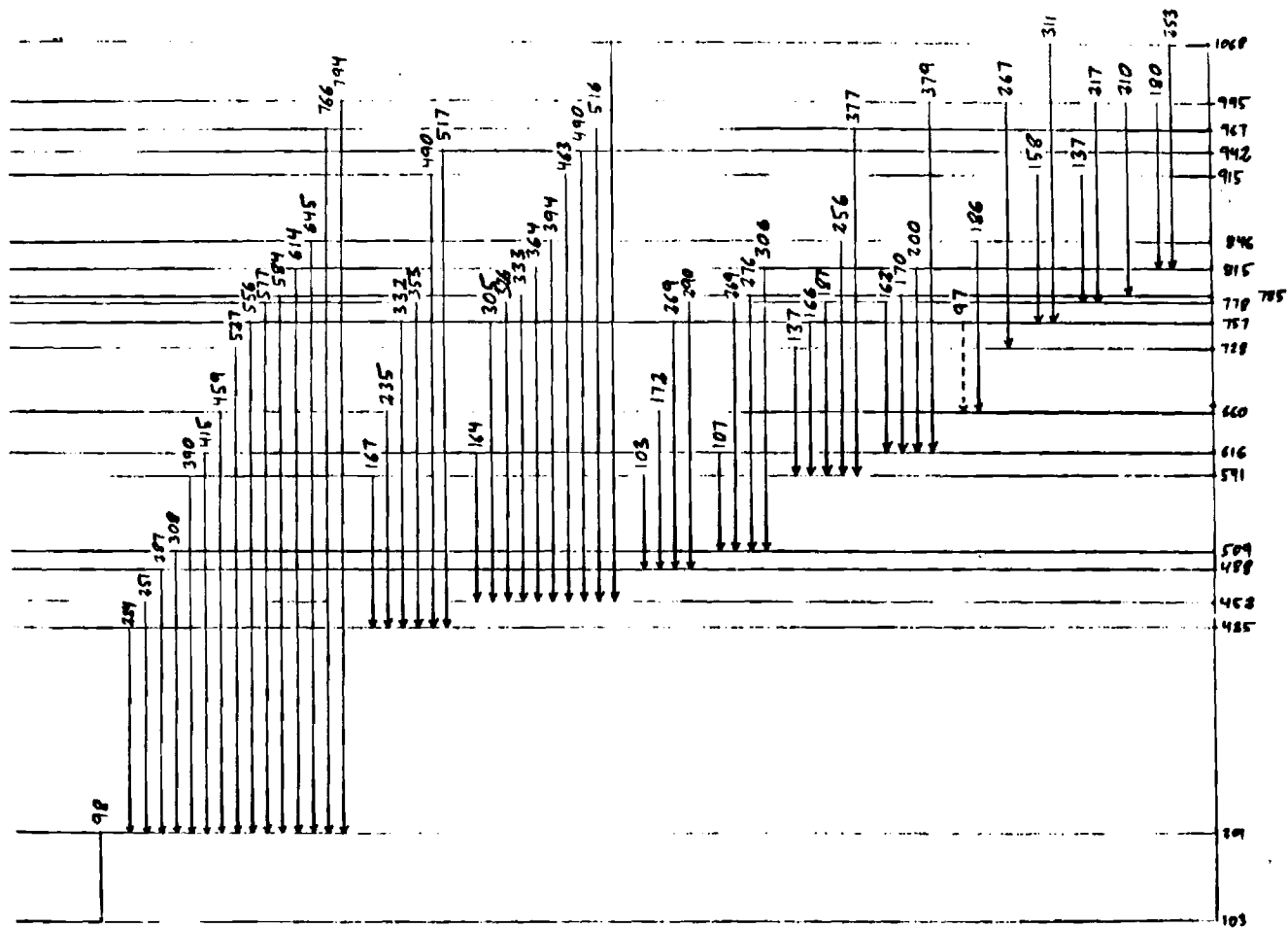


Fig. 3 Decay of ^{185}Au to ^{185}Pt
 Gamma-rays in coincidence with the 98 keV transition
 (all energies in keV)

2.7 Nuclear Laser Spectroscopy at UNISOR

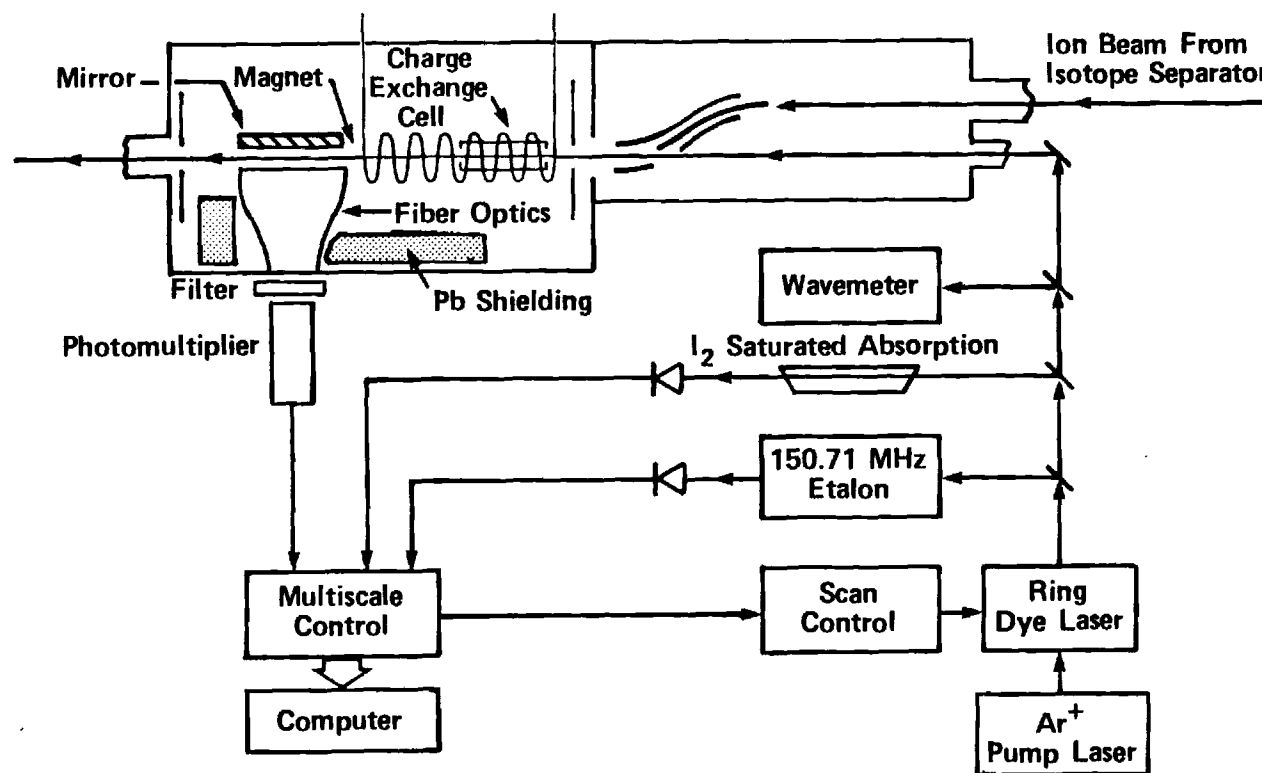
This work is from a thesis by J. C. Griffin (June, 1987), previously submitted to DOE as report ORO-3346-277. What is presented here is a summary of the results on Pb isotopes.

The collinear fast ion/atom beam technique was adapted and applied at the UNISOR laser facility for isotope shift measurements on mass separated, neutron-deficient Pb isotopes. The system was used on the stable $^{204,206,207,208}\text{Pb}$ isotopes and, in an on-line experiment, for the neutron-deficient radioactive isotope, ^{196}Pb (37 min). Changes in the mean-square charge radius of the nuclei, $\langle\delta r^2\rangle$ have been extracted from our measured isotope shifts. The overall system sensitivity was determined to be approximately 2.0×10^{-3} counts/Pb atom.

Examples of the data acquired on $^{204,206,208}\text{Pb}$ are shown in Fig. 1, with an example of the ^{207}Pb data shown in Fig. 2. Spectra on the stable beams are relatively easy to acquire owing to essentially unlimited intensity, but can be much more difficult to acquire on neutron-deficient nuclei, such as ^{196}Pb , produced in heavy ion reactions, because the overall system efficiency and photomultiplier tube (PMT) background demand a sufficient mass separator beam intensity, in order to acquire data in a reasonable time. In these radioactive Pb experiments, this minimum intensity requirement was at the limit of the maximum Pb beam the mass separator ion source was capable of producing.

In Fig. 3, the best data obtained in this work on ^{196}Pb is shown. These data represent a total of 67 30-sec scans at an average ^{196}Pb mass separated beam rate of 10^5 atoms/sec and an average PMT background of 750 counts/sec. For calibration, ^{208}Pb spectra were taken before and after each ^{196}Pb run, in order to correct any drifts in the mass separator acceleration voltage. These drifts were found to be small (~ 40 MHz). The observed isotope shift determination also was made by direct comparison of the ^{196}Pb and ^{208}Pb peaks, using the 150.710 MHz etalon spectrum as a ruler.

The Doppler shifts were removed from the experimentally observed shifts (for details, see ORO-3346-277) to give the actual isotope shift. The nuclear component $\lambda^{\text{AA}'}$ of the FS was then extracted directly by means of a King plot (shown in Fig. 4) of the measured 722.9 nm isotope shift values vs. $\lambda^{\text{AA}'}$ values (shown in Table 1) determined by a combined analysis of muonic x-ray and elastic electron scattering data [Anselment, 1986]. The value of $\langle\delta r^2\rangle$ for each isotope



The UNISOR On-Line Collinear Fast Ion/
atom Beam Laser Spectroscopy System

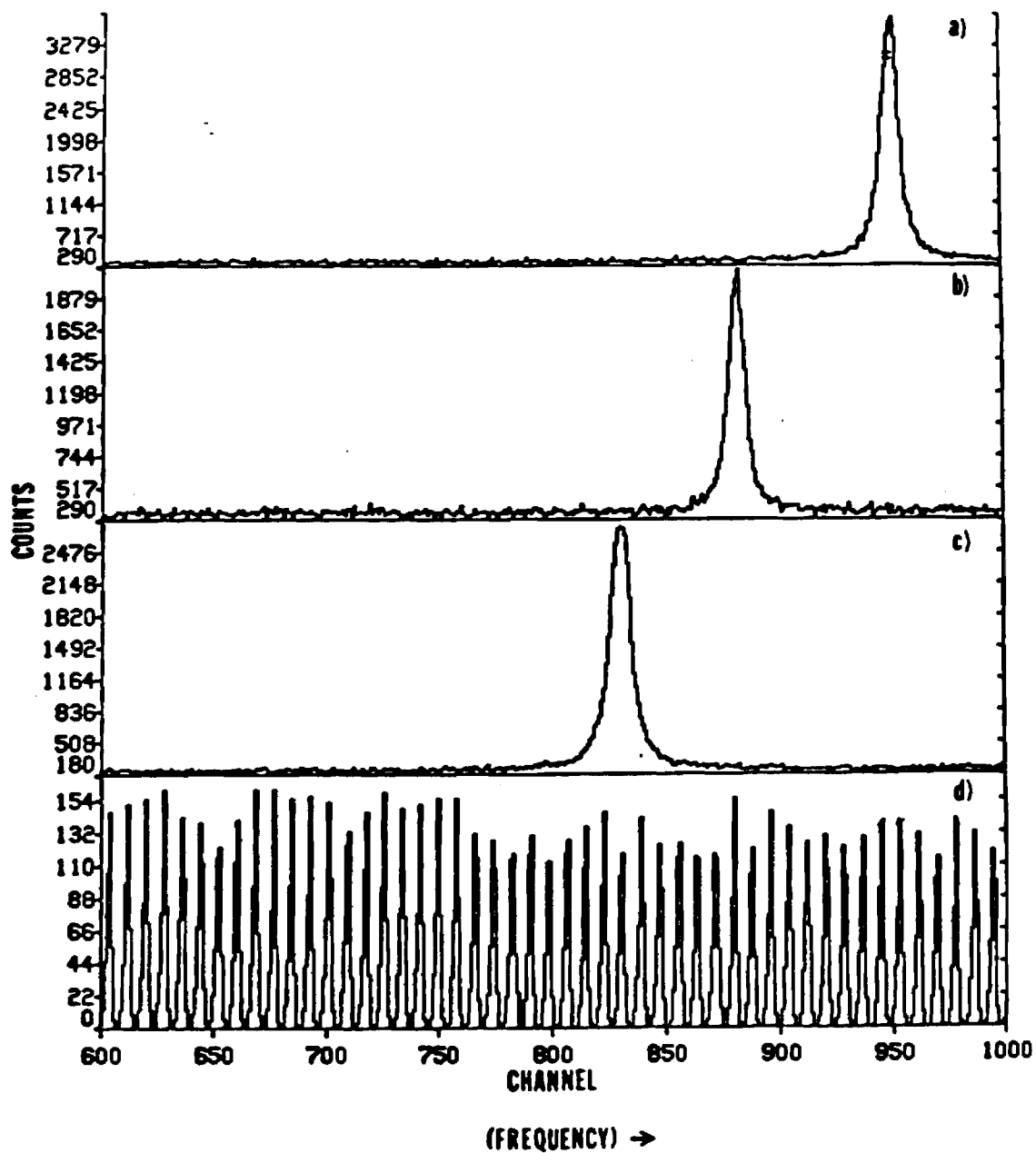


Fig. 1. PMT spectra acquired on stable, even-mass Pb isotopes. The observed shift in peak position between each Pb isotope is due to a combination of the isotope shift and the difference in Doppler shifts. a) ^{208}Pb , b) ^{206}Pb , c) ^{204}Pb , and d) 150.71 MHz frequency markers.

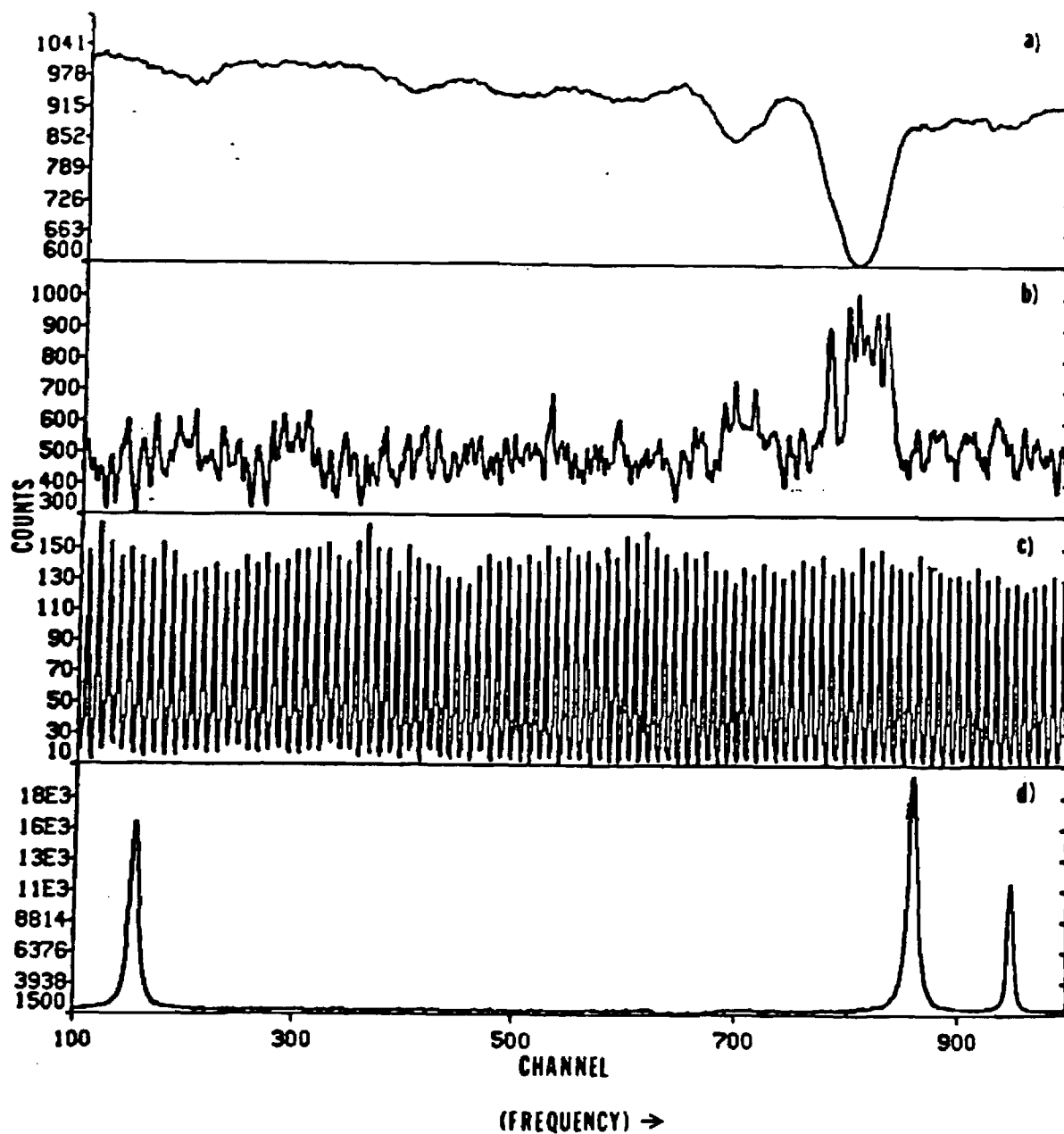


Fig. 2. PMT spectrum acquired on ²⁰⁷Pb. a) I₂ absorption spectrum, b) I₂ saturated-absorption spectrum, c) 150.71 MHz frequency markers, and d) ²⁰⁷Pb hyperfine structure.

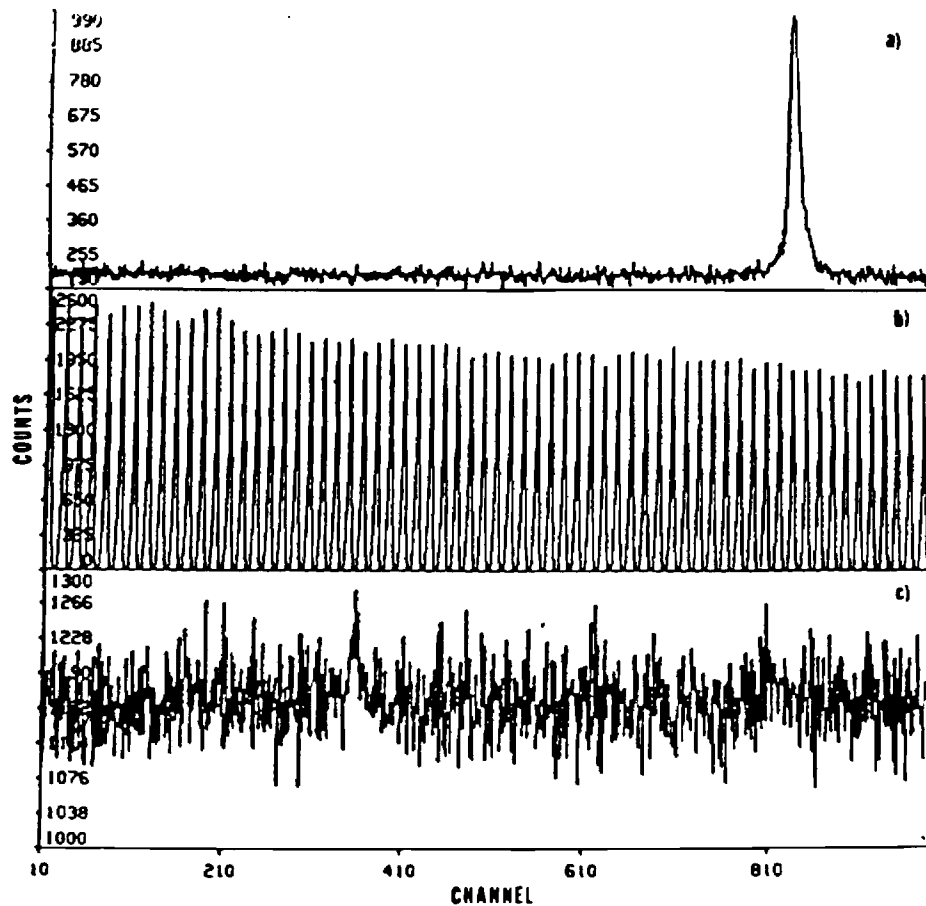


Fig. 3. ^{196}Pb isotope shift spectrum. a) PMT signal for ^{208}Pb , b) 150.71 MHz frequency markers, and c) PMT signal for ^{196}Pb . The ^{196}Pb signal represents a total of sixty-seven 30 second scans.

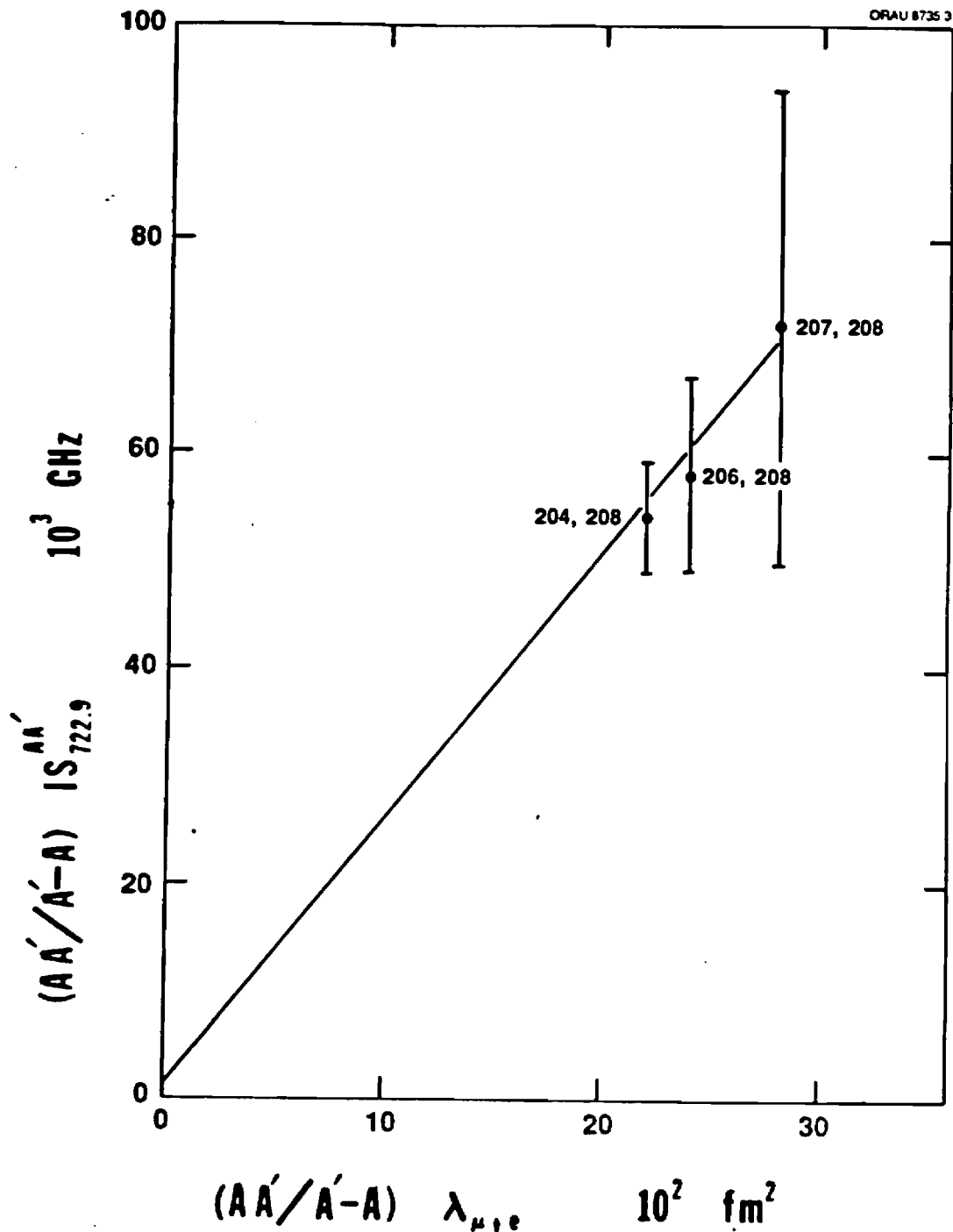


Fig. 4 . King plot of modified isotope shifts for the 722.9 nm Pb I line versus values of the nuclear parameter, λ , obtained from a combined analysis of elastic electron scattering and muonic x-ray data. The slope of the line (F) is 24.7 GHz/fm² and the y-intercept (M) is 5.1 GHz.

Table 1. Values of λ for Pb Isotopes Determined from a Combined Analysis of Elastic Electron Scattering and Muonic X-ray Isotope Shift Data. Values from [Anselment, 1986].

Isotope Pair	$\lambda_{\mu+e}/\text{fm}^2$
207-208	0.0664 (61)
206-208	0.1115 (61)
204-208	0.2072 (61)

For each isotope pair, the value of $\delta\langle r^2 \rangle$ for each isotope pair was subsequently calculated from $\lambda^{AA'}$ using the expression

$$\lambda^{AA'} = 0.93 \delta\langle r^2 \rangle$$

as given by Thompson, et al. [1983].

R. C. Thompson, et al. J. Phys. (London) G9, 443 (1983)

Table 2 gives the measured isotope shifts, relative to ^{208}Pb , together with the derived values of the nuclear parameter $\lambda^{AA'}$ and the calculated values of $\delta\langle r^2 \rangle$ for the Pb 722.9 nm resonance line. Table 2 also lists the values reported by Anselment [1986] from the work on the 283.3 nm Pb resonance line. (J.C. Griffin)

Table 2. Measured Isotope Shifts (Relative to ^{208}Pb) and Derived Values of λ and $\delta\langle r^2 \rangle$, for the 722.9 nm Pb I Line. The isotope shifts were calibrated using data obtained from [Anselment, 1986].

Present Work				
Isotope	$IS_{722.9}$ (MHz)	λ (fm ²)	$\delta\langle r^2 \rangle$ (fm ²)	$\delta\langle r^2 \rangle$ (fm ²) a)
208	0.0	0.0	0.0	0.0
207	1672 (524)	0.068 (25)	0.073 (27)	0.0737 (6)
206	2718 (439)	0.110 (27)	0.118 (29)	0.1179 (10)
204	5139 (439)	0.208 (43)	0.223 (46)	0.2231 (18)
196	13865 (774)	0.560 (109)	0.603 (118)	0.6057 (52)

a) [Anselment et al., 1986].

2.8 L-Subshell X-ray and Coster-Kronig Yields at Z = 60 and 70

This work was completed several years ago when Dr. Mustafa Tan was a postdoctoral visitor and it is now fully analyzed and in the process of publication. X-ray spectra emitted in the radioactive decay of 17.7 year ^{145}Pm and 1.9 year ^{171}Tm were studied using a three-parameter technique for XX-t coincidence measurements. The following L_2 and L_3 subshell x-ray fluorescence yields, ω_2 , ω_3 , Coster-Kronig transition probabilities, f_{23} , and radiative decay branching ratios, s_2, s_3 , were determined for Nd ($Z = 60$) and Yb ($Z = 70$): At $Z = 60$, $\omega_3 = 0.108 \pm 0.010$, $\omega_2 = 0.128 \pm 0.018$, $f_{23} = 0.123 \pm 0.013$, $s_3 = 0.178 \pm 0.006$, and $s_2 = 0.205 \pm 0.010$. At $Z = 70$: $\omega_3 = 0.227 \pm 0.022$, $\omega_2 = 0.217 \pm 0.030$, $f_{23} = 0.141 \pm 0.007$, $s_3 = 0.175 \pm 0.003$, $s_2 = 0.197 \pm 0.004$. The error limits are 95% confidence (2σ + linear addition of systematic error). These results are compared with available theoretical calculations in the manuscript submitted for publication to Physica Scripta (Stockholm).

" $L_{2,3}$ -Subshell X-ray Fluorescence Yields and Coster-Kronig Transition Probabilities of Nd and Yb," M. Tan, R. A. Braga, R. W. Fink, and P. V. Rao, Phys. Scripta (Stockholm), submitted (1987). [See ORO-3346-275 (1987)]

3.0 TECHNICAL CONTRIBUTIONS TO UNISOR

3.1 FEBIAD-B Ion Source Tests

The new FEBIAD-B ion source was used for the first time at UNISOR in extracting Au activities for the study of ^{185}Au to levels in ^{185}Pt (see Sect. 2.6 above). The efficiency for gold activities was so superior to that of ion sources used previously at UNISOR that a detailed study of the decay of mass separated ^{183}Au to levels in ^{183}Pt is now possible (see Renewal Proposal).

The enhanced efficiency of the FEBIAD-B ion source has also resulted in increased activities of rare earth nuclei. In order to quantify the performance of this ion source for rare earth extraction, a test was conducted for production of ^{139}Sm activities, using identical conditions as a previous study (namely, $^{48}\text{Ti}^{+11}$ ions on natural Mo targets at 230 MeV) that utilized the old UNISOR high temperature ion source. The FEBIAD-B provided a 600% increase in ^{139}Sm activity mass separated compared to that previously obtained. A test of the operating parameters of the FEBIAD-B indicated that maximum activity is obtained when the anode current and electron bombardment voltage are maximized. The use of the FEBIAD-B ion source will enhance greatly our ability to extend detailed nuclear spectroscopy in the rare earth region to more neutron-deficient species.

3.2 Computer Operations

The HHIRF package of computer codes for data manipulation and analysis has been fully implemented on the Georgia Tech Chemistry VAX-780 computer. These programs operate in an identical manner to those used at HHIRF on the Perkin-Elmer 3230 mainframe.

The principal benefit in using these codes is in the processing of coincidence data. This ability eliminates the time consuming process of scanning individual tapes on the Georgia Tech Cyber-990 mainframe computer. Instead, coincidence gates can be placed on a two-dimensional "matrix" spectrum which is generated from the coincidence data on the HHIRF Perkin-Elmer 3230 system and easily loaded onto the VAX.

The ease and usefulness of this procedure has resulted in the analysis of the $\gamma\gamma$ coincidence data from the rare earth He-jet run (Sect. 2.2 above) and the $\gamma\gamma$ and $\text{ce}^{-}\gamma$ coincidence data from the ^{185}Au experiment (Sect. 2.6 above) being undertaken completely on the Chemistry VAX-780 system at Georgia Tech.

3.3 Equipment Added or Fabricated

This past year the Georgia Tech Chemistry Machine Shop fabricated two beam entrance window mounts for the He-jet system at UNISOR. These were of aluminum with 0.25 and 0.50 inch dia. entrance ports fitted with windows of 0.002 and 0.005-inch Be, respectively.

Two highly regulated Fluke power supplies of 5 KV and 10KV were given to UNISOR to provide high voltage for steering deflection plates on the isotope separator experiment lines.

4.0 PERSONNEL

Senior Staff:

Dr. R. W. Fink, Professor & Principal Investigator
(38% time, including summer)

Dr. R. A. Braga, Research Scientist
(1/12 time, 12 months)

Graduate Students:

Dr. Jeffrey C. Griffin (PhD, Nuclear Chem. June, 1987)
(Graduated and presently at Savannah River Laboratory,
Nuclear Chemistry Division, Aiken, S. C.)

Cesar P. Perez (Chemistry). Continuing PhD thesis research
(UNISOR). Supported 12 months by teaching assistantship

Johannes Schwarzenberg (Chemistry). Began PhD thesis research
April, 1987. Supported 9 months by teaching assistantship
+ 2 months summer from this contract as Graduate Research
Assistant. (UNISOR)

5.0 LIST OF PUBLICATIONS, ABSTRACTS, AND MEETINGS

- 1) "Energy Levels and Structure of Light Rare Earth Nuclei via Beta Decay: $^{136,138,140}\text{Sm}$ and $^{132,134,136}\text{Nd}$," R.L. Mlekodaj, G.A. Leander, H.K. Carter, M.O. Kortelahti, E. F. Zganjar, B. D. Kern, R.A. Braga, R. W. Fink, C.P. Perez, P. B. Semmes, and W. Nazarewicz, Proc. 5th Int. Conf. Nuclei far from Stability, Rosseau Lake, Ontario, Canada [September, 1987]
- 2) "Transition through Triaxial Shapes of the Light Samarium Isotopes and the Beta Decay of $^{136,138,140}\text{Eu}$," B.D. Kern, R.L. Mlekodaj, G.A. Leander, M.O. Kortelahti, E.F. Zganjar, R. A. Braga, R. W. Fink, C. P. Perez, W. Nazarewicz, and P. B. Semmes, *Phys. Rev. C* (1987)(submitted).
- 3) "Decay of ^{136}Sm and ^{136}Pm Isobars," B.D. Kern, R. L. Mlekodaj, M. O. Kortelahti, E. F. Zganjar, R. A. Braga, R. W. Fink, C. P. Perez, *Z. Physik A* (1987)(submitted).
- 4) "Beta Decay of Light Rare Earth $^{130,132}\text{Pr}$ and $^{132,134}\text{Pm}$ Nuclei," M. Kortelahti, E. F. Zganjar, R. A. Braga, R. W. Fink, and C. P. Perez, *Z. Physik A* 237, 231 (1987).
- 5) "The L_2-L_3 Coster-Kronig Transition Probability for $Z = 54$," P. B. Semmes, J. C. $^{23}\text{Griffin}$, R. A. Braga, and R. W. Fink, *Phys.Rev.* C35, 749-751 (1987)
- 6) "Decay of the Low-Spin Isomer of ^{195}Pb ," C.R. Bingham, R. A. Braga, R. W. Fink, and other UNISOR coauthors, *Bull. Am.Phys. Soc.* 31, 1236 (1986) [Vancouver, Canada, October, 1986]
- 7) "Decay of Mass Separated 7.4 min ^{203}At ," P.B. Semmes, R. A. Braga, R. W. Fink, J. L. Wood, and J.D. Cole, *Nucl. Phys.* A464, 381 - 394 (1987)
- 8) BOOK REVIEW: "Americium and Curium Chemistry & Technology," edited by Edelstein, Navratil, and Schulz (D. Reidel Publishing Co., Dordrecht, Holland, 1985), by R. W. Fink, *J. Am. Chem. Soc.* 108, 5048 (1986)
- 9) "Shape Coexistence in ^{185}Au ," E.F. Zganjar, C.D. Papanicolopoulos, J.L. Wood, R. A. Braga, R. W. Fink, and other UNISOR coauthors, Proc. Symp. Nuclei far off Stability, Am. Chem.Soc. Symposium Series 324, 245 - 251 (1986)
- 10) "Decay of Mass Separated ^{201m}Po and ^{201g}Po ," R. A. Braga, P. B. Semmes, W. R. Western, and R. W. Fink, *Nucl. Phys.* A459, 359 - 373 (1986)
- 11) " $L_{2,3}$ Subshell Fluorescence Yields and Coster-Kronig Transition Probability for Nd and Yb," M. Tan, R. A. Braga, R. W. Fink, and P. V. Rao, *Bull. Am. Phys. Soc.* 32, 1050 (1987); full paper in *Phys. Scripta* (Stockholm) (submitted, 1987)
- 12) "Testing interacting boson model cores through particle-core coupling: Negative parity states in the odd-mass Tl and Au isotopes," P.B. Semmes, A.F. Barfield, B. R. Barrett, and J.L. Wood, *Phys.Rev.* C35, 844 - 847 (1987)
- 13) "Decay of ^{138}Eu and ^{136}Eu and Deformation in the Light Sm Region," R. L. Mlekodaj, R. A. Braga, B. D. Kern, G. A. Leander, K.S. Toth, and B. Gnade, Proc. Symp. Nuclei Off the Line of Stability, Am. Chem.Soc. Symposium Series 324, 502 - 507 (1986)

NUCLEAR CHEMISTRY RESEARCH AND SPECTROSCOPY WITH RADIOACTIVE NUCLEI

**24th Annual Progress Report and Final Report
U.S. Department of Energy
Contract DE-AS05-76ERO-3346**

**R. W. Fink
Professor of Chemistry Emeritus and Principal Investigator**

August 31, 1988

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF CHEMISTRY
ATLANTA, GEORGIA 30332



NUCLEAR CHEMISTRY RESEARCH AND SPECTROSCOPY
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ABSTRACT

NUCLEAR CHEMISTRY RESEARCH AND SPECTROSCOPY WITH RADIOACTIVE NUCLEI

This research involves the study of far-from-stable radioactive nuclei mass separated with the UNISOR facility on-line to heavy ion beams from HHIRF at Oak Ridge. The purpose is to investigate low-spin ($< 21/2$), low-energy (< 3 MeV) nuclear structures, most of which are not generally accessible by in-beam methods. Experiments of interest center on cases where an odd valence nucleon or valence pair act as probes of the underlying core. This leads to observations of abrupt shape changes, shape coexistence, and shell-model intruder states at low nuclear excitation energies. In particular, two distinct neutron-deficient regions are under investigation, one around the $Z = 82$ closed shell ($^{183,185}\text{Au}$ decays, etc.) and the other in the rare earths around the new region of deformation $N < 76$ and $Z > 56$ ($^{133,135}\text{Sm}$ and rotational gamma-bands in even-even nuclei, $^{132,134}\text{Eu}$, $^{130,132}\text{Nd}$ decays, etc.) Detailed singles and $\gamma\gamma$, $e^-\gamma$, $X\gamma$, $\alpha\gamma$ coincidence measurements are performed. Nuclear orientation with the $^3\text{He}/^4\text{He}$ dilution refrigerator on-line to the isotope separator will begin this year for measurements of nuclear spins, g-factors, and magnetic moments. Initial on-line studies will be on the decays of oriented $^{189\text{m}}\text{Hg}$, $^{199,201}\text{Po}$, and $^{183,185}\text{Au}$ nuclides. The results of these nuclear spectroscopic and orientation experiments, when combined with those from available in-beam spectroscopy, permits critical testing of competing theoretical concepts and nuclear model calculations.

1.0 INTRODUCTION AND FINAL WORD

This 24th and Final Annual Report summarizes our research progress since the previous annual report [ORO-3346-278, August 31, 1987], together with a list of graduate students, postdoctorates, and publications supported since February 1, 1965, under this, the longest-running contract or grant at Georgia Tech.

In the report of the most recent UNISOR workshop [June 21 - 22, 1988], the following comments on the manpower aspects of nuclear science appeared:

"Over the past few decades, much of the growth in the United States efforts in medium- and high-energy particle physics has been at the expense of research programs in nuclear structure... Many university faculty have "crossed over" into what they perceived to be...a better funded research environment, and they were followed by a large share of graduate students. (This is in contrast to the European effort, in which nuclear structure is well supported and maintained at university and national laboratories.)

"In the opinion of the UNISOR workshop participants, maintenance of a viable research program in nuclear structure is essential to the U.S. national interest, not necessarily because of the information directly gained, but because a pool of talented university researchers and their students will provide a continuing source of expertise...Nuclear structure research will not survive unless university researchers continue their efforts." Without support at both the university and national laboratory level, "university faculty will seek other research fields and the supply of graduate students will dwindle, thereby further reducing the number of future workers."

"Despite the erosion of support for basic research in nuclear science, the need for trained workers continues to increase. Examples of current interest include the following: (1) Environmental applications, such as radon monitoring; (2) Material science, including implanting and alloying radioactive atoms, which are needed as dopants to study new materials such as high T_c superconductors, thereby providing one of the few probes of the microscopic (vs. bulk) properties of materials; and (3) Nuclear medicine and other biomedical applications. Workers in these areas, among others, received their training as nuclear scientists or were trained by university nuclear science faculty and use techniques or instruments developed by nuclear scientists. Finally, ...a time will come in the not too distant future when we may be forced to resort to nuclear power." This is becoming especially obvious by the greenhouse effect of CO_2 from fossil fuels. "The only pool of nuclear scientists trained to handle the situation will be those in nuclear research."

With the ending of DOE support for nuclear chemistry research at Georgia Tech (August 31, 1988), our two large nuclear laboratories in the Chemistry Building have been converted to X-ray diffraction laboratories for protein crystallography for biochemistry research. Although we retain our small radiochemistry "hot" lab, nuclear chemistry, for lack of Federal support, has been discontinued as a field of graduate study at Georgia Tech, and no additional graduate students will be accepted in this field, nor will the graduate level courses in nuclear chemistry continue to be taught. Thus, one of the few remaining sources of PhD nuclear chemists in the U.S. has been closed.

Upon the termination of the Chemistry Dept. nuclear laboratories, we delivered to UNISOR a considerable quantity of state-of-the-art NIM modules, bins, cables, power supplies, etc. and radioactive sources, valued at more than \$12,000, on permanent loan. This will also facilitate the continued participation in UNISOR research on a personal basis of R. W. Fink and R. A. Braga, even though the School of Chemistry will no longer have any connection with nuclear research.

Finally, we have one outstanding graduate student, Mr. Johannes Schwarzenberg, who will complete his PhD in nuclear chemistry about June, 1989, based on UNISOR research. He is the last one.

2.0 NUCLEAR SPECTROSCOPIC AND STRUCTURE STUDIES

2.1 Decay of Mass Separated ^{195}Bi to Levels in ^{195}Pb

An extensive report on ^{195}Bi decay was given in last years Annual Progress Report [ORO-3346-278], based on the PhD thesis of Dr. J. C. Griffin. These results are being prepared for full publication [Nucl. Phys. A] and an abstract was presented at the Nashville, Tennessee meeting of the American Physical Society.

The radioactive decay of ^{195}Bi to ^{195}Pb has been studied with mass separated sources from the UNISOR facility. Time-sequenced spectra of γ -rays, X-rays, and conversion electrons have been obtained, together with $\gamma\gamma\text{t}$, γXt , e^-Xt , and $\text{e}^-\gamma\text{t}$ coincidence data. From this information, a decay scheme has been constructed, consisting of 26 excited states and 34 transitions. Electric monopole, E0 , transitions, strongly indicative of shape coexistence, have been found to de-excite positive-parity levels at 1125.8 and 1177.0 keV above the $13/2^+$ isomeric level in ^{195}Pb . The ground-state decay energy of ^{195}Bi is deduced to be $Q_{\text{EC}} = 4980 \pm 600$ keV from a γ -ray-gated K/β^+ ratio.

[J.C. Griffin, R. W. Fink, J. L. Wood, and other UNISOR coauthors],
Bull. Am. Phys. Soc. 32, 2145 (19870).

2.2 Decay of Mass Separated ^{185}Au to Levels in ^{185}Pt

This research constitutes part of the PhD thesis of Mr. Johannes Schwarzenberg in nuclear chemistry. The decay of 4.2 min ^{185}Au ($5/2^-$) to ^{185}Pt has been studied with mass separated sources from the UNISOR facility. The ^{185}Au activity was produced by the reaction $^{181}\text{Ta}(^{12}\text{C}, 8\text{n})$ at the Holifield Heavy Ion Research Facility. Multiscaled spectra, as well as $\gamma\gamma\text{t}$, $\text{X}\gamma\text{t}$, $\text{e}^-\gamma\text{t}$, and e^-Xt coincidence data, were obtained. These data are of high statistical quality (215 million $\gamma\gamma$ and 152 million $\text{e}^-\gamma$ coincidence events). A number of very highly converted low-energy (300 - 600 keV) transitions have been identified and located in a level scheme for ^{185}Pt . We find significant disagreement with a previous study¹⁾. These very converted transitions are consistent with $\text{E0} + \text{M1}$ multipolarity, contrary to ref. 1. The structure

¹ B. Roussiere, et al., Nucl. Phys. A438, 93 (1985)

of ^{185}Pt , and in particular the E0 transitions, are discussed in terms of shape coexistence in this mass region. A preliminary report will be presented at the Santa Fe meeting of the American Physics Society in October, 1988.

2.3 Decay of Neutron-Deficient Rare Earth Nuclei

Leander and Moeller [1] have predicted the existence of large deformations in neutron-deficient nuclei with $N < 82$ and $Z > 50$. This region of deformation is close enough to the line of stability in the neutron-deficient Sm and Pm isotopes that the possibility of producing and studying their structure exists. Macroscopic calculations by Ragnarsson, et al. [2] around the neutron-deficient Sm, Gd nuclei have predicted stable prolate shapes except for the $N=76$ isotones where the gamma-degree of freedom is expected to give major effects. The nucleus ^{138}Sm has been found [3] to have not only a small prolate-oblate energy difference, but also a triaxial equilibrium shape.

Our interest in this region involves the systematic study of the change from spherical, through transitional, to deformed nuclei as the proton drip line is approached. In addition, the rotational gamma-bands in many of the even-even nuclei have yet to be identified. A transition from spherical to deformed shape in Sm isotopes with $N < 82$ has long been predicted on the basis of elementary shell structure considerations [4], and has been borne out by measurements [5] of yrast level energies down to $N=72$. The detailed nature of this shape transition is of interest in nuclear structure for comparison with the analogous shape transition at $N > 82$. Papers on the transition through triaxial shapes of the light Sm isotopes and on the structure of the gamma-soft ^{136}Pm nucleus have been published [3,6].

These studies support the characterization of the $^{136},^{138},^{140}\text{Sm}$ nuclei in terms of a triaxial intrinsic shape. Furthermore, the large change in the $2+$ energy between ^{134}Sm and ^{140}Sm can be understood within the framework of the deformed shell model by taking into account triaxial rotation of the heavier isotopes, which tends to increase the $2+$ energy.

Our studies of even-even rare-earth nuclei consisted of a series of experiments carried out using the He-jet transport system on-line to HHIRF. While the He-jet system has the advantage of enhancing the yields of rare-earth activities, it is at the sacrifice of mass identification. The activities were produced by bombarding enriched ^{92}Mo foil targets with 250 MeV ^{46}Ti ion beams and ^{112}Sn targets with 190 MeV ^{28}Si beams. The data consisted of gamma-gamma-t coincidence and time-sequenced gamma-ray spectra, with typical counting rates of 12,000 and 40,000 counts/sec, respectively.

Our studies of odd-mass nuclei in this deformed region centers on the 135 and

137 mass chains. Of particular interest are the studies of the decay of ^{137}Sm to levels in ^{137}Pm and of ^{135}Pm to levels in ^{135}Nd .

It is in the $N=76$ isotones that the gamma-degree of freedom is expected to come into play. The activities of ^{137}Sm were produced by bombarding stacked foils of natural Mo with ^{48}Ti beams with on-line mass separation at UNISOR. The experiments consisted of gamma-gamma-t and ce-gamma-t coincidence as well as gamma-ray singles and ce- singles spectrometry. The level scheme is in essential agreement with that of Redon, et. al.[7] with the exception of the spin-parity assignments, which in their case were based solely on systematics. Whereas in the heavier odd-mass Pm isotopes, the $11/2^-$ state is observed to be an excited state, in ^{137}Pm , this odd-proton state drops in energy to become the ground state.

The $11/2^-$ assignment for the ground state of ^{137}Pm is of particular interest in relation to the heavier odd-mass Pm isotopes. In the heavier odd-A Pm isotopes, E3 transitions are observed between the $11/2^-$ excited state and the $5/2^+$ ground state. In ^{137}Pm , however, no transition with E3 multipolarity is established. The lack of this observation reinforces our conclusion that, as with other $N=76$ isotones, a decoupled band structure exists with both the $11/2^-$ and $7/2^-$ members coming low enough in energy to both be below the $5/2^+$ state. A paper on the decay of 45 sec ^{137}Sm to levels in ^{137}Pm is in preparation.

The non-yrast structure of ^{135}Nd has been studied following the beta-decay of mass-separated ^{135}Pm . The parent ^{135}Pm has $11/2^-$ and $5/2^+$ isomers with half-lives of 40 ± 3 sec and 49 ± 3 sec, respectively. The low-spin structure of ^{135}Nd (Fig. 1) is shown to consist of a group of levels which decay to a 65.1-keV isomeric state, not populated in the yrast cascade. The expected 65.1-keV, $(1/2^+) \rightarrow 9/2^-$, highly converted M4 transition was not observed.

Besides this low-spin, positive-parity structure, a number of transitions populating a negative parity band were observed. The strongest of these gamma-rays is the 198.8-keV transition deexciting the $11/2^-$ state and populating the $9/2^-$ ground state. This transition is also observed in the yrast ground-state band. The 713.2-keV level is the only level observed to decay to both band structures, thus connecting the two structures. A short paper on the decay of ^{135}Pm to levels in ^{135}Nd has been submitted for publication [8].

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Z. Physik (1988) (submitted)

LIST OF POSTDOCTORATES SUPPORT IN FULL OR IN-PART SINCE February 1, 1965

Dr. Robert A. Braga (Presently: Staff Member, Chemistry, Georgia Tech)
Dr. John L. Wood (Presently: Assoc. Prof., Physics, Georgia Tech)
Dr. Kenneth R. Baker (Presently: Nuclear Regulatory Commission, Washington, D. C.)

Dr. H. U. Freund (Presently: Battelle Institut, Frankfurt, West Germany)
Prof. E. Kondaiah (Presently: Retired; Formerly: Tata Institute for Fundamental Research, Bombay, India; NSF Senior Postdoctorate under this contract)

Dr. K. W. D. Ledingham (Presently: Professor, Physics, Univ. of Glasgow, Scotland)
Dr. J. C. McGeorge (Presently: Research Associate, Physics, Univ. of Edinburgh, Scotland)
Prof. J. G. Pengra (Presently: Professor, Physics, Whitman College, Walla Walla, Wash.)

Dr. N. RanaKumar (Presently: Professor, Physics, Southern Tech Univ., Marietta, Georgia)
Prof. P. Venugopala Rao (Presently: Professor, Physics, Emory Univ., Atlanta, Georgia)
Dr. M.S. Rapaport (Presently: Soreq Nuclear Research Center, Yavne, Israel)
Dr. W.D. Schmidt-Ott (Presently: Professor, Univ. of Göttingen, West Germany, and GSI, Darmstadt, West Germany)

Dr. Mustafa Tan (Presently: Assoc. Prof., Univ. of Ataturk, Physics, Erzurum, Turkey)
Dr. Warren R. Western (Presently: Nuclear Data Corp., Schaumburg, Illinois)

Dr. Alexander C. Xenoulis (Presently: Nuclear Research Center Demokritos, Athens, Greece)
Dr. E. Vatai (Presently: Inst. of Nuclear Physics, Hungarian Academy of Science, Debrecen, Hungary)
Dr. R. E. Wood (Presently: Computer Operations, Southern Railroad, Atlanta, Georgia)
(Formerly: Asst. Prof., Physics, Emory Univ., Atlanta, Georgia)

LIST OF GRADUATE STUDENTS WHO OBTAINED DEGREES UNDER THIS CONTRACT SINCE Feb. 1, 1965

Johannes Schwarzenberg, PhD, Nuclear Chemistry (expected completion: June, 1989)

Dr. Paul Semmes, PhD, Nuclear Chemistry (June, 1985) (Presently: Inst. of Theoretical Physics, Univ. of Lund, Sweden)

Dr. Jeffrey C. Griffin, PhD, Nuclear Chemistry (1986) (Presently: Savannah River Laboratory, Aiken, South Carolina)

Dr. Bruce E. Gnade, PhD, Nuclear Chemistry (1982) (Presently: Texas Instrument Co., Dallas, Texas)

Major Allen D. Stroupauer, M.S. (June, 1983) (Presently: Sandia Lab, Albuquerque, N.M.) Nuclear Chemistry

Dr. William M. Chew, M.S. (March, 1972) and PhD (June, 1974), Nuclear Chemistry (Presently: Chevron Oil Field Research Co., California)

Dr. Gregory M. Gowdy, PhD, Nuclear Chemistry, (December, 1976) (Presently: South Carolina Electric and Gas Co., Nuclear Division; Formerly: Postdoct. at ORAU, GSI, Darmstadt, West Germany, and ORSAY, France)

Dr. Harald Genz, PhD, Nuclear Physics, Emory Univ., (November, 1971) (Presently: Prof. Physics, Technisches Hochschule, Darmstadt, West Germany)

Dr. Dale W. Nix, PhD, Nuclear Chemistry (August, 1974) (Presently: Radiochemist, TVA Nuclear Reactors, Sequoia, Chattanooga, Tennessee)

Ali Saleh, M.S., Nuclear Chemistry, Georgia Tech (August, 1976); PhD, Nuclear Chemistry, Univ. Arkansas (1981) (Presently: Asst. Prof., Chemistry, Univ. of Tripoli, Libya)

Dr. Marvin A. Grimm, Jr., PhD, Nuclear Physics (Nov. 1978) (Presently: Private Company)

Dr. Florian Tolea, PhD, Nuclear Chemistry (June, 1974) (Presently: Professor, Chemistry, Babesh-Bolyai Univ., Cluj, Romania)

Dr. J. Steven Hansen, PhD, Nuclear Engineering (March, 1971) (Presently: Theoretical Physics Division, Los Alamos Scientific Laboratory, Los Alamos, New Mexico)

Dr. Esko I. Karttunen, PhD, Nuclear Engineering (Feb. 1971) (Presently: Prof., Dept. of Radiochemistry, Univ. of Helsinki, Finland)

Dr. Saradamandiram Mohan, PhD, Nuclear Engineering (Sept., 1972) (Presently: Assoc. Prof. Physics, Regional Engineering College, Calicut, Kerala State, India)
Dr. Alice K. Hankla, PhD, Nuclear Physics (June, 1971) (Vanderbilt Univ.)
Dr. Wen-deh Lu, PhD, Nuclear Chemistry (August, 1970) (Presently: Institute of Nuclear Energy Research, Taiwan, Republic of China)
Jean Paul Renier, M.S. Nuclear Chemistry (June, 1975) (Presently: Consultant in Nuclear Power, Oak Ridge, Tennessee)
Major John Uecke, M.S. Nuclear Chemistry (June, 1975). (Presently: U.S. Army)
Major Jerry C. Pate, M.S., Nuclear Chemistry (June, 1974) (Presently: U.S. Army)
I. Unus, M.S. Nuclear Engineering (1972), Georgia Tech, and PhD, Nuclear Physics, Emory Univ.)

OTHER STUDENTS:

Cesar P. Perez, Nuclear Chemistry (1983-1988) Completing M.S. degree
Chris Papanicolopoulos, Nuclear Chemistry (1975-1980) Completed PhD degree in Nuclear Physics (1987). (Presently: Georgia Tech Research Institute, Atlanta, Georgia)

LIST OF PUBLICATIONS SINCE FEB. 1, 1965, RESULTING FROM THIS CONTRACT
(Publication number is that on the master list going back to 1950)

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