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Radiochemical Investigations of Nuclear Properties

Patrick J. Daly, Principal Investigator

Progress Report for the period October 1972 to September 1973

A.E.C. Contract AT(11-1)-1672

Department of Chemistry

**Purdue University
Lafayette, Indiana**

September 1973

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I Research Activities

In the past year, our research has again emphasized studies of the structure of nuclei in the transitional region $A = 180-200$, using various types of nuclear spectroscopy. It has been an unusually productive year during which three excellent graduate students attained their Ph.D. degrees and the results of many of our recent studies have either been published or are in the process of publication. Only a brief survey of our research activities is given below, since the detailed results of the investigations are mostly available in the recent literature.

1.1 The new 12^- isomer ^{198m}Au

(Cunnane, Daly)

A paper describing our discovery¹⁾ and characterization of 2.3 d ^{198m}Au and the elucidation of the ^{198}Au low-energy level structure has been published. (Phys. Rev. C6 (1972) 1407). Subsequently, Pakkanen et al²⁾ and Bacon³⁾ have studied the properties of ^{198m}Au and their results support our proposal of $(h_{11/2}^{\pi}, i_{13/2}^{\nu})12^-$ for the configuration of the 2.3 d isomeric state. Furthermore very recent (n,γ) measurements by Mirza et al⁴⁾ have confirmed our interpretation of the 123 ns 5^+ state at 312 keV in this nucleus.

1.2 Levels in ^{200}Hg from ^{200m}Au decay and $^{198}\text{Pt}(\alpha, 2n\gamma)$ in-beam spectroscopy

(Cunnane, Hochel, Yates, Daly)

The results¹⁾ of this investigation have also been published (Nucl. Phys. A196 (1972) 593) and they have been subsequently confirmed by Bacon et al⁵⁾. Of particular interest in ^{200}Hg is a $5^-, 7^-, 9^-, 11^-$ sequence of levels which are connected by enhanced E2 transitions and appear to constitute a favoured

band of yrast levels. In the odd-mass Hg isotopes, Proetel et al⁶⁾ have recently reported well developed decoupled bands built on the known $i_{13/2}^v$ states. At present it seems that the 5^- , 7^- , 9^- , 11^- sequence in ^{200}Hg is probably analogous to the decoupled bands in the odd Hg nuclei and may be describable by the rotation-aligned scheme in terms of coupling of the $i_{13/2}^v$ with low-j neutrons in the $p_{3/2}$, $p_{1/2}$ and $f_{5/2}$ orbitals. Unfortunately the computational difficulties involved in performing rigorous Coriolis coupling calculations for the case of two particles outside an even-even core are formidable, but we have been encouraging several interested nuclear theorists to tackle the problem. In any case, the discovery of the 5^- , 7^- , 9^- , 11^- sequence in ^{200}Hg has stimulated us to search for and study similar sequences of levels in other even-even Hg, Pt and Os nuclei. (See Section 1.7).

1.3 Levels of ^{184}W from the decay of ^{184}Ta

(Yates, Daly - with Johnson, Aras, ORNL)

and

Collective and two-quasiparticle excitations in ^{182}W and ^{184}W

(Daly - with Kleinheinz, Casten, Niels Bohr Institute)

The results of these complementary studies of excitation modes in even W nuclei by radioactive decay and single neutron transfer spectroscopy were summarized in last year's report¹⁾ and they have since been written up and published (Nucl. Phys. A204 (1973) 33 and Nucl. Phys. A208 (1973) 93).

1.4 The Level Structure of ^{184}Os from ^{184}Ir decay and $^{185}\text{Re}(p,2n\gamma)$ In-beam Spectroscopy

(Hochel, Daly - with Hofstetter, University of Kentucky)

This first detailed study of levels in ^{184}Os extended over several years,

since the decay of 3.1 h ^{184}Ir is extremely complicated and extensive measurements were necessary to establish a decay scheme accommodating all the strong transitions observed in the decay and in-beam work. A simplified level diagram showing only the ground state, γ -vibrational and $K^\pi=3^-$ octupole bands established in this nucleus is shown in Fig. 1 and the more detailed results and a discussion of their significance may be found in our recent article (Nucl. Phys. A211 (1973) 165).

1.5 Strong Rotation-Particle Coupling and the ground-state configurations of ^{184}Ir and ^{186}Ir

(Hochel, Daly - with Emery, Indiana University and Hofstetter, University of Kentucky)

A strange feature of the decay of the odd-odd nucleus ^{184}Ir (see preceding section) is that the 4^+ and 6^+ members of the ^{184}Os ground band are directly populated in the EC with log ft values indicative of allowed or first forbidden transitions. This implies a spin of 5 and a K-value of 0 or 1 for the ^{184}Ir ground state. A re-examination of the available data for the ^{186}Ir EC decay revealed that the ^{186}Ir ground state probably also has $J=5$ and $K=0$ or 1. When we considered the possibility that the Nilsson proton orbital $[541\frac{1}{2}]$ might be involved in the light odd-odd iridium nuclei we found some interesting properties of coupled rotational bands involving an orbital with $\Omega = 1/2$ and a large decoupling parameter. The $[541\frac{1}{2}]$ assignment for the proton in the ground state configurations of ^{184}Ir and ^{186}Ir was seen to be plausible and the level ordering in these nuclei may be largely determined by the properties of the $[541\frac{1}{2}]$ orbital stemming from the $j = 9/2$ spherical state, while the perturbing effects of a low- Ω neutron partner ($[510\frac{1}{2}]$ or

[512+]) should be relatively insignificant.

1.6 The ^{190}Os Level Structure from the decay of the ^{190}Re and ^{190}Ir isomers and from the $^{189}\text{Os}(d,p)^{190}\text{Os}$ Reaction

(Yates, Cunnane, Daly - with Thompson, Sheline, Florida State University)

Our preliminary results on the decay of the 3 min and 3 h isomers of ^{190}Re were summarized in last year's annual report¹⁾. Since then, these studies have been completed and a re-investigation of the EC decay of ^{190}Ir has also been carried out because many of the same ^{190}Os levels are populated in the ^{190}Ir and ^{190m}Re decays. Extensive decays schemes based on all the measurements have been constructed. Near the conclusion of this work, we learned that Thompson and Sheline (Florida State) were investigating the ^{190}Os level structure by means of the (d,p) reaction. Since it has been our experience that a combination of radioactivity and transfer reaction results leads to a much deeper insight into nuclear structure phenomena, we decided to pool our results. The outcome has been an article, discussing many aspects of the ^{190}Os level structure, which has recently been accepted for publication in Nucl. Phys.

1.7 High-spin Negative Parity States in Even-Even Os, Pt and Hg Nuclei

(Yates, Cunnane, Hochel, Daly)

Following our discovery of the 5^- , 7^- , 9^- , 11^- sequence of levels in ^{200}Hg , we undertook a systematic search for similar level sequences in other even-even Hg, Pt and Os nuclei by means of in-beam γ -ray spectroscopy at the Purdue Tandem Laboratory. The reactions investigated included (p,2n γ) on enriched Re and Ir targets and (α ,2n γ) on W, Os and Pt targets. Gamma-ray singles, γ - γ coincidence and γ -ray anisotropy measurements were performed.

The level energies in (keV) of the negative parity levels are summarized in the following table.

Nucleus	5^-	7^-	9^-	References
^{186}Os	1629	1775		
^{188}Os	1668	1771		
^{190}Pt	1464	1631	2222	
^{192}Pt	1384	1518	2103	
^{194}Pt	1374	1485	2048	7), 8)
^{196}Pt	1271	1374	1821	9), 8)
^{196}Hg	1757	1841		8), 10)
^{198}Hg	1636	1684		8), 10)
^{200}Hg	1852	1963	2144	

In the Pt and Hg nuclei these levels are connected by enhanced E2 transitions and they play a major role in the yrast cascades. The E1 transitions to members of the quasi-ground state bands (such as $7^- \rightarrow 6^+$ or $5^- \rightarrow 4^+$) are generally retarded by about a factor of 10^5 . The available evidence suggests that these sequences (see also Section 1.2) involve combinations of the decoupled $i_{13/2}$ neutron with low-j neutron partners, although two-proton components involving the $h_{11/2}$ proton may also contribute.

In the $(\alpha, 2n)$ reactions into the even-even Os nuclei the negative parity levels are much less strongly populated. Here, the 5^- levels de-excite predominantly to $K^\pi = 4^+$ bands (based at 1352 keV in ^{186}Os and 1278 keV in ^{188}Os), which are almost certainly analogous to the 1163 keV $K^\pi = 4^+$ two-phonon γ -vibration in ^{190}Os . Since in this region, decoupled $i_{13/2}$ bands are expected only in oblate nuclei, the observed difference between the negative parity levels in Os and those in Pt, Hg may be due to the change from oblate to prolate shapes in passing from Pt to Os nuclei.

These results were reported at the Nuclear Chemistry Gordon Conference and at the Munich Conference, and they will soon be written up for publication.

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II Publication Abstracts

Abstracts are given for articles published or submitted to journals during the period covered by this report.

New High-Spin Isomer 2.3-Day ^{198m}Au and the ^{198}Au Level Structure, J. C. Cunnane and P. J. Daly, Phys. Rev. C6 (1972) 1407

In 18-MeV deuteron bombardments of enriched ^{200}Hg , we have produced a new isomer 2.27 ± 0.05 -day ^{198m}Au , which is believed to be analogous to the $(h_{11/2}^{\pi}, i_{13/2}^{\nu})12^{-}$ isomer in ^{196}Au . No β^{-} branching is observed in the decay of ^{198m}Au . The isomeric transition is followed by a cascade of 204.10- and 180.31-keV γ rays to a 123-nsec level at 312.10 keV which deexcites to ground by a sequence of 97.21-keV (E1) and 214.89-keV (E2) transitions. A revised interpretation of the results of earlier (n, γ) and (d,p γ) studies of the ^{198}Au level structure is presented and shell-model assignments for the levels populated in the isomeric decay are proposed. It is argued that the E1 deexcitation of the 123-nsec isomer involves the 1-forbidden single-particle transition $(d_{3/2}^{\pi}, i_{13/2}^{\nu})5^{+} \rightarrow (d_{3/2}^{\pi}, f_{5/2}^{\nu})4^{-}$.

High-Spin Negative-Parity States in ^{200}Hg from ^{200m}Au Decay and $^{198}\text{Pt}(\alpha, 2n\gamma)$ Reaction Spectroscopy, J. C. Cunnane, R. Hochel, S. W. Yates and P. J. Daly, Nucl. Phys. A196 (1972) 593

Levels in ^{200}Hg populated in the β^{-} decay of the 19 h isomer of ^{200}Au and in the reaction $^{198}\text{Pt}(\alpha, 2n\gamma)^{200}\text{Hg}$ have been investigated. The β -decay populates an 11^{-} level in ^{200}Hg at 2642 keV, which de-excites through levels at the following energies (spin-parities): 2144(9^{-}), 1963(7^{-}), 1852(5^{-}), 1707(6^{+}), 947(4^{+}) and 368(2^{+}) keV. The relative γ -ray intensities measured

in the in-beam experiment were invaluable in the construction of an unambiguous ^{200}Hg level spectrum. The $9^- \rightarrow 7^-$ and $7^- \rightarrow 5^-$ E2 transitions are considerably enhanced suggesting that the negative-parity levels constitute a collective "band." It is proposed that the β^- decay involves a one-particle transition between the $(h_{11/2}^\pi, i_{13/2}^\nu)12^-$ isomer of ^{200}Au and a $(h_{9/2}^\nu, i_{13/2}^\nu)$ two-neutron admixture in the ^{200}Hg 11^- state. Indications of the systematic occurrence of similar sequences of negative-parity levels in other $A = 190$ - 200 transitional nuclei are discussed.

The Level Structure of ^{184}W from the β^- Decay of ^{184}Ta , S. W. Yates, P. J. Daly, Noah R. Johnson and N. K. Aras, Nucl. Phys. A204 (1973) 33

Levels of ^{184}W populated in the decay of 8.7 h ^{184}Ta have been studied by a variety of experimental techniques. As a result of β^- and γ -ray energy and intensity determinations and extensive β - γ and γ - γ coincidence measurements, a detailed ^{184}Ta decay scheme accommodating more than 99.5% of the decay intensity has been established. Intense β -ray groups of end-point energies 1165 ± 26 and 1123 ± 26 keV populate levels in ^{184}W at 1699 and 1746 keV, which deexcite predominantly to the 8.3 μs isomeric level at 1285 keV, recently identified as the $1/2^- [510]\nu - 11/2^+ [615]\nu$ $K^\pi = 5^-$ band origin. The 1699 keV level also de-excites to members of a $1/2^- [510]\nu - 7/2^- [503]\nu$ $K^\pi = 3^+$ band based at 1425 keV. New information about the properties of the γ -vibrational and $K = 2$ octupole bands in ^{184}W is presented and the possible configurations of the levels directly populated in the β^- decay are discussed. The configuration $7/2^+ [404]\pi - 3/2^- [512]\nu$ $K^\pi = 5^-$ is indicated for the ^{184}Ta ground state.

Properties of Nuclear States in $^{182}_{75}\text{Re}$ Populated in the Decay of $^{182}_{76}\text{Os}$ (22 h),
S. B. Burson, P. J. Daly, P. F. A. Goudsmit and A. A. C. Klaasse, Nucl. Phys.
A204 (1973) 337

Information about the excited states of the doubly odd nucleide $^{182}_{75}\text{Re}$ has been deduced from studies of the radioactive precursor, $^{182}_{76}\text{Os}$ (22 h). The γ -ray spectra were measured with several Ge(Li) detectors; the internal-conversion-electron groups were studied with Si(Li) and magnetic spectrometers. Delayed as well as prompt γ - γ coincidence experiments were performed. Fifty-seven transitions are reported in the energy region below 800 keV; 41 of these are assigned between 14 excited states (not including the ground state). The energies of the excited states are determined by making a least-squares fit to the γ -rays assigned between the various pairs of levels. Spin and parity assignments are proposed for most of the levels. An interpretation of some of the states is presented in terms of the Nilsson model and the Gallagher-Moszkowski coupling rules. The half-life of the level at 235.77 keV was measured to be 570 ± 30 ns (in agreement with the value reported by Akhmadzhanov et al.) Reasons are presented for interpreting this level as the $(p[402]\uparrow - n[521]\downarrow)$, $I^\pi = 2^-$ configuration; decay to the ground-state band is thus threefold Ω -forbidden. The influence of this forbiddenness on transition probabilities is discussed.

Two-Quasiparticle States and the Microscopic Composition of $K^\pi = 2^+$ Collective Excitations in ^{182}W and ^{184}W , P. Kleinheinz, P. J. Daly and R. F. Casten, Nucl. Phys. A208 (1973) 93

Energy levels of ^{182}W and ^{184}W have been investigated by (d,p), (d,t) and (τ , α) reactions on enriched ^{183}W targets. In the deuteron induced reactions, the reaction products at 60°, 90° and 125° were magnetically analysed

and approximate 1-transfer values were deduced from the cross-section ratios at these angles. The (τ, α) measurements provided important complementary data locating several ^{182}W states populated with $l = 6$ transfer. The two-neutron configurations identified include $9/2[624]$, $1/2[510]$ $K^\pi = 4^-$ and 5^- , $3/2[512]$, $1/2[510]$ $K^\pi = 2^+$ and 1^+ , and tentatively $1/2[521]$, $1/2[510]$ $K^\pi = 1^+$ in ^{182}W , and $11/2[615]$, $1/2[510]$ $K^\pi = 5^-$ and (6^-) , $7/2[503]$, $1/2[510]$ $K^\pi = 3^+$ and (4^+) , and $3/2[512]$, $1/2[510]$ $K^\pi = 2^+$ and (1^+) in ^{184}W . The results also provide valuable insight into the microscopic structure of the γ -vibrations and higher-lying $K^\pi = 2^+$ excitations in these nuclei and made possible a detailed test of the predictions of microscopic calculations. Our analysis indicates that the distinct difference in the observed collective character of the higher-lying $K^\pi = 2^+$ excitations in the two nuclei is associated with the $N = 108$ energy gap in the Nilsson diagram.

The Level Structure of ^{184}Os from ^{184}Ir Decay and $^{185}\text{Re}(p, 2n\gamma)$ In-Beam Spectroscopy, R. Hochel, P. J. Daly and K. J. Hofstetter, Nucl. Phys. A211 (1973) 165

Levels of ^{184}Os populated in the decay of $3.1\text{ h }^{184}\text{Ir}$ and in the $^{185}\text{Re}(p, 2n\gamma)$ reaction have been investigated. The measurements included γ -ray singles, β^+ ray endpoint, conversion coefficient, $\beta^+-\gamma$ coincidence and detailed γ - γ coincidence determinations. The results have established an extensive ^{184}Os level scheme, which includes well developed ground state, γ -vibrational and $K = 3$ octupole bands and which accommodates all the intense transitions observed in both the radioactivity and in-beam γ -ray measurements. Deviations of the level energies in the $K^\pi = 0^+$ and $K^\pi = 2^+$ bands and of the interband reduced transition probabilities from the predictions of the strong-coupling model are discussed in terms of the rotation-vibration interaction, and the

systematics of the octupole vibrational excitations in even-mass W and Os nuclei are reviewed. It is concluded that the ^{184}Ir ground state configuration has a spin of 5, and that it contains large admixtures of $K = 0$ or $K = 1$ character.

Effects of Strong Rotation-Particle Coupling on the Energy Levels of Two-Quasiparticle Systems with Possible Application to ^{184}Ir and ^{186}Ir , G. T.

Emery, R. Hochel, P. J. Daly and K. J. Hofstetter, Nucl. Phys. A211 (1973) 189

The consequences of the availability of the $[541\frac{1}{2}^+]$ proton orbital in light even-mass Ir nuclei are examined. The structure of rotational bands in which the state of lowest energy is not the state of minimum angular momentum is described in terms of an effective decoupling parameter. The $[541\frac{1}{2}^+]$ assignment for the proton in the ground state configurations of ^{184}Ir and ^{186}Ir is seen to be plausible and the level ordering in these nuclei may be largely determined by the properties of the $[541\frac{1}{2}^+]$ orbital stemming from the $j = 9/2$ spherical state, while the perturbing effects of a low- Ω neutron partner ($[510\frac{1}{2}^+]$ or $[512\frac{1}{2}^+]$) should be relatively insignificant. Other interesting consequences of this description are also discussed.

Levels of ^{190}Os Populated in the Decays of $3.3\text{ h }^{190\text{m}}\text{Re}$ and $12\text{ d }^{190}\text{Ir}$ and in the $^{189}\text{Os}(d,p)^{190}\text{Os}$ Reaction, S. W. Yates, J. C. Cunnane, P. J. Daly, Roger Thompson and R. K. Sheline, submitted to Nucl. Phys.

The level structure of ^{190}Os has been investigated by the techniques of radioactive decay and neutron transfer reaction spectroscopy. The existence of $3.3\text{ h }^{190}\text{Re}$ has been confirmed; it decays ~49% by isomeric transitions and ~51% by β^- decay to levels in ^{190}Os with spins ≥ 5 . In a re-investigation of the $12\text{ d }^{190}\text{Ir}$ decay, a virtually complete decay scheme has been established

and discrepancies between the I^π values assigned to several ^{190}Os levels by earlier workers have been resolved. The reaction $^{189}\text{Os}(d,p)^{190}\text{Os}$ has been studied and information about the locations of two-quasiparticle states involving the $3/2[512]v$ orbital and about the microscopic compositions of collective excitations has been derived. Various aspects of the ^{190}Os level structure are discussed in the light of the combined radioactivity and transfer reaction results.

III Personnel

Senior Staff

Dr. P. J. Daly, Associate Professor of Chemistry, Principal Investigator

Dr. J. C. Cunnane, Research Associate^{*}

Dr. Matti Piiparinen, Research Associate (from Sept. 1973)

Graduate Students

R. C. Hochel^{**}

S. W. Yates^{***}

S. K. Saha (from Sept. 1973)

Service Staff

E. Grenat, part-time electronics technician

^{*} Half-time Appointment.

^{**} Graduated May 1973; Now at Savannah River.

^{***} Graduated June 1973; Now at Argonne N. L.

IV Publications, Theses and Talks

New High-spin Isomer 2.3-day ^{198}Au and the ^{198}Au Level Structure, J. C.

Cunnane and P. J. Daly, Phys. Rev. C6 (1972) 1407.

High-spin Negative Parity States in ^{200}Hg from $^{200\text{m}}\text{Au}$ Decay and $^{198}\text{Pt}(\alpha, 2n\gamma)$

Reaction Spectroscopy, J. C. Cunnane, R. Hochel, S. W. Yates and P. J. Daly,

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The Level Structure of ^{184}W from the β^- -decay of ^{184}Ta , S. W. Yates, P. J.

Daly, N. R. Johnson and N. K. Aras, Nucl. Phys. A204 (1973) 33

Properties of Nuclear States in ^{182}Re Populated in the Decay of ^{182}Os , S. B.

Burson, P. J. Daly, P. F. A. Goudsmit and A. A. C. Klaasse, Nucl. Phys. A204

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Two-Quasiparticle States and the Microscopic Composition of $K^\pi = 2^+$ Collective

Excitations in ^{182}W and ^{184}W , P. Kleinheinz, P. J. Daly and R. F. Casten,

Nucl. Phys. A208 (1973) 93

The Level Structure of ^{184}Os from ^{184}Ir Decay and $^{185}\text{Re}(p, 2n\gamma)$ In-Beam Spectro-

scopy, R. Hochel, P. J. Daly and K. J. Hofstetter, Nucl. Phys. A211 (1973) 165

Effects of Strong Rotation-Particle Coupling on the Energy Levels of Two-

Quasiparticle Systems with Possible Application to ^{184}Ir and ^{186}Ir , G. T. Emery,

R. Hochel, P. J. Daly and K. J. Hofstetter, Nucl. Phys. A211 (1973) 189

High Spin Negative Parity States in Even-even Os, Pt and Hg Nuclei, P. J. Daly,

J. C. Cunnane, S. W. Yates and R. Hochel, Proc. Int. Conf. on Nucl. Physics,

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Levels of ^{190}Os Populated in the Decays of 3.3 h $^{190\text{m}}\text{Re}$ and 12 d ^{190}Ir and in the $^{189}\text{Os}(d,p)^{190}\text{Os}$ Reaction, S. W. Yates, J. C. Cunnane, P. J. Daly, R. Thompson and R. K. Sheline, accepted for publication in Nucl. Phys. (1973)

Ph.D. Theses

Level Structures in Even Os Nuclei from Radioactive Decay and In-Beam γ -ray Spectroscopy, R. Hochel, May, 1973

Nuclear Level Structure Investigations in Even-Even Tungsten, Osmium and Platinum Nuclei by Radioactive Decay and In-Beam Gamma-Ray Spectroscopy, S. W. Yates, June, 1973

Studies of Levels in Even Mass Hg and Au Nuclei in the Range A - 196-200 Using Radioactive Decay and In-Beam γ -ray Spectroscopy, J. C. Cunnane, July, 1973

Talks

"The Structure of Nuclei," Physical Chemistry Seminar, Purdue University, Oct. 1972 - P. J. Daly

"High-Spin Isomers in ^{198}Au and ^{200}Au ," Nuclear Chemistry Seminar, Purdue University, Nov. 1972 - J. C. Cunnane

"High-Spin Negative Parity States in ^{200}Hg from $^{200\text{m}}\text{Au}$ Decay and ^{198}Pt ($\alpha, 2n\gamma$) Spectroscopy," American Physical Society, Seattle, Nov. 1972 - P. J. Daly; Bull. Am. Phys. Soc. 17 (1972) 927

"Level Systematics in ^{184}Os , ^{186}Os , ^{188}Os and ^{190}Os from Combined Radioactivity and In-Beam γ -ray Studies," American Physical Society, Washington, D. C., April, 1973 - S. W. Yates; Bull. Am. Phys. Soc. 18 (1973) 700

"Studies of ^{184}Os , ^{186}Os and ^{188}Os by Decay and In-Beam Spectroscopy,"

Nuclear Chemistry Seminar, Purdue University, April 1973 - R. Hochel

"Negative Parity Decoupled Bands in Even Hg, Pt and Os Nuclei," Gordon Conference on Nuclear Chemistry, New Hampshire, June 1973 - P. J. Daly

"Levels in ^{190}Pt , ^{192}Pt and ^{194}Pt from $(p,2n\gamma)$ and $(\alpha,2n\gamma)$ Spectroscopy,"

American Chemical Society, Chicago, Aug. 1973 - S. W. Yates

"The Level Structure of ^{188}Os and ^{190}Os from Radioactivity and In-beam

γ -ray Measurements," American Chemical Society, Chicago, Aug. 1973 -

J. C. Cunnane

"Spectroscopy Studies in the $A = 180$ -200 Transitional Region," Nuclear

Seminar, Institut für Kernphysik, Jülich, Aug. 1973 - P. J. Daly