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Progress Report

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Patrick J. Daly
Principal Investigator

MASTER

Purdue University, West Lafayette, Indiana 47907

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Abstract

Investigations of the high-spin level spectra of the nuclei ^{200}Pb , ^{202}Pb and ^{188}Os have been completed and the results are summarised. The results of collaborative studies of high-spin excitations in ^{147}Tb and ^{148}Tb are also briefly reported. New studies of $A \sim 150$ nuclei at very high angular momenta have been started using heavy-ion beams from the Argonne Tandem-Linac.

I. Research Activities

This past year has been a period of transition for our research program. In the early part of the year all efforts were concentrated on the completion of our experimental projects at the Michigan State University Laboratory before the shutdown of the 50 MeV machine. The planned investigations of the high-spin level spectra of the nuclei ^{200}Pb , ^{202}Pb and ^{188}Os were carried through and the results are summarized below. Later in the year we transferred operations to Argonne National Laboratory and started on new collaborative investigations of nuclear structure using heavy ion beams from the ANL superconducting Linac. The initial experiments at Argonne are also described briefly below. Our work in the high-spin excitation modes of nuclei near doubly magic ^{146}Gd has also been continued in collaboration with P. Kleinheinz (Jülich) and J. Blomqvist (Stockholm) and interesting new results have been obtained.

High-spin yrast states in ^{200}Pb and ^{202}Pb

We have investigated the high-spin level structures of these neutron deficient Pb nuclei by (α, xn) and $(^{13}\text{C}, 5n)$ reactions. The measurements have included γ -ray singles, comprehensive $(\gamma\gamma t)$ coincidences, t_{YRF} determinations over a 2-500ns time range, and γ -ray angular distributions. Conversion electron spectra were also recorded using a solenoid spectrometer, but the data were extremely complex and ultimately did not yield much useful information. The γ -ray measurements established extensive level schemes built on the known 9^- isomers of $\nu i_{13/2}^{-1} f_{5/2}^{-1}$ character, as shown in Figs 1 and 2. In interpreting the data, two formidable sources of difficulty were encountered. While clear evidence was obtained for the four Δ - transitions shown in the figures, none of these transitions was directly observed and all we can say about their energies is that they are less than 60 keV. The other big problem was that

the many isomers limited the usefulness of the angular distribution results in deciding transition multipolarities. Consequently, the spin-parity assignments for the higher-lying levels in Figs 1 and 2 are not as firmly based as those obtained in our earlier MSU studies.

The $(\nu i_{13/2}^{-2}) 12^{+}$ isomers at about 3 MeV excitation in ^{200}Pb and ^{202}Pb mark the dividing line between the seniority-two neutron hole states and higher-lying more complex excitations. The observed level spectra strongly indicate that the alignment of two $i_{13/2}$ holes, which generates 12 units of angular momentum at low cost in excitation energy, also has a crucial influence in the extension of the yrast lines above the 12^{+} isomers. It appears that the higher yrast states in the Pb nucleus A are closely related to the known low-lying states of the Pb nucleus A+2. For example, the yrast 12^{+} , 14^{+} , 16^{+} , 17^{-} and 19^{-} states in ^{200}Pb are interpreted as the 0^{+} , 2^{+} , 4^{+} , 7^{-} and 9^{-} states of ^{202}Pb coupled with two fully aligned $i_{13/2}$ holes; the spins of the negative parity states, which involve three $i_{13/2}$ holes, are naturally limited by the Pauli blocking.

With the expert assistance of Jan Blomqvist, we are attempting a more quantitative interpretation of these level spectra using empirical single particle energies and nucleon-nucleon interactions derived from simpler nuclei in the Pb region.

Negative Parity Isomers in Even-A Os Nuclei

Several years ago, we reported¹⁾ the systematic occurrence of 5^{-} , 7^{-} , 9^{-} level sequences in even A Hg, Pt, and Os nuclei, and speculated that they might all involve the coupling of a rotation-aligned $i_{13/2}$ neutron with a low j neutron partner. Subsequent experimental²⁾ and theoretical³⁾ work has confirmed that this is indeed the nature of these semi decoupled bands in the oblate Pt and Hg nuclei, but the situation in the prolate Os nuclei

has not been clarified hereto.

We have therefore performed a detailed in-beam study of the negative parity level structure in ^{188}Os using the reaction $^{186}\text{W}(\alpha, 2n\gamma)$. It turned out that in this nucleus both the 7^- and 9^- levels are isomeric. The relevant portion of the ^{188}Os level scheme is shown as an inset in Fig. 3. The half-life of the 9^- state was straight forwardly determined from a $t_{\gamma\text{RF}}$ measurement (Fig. 3a)

$$T_{1/2}(9^-) = 10 \pm 1 \text{ ns}$$

while the 7^- half-life was obtained from $t_{\gamma\gamma}$ coincidence data (fig. 3b)

$$T_{1/2}(7^-) = 16 \pm 2 \text{ ns.}$$

We also remeasured the half-life of the 7^- level in ^{186}Os to be $8 \pm 1 \text{ ns}$.

The reduced transition probabilities for the $7^- \rightarrow 5^-$ in ^{186}Os and ^{188}Os are given in Table 1 together with the previously known values for $7^- \rightarrow 5^-$ transitions in ^{184}W , ^{190}Pt , ^{192}Pt and for the $2^+ \rightarrow 0^+$ transitions in all five nuclei.

Table 1. Reduced transition probabilities in W, Os and Pt nuclei.

Nucleus	<u>B(E2) in Weisskopf Units</u>	
	$7^- \rightarrow 5^-$	$2^+ \rightarrow 0^+$
^{184}W	3.0	430
^{186}Os	8.8	220
^{188}Os	10.4	140
^{190}Pt	33	70
^{192}Pt	37	70

In the Pt nuclei, the $7^- \rightarrow 5^-$ transitions are obviously collective and are as fast, within a factor of two, as the $2^+ \rightarrow 0^+$ transitions; this is in fact the principal argument for the rotation alignment interpretation of the 5^- , 7^- , sequences in Pt. At the other extreme the $7^- \rightarrow 5^-$ transition in ^{184}W is more than 100 times slower than the $2^+ \rightarrow 0^+$ and is described⁴⁾ in strong coupling terms as a transition between the Nilsson two quasiparticle states $3/2[512] - 11/2[615]$ $I, K^\pi = 7, 7^-$ and $1/2[510] - 11/2[615]$ $I, K^\pi = 5, 5^-$. The present results establish intermediate characteristics for the $7^- - 5^-$ transitions in the Os

nuclei. Since they are much less collective than the corresponding transitions in Pt, we can firmly conclude that the semidecoupled band description is not applicable to the negative parity levels in even - A Os nuclei.

The high quality $\gamma\gamma$ coincidence data also revealed many new negative parity levels in ^{188}Os . These could be arranged into well developed bands and classified using the Nilsson Model, although clearly this model also has limitations in this region of nuclei. The bands identified include $11/2[615] - 1/2[510]$ $K^\pi = 5^-$ and 6^- , $11/2[615] - 3/2[512]$ $K^\pi = 7^-$, $11/2[615] - 7/2[503]$ $K^\pi = 9^-$ and $11/2[615] - 9/2[505]$ $K^\pi = 10^-$. In this scheme the 284 keV transition (Fig. 3) occurs between the 9^- and 7^- bandheads by a $7/2^-[503] \rightarrow 3/2^-[512]$ one particle E2 transition. The $B(E2)$ value extracted from the 9^- half-life is consistent with this interpretation.

Structure of ^{146}Gd and adjacent few-particle nuclei

Our last annual report⁵⁾ summarized the Jülich-Stockholm-Purdue investigations which showed that the $Z=64$, $N=82$ nucleus ^{146}Gd has many of the properties of a doubly closed shell nucleus. The detailed results of our spectroscopic studies of ^{146}Gd and ^{147}Gd were published⁶⁾ this year. They aroused much interest among nuclear structure scientists, and the magic character of ^{146}Gd was thoroughly discussed at the Argonne High-Spin Conference, the Nuclear Chemistry Gordon Conference and at several other meetings.

We have now also completed our studies of the $Z = 65$ nuclei ^{147}Tb and ^{148}Tb , with one and two valence nucleons, respectively, outside the ^{146}Gd core. The yrast level schemes have been established up to about 5 MeV (see Fig.4), and the observed states have been interpreted as the shell model particle-hole excitations indicated in the figure by using empirical single particle energies and interaction strengths.

The most remarkable features of the ^{147}Tb and ^{148}Tb level spectra are the uncommon low-lying M2/E3 isomers which de-excite to the ground states of the two nuclei. A comparison of the E3 enhancement factors (Fig. 5a) shows that the $15/2^+$ and 11^- isomers in $^{147,148}\text{Tb}$ and the $13/2^+$ isomer in the one neutron nucleus ^{147}Gd all involve the coupling of the valence nucleon(s) to the 3^- octupole excitation of the ^{146}Gd core. In ^{147}Tb one would expect a $\pi h_{11/2} \times 3^-$ multiplet of states about 1.6 MeV above the $\pi h_{11/2}$ ground state. However the dominant component of the ^{146}Gd octupole excitation is $\pi h_{11/2} d_{5/2}^{-1}$, which will be effectively blocked out by the Pauli principle in some of the ^{147}Tb coupled states. Likewise in ^{148}Tb , which has a $\pi h_{11/2} \nu f_{7/2}$ ground state, similar Pauli interference effects come into play. The particle-phonon coupling in $^{147,148}\text{Tb}$ and in ^{147}Gd has been analyzed by second order perturbation theory using the particle-phonon exchange interactions illustrated in the lower part of Fig. 5. This analysis gave a satisfactory understanding of the experimental data and showed ^{147}Tb to be a particularly interesting and favorable nucleus for the investigation of the influence of the Pauli principle on particle-phonon exchange coupling. A fuller account of the results of this study can be found in Ref. 7.

We have also done a considerable amount of work on the spectra of the $Z=66$ nuclei ^{148}Dy and ^{149}Dy , which display several unusually interesting structural features. Furthermore, as an important byproduct of these spectroscopic studies, we hope to obtain rather precise estimates of the previously unknown ground state masses of $^{148,149}\text{Dy}$ and several other nuclei in this region. These highly promising investigations should be completed in the coming year.

Nuclear structure studies with the Argonne Superconducting Linac

The study of nuclei at very high angular momenta has been stimulated by recent speculations that nuclei may undergo drastic shape changes at spins greater than $30\hbar$. Specifically, the existence of deformed yrast "traps" in certain regions of the nuclidic chart have been predicted by leading theoretical groups. An island of high-spin isomers discovered⁸⁾ in the $A \sim 150$ region was for a while associated with the predicted yrast traps, but subsequent experimental studies have indicated that instead the isomers arise from the alignment of many single particle spins along the nuclear symmetry axis. In a notable recent experiment, Khoo et al.⁹⁾ took advantage of the occurrence of high-spin nanosecond isomers in ^{152}Dy to identify discrete γ - transitions from states with spins up to $37\hbar$.

The current Argonne-Purdue collaboration aims at developing experimental techniques to probe still higher spin yrast transitions and to investigate properties of transitions feeding into and decaying parallel to the yrast line of ^{152}Dy and neighboring nuclei. In a typical experiment isotopically enriched $^{120,122}\text{Sn}$ targets on lead backing were bombarded with pulsed beams of 130-160 MeV ^{32}S ions from the Argonne Tandem-Linac combination. Selection of the desired reaction channel and, more important, of the highest lying transitions was achieved by using a large eight-sector NaI(Tl) sum spectrometer surrounding the target. Ports along the 0° and 90° directions allowed the use of other Ge(Li) or NaI detectors in coincidence with the sum detector. Typically, a 10% Ge(Li) detector was placed at 0° , and seven parameter list mode data were accumulated; the parameters include energies in both detectors, the time distributions between detectors and with respect to the beam pulse, and the γ -ray multiplicity. A test run showed that excellent separation between the $4n$ and $5n$ exit channels could be achieved by gating on suitable energy slices in the sum spectrometer.

The first full experiment was a rather ambitious one in which we tried to detect rotational bands built on high spin yrast states (probably oblate) of ^{152}Dy . Such rotational states would be expected to decay by fast E2 transitions, and a special "recoil" target was constructed so that rotational transitions might be distinguished from non collective transitions by examining doppler shifts. The Ge(Li) was placed at 0° and extensive multiparameter data were accumulated. These data were analyzed by setting TAC gates to select prompt events feeding isomers, with sum spectrometer energy slices chosen to enhance γ -rays feeding into the chosen final nucleus (^{152}Dy or ^{151}Dy) at high angular momentum. Finally the areas of doppler shifted and unshifted components were inspected and a list of candidate γ -rays for placement above the yrast line was compiled. Although the data analysis is still incomplete, we are not optimistic that discrete transitions belonging to high-lying rotational bands in $^{151,152}\text{Dy}$ can be identified without very much better statistics than we have now.

Very recently we performed a different type of experiment designed to study the γ -ray continuum arising from the multi-pathway decay of the excited final nucleus to the yrast line. Here, a large NaI detector located 30cm from the target replaced the previous Ge(Li) detector and the sum spectrometer was again used for reaction channel and high angular momentum selection. The preliminary results are highly promising, with clear evidence for a prominent broad bump of mainly E2 transitions just above 1 MeV in the continuum spectrum. In the light of recent Berkeley results for other nuclei, this seems to be a strong indication of rather strongly deformed prolate shapes at high angular momenta in $^{151,152}\text{Dy}$. These studies are continuing.

Argonne participants in this work are T. L. Khoo, R. K. Smither, I. Ahmad, W. Kutchera and J. Borggreen, and Purdue participants are C. L. Dors, S. R. Faber, J. Wilson and P. J. Daly.

Summary

The research performed during the contract period followed closely the outline submitted in our renewal proposal. The principal investigator devoted approximately 50% of his time and effort to this project during the period.

References

1. Yates, Cunnane, Hochel and Daly, Nucl. Phys. A222 (1974) 301
2. Cunnane, Piiparinen, Daly, Dors, Khoo and Bernthal, Phys. Rev. C13 (1976) 2197
3. Neergard, Vogel and Radomski, Nucl. Phys. A238 (1975) 199
4. Glatz and Löbner, Z. Physik. 227 (1969) 83
5. P. J. Daly, D.O.E. Annual Report (1979)
6. Kleinheinz, Broda, Daly, Lunardi, Ogawa and Blomqvist, Z. Physik A290 (1979) 279
7. Broda, Behar, Kleinheinz, Daly and Blomqvist, Z. Physik A293 (1979) 135
8. J. Pedersen et al., Phys. Rev. Lett. 39 (1977) 990
9. T. L. Khoo et al., Phys. Rev. Lett. 41 (1978) 1027

Figure Captions

- Fig. 1 The high-spin level spectrum of ^{200}Pb
- Fig. 2 The high-spin level spectrum of ^{202}Pb
- Fig. 3 Lifetime data for the 7^- and 9^- isomers in ^{188}Os
- Fig. 4 The yrast level spectra of ^{147}Tb and ^{148}Tb . On the left are shown the calculated level spectra obtained from the shell model treatment.
- Fig. 5 Octupole excitations and E3 transition strengths in ^{146}Gd and its neighbors. Below are shown the particle-phonon exchange interaction diagrams; the labels in diagram(a) refer to ^{147}Gd , those in diagram (d) to ^{147}Tb .

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

II. Personnel

Senior Staff

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

Dr. C. L. Dors, Research Associate

Dr. S. R. Faber, Research Associate

Graduate Students

John Wilson

Yong Hee Chung

Service Staff

J. Hoffman, part-time electronics technician

J. Biddle, part-time secretary

J. Cunningham, part-time secretary

Short Term Consultants

Dr. H. Helppi

Dr. P. Kleinheinz

III. Publications and Talks

Particle-Hole Yrast States in ^{146}Gd and ^{147}Gd and the Z=64 Shell Closure, P. Kleinheinz, R. Broda, P. J. Daly, S. Lunardi, M. Ogawa and J. Blomqvist, Z. Physik A290 (1979) 279

Particle plus Octupole M2/E3 Isomers and High-Spin Particle-Hole States in ^{147}Tb and ^{148}Tb , R. Broda, M. Behar, P. Kleinheinz, P. J. Daly and J. Blomqvist, Z. Physik A293 (1979) 135

High Spin Isomers in ^{200}Pb , ^{201}Pb and ^{202}Pb , American Physical Society, Washington D.C., April 1979 - given by C. L. Dors. Abstract in Bull. Am. Phys. Soc. 24 (1979) 685

Particle plus Octupole Isomers and Multiparticle Yrast States in ^{147}Tb and ^{148}Tb , R. Broda, M. Behar, P. Kleinheinz, P. J. Daly and J. Blomqvist, Argonne Symposium on High-Spin Phenomena in Nuclei, March 1979

Yrast Isomers in the A=150 Region and the Z=64 Shell Closure, Nuclear Structure Seminar, University of Kentucky, May 1979 - P.J. Daly

Particle plus Octupole Isomers in ^{147}Tb and ^{148}Tb , Nuclear Physics Seminar, Oak Ridge National Laboratory, May 1979 - P. J. Daly

Collective Band Structure at High Spin, Discussion Leader P. J. Daly, Gordon Conference in Nuclear Chemistry, New London, N.H. June 1979

How Magic is ^{146}Gd ?, Körnö Workshop on Very Stable Nuclear Systems, Körnö, Sweden, September 1979 - P. Kleinheinz, J. Blomqvist, P. J. Daly

Negative Parity Isomers in Even-A Os Nuclei, American Physical Society, Knoxville, Tenn., October 1979 - given by J. Wilson. Abstract in Bull. Am. Phys. Soc. 24 (1979)