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NUCLEAR STRUCTURE STUDIES OF TRANSITIONAL NUCLEI

PROGRESS REPORT

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Abstract

Systematic investigations of the nuclear level structures of stable heavy transitional nuclei are being performed by $(n,n'\gamma)$ reaction spectroscopy. Detailed γ -ray excitation functions and angular distributions permit us to characterize low-lying states, with particular emphasis placed on understanding collective excitations of both positive and negative parity. Questions regarding nuclear shapes, deformation effects, and the applicability of various nuclear models to these nuclei have been addressed. Completed studies of ^{194}Pt and ^{198}Pt reveal significant structural differences between these nuclei and have led us to initiate studies of other transitional nuclei as the next step in a comprehensive examination of this mass region. Cross section systematics for the $(n,n'\gamma)$ reaction are being developed and, where possible, our γ -ray studies have been complemented by neutron detection time-of-flight measurements.

I. INTRODUCTION

A primary objective of our research is to understand the collective properties of nuclei in the shape transition region between the well-deformed rare earth nuclei and the spherical lead nuclei. To address questions regarding nuclear shapes and the applicability of nuclear models, we have turned to a probe, inelastic neutron scattering, which has not been extensively employed in this region. Our recent $(n,n'\gamma)$ studies have significantly extended existing data and have clearly demonstrated the advantages of these measurements. The combination of complementary time-of-flight neutron detection measurements and the development of inelastic scattering cross section systematics promises still further contributions to our knowledge of these nuclei.

In the past year, good progress has been made in our investigations of the structures of even-mass nuclei. Our studies of ^{194}Pt and ^{198}Pt have been completed, while several new projects have been initiated and are progressing well. A brief review of the significant results of these studies will be presented.

II. RESEARCH ACTIVITIES

A. Positive and negative parity level structures of ^{194}Pt

The platinum nuclei fall in a region which is not easily characterized in terms of the more traditional nuclear models. Recent calculations^{1,2} using the interacting boson model (IBM) and the boson expansion theory (BET) have been quite successful and emphasize the need for more detailed data on the properties of collective states. The well-studied nuclide ^{194}Pt provided a judicious starting point for our studies by the $(n,n'\gamma)$ reaction and has

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served as a cornerstone for other investigations in this region. A manuscript³ detailing this study has been submitted for publication, but it is worthwhile to give a brief summary of the most significant results.

1. We observe (see Fig. 1) essentially all of the known states below 2 MeV having $J \leq 6$. This observation points to the relatively non-selective nature of the $(n, n'\gamma)$ reaction at low bombarding energies and demonstrates the power of these measurements.
2. A comparison of γ -ray branching ratios of low-lying collective states with the IBM and BET suggests that both approaches are reasonably successful in explaining the level structures.
3. By combining our data with that from in-beam γ -ray measurements^{4,5} we have constructed a negative-spin level sequence with spins from 1^- to 11^- . This structure is successfully interpreted within the semi-decoupled model.^{6,7}
4. We have examined the question of γ softness of the ^{194}Pt core and believe, as suggested by Girod and Grammaticos⁸, that these transitional nuclei have non-zero dynamic mean values of γ while remaining soft.
5. The inelastic scattering cross sections from this work have been combined with neutron detection time-of-flight results. The anomalously large cross section of the 5^- state (see Table I) at low incident neutron energies remains unexplained. A manuscript reporting this work is in progress.

B. Collective states in ^{198}Pt

Our study of ^{198}Pt has also come to a successful conclusion with the submission of a Letter⁹ on the properties of this nuclide. A more detailed

Fig. 1. Level scheme of states in ^{194}Pt observed with the $(n,n'\gamma)$ reaction.

Table I. A comparison of measured inelastic scattering cross sections for ^{194}Pt with Wolfenstein-Hauser-Feshbach (WHF) calculations.

Level	J^π	Cross section		WHF
		(n,n' γ) (mb)	(n,n') (mb)	
328.5	2^+	726	781	183
622.0	2^+	236	221	157
811.0	4^+	202	124	111
922.8	3^+	114	121	130
1229.6	4^+	98	81	79
1267.2	0^+	23	---	33
1373.9	5^-	130	385	49
1411.8	6^+	12		26
1422.4	(4)	84		68
1432.5	3^-	133		106
1479.2	0^+	21		29
1498.7	5^+	25		36
1511.9	2^+	63		90

manuscript will also soon be prepared. Although this study was difficult because of the small size (~5g) of the ^{198}Pt sample, high quality γ -ray spectra (Fig. 2), excitation functions (Figs. 3 and 4), and angular distributions (Fig. 5) were obtained.

Considering the paucity of data¹⁰ about ^{198}Pt which was available at the beginning of this study, the amount of new information (shown in part in Fig. 6) is quite impressive. This level scheme, which approximates that expected for an anharmonic vibrator, is consistent with BET calculations. These calculations place ^{198}Pt naturally in a systematic development of nuclear structure through the Pt isotopes and explain the γ -ray decay intensities of excited levels. The $O(6)$ limit of the IBM, on the other hand, appears inappropriate for ^{198}Pt and does not predict a phase transition ($O(6) \rightarrow SU(5)$) in going from ^{196}Pt to ^{198}Pt . This study may indicate five active bosons is too small a space for collective-excitation symmetry classifications. The BET, unconstrained by predicted symmetries, seems to follow successfully the development of configurations in Pt nuclei, through ^{198}Pt .

C. The ^{192}Os (n,n' γ) reaction

It is generally believed that a prolate-oblate shape transition occurs in going from the stable Os nuclei to the stable Pt nuclei. To better elucidate this change we have begun a study of ^{192}Os , the heaviest stable Os isotope.

In contrast to most of the stable nuclei in this region, the high-spin states of ^{192}Os appear to be better characterized¹⁰ than the low-spin states. In this case one of the advantages of our methods, the relative non-selectivity of level population, is quite apparent and we should be able to study states which are inaccessible by other reactions. The important branching ratios from the 0^+ states identified in (t,p) reaction studies¹¹

Fig. 2. Gamma-ray spectrum from the ^{198}Pt (n,n' γ) reaction at $E_n = 2.5$ MeV.

Fig. 3. Excitation functions for γ rays from low-spin states of ^{198}Pt .

Fig. 4. Excitation functions for γ rays from states in ^{198}Pt .

Fig. 5. Angular distributions of γ rays produced by the $^{198}\text{Pt} (n, n'\gamma)$ reaction at $E_n = 2.5 \text{ MeV}$.

Fig. 6. Partial level scheme for states in ^{198}Pt . Energies predicted by BET calculations are shown for comparison.

should easily be obtained. Moreover, the suggestion by Burke et al.¹² that the 4^+_3 states in the heavy Os nuclei are hexadecapole vibrations rather than two-phonon excitations may be reflected in the cross sections for population by inelastic scattering.

Preliminary γ -ray excitation function and angular distribution measurements have been performed on an enriched ^{192}Os sample. The size of this sample (~75g) coupled with our large-volume Ge(Li) detector has provided higher sensitivity than we have had in any previous experiment. Concomitant, however, with this large sample is a greater reliance on the neutron scattering, attenuation, and γ -ray absorption corrections which must be applied. Indeed, the corrections become quite large for low-energy photons, and this sample provides a stringent test of our ability to perform these corrections. Not only known γ -ray branching ratios but also the angle dependent γ -ray yields are being used to examine the corrections.

Although the excitation function data is in the early stages of analysis, we have placed approximately twenty new levels in this nuclide. While speculation regarding the nature of these states must necessarily await further work, we must point again to the advantages of $(n,n'\gamma)$ reaction spectroscopy in obtaining detailed spectroscopic information.

D. Population of levels in ^{200}Hg by $(n,n'\gamma)$ reaction spectroscopy

Our study of ^{200}Hg was initially motivated by a desire to compare the level population and γ -ray production cross sections with ^{198}Pt , its isotone. The shapes of the stable Hg nuclei have long been regarded as oblate, and recent reorientation effect measurements¹³ support this conclusion. Peker and Hamilton¹⁴ have suggested that ^{198}Hg and ^{200}Hg are triaxial in their ground states. While probably not resolving the question of triaxiality, a

comparison of ^{200}Hg with ^{198}Pt will likely prove instructive. It is interesting that no 3^- (so-called octupole) states have been identified in the heavier Hg nuclei, while a number of high-spin negative-parity states are evident. A search for this 3^- excitation is an integral part of our work.

Only one experiment has been performed on ^{200}Hg , but a cursory examination of the data is very gratifying. At an incident neutron energy of 2.5 MeV, all excited states (including the known 7^- state at 1.926 MeV) below 2.1 MeV are observed. The relative simplicity of the spectrum opens the possibility of our proceeding to still higher bombarding energies to populate states of higher energy and angular momentum.

E. An examination of odd-A nuclei: ^{195}Pt

There are a great many reasons for studying odd-mass nuclei in this region, and the success of our measurements in even-even nuclei suggests that a wealth of data might be available from these studies. The IBM for odd-A nuclei, i.e. the interacting boson-fermion model,¹⁵ based on the $O(6)$ boson symmetry¹⁶ has been suggested to describe nuclei toward the end of major shells, and Iachello¹⁷ has suggested that dynamical supersymmetries may be manifested in odd-A spectra. Certainly, examinations of these ideas as well as comparisons with the triaxial rotor model and Nilsson model with Coriolis coupling calculations require detailed data which may only be available from measurements such as ours.

With these thoughts in mind we have performed an initial experiment to examine the feasibility of this task. As expected, the spectra are extremely fertile, even at incident neutron energies as low as 0.7 MeV, and increase in complexity with energy. We are optimistic, however, that this study will prove successful and yield new insights into questions relevant for these nuclei.

F. Other studies of transitional nuclei.

1. Time-of-flight studies

Our $(n,n'\gamma)$ reactions often expose problems which can be examined best by neutron detection time-of-flight measurements. For these experiments the principal investigator has established a very successful collaboration with Drs. M.T. McEllistrem, J.L. Weil, and M.C. Mirzaa of the Department of Physics and Astronomy of the University of Kentucky. Their interests include reaction mechanisms and shape effects, and nicely complement our nuclear structure studies. Reaction cross sections from our $(n,n'\gamma)$ and (n,n') measurements have been shown to be in good agreement (see Table I). However, the (n,n') measurements provide much more information about the reaction dynamics.

Our (n,n') angular distribution measurement for ^{198}Pt at 1.7 MeV, on the other hand, was used for spectroscopic purposes and was fundamental in identifying the 0^+ state at 914 keV. The cross section enhancement at low energy (see Table I) of the 5^- state in ^{194}Pt remains unexplained. Higher energy measurements on both ^{194}Pt and ^{192}Os have been used to explore the reaction mechanisms.

2. Cross sections in the Hg isotopes

An attempt to determine γ -ray cross sections for Hg isotopes and to search for cross section enhancements was made using a natural Hg target. While the γ -ray cross section were easily obtained the determination of level cross sections is, in general, impractical until a more detailed understanding of the level schemes is obtained. This experiment does, however, provide a good γ -ray production cross section normalization for these nuclei.

3. Population systematics and excitation functions

While we have studied too few nuclei to establish detailed population systematics (or to confirm the 5^- state's cross section enhancement as a general feature, for example), progress is made with the study of each new nuclide.

We have confirmed earlier observations that γ -ray excitation functions have greater significance than merely as threshold determinations. When transitions from low-spin ($J \leq 2$) states exhibit little feeding from higher-lying states, their excitation functions are characterized as rising sharply above threshold, leveling off a few hundred keV above threshold, and (in many cases) then decreasing. The excitation functions from intermediate-spin ($J = 3$ or 4) states tend to increase nearly linearly, while the slopes of the excitation functions of higher-spin ($J \geq 5$) states always increase, or the curvature is positive, with bombarding energy. The excitation functions can be used, therefore, not only to obtain thresholds and level placements but also to deduce limits on the transferred angular momentum.

The research performed at the University of Kentucky Van de Graaff accelerator has closely followed the course outlined in our proposal. Only the proposed heavy-ion transfer reactions to study neutron rich nuclei have not yet begun. We believe these measurements to be important and will continue to pursue them.

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III. PERSONNEL

Principal Investigator:

Dr. Steven W. Yates, Associate Professor

The principal investigator has devoted approximately 30% of his time during the academic year and 100% of his efforts during the summer to this project. The remainder of his time is attributed to his teaching (45%) and service (10%) duties to the University of Kentucky and research at Oak Ridge National Laboratory in studies of nuclear structure via heavy-ion reactions and in-beam γ -ray spectroscopy.

Graduate Students:

A. Ghatak-Roy

J.W. Gilbert

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A. Khan

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Undergraduate Student:

R.J. Moore^{*}

^{*}Terminated in the course of the contract year.

IV. TALKS AND PUBLICATIONS

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