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STUDIES OF YRAST AND CONTINUUM STATES IN $A=140-160$ NUCLEI

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ABSTRACT

The structure of nuclei in the $A \sim 150$ region have been investigated by in-beam γ -ray spectroscopy using heavy ion beams, mostly from the Argonne Tandem-Linac. Results for the nuclei ^{148}Dy , ^{149}Dy , ^{153}Dy , ^{154}Dy , ^{149}Ho and ^{150}Ho are summarized. The feeding of yrast states in these nuclei and the link between the highest known yrast states and the continuum region have also been studied.

I. Research Activities

During the past year our research program has concentrated on investigations of nuclear structure in the $A \sim 150$ region. This region has become the focus of recent theoretical speculations concerning the prospects of dramatic shape changes in nuclei at high angular momenta and of the occurrence of yrast trapping. One of our main lines of inquiry is based on the Jülich-Stockholm-Purdue finding that the $Z=64$, $N=82$ nucleus ^{146}Gd has many properties of a doubly closed shell system. We are currently investigating the spectra of several adjacent few-particle nuclei to determine how accurately their structure can be described in terms of the coupling of the valence particles to the ^{146}Gd core states. In this report we summarize the progress made in our studies of the nuclei ^{148}Dy , ^{149}Dy , ^{153}Dy , ^{154}Dy , ^{149}Ho , and ^{150}Ho . Our second main line of investigation involves studies of the feeding of yrast states in $A \sim 150$ nuclei and the link between the highest known yrast states and the continuum region. Most of this work has been performed by an Argonne-Purdue collaboration using heavy ion beams from the Argonne Superconducting Linac Booster.

Spectroscopy of Few Valence Particle Nuclei near ^{146}Gd

a) The Nuclei ^{148}Dy and ^{149}Dy .

The yrast states of ^{148}Dy and ^{149}Dy have been studied by γ -ray and conversion electron measurements in (α, xn) and $(^{16}\text{O}, xn)$ reactions on enriched ^{152}Gd and ^{136}Ce targets, and level schemes to above 4 MeV for the two nuclei have been established (Fig. 1). The complete $(\pi h_{11/2})^2$ spectrum in ^{148}Dy has been identified, furnishing the nucleon-nucleon interaction matrix elements for $h_{11/2}$ protons. In addition the $\pi h_{11/2}$ effective charge has been determined

to be

$$e_{\text{eff}} = 1.52 \pm 0.05 e$$

from the measured E2 transition rate between the $(\pi h_{11/2})^2 10^+$ and 8^+ states. The yrast cascades in ^{148}Dy and ^{149}Dy continue above the $(\pi h_{11/2})^2 10^+$ and $(\pi h_{11/2})^2 \nu f_{7/2} 27/2^-$ states by ~ 1 MeV E1 transitions de-exciting the lowest members of octupole multiplets built on these states. The energy shifts for the observed members of the $(\pi h_{11/2})^2 \times 3^-$ multiplet have been analyzed in terms of two particle-phonon exchange coupling using an empirical coupling strength extracted from the one valence particle nucleus ^{147}Tb .

This work was performed in collaboration with P. Kleinheinz, R. Broda, S. Lunardi, H. Backe and J. Blomqvist. The detailed results are given in a very recently published paper¹⁾.

b) The $(\pi h_{11/2})^3$ Spectrum in the Three Valence Proton Nucleus $^{149}_{67}\text{Ho}_{82}$

As described in the preceding section, the nucleon-nucleon interaction matrix elements for $\pi h_{11/2}$ protons are now known from the complete $(\pi h_{11/2})^2$ spectrum in ^{148}Dy . With this information the level spectra of $(\pi h_{11/2})^n$ configurations in the N=82 nuclei with $Z > 66$ can be calculated.

We have performed at Argonne NL the first study of yrast states in the three proton N=82 nucleus ^{149}Ho using 155-180 MeV ^{32}S beams on enriched ^{121}Sb and ^{122}Te targets. These targets were located at the center of a sum-spectrometer consisting of two 33 cm x 15 cm NaI crystals with ports at 90° to the beam direction for two 15% Ge(Li) detectors. With this arrangement, five parameter $E_{\gamma 1}$, $E_{\gamma 2}$, E_{sum} , $t_{\gamma\gamma}$ and $t_{\gamma\text{sum}}$ data were accumulated. In the analysis, attention was focussed on γ -rays delayed with respect to the sum signal and particularly on a group of eight γ -rays which were observed to be doubly delayed; specifically, they de-excite the lower of two isomers with half-lives exceeding 50 ns in

the residual nucleus. These eight lines are assigned to ^{149}Ho because they showed the same excitation function behavior as a strong 1091 keV decay line of ^{149}Ho , and their intensities accounted for virtually the entire population of the ^{149}Ho $11/2^-$ "ground state" in all the bombardments.

The $\gamma\gamma$ coincidence results establish the level scheme shown in Fig. 2, although the transition ordering within the two cascades is largely based on theoretical considerations. The main cascade of 144, 307, 727 and 1560 keV transitions matches the theoretical predictions for the $(\pi h_{11/2})^3$ level spectrum rather well. Since the 0^+ , 2^+ and 4^+ states in ^{148}Dy must contain admixed components from other orbitals, especially $\pi s_{1/2}$, $\pi d_{3/2}$ and $\pi d_{5/2}$, the relative energies of the $11/2^-$, $15/2^-$ and $19/2^-$ states calculated assuming pure $(\pi h_{11/2})^n$ configurations cannot be expected to agree perfectly with the experimental values. However, the $23/2^- - 27/2^-$ spacing depends only on the energies of the ^{148}Dy 6^+ , 8^+ and 10^+ levels, which should be rather pure $(\pi h_{11/2})^2$ states, and it is noteworthy that this feature of the $(\pi h_{11/2})^3$ spectrum is accurately reproduced. If one assumes the same $\pi h_{11/2}$ E2 effective charge for the $27/2^- \rightarrow 23/2^-$ transition in ^{149}Ho as was earlier found for the $10^+ \rightarrow 8^+$ transition in ^{148}Dy , the predicted transition probability is $B(E2, 27/2^- \rightarrow 23/2^-) = 92 \pm 6 e^2 \text{fm}^4$. From the measured 59 ± 4 ns half-life, the experimental value is $B(E2, 144 \text{ keV}) = 88 \pm 6 e^2 \text{fm}^4$, corresponding to an effective charge $e_{\text{eff}}(144 \text{ keV})/e = 1.50 \pm 0.06$. This result is in excellent agreement with the value 1.53 ± 0.05 obtained for the ^{148}Dy $10^+ \rightarrow 8^+$ transition, confirming that the transitions are associated with the recoupling of the $(\pi h_{11/2})^2$ and $(\pi h_{11/2})^3$ configurations.

In addition to the $(\pi h_{11/2})^2$ levels, three other states below 3 MeV

are known in ^{148}Dy - a 3^- octupole excitation at 1688 keV, and higher-lying 5^- and 7^- states. We interpret the 1380, 2025 and 2409 keV levels in ^{149}Ho as the expected $15/2^+$, $19/2^+$ and $23/2^+$ yrast states arising from the coupling of the additional $h_{11/2}$ proton to the 3^- , 5^- and 7^- ^{148}Dy states. For these positive parity states the agreement between experimental and predicted energies is also good.

Overall, the results of this study, which have already been briefly reported in a Short Note ²⁾, lend further support to the contention that ^{146}Gd acts as a closed shell nucleus.

c) Yrast Spectroscopy of the N=83 Nucleus ^{150}Ho

In addition to the ^{149}Ho results described in the preceding contribution, the γ -ray studies with the $^{32}\text{S} + ^{121}\text{Sb}$ and $^{32}\text{S} + ^{122}\text{Te}$ reactions also yielded the first information about high-spin excitations in the N=83 nucleus ^{150}Ho . Isotopic identification of the ^{150}Ho γ -rays was based on

- 1) excitation function and $\gamma\gamma$ coincidence results
- 2) intensity balance with known radioactivity γ -rays accompanying the β -decay of the ^{150}Ho ($\pi h_{11/2} \nu f_{7/2}$) 9^+ "ground state"
- 3) the observed coincident sum-spectra.

A few of these γ -rays have been observed by other workers in survey studies of isomerism in the A=150 region. The present work has identified three isomers in ^{150}Ho with half-lives of 17 ± 4 ns, 86 ± 12 ns and > 500 ns. The $\gamma\gamma$ coincidence and timing measurements have established the level scheme up to the 86 ns isomer at 2625 keV, as shown in Fig. 3. (The ordering of the 226 and 313 keV transitions may be reversed). Although transition multipolarities have not been determined, knowledge of the excitation modes in adjacent Tb, Dy and Ho nuclei allow us to assign spin-parity values with some confidence.

On the left of the figure is shown the predicted yrast sequence of $(\pi h_{11/2})^3 \nu f_{7/2}$ levels, calculated in the shell model using empirical nucleon-nucleon interactions for $h_{11/2}$ protons from the ^{148}Dy spectrum and $\pi h_{11/2} \nu f_{7/2}$ interactions determined using the Schiffer-True central potential. As can be seen, the agreement between the experimental and theoretical level energies is satisfactory.

The transition probability obtained from the measured half-life of the 17^+ isomeric state

$$B(E2, 17^+ \rightarrow 15^+) = 176 \pm 24 \text{ e}^2 \text{ fm}^4$$

is about twice as large as the value determined for the $27/2^- \rightarrow 23/2^- (\pi h_{11/2})^3$ transition in ^{149}Ho , clearly demonstrating that the $f_{7/2}$ neutron is not limited to a spectator role in the ^{150}Ho $17^+ \rightarrow 15^+$ transition. The wave functions of these ^{150}Ho states can be written as

$$\begin{aligned} \psi_{17^+} &= [(\pi h_{11/2})^3_{27/2} \times \nu f_{7/2}]_{17} \quad \text{and} \\ \psi_{15^+} &= \sqrt{1-\alpha^2} [(\pi h_{11/2})^3_{23/2} \times \nu f_{7/2}]_{15} + \alpha [(\pi h_{11/2})^3_{27/2} \times \nu f_{7/2}]_{15} \end{aligned}$$

With the value $\alpha=0.26$ and the neutron effective charge $e_\nu=3.546e$ deduced from the $16^+ \rightarrow 14^+$ transition speed in ^{150}Dy , the shell model calculation gives for ^{150}Ho $B(E2, 17^+ \rightarrow 15^+) = 148 \text{ e}^2 \text{ fm}^4$, in quite good agreement with experiment.

The negative parity states are also rather interesting, all with close structural relationships to known states of the adjacent nuclei ^{149}Dy , ^{149}Ho , and of the odd-odd isotone ^{148}Tb . The last-named nucleus features an M2/E3 isomeric 11^- state at 1006 keV, interpreted as the lowest member of a $\pi h_{11/2} \nu f_{7/2} \times 3^-$ multiplet, and a 12^- state at 1290 keV of dominant $\pi h_{11/2} \nu i_{13/2}$ character. The 11^- isomer and 12^- state in ^{150}Ho are obvious counterparts of those ^{148}Tb states.

Investigation of the ^{150}Ho yrast states lying between the 86 ns isomer and the much higher-lying ~ 500 ns isomer is continuing.

d) Yrast Levels in the Transitional Nuclei ^{153}Dy and ^{154}Dy

In the $N=86$ nucleus ^{152}Dy the yrast states are known³⁾ up to a spin of 38, and they appear to be dominated by single particle structures up to the maximum spins observed. On the other hand, the $N=90$ nucleus ^{156}Dy shows⁴⁾ well developed rotational bands typical of a prolate rotor. In the intermediate $N=88$ nucleus ^{154}Dy the yrast levels are firmly known up to 16^+ only; our aim in the present study is to locate higher-lying states in this transitional nucleus, and to determine their character. Concurrently we are also studying the high-spin excitations of the neighbouring odd-A nucleus ^{153}Dy .

We have performed in-beam γ -ray measurements by means of the reactions $^{124}\text{Sn}(^{34}\text{S}, xn)^{153,154}\text{Dy}$, induced by 150-165 MeV ^{34}S beams from the Argonne Linac. Extensive coincidence data were recorded using an array of three Ge(Li) detectors and the large NaI sum-spectrometer. Detection of γ -rays belonging to the desired reaction channels could be enhanced by selecting suitable energy slices on the sum spectrum. The results obtained establish the even-spin yrast states of ^{154}Dy up to a (32^+) level at 10185 keV and an odd-spin level sequence up to an $I=29$ level at 9254 keV. No isomers with $t_{1/2} > 2$ ns were observed. The analysis of the ^{153}Dy data is in progress.

The yrast states of ^{152}Dy and ^{154}Dy show contrasting behavior on an excitation energy versus $I(I+1)$ plot. Whereas the effective moment of inertia for ^{152}Dy is about 147 MeV^{-1} , considerably larger than the value of 120 MeV^{-1} for a rigid sphere, the result for ^{154}Dy of 124 MeV^{-1} is close to the rigid sphere value. The large effective moment of inertia in ^{152}Dy may indicate³⁾ the onset of oblate deformation at high-spin, but there is no such indication

in ^{154}Dy , where the highest even-spin yrast states identified apparently belong to rotational bands.

We plan to continue our ^{154}Dy study to still higher spins to see if single-particle yrast states can be observed.

Very High Spin Yrast States and the Link to the Continuum

In this section we discuss three related topics: the population intensities of high spin yrast states; the discrete γ rays directly feeding the yrast states; and the continuum γ rays which connect states several MeV above the yrast line. By studying these three phases of the γ -deexcitation we might hope to gain insight into the character of the states which lie above the yrast line. In particular we are interested in the nature of the collective excitations which might be built on the very high spin single particle yrast states and the manner in which these collective states might evolve with increasing angular momentum.

Most of the experiments have been performed on the nuclei ^{151}Dy and ^{152}Dy , for which the level schemes have been determined up to $I = 7\ 1/2$ and 38, respectively

a) Feeding of YRAST States

In order to investigate the unusually high yrast feeding in ^{152}Dy , we have measured the intensities of the yrast transitions as a function of bombarding energy in the (^{34}S , 4 n) reaction. Beams with energies of 144, 151, 160, 168, 176 and 184 MeV were provided by the Argonne Linac. Fig. 4 shows the observed population intensities as a function of spin. At 144 MeV bombarding energy the intensity is almost 100% up to spin 15 and then gradually decreases at higher spins. The population of the higher spin

states increases with bombarding energy up to 160 MeV, but when the beam energy is further increased to 168, 176 and 184 MeV, the yrast population remains the same as at 160 MeV; the population of the highest spin yrast states saturates at this energy. The yrast intensities have also been measured as a function of the total γ -ray energy emitted in the reaction. These results confirmed that the selection of events with larger initial angular momentum does not lead to enhanced population of the highest spin states.

At ^{34}S bombarding energies of 160 MeV or higher, there is little side-feeding into the yrast states below $I = 29$, as can be deduced from the constancy of population below that spin (see Fig. 4). On the other hand, the rapid decrease in population above that spin value implies that the side-feeding is confined within a fairly narrow spin interval of $30 \leq I \leq 38$. This feeding intensity exceeds 10% for certain levels, a strength which should be observable if concentrated in a single cascade.

b) Search for Discrete Non-Yrast Transitions Feeding

Yrast States

We have performed a search for discrete γ rays feeding the yrast states in an extensive γ - γ coincidence experiment. Three Ge(Li) detectors in the forward direction were used to observe a target located inside the NaI sum spectrometer. The evaporation residues were allowed to recoil into vacuum to avoid the lineshape broadening which would occur for γ rays from short-lived cascades if the residues stopped (in ~ 2 ps) in the usual Pb backing. By setting appropriate windows on the sum energy, prompt transitions in ^{152}Dy could be enhanced.

A few previously unidentified γ rays in ^{152}Dy have been found but there so far appears to be no strong non-yrast transitions (with intensity greater than 10%) feeding the yrast states. One would conclude that the side-feeding into each yrast level is either by several pathways or, even if in single pathways, by γ rays in the different cascades which have similar but nonetheless slightly different energies. The latter situation would give rise to an unresolved continuum, making detection of discrete lines very difficult.

c) Continuum γ -rays

To investigate the nature of the continuum states feeding the yrast line, we have observed the continuum γ -rays using a 25 cm x 30 cm NaI crystal, with a 7.5 cm central collimator. The target, located 75 cm away was inside the sum spectrometer, and the γ -ray spectra were measured at 0° and 90° in coincidence with the sum energy signal.

In the analysis, the NaI spectra coincident with different sum energy slices were examined. The lower energy slices contain mainly statistical transitions, with the characteristic exponential fall-off, and the discrete lines. With increasing slice energy, emphasizing the higher angular momentum events, the multiplicity increases and also a prominent "bump" around 1.3 MeV begins to grow. Samples of the spectra at 0° and 90° (with discrete line contributions subtracted) are shown in Fig. 5. By assuming the presence of only stretched dipole and quadrupole components it is possible to decompose the two components as shown in Fig. 6. The stretched quadrupole (presumably E_2) component is concentrated in the bump around 1.3 MeV, which grows with increasing sum energy, but the mean energy of the bump remains fairly constant. In contrast, the edge of the quadrupole bump observed⁵⁾ in well deformed prolate rotors increases with increasing input angular momentum.

We deduce the existence of collective structures above the yrast line from their influence on the population intensities of the yrast states and from the occurrence of the E2 continuum bump at ~ 1.3 MeV. The nature of the excited collective states is not yet determined, but we speculate⁶⁾ that they may arise from collective excitations coupled to the large-j few particle yrast states. These may initially be γ -vibrations and evolve, as more γ -phonons are coupled, into a triaxial rotor with the particle spin and rotation vector aligned.

Other Investigations in Progress

Several other experiments have also been performed using heavy ion beams from the Linac, but the data analysis is still in an early stage. The most noteworthy of these are a study of the continuum γ -ray systematics in $^{148-154}\text{Dy}$ and $^{152-160}\text{Er}$, and measurements of the average lifetimes of the continuum γ -rays using a doppler shift attenuation technique. These investigations will be carried forward in the coming year.

Summary

The research performed during the report 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. The Argonne NL participants in our collaborative experiments are T. L. Khoo, I. Ahmad, R. K. Smither, P. Chowdhury and J. Borggreen.

References

1. P. J. Daly et al., Z. Physik A298 (1980) 173.
2. J. Wilson et al., Z. Physik A296 (1980) 185.
3. T. L. Khoo et al., Phys. Rev. Lett 41 (1978) 1027.
4. D. Ward et al., preprint and priv. communication.
5. e. g. M. A. Deleplanque et al., Phys. Rev. Lett. 41 (1978) 1105.
6. T. L. Khoo et al., Proc. Nobel Symposium on Nuclei at Very High Spin (1980) to be published.

Figure Captions

- Fig. 1 The level schemes of the N=82 nucleus ^{148}Dy and the N=83 nucleus ^{149}Dy . Shell model level assignments are also shown.
- Fig. 2 Level scheme of the N=82 nucleus ^{149}Ho below the 59 ns isomer. The calculated $(\pi h_{11/2})^3$ yrast levels are shown on the left.
- Fig. 3 Experimental and calculated level schemes for the N=83 nucleus ^{150}Ho .
- Fig. 4 Population intensities of yrast states in ^{152}Dy as a function of spin for different beam energies in the $^{122}\text{Sn}(^{34}\text{S}, 4n)^{152}\text{Dy}$ reaction.
- Fig. 5 Continuum spectra measured at 0° and 90° in coincidence with various sum energy slices. Discrete line contributions have been subtracted.
- Fig. 6 Stretched quadrupole and dipole components of the γ -ray continuum.

Fig. 1

Fig. 2

Fig. 3

PHG-15,828

Fig. 4

ANL-P-15,932

~~Fig. 5~~
Fig. 5

ANL-P-15,988

~~Fig. 6~~
Fig. 6

II. Personnel

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III. Publications and Talks (1980)

"The $\pi h_{11/2}^3$ Spectrum in the Three Valence Proton Nucleus ^{149}Ho ",

J. Wilson, S. R. Faber, P. J. Daly, I. Ahmad, J. Borggreen, P. Chowdhury,
T. L. Khoo, R. D. Lawson, R. K. Smither, J. Blomqvist, Z. Phys. A296
(1980) 185

"How Particle-Octupole Coupling Affects the Yrast Lines of Dysprosium
Nuclei", P. J. Daly, P. Kleinheinz, R. Broda, S. Lunardi, H. Backe,
J. Blomqvist, Proc. Int. Conf. on Nuclei at High Angular Momentum,
Strasbourg (1980) 56

"Very High Spin Yrast States and the Link to the Continuum", T. L.
Khoo, J. Borggreen, P. Chowdhury, I. Ahmad, R. K. Smither, S. R. Faber,
P. J. Daly, C. L. Dors, J. Wilson. Phys. Scripta (1980) in press

"Proton $h_{11/2}^2$ and Octupole Excitations in ^{148}Dy and ^{149}Dy ", P. J.
Daly, P. Kleinheinz, R. Broda, S. Lunardi, H. Backe, J. Blomqvist,
Z. Phys. A298 (1980) 173

"High-spin Level Spectra of the Nuclei ^{195}Pb , ^{197}Pb , ^{199}Pb and ^{201}Pb ",
H. Helppi, S. K. Saha, P. J. Daly, S. R. Faber, T. L. Khoo, F. M. Bernthal,
submitted to Phys. Rev. C, Nov. 1980

"The High-spin Level Structure of ^{200}Hg ", H. Helppi, S. K. Saha,
M. Piiparinen, C. L. Dors, P. J. Daly, T. L. Khoo, submitted to Phys. Rev.
C, Dec. 1980

"Spectroscopy of Few Valence Particle Nuclei in the $A \sim 150$ Region",
Nuclear Physics Seminar, Argonne National Lab, April 18, 1980 - given by
P. J. Daly.

"Continuum γ -ray Spectra and Excitation Functions of Yrast States in ^{152}Dy ", Contribution to Int. Conference of Nuclei at High Angular Momentum, Strasbourg, April 23, 1980.

"Unusual Excitation Functions of Yrast States in ^{152}Dy ", American Physical Society, Washington D.C., May 1, 1980 - given by R. K. Smither.

"Proton $h_{11/2}^2$ and Octupole Excitations in ^{148}Dy and ^{149}Dy ", American Physical Society, Washington D.C., May 1, 1980 - given by P. J. Daly.

"Study of Continuum γ -ray Spectra of ^{152}Dy ", American Physical Society, Washington D. C., May 1, 1980 - given by J. Borggreen.

"The $\pi h_{11/2}^3$ Spectrum in the Three Valence Proton Nucleus ^{149}Ho ", Nuclear Physics Seminar, FKA Jülich, May 30, 1980 - given by P. J. Daly.

"Gamma-ray Spectroscopy Studies with the Argonne Tandem-Booster Facility", Nuclear Seminar, Istituto di Fisica, Legnaro, Padova, June 9, 1980 - given by P. J. Daly.

"Elementary Nuclear Excitation Modes in the $A \sim 150$ Region", Conference on Interacting Bose-Fermi Systems in Nuclei, Erice, Sicily, June 17, 1980 - given by P. J. Daly.

"Very High Spin States and the Link to the Continuum", Nobel Symposium on Nuclei at Very High Spin, Örenas, Sweden, June 25, 1980 - given by T. L. Khoo.

"Continuum γ -ray Spectra and Excitation Functions of Yrast States in ^{152}Dy ", International Conference on Nuclear Physics, Berkeley, California, Aug. 26, 1980 - given by S. R. Faber.

"Two particle-phonon Exchange Coupling in Yrast States of Dysprosium Nuclei", International Conference on Nuclear Physics, Berkeley, California, Aug. 27, 1980 - presented as a Poster by P. J. Daly.

"Spectroscopy of the Three Valence Proton Nucleus ^{149}Ho " American Physical Society, Minnesota, Oct. 10, 1980 - given by J. Wilson.

"Nuclear Spectra and Nuclear Structure", Honors Seminar, Purdue University, Oct. 15, 1980 - given by P. J. Daly.