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

Progress Report

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ABSTRACT

Nuclear structure studies in the A $\sim$ 150 region by γ-ray spectroscopy following heavy ion induced reactions are summarized. Yrast states of N=82 nuclei close to the proton drip line have been identified as rather pure $(\pi h_{11/2})^n$ excitations of seniority 2 and 3. The high-spin level structure of ^{154}Dy has been determined through the ^{124}Sn(^{34}S,4nγ) reaction. Both the structure and the level lifetimes indicate a transition at I $\sim$ 32 from collective to few-particle character, with possible shape changes from prolate-to-triaxial-to-oblate.

I. Research Activities

We have continued our nuclear structure investigations in the A ∿ 150 region using heavy ion beams from the Argonne Tandem-Linac. During 1981 we were involved in experiments requiring 22 days of beam time. The research performed followed the lines proposed, with rather more emphasis on the spectroscopy of discrete high-spin nuclear states than on studies of the continuum. Progress is summarized in the following sections.

Spectroscopy of very proton-rich N=82 nuclei.

^{146}Gd, with Z=64, N=82, has many properties of a doubly closed shell nucleus[1)], and in the two-proton nucleus ^{148}Dy a complete $(\pi h_{11/2})^2$ spectrum has been identified[2)], furnishing the two-body interaction matrix elements for $h_{11/2}$ protons. With this knowledge one can calculate[3)] the $(\pi h_{11/2})^n$ excitations which are expected to dominate the yrast spectroscopy of N=82 nuclei with n valence protons. Recently we performed the first studies of the N=82,83 ^{149}Ho and ^{150}Ho nuclei with three valence protons. The yrast states in ^{149}Ho were found[4)] to be in excellent agreement with the predictions for $(\pi h_{11/2})^3$, but in ^{150}Ho a large effective neutron charge of ∿ 4.0e was needed[5)] to reproduce the data, indicating considerable polarization of the core by the valence neutron.

We have now extended the investigations to the very proton rich N=82 nuclei ^{150}Er and ^{151}Tm, with four and five valence protons, respectively, outside the ^{146}Gd core. One of the points of interest here is that for $n > 3$, a state of given angular momentum can usually be made in more than one way, and thus the residual interaction could give rise to states of mixed seniority. However, Lawson [3] has shown , using the effective two-body interactions from the ^{148}Dy spectrum, that for $(\pi h_{11/2})^n$ configurations there should be little seniority mixing. When seniority is conserved, the dependence on occupation number n of the E2 transition rates between $(\pi h_{11/2})^n$ states of the same seniority, v, is given by

$$\begin{aligned} &B(E2;(h_{11/2})^n_{I_i}v \rightarrow (h_{11/2})^n_{I_f}v) \\ &=(\frac{6-n}{6-v})^2\ B(E2;(h_{11/2})^v_{I_i}v \rightarrow (h_{11/2})^v_{I_f}v). \end{aligned} \qquad (1)$$

Accordingly, the E2 rates between $(\pi h_{11/2})^n$ states of the same seniority are predicted to decrease sharply with increasing n, and to become identically zero when the $h_{11/2}$ subshell is half-filled at n=6. B(E2) determinations in the series of N=82 nuclei can thus provide stringent tests of the configuration assignments.

Nothing was previously known about ^{150}Er and ^{151}Tm, which lie close to the proton drip line, in a region where charged particle evaporation from excited compound nuclei competes strongly with neutron evaporation. In bombardments of proton-rich targets with proton rich Ni beams we were able to form appropriate compound nuclei at low excitation energies, favouring two or three nucleon evaporation to the residual nuclei of interest. By means of a novel combination of sum spectrometer and recoil catching techniques, clean γ-ray spectra from the residual nuclei of interest could be extracted. Isotopic identifications were based on a) excitation function and cross bombardment results b) coincidences with characteristic X-rays c) energy distributions of coincident sum-spectra.

To illustrate the exit channel selectivity that can be attained using the sum spectrometer, the γ-ray spectra observed in coincidence with low-, medium-, and high-energy slices of the sum spectrum for the reaction system ^{92}Mo + 225 MeV ^{60}Ni $\rightarrow$ ^{152}Yb* (E_{ex}=32 MeV) are shown in Fig. 1. In the topmost spectrum, known ^{149}Ho γ-rays, corresponding to 3p emission, are among the strongest lines; the only strong lines in the middle spectrum are the γ-rays here assigned to ^{150}Er, formed by 2p emission; the ^{150}Er γ-rays are again the strongest in the bottommost spectrum, but, in addition, weak lines with energies 140, 339, 699, and (off-scale) 1478 keV appear. Subsequent experiments showed that these four lines belong to ^{151}Tm, formed here by the emission of a single proton from the ^{152}Yb compound nucleus.

Detailed measurements established the ^{150}Er level scheme shown in Fig. 2 along with the theoretical $(\pi h_{11/2})^4$ yrast levels. The 2.55 μs isomeric state at 2797 keV is interpreted as the expected $(\pi h_{11/2})^4$ seniority 2, $I^{\pi} = 10^{+}$ isomer. Since configurations other than $(\pi h_{11/2})^4$ undoubtedly contribute substantially to the ^{150}Er ground state, the 119 keV discrepancy in the calculated 0^{+} energy is unsurprising. On the other hand, the calculated and experimental energies for the 8^{+}, 6^{+}, and even the 2^{+} states agree within < 18 keV, in line with the view that effects of 0^{+} pair admixtures should be approximately the same for states of the same seniority. Moreover,the E2 transition probability obtained from the 10^{+} half-life

$$B(E2;\ 10^{+} \rightarrow 8^{+})_{exp} = 12.1 \pm 0.7\ e^2 fm^4$$

is close to the predicted factor of 4 smaller than the B(E2) determined for the corresponding transition in ^{148}Dy. For the transition between $(\pi h_{11/2})^4$ v=2 10^{+} and 8^{+} states, eqn. (1) gives

$$B(E2;\ 10^{+} \rightarrow 8^{+})_{calc} = 10.8 \pm 0.8\ e^2 fm^4$$

in excellent agreement with the experimental result. Indeed, the agreement is rather better than one might have anticipated, since the probability of

0^+ pairs being scattered across the Z=64 gap is not negligible. The simplest explanation would be that in these ^{150}Er v=2 states, the number of $g_{7/2}$ and $d_{5/2}$ hole pairs is about equal to the number of $s_{1/2}$ and $d_{3/2}$ particle pairs, leaving on average close to four protons in the $h_{11/2}$ orbital.

The 140, 339, 699 and 1478 keV γ-rays noted in Fig. 1(c) appeared much more strongly in the reactions ^{58}Ni + ^{95}Mo → ^{153}Yb* and ^{60}Ni + ^{93}Nb → ^{153}Tm*. Since in addition the lines were found to be coincident with Tm X-rays, they are assigned to the N=82 nuclei ^{151}Tm. The proposed ^{151}Tm level scheme is shown in Fig. 3, together with the ^{149}Ho scheme, and the calculated yrast levels for $(\pi h_{11/2})^3$ and $(\pi h_{11/2})^5$ configurations. The $27/2^- \rightarrow 23/2^-$ transition probability in ^{151}Tm

$$B(E2;\ 140\ \text{keV}) = 11.7 \pm 1.3\ e^2\text{fm}^4$$

is much smaller than the value 88±6 e^2fm^4 obtained for the corresponding 144 keV transition in ^{149}Ho. According to eqn. (1) the ratio of these B(E2) values would be 1:9 for pure $(\pi h_{11/2})^5$ and $(\pi h_{11/2})^3$ v=3 states. Again, the agreement between experiment and theory is remarkable, and is moreover consistent with the ^{150}Er findings, since the number of 0^+ pairs is the same in v=3 states of ^{151}Tm as in v=2 states of ^{150}Er.

These spectroscopic studies of N=82 nuclei very near the proton drip line were possible because suitable proton-rich compound nuclei could be produced at low excitation energies in ^{58,60}Ni induced reactions, and clean γ-ray spectra from the residual nuclei of interest could be obtained by the combination of sum spectrometer and recoil catching techniques. We plan further to investigate the higher seniority $(\pi h_{11/2})^n$ yrast states above the ^{150}Er 10^+ and ^{151}Tm $27/2^-$ isomers, and to search for the very long-lived $(\pi h_{11/2})^6$ v=2 10^+ isomer expected in ^{152}Yb.

Transition from Collective to Aligned-Particle Nature at High-Spin in ^{154}Dy

Bohr and Mottelson have pointed out[6] that rapid rotation of nuclei may induce a transition to oblate shapes, manifested inter alia by the occurrence of high spin isomers. The subsequent discovery[7] of an island of isomers around A ∿ 150 has generated considerable research on nuclei in this mass region. For Z=64-68, N=83-86 nuclei, which are spherical in their ground states, the high-spin yrast configurations have been shown to be of few-particle character, with the spins of the individual nucleons aligned along a symmetry axis. The oblate mass distribution of these aligned particles, together with the resultant core polarization, leads to an overall oblate shape. However, nuclei which are prolate in the ground state (such as those with $N \geq 90$) contain no high-spin isomers and appear not to become oblate.

One might hope to observe the predicted prolate-to-oblate shape change in N=87 and 88 nuclei, where the prolate-driving shell effects might be overcome at high spins by the oblate-driving effects associated with particle alignment. Since the yrast configurations of Dy isotopes with N=82-86 are of aligned particle character[2,8], while those of $N > 89$ are collective, we chose to investigate the high spin structure of ^{154}Dy (N=88).

We have employed the ^{124}Sn(^{34}S,4n)^{154}Dy reaction, with 145-175 MeV beams. A very extensive set of in-beam experiments were performed, including γ-γ coincidence, angular distribution, excitation function, and lifetime measurements. A large NaI detector was used, either as a sum spectrometer or as a multiplicity filter, to enhance ^{154}Dy lines. The resulting level scheme, determined up to spin 34 or 35, is shown in Fig. 4. Since electronic timing measurements with respect to the pulsed beam revealed no ns isomers in ^{154}Dy, additional experiments, using the recoil distance technique, were performed to determine the state lifetimes.

Up to spin 32 the positive parity yrast levels are typical of a weakly deformed prolate rotor. The yrast transition energies increase monotonically (except near the I=14 and I=28 backbends) and the levels are connected by stretched E2 transitions which are enhanced (60-300 Weisskopf units). However, above spin 32 a transition to few-particle structures occurs. The transition energies cease to increase smoothly and some predominantly dipole transitions appear, terminating the hitherto uninterrupted cascade of stretched E2 gamma rays. Finally, the combined state-plus-feeding times of the 11.0 and 12.3 MeV levels (6 and 5ps) are significantly slower than the values typically observed at high-spin in collective rotors like ^{158}Dy, but are similar to those measured[8)] in ^{152}Dy. It is likely that aligned-particle configurations such as those in neighboring ^{152}Dy are involved, since only these would lie at sufficiently low energy. As in ^{152}Dy, these configurations would lead to an oblate mass distribution.

From the measured lifetimes, we have deduced that the effective quadrupole moment Q_0(eff) decreases gradually between I=14 and I=26, reflecting the steady decrease in collectivity. This decrease in Q_0(eff) may be due to an increased axial asymmetry, and we speculate that the prolate-to-oblate transition may occur gradually through a series of triaxial shapes. The evolution from prolate to oblate shapes via rotation-aligned structures is envisaged to be smooth. For the prolate ground band the angular momentum has only a collective component, which is perpendicular to the symmetry axis; in the rotation-aligned bands the angular momentum is generated by both aligned particle and collective spins along an axis perpendicular to the original symmetry axis; this perpendicular axis becomes the symmetry axis along which the particle spins align in the oblate limit.

In summary, the level structure and lifetimes in the transitional nucleus ^{154}Dy suggest a change from collective to few-particle character with increasing spin. This is probably accompanied by a prolate-to-triaxial-to-oblate shape change, which is the outcome of the delicate interplay of prolate-driving shell effects (which dominate for $N \geq 90$) and oblate-driving effects (which prevail for $N \leq 86$).

Other Projects

Building on the results described in the preceding sections, we have made a start on studying the ^{150}Er $v=4$ levels above the 10^+ isomer, and on a detailed spectroscopic study of the N=87 nucleus ^{153}Dy. The Purdue group has also participated in Linac investigations of continuum γ-ray properties and of yrast feeding patterns in $A \sim 150$ nuclei; in these cases, much of the data analysis remains to be done.

Our Argonne NL collaborators are T. L. Khoo, I. Ahmad, P. Chowdhury, R. Janssens, and R. D. Lawson, while G. Sletten and J. Borgreen (Niels Bohr Institute) are leading the yrast feeding pattern study.

References

1. P. Kleinheinz et al., Z. Phys. A290 (1979) 279.
2. P. J. Daly et al., Z. Phys. A298 (1980) 173.
3. R. D. Lawson, Z. Phys. A303 (1981) 51.
4. J. Wilson et al., Z. Phys. A296 (1980) 185.
5. J. Wilson et al., Phys. Lett. 103B (1981) 413.
6. A. Bohr and B. R. Mottelson, Phys. Scr. 10A (1974) 13.
7. J. Pedersen et al., Phys. Rev. Lett. 39 (1977) 990.
8. B. Haas et al., Phys. Lett. 84B (1979) 178; Nucl. Phys. A362 (1981) 254.

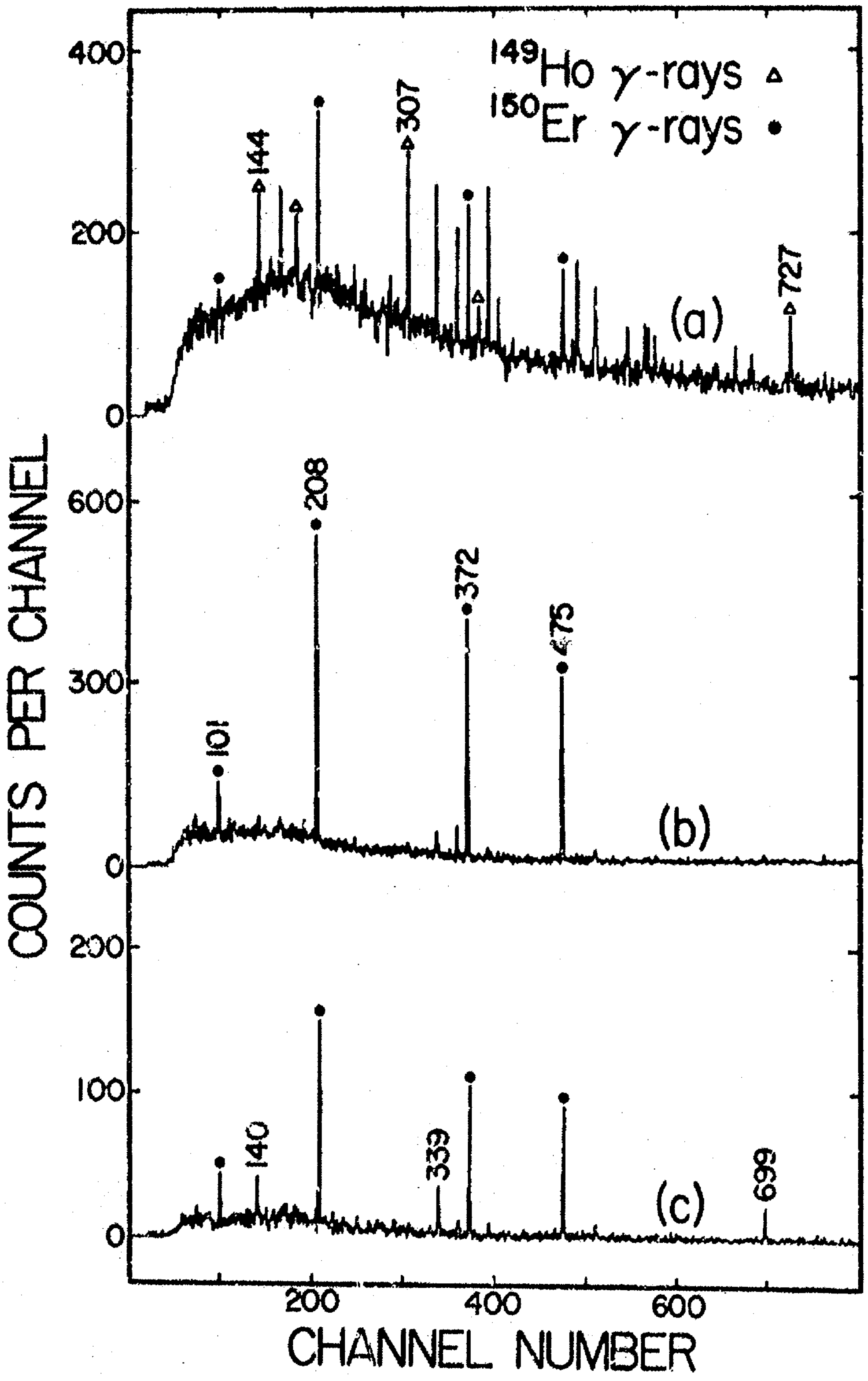
Figure Captions

Fig. 1. Gamma-ray spectra recorded in coincidence with a) low b) medium c) high energy slices of the prompt γ-ray sum spectrum in the reaction ^{92}Mo + 225 MeV ^{60}Ni.

Fig. 2. The ^{150}Er level spectrum up to the 10^+ isomer and the calculated $(\pi h_{11/2})^4$ yrast levels.

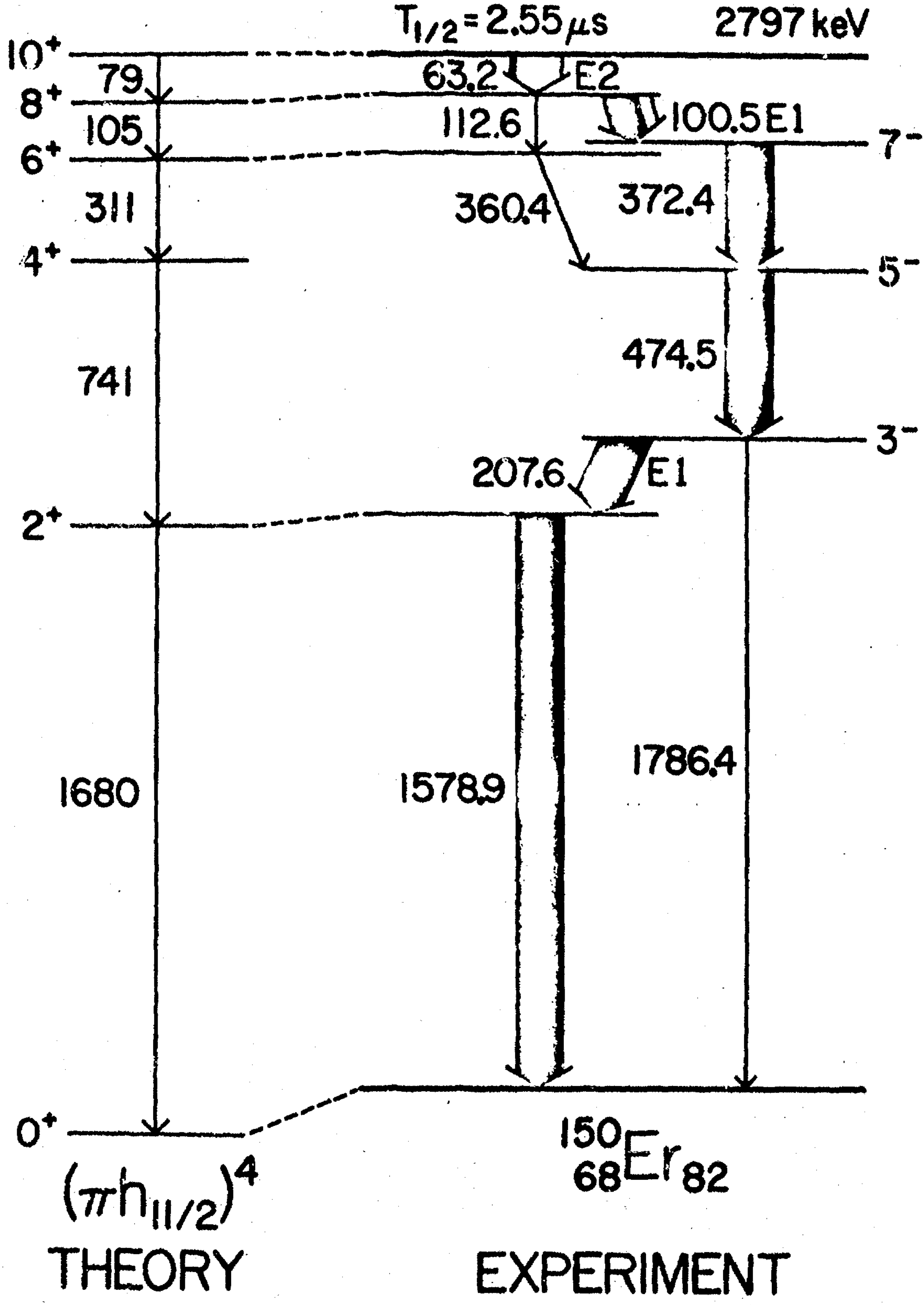
Fig. 3. The level spectra of ^{149}Ho and ^{151}Tm up to the $27/2^-$ isomers, and the calculated $(\pi h_{11/2})^3$ and $(\pi h_{11/2})^5$ yrast levels.

Fig. 4. The ^{154}Dy level scheme established using the ^{124}Sn(^{34}S,4nγ) reaction.



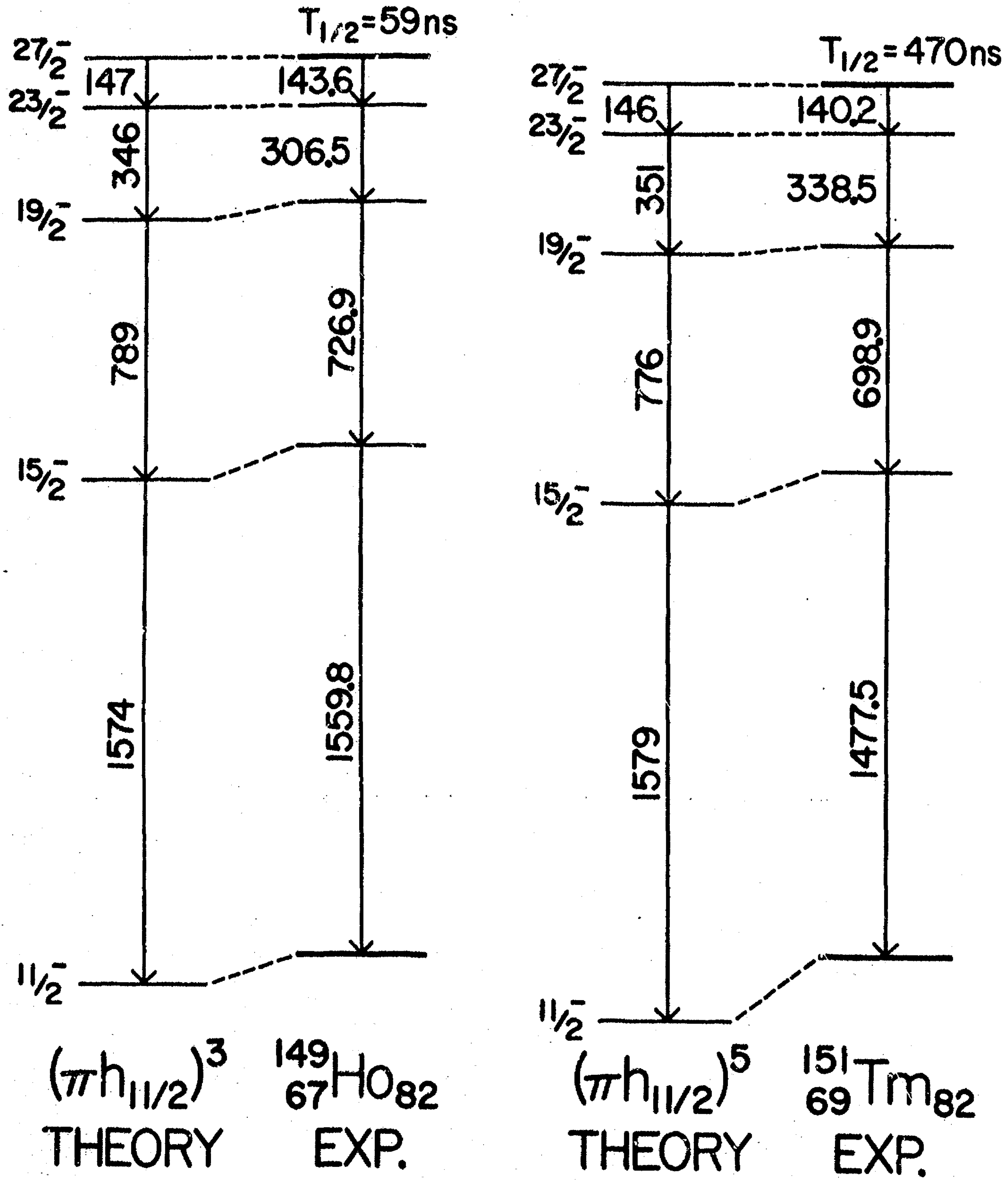
^{149}Ho γ-rays △
^{150}Er γ-rays ●
COUNTS PER CHANNEL
CHANNEL NUMBER
400
200
0
600
300
0
200
100
0
200
400
600
144
307
727
208
101
372
475
140
339
699
(a)
(b)
(c)

Fig. 1



$T_{1/2}$=2.55 μs
2797 keV
10⁺
8⁺
6⁺
4⁺
2⁺
0⁺
79
105
311
741
1680
63.2
E2
112.6
100.5 E1
7⁻
5⁻
3⁻
360.4
372.4
474.5
207.6
E1
1578.9
1786.4
$^{150}_{68}Er_{82}$
$(\pi h_{11/2})^4$
THEORY
EXPERIMENT

Fig. 2



T1/2=59ns
27/2-
23/2-
19/2-
15/2-
11/2-
147
143.6
346
306.5
789
726.9
1574
1559.8
(πh11/2)3
THEORY
149 67 Ho82
EXP.
T1/2=470ns
27/2-
23/2-
19/2-
15/2-
11/2-
146
140.2
351
338.5
776
698.9
1579
1477.5
(πh11/2)5
THEORY
151 69 Tm82
EXP.

Fig. 3

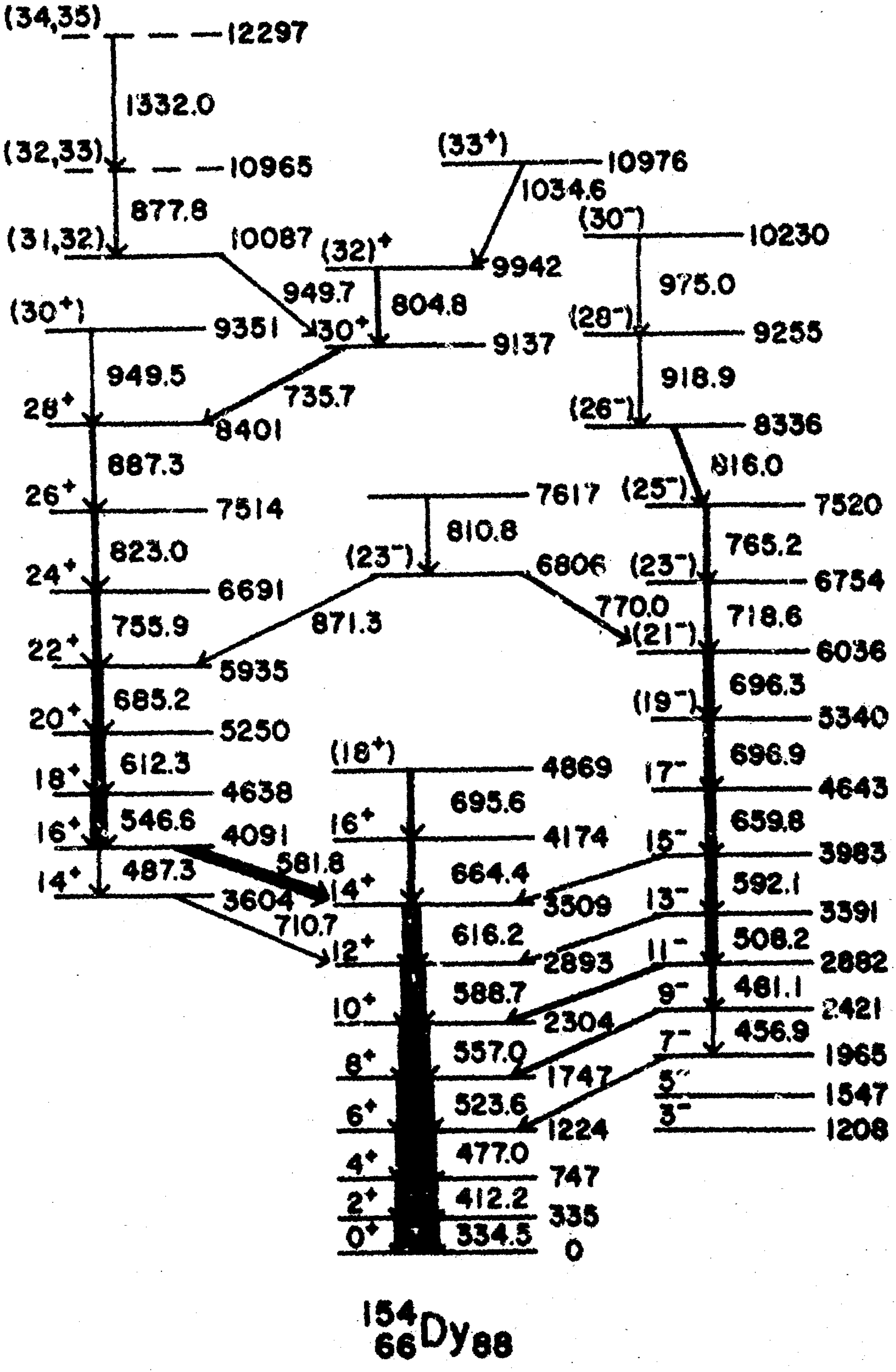

(34,35)
12297
1332.0
(32,33)
10965
877.8
(31,32)
10087
(33+)
10976
1034.6
(30−)
10230
(32)+
9942
949.7
804.8
975.0
(30+)
9351
30+
9137
(28−)
9255
949.5
735.7
918.9
28+
8401
(26−)
8336
887.3
816.0
26+
7514
7617
(25−)
7520
823.0
810.8
765.2
24+
6691
(23−)
6806
(23−)
6754
755.9
871.3
770.0
718.6
22+
5935
(21−)
6036
685.2
696.3
20+
5250
(19−)
5340
612.3
(18+)
4869
696.9
18+
4638
695.6
17−
4643
546.6
16+
4091
16+
4174
659.8
581.8
15−
3983
14+
487.3
14+
664.4
3509
592.1
3604
710.7
13−
3391
12+
616.2
2893
508.2
11−
2882
10+
588.7
2304
461.1
9−
2421
8+
557.0
1747
456.9
7−
1965
6+
523.6
1224
5−
1547
3−
1208
4+
477.0
747
2+
412.2
335
0+
334.5
0
$^{154}_{66}Dy_{88}$

Fig. 4

II. Personnel

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** Terminated August 1981

*** Terminated October 1981

[+] Terminated May 1981

[++] Started August 1981

[+++] Terminated with Final Ph.D. Exam, September 1981

III. Publications and Talks (1981)

"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, Phys. Rev. C23 (1981) 1446.

"The High-spin Level Structure of ^{200}Hg", H. Helppi, S. K. Saha, M. Piiparinen, C. L. Dors, P. J. Daly, T. L. Khoo, Phys. Rev. C23 (1981) 2345.

"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, 24 (1981) 283.

"Atomic Masses Above ^{146}Gd Derived from a Shell Model Analysis of High Spin States", J. Blomqvist, P. Kleinheinz, R. Broda, P. J. Daly, Proc. 4th Int. Conf. on Nuclei Far From Stability, Helsingør, (1981) p. 545.

"Yrast Isomers and Very High Spin States in ^{148,149,151,152}Dy and ^{147}Gd", B. Haas et al., Nucl. Phys. A362 (1981) 254.

"Shell Model Yrast States of the N=83 Nucleus ^{150}Ho", J. Wilson, Y. H. Chung, S. R. Faber, A. Pakkanen, P. J. Daly, I. Ahmad, P. Chowdhury, T. L. Khoo, R. D. Lawson, R. K. Smither, Phys. Lett. 103B (1981) 413.

"Feeding of High-Spin Particle Yrast States by Collective Structures in the Continuum", P. Chowdhury, J. Borggreen, T. L. Khoo, I. Ahmad, R. K. Smither, S. R. Faber, P. J. Daly, C. L. Dors, J. Wilson, Phys. Rev. Lett. 47 (1981) 778

"Elementary Nuclear Excitation Modes in the A ∿ 150 Region", Heavy Ion Seminar, Argonne NL, Feb. 1981, given by P. J. Daly.

"Yrast Level Structure of ^{154}Dy" Heavy Ion Seminar, Argonne NL, March 1981, given by A. Pakkanen.

"Yrast Spectroscopy of the N=83 Nucleus ^{150}Ho" Amer. Phys. Soc., Baltimore, April 1981, given by A. Pakkanen; abstract in BAPS 26 (1981) 620.

"High-spin Yrast States in ^{154}Dy" Amer. Phys. Soc., Baltimore, April 1981, given by A. Pakkanen; abstract in BAPS 26 (1981) 620.

"Shell Model Yrast States of Proton Rich N=82,83 Nuclei", AVA Program Review, Argonne NL May, 1981 - given by P. J. Daly.

"Shell Model Yrast States of Proton Rich N=82,83 Nuclei", 4th Int. Conf. on Nuclei Far From Stability, Elsinore, Denmark, June, 1981, presented by P. J. Daly.

"Shell Model Yrast States of Proton Rich N=82,83 Nuclei" Amer. Chem. Soc., New York, August 1981 - given by P. J. Daly.

"Yrast $(\pi h_{11/2})^n$ Excitations in Proton Rich N=82 Nuclei" Nucl. Structure Seminar, Purdue University, September 1981 - given by P. J. Daly.

"Transition from Collective to Single - Particle Nature at High Spin in ^{154}Dy" Amer. Phys. Soc., Asilomar, October 1981 - given by T. L. Khoo; abstract in BAPS 26 (1981) 1116.

"$(\pi h_{11/2})^4$ Spectrum of the N=82 Nucleus ^{150}Er", Amer. Phys. Soc., Asilomar, October 1981 - given by P. J. Daly; abstract in BAPS 26 (1981) 1155.

"The Five Valence Proton N=82 Nucleus ^{151}Tm", Amer. Phys. Soc. Asilomar, October 1981 - given by P. J. Daly; abstract in BAPS 26 (1981) 1155.