CONF-800452-79

MASTER

YRAST SPECTROSCOPY: STATUS OF YRAST ISOMERS,
OBLATE SHAPES AND FEEDING OF YRAST STATES

by

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Prepared for
International Conference
on
Nuclear Behavior at High Angular Momentum
Strasbourg Cedex, France
April 22-24, 1980

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**Operated under Contract W-31-109-Eng-38 for the
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Invited Talk Presented at
International Conference on Nuclear Behavior at High Angular Momentum
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YRAST SPECTROSCOPY: STATUS OF YRAST ISOMERS, OBLATE SHAPES AND FEEDING OF YRAST STATES

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In this talk, the emphasis is on the properties of very high spin states at the yrast line. Three different but related topics will be discussed:

(i) the status of yrast isomers (I shall restrict myself to those with $A > 140$ and shall focus mainly on the $A \sim 150$ region); (ii) the nuclear shape along the yrast line; and (iii) the feeding of the yrast states as a function of spin. A recurrent theme in the talk will be the response of the core to the polarizing effects of a successively increasing number of valence particles and how the investigation of very high spin states bears on this problem.

Status of Yrast Isomers

The known yrast isomers with mass number larger than 140 are shown in Figure 1. For this figure, an isomer has been arbitrarily defined as having a half-life longer than 1 ns — which roughly

corresponds to the shortest half-life measurable by electronic techniques. Isotopes having $I \geq 10$ or $I \geq 20$ are distinguished in the figure.

A striking feature is that the isomers occur in four distinct clusters of the periodic table: one with $A \sim 150$, another in the Hf region where many K-forbidden isomers occur, a third in the Hg-Pt region, and a fourth in the trans-lead region. The largest concentration of isomers with $I \geq 20$ occurs in the $A \sim 150$ region, partially because more isotopes in this island are more readily accessible by (heavy ion, xn) reactions.

In the Hg-Pt cluster, a frequent cause of isomerism is the sharp intersection between the ground and rotation-aligned bands, which lead to small transition energies at the intersection.

In the other three regions, two common features

Figure 1. Partial chart of isotopes showing known isomers. An isomer is defined as a state with half-life larger than 1 ns. Isomers with $I \geq 10$ are indicated by triangles (▲) and those with $I \geq 20$ by circles (●).

are the occurrence of single particle type structures at or close to the yrast line at high spin, and the fact that the total spin is aligned along a symmetry axis. One might thus infer that the occurrence of high spin isomers in fact is a signature of these two features.

There are very few isomers with $I \geq 30$; ^{212}Rn is the only published example,¹ although preliminary evidence exists for such isomers in ^{152}Er (Ref. 2) and ^{147}Gd (Ref. 3). The paucity of this class of isomers may be partly attributed to the increasing steepness of the yrast line with increasing spin, partly to the decreasing population of yrast states with $I > 30$, and perhaps even to a change of the yrast character from single-particle to collective for spins in excess of 30.

Isomerism arising from spin inversion ($E_I < E_{I-2}$) is also very rare. Two well-known examples are the $31\gamma\text{K}^\pi = 16^+$ yrast trap in ^{178}Hf (due to K-forbiddenness and the very small energy differences in the quasiparticle excitations of this nucleus), and the $45\text{s}1^\pi = (16^+)$ α -decaying isomer in ^{212}Po (due to the large residual interactions in the highly aligned 2π - 2ν configuration). So far, no examples have been found in the $A \sim 150$ region.

A striking feature of the $A \sim 150$ island is the sudden disappearance of isomers for $N \geq 87$. This is probably correlated with the smoothing out of the yrast line, which in contrast is irregular for $N \leq 86$ (see Figure 2). This presumably reflects the onset of prolate deformation at high spin at a smaller neutron number than at the ground state, where the transition to prolate shapes is believed to occur at $N = 90$. This sudden transition of the yrast character at $N = 87$ from single particle to collective nature is partly due to Coriolis decoupling, which aligns⁴ the particle spin, $\underline{J}$,

along the rotation vector, $\underline{R}$. As indicated in Figure 3(a), it is efficient to align $\underline{J}$ and $\underline{R}$ in the same direction when combining single particle and collective spin contributions. In contrast, in the strong-coupled situation for high-K states [Figure 3(b)], the two vectors are perpendicular, giving rise to a smaller total spin, $\underline{I}$, for the same magnitudes of $\underline{J}$ and $\underline{R}$ as in Figure 3(a).

The sudden onset of prolate deformation with only 5 neutrons outside the $N = 82$ closed shell emphasizes the polarizability of the core — or its vulnerability towards deformation — when only a few particles are added to it. (For the purposes of this talk, $N = 82$ and $Z = 64$ are assumed to constitute the core.) The question of core polarization will be discussed again shortly.

The importance of isomers in experimental investigations are threefold. First, their decays can be studied in a "clean" out-of beam environment — although the decay scheme need not be at all simple. Second, they may be used as stepping stones to higher spin states through the use of delayed coincidence techniques to

Figure 2. Plots of E vs $I(I+1)$ for yrast states of $^{148}, ^{150}, ^{152}, ^{154}\text{Dy}$. For ^{154}Dy , the yrast line is smooth, but for the others, it is irregular.

(a) CORIOLIS ALIGNMENT

(b) HIGH-K BAND
 $J_2 = K = \sum \Omega_i$

Figure 3. Coupling of the particle spin vector, $J = \frac{1}{2} I$, and the rotation vector, R , in the rotational aligned case (a) and in the strong-coupled limit (b).

isolate structures feeding the isomers. Third, they make it feasible to perform measurements of detailed spectroscopic properties, e.g., $B(E2)$, $B(M1)$, g-factors, quadrupole moments, and isomer shifts ($\langle r^2 \rangle_{\text{isomer}} - \langle r^2 \rangle_{\text{ground state}}$) by optical (laser) pumping techniques.

In fact, the highlight concerning isomers in the past year is the measurement^{5,6} by the Chalk

River group of the quadrupole moments of a number of isomers in some Gd isotopes. In ^{147}Gd , the quadrupole moments are found to increase with the spin of the isomer, implying an increasing deformation (in all likelihood oblate). Table I, which has been reproduced from Ref. 6, summarizes the results.

Oblate Shapes Along the Yrast Line

In this section, we are concerned with the average shape which is sampled as one proceeds from one yrast state to the next. In the $A \sim 150$ region and trans-Pb regions, it is important to recognize that the yrast states consist of a succession of configurations with maximal or near maximal spin alignment, as illustrated in Figure 4.

It is instructive to first consider the deformation involved in the notion of a single particle outside a closed core. In this case, one might first expect the particle to move in a spherically symmetric potential. However, since the particle orbit has an oblate mass distribution, and since the average potential is generated by all nucleons, this situation is not self-consistent. To achieve this condition,

Table I. Quadrupole moments in ^{147}Gd ($1b = 10^{-28} \text{ m}^2$) (from Ref. 6).

$T_{1/2}$ (ns)	I^π	Quasiparticle Structure	$ Q_{\text{exp}} $ (b)	QSM (b)	μ (a)
22	$13/2^+$	$\nu i_{13/2}$	0.73(7)	-0.36	-0.05 [0.05]
		$\pi 3^- \nu f_{7/2}$			
27	$27/2^-$	$\pi 10^+ \nu f_{7/2}$	1.26	-0.78	-0.06 [0.10]
500	$49/2^+$	$\pi 10^+ \nu h_{11/2}^{-1} f_{7/2} i_{13/2}$		-0.84	-0.18 [0.20]
			3.14(17)		
	$49/2^+$	$\pi 10^+ \nu f_{7/2} i_{13/2} h_{9/2}$		-1.36	
	$59/2^-$	$\pi 15^- \nu f_{7/2} i_{13/2} h_{9/2}$	3.80(20)	-1.40	-0.22 [0.23]

(a) The oblate solution with negative sign is preferred over the prolate solution in square brackets.

the core also has to acquire an oblate shape, as illustrated in Figure 5. With harmonic oscillator wave functions,⁷ self-consistency is achieved when the core acquires a mass quadrupole moment equal to that of the particle orbit, as first shown by Mottelson.⁷ Thus the total mass quadrupole moment is the sum of that of the polarized core and of the single particle orbit. For an $h_{11/2}$ particle in the $n = 11/2$ substate, this translates into an equivalent deformation of $\delta \sim 0.01$. In real nuclei, the core is somewhat more polarizable and acquires a mass quadrupole moment up to twice that of the single particle.⁷ For a multi-particle state, one adds the total mass quadrupole moments of the individual components. Thus, for example, the configuration $1^{\pi} = 49/2^{+} (\pi h_{11/2}^2)_{10^{+}} (2f_{7/2} h_{9/2} i_{13/2})_{27/2^{+}}$ has a contribution to the mass quadrupole moment from the single particle orbits of 120 fm^2 and a core contribution of between 120 and 240 fm^2 , implying a total oblate deformation of $\delta \sim 0.05 - 0.08$.

Figure 4. Aligned configuration with high density of equatorial orbits.

Figure 5. Single particle orbit induces a deformation in the core.

In the above example, it has been assumed that the polarization effects add linearly. If the response is linear, as might be expected with many particles, the deformation may be even larger. In fact, the study of non-linear effects, which probably play an important role in achieving large deformation, is itself an interesting subject.

An alternate way to estimate the deformation is to consider the balance between the energy gain of the single particles and the energy cost in deforming the core — see Figure 6. For small deformation ($\delta < 0.1$), the total energy is given⁸ by

$$E = \sum_i \epsilon C_i \delta + C_0 \delta^2. \quad (1)$$

The contribution of particle i is given by

$$C_i \delta = \alpha \left(\frac{m^2}{j_i(j_i+1)} - \frac{1}{3} \right) \delta,$$

with $\alpha \sim 27 \text{ MeV}$ in the $A \sim 150$ region. The coefficient C_i is the slope of the Nilsson orbit in Figure 6; C_0 is a measure of the stiffness of the core. The energy is a minimum when

$$\delta = - \frac{\sum_i C_i}{C_0} \quad (2)$$

The stiffness parameter C_0 is related to the quantity $B(E2 \ 0^+ \rightarrow 2^+)$. Since an accurate measurement of the latter does not exist for ^{146}Gd , the value of C_0 is undetermined. However, from the systematics shown in Figure 6—28 of

Figure 6. (a) Nilsson diagram illustrating that energy is gained from deformation by occupying high- κ orbits. (b) Energy to deform a closed core.

Ref. 9, C_0 for ^{146}Gd is estimated to be between 0.5–1 GeV. With the use of Eq. (21), this implies an oblate deformation of $\epsilon = 0.06$ –0.17 for the configuration

$1^\pi = 49/2^+ [(h_{11/2}^2)_{10^+} (v(f_{7/2} h_{9/2} i_{13/2})_{27/2^+})]$ in ^{151}Dy , to take an example. This is to be compared with the above estimate of 0.05–0.09, made using self-consistency arguments.

For spins larger than the maximum values possible by coupling valence particles, core excitations will be involved. Since a closed core implies an extra stability associated with a spherical shape, excitations out of the core is expected to lead to a reduction of C_0 . Thus, for example, the core-excited configuration in ^{147}Gd

$$1^\pi = 49/2^+ [(h_{11/2}^2)_{10^+} (d_{5/2}^{-2})_{0^+} v(f_{7/2} h_{9/2} i_{13/2})_{27/2^+} (d_{3/2}^{-2})_{0^+}],$$

would be expected to have larger deformation than that of the above state in ^{151}Dy with the same valence orbits occupied. Indeed Döbbing, Reepård and Sagawa¹⁰ calculate an oblate deformation of $\epsilon = 0.19$ for the $1^\pi = 49/2^+$ state in ^{147}Gd , in excellent agreement with the value of 0.18 implied by the quadrupole moment measured by Häusser et al.^{5,6}

It should be remarked that the energy of a 2 particle–2 hole excitation is not necessarily larger than that of a 1p–1h excitation, as might be expected for $\beta = 0$. This is because the 1p–1h state does not add to the oblate mass distribution as does a $(2p)_{\frac{1}{2}} (2h)_{\frac{1}{2}} = 0^+$ state. The resultant larger polarization in the latter should lead to a larger oblate deformation. This results in a smaller gap above the shell closure, which in turn implies smaller excitation energies.

In order to examine the role of core excitations in obtaining oblate deformations, let us examine the yrast lines of the Dy isotopes as N increases from 82 to 86. The level scheme of $^{148}\text{Dy}_{82}$ is shown in Figure 7; those for the heavier isotopes are given in Refs. 3 and 11–13. Plots of E vs $I(I+1)$ for the supposed yrast states in a series of Dy isotopes are shown in Figures 2 and 8. For ^{148}Dy , the maximum valence spin is obtained in the $(\pi h_{11/2}^2)_{10^+}$ configuration. The steep rise in the yrast line just beyond $I = 10$ reflects the energy cost in promoting a particle across either the $Z = 64$ or $N = 82$ gap. The yrast lines for ^{151}Dy and ^{152}Dy (Figure 3), on the other hand, do not display a similar steep rise beyond $I = 53/2$ and 30, the respective maximum valence spins. However, the yrast lines constructed in a shell model approach, described in Ref. 11, do display a break symptomatic of the onset of core excitation (see Figure 8). (Note that there is very good agreement between the calculated and experimental points up this juncture.) The absence of a sharp rise in the data probably reflects the presence of an oblate deformation at high spin, which diminishes the shell gap. It is also responsible for the gentler slopes of

the experimental yrast lines compared to the calculated ones.

Figure 7. Level scheme of ^{148}Dy .

It should be recognized that the calculated yrast line is constructed from aligned configurations. These configurations have an oblate deformation, as was pointed out earlier. Thus the slope of the calculated line already reflects the average deformation of the aligned configurations constituting the yrast states. In ^{151}Dy , the deformation of the $I = 49/2$ state is probably representative of this average and, as estimated above, is of the order of $\beta \approx 0.05-0.62$. The larger effective moment of inertia of the experimental yrast line thus reflects an average deformation in excess of this. The breaking of the core is the likely cause of this incremental deformation.

The occurrence of an oblate shape naturally implies that the single particle spectra may be calculated using an oblate deformed potential. In principle, it should also be possible to do the calculation using the "spherical" shell model, with of course the inclusion of the residual

Figure 8. Plots of energy vs $I(I+1)$ for experimental and calculated yrast states of ^{151}Dy and ^{152}Dy . Straight lines have been fitted through the data points (o) and calculated points (x) for levels with $I \geq 29/2$ for ^{151}Dy and $I \geq 14$ for ^{152}Dy . The data yield effective moments of inertia, $\frac{2f}{h^2}$, of 133 ± 3 and $142 \pm 3 \text{ MeV}^{-1}$ (solid lines); the calculated points yield 123 ± 4 and $135 \pm 4 \text{ MeV}^{-1}$ (dashed lines) for ^{151}Dy and ^{152}Dy , respectively.

interactions. However, when the number of active particles increases beyond 4 or 6, the number of interactions becomes very large in general. Furthermore, when the core is broken then the shell model basis becomes prohibitively large. The use of a deformed potential—either oblate or prolate—circumvents these problems: the many two-body interactions required with a spherical core are subsumed by a deformed field. In addition, the shape of the nucleus is explicitly identified in the process.

Feeding of Yrast States

Some interesting trends concerning the population in (heavy ion, xn) reactions of yrast states in the A = 150 region are beginning to emerge. In general, this population tends to be larger in this mass region than for rare earth prolate nuclei. (We have previously suggested

Figure 9. Fractional population of yrast states of ^{152}Dy as a function of spin for 144, 151, 160 and 176 MeV bombarding energy in the ($^{34}\text{S}, 4n$) reaction. The $2^+ \rightarrow 0^+$ transition defines 100% population. Curves for 168 and 184 MeV, which are essentially the same as those for 160 and 168 MeV, are omitted for clarity.

reasons for this in Refs. 11 and 12.) However, this is not uniformly true. Using ^{32}S - and ^{34}S -induced reactions to populate yrast states in $^{148,150,151,152}\text{Dy}$, we have observed that states with spins up to the valence limit can receive close to 100% of the channel population. (The maximum valence spins in these Dy isotopes are 10, 22, $53/2$ and 30, respectively.) For larger spins, the yrast population decreases rapidly.

In ^{152}Dy , we have measured the yrast population in the ($^{34}\text{S}, 4n$) reaction as a function of increasing angular momentum input by varying the bombarding energy. Figure 9 shows the fractional population of the yrast states as a function of spin at different beam energies. It is seen that the population of the highest spin states increases between 144 and 160 MeV. However, at higher beam energies (168, 176, 184 MeV) this population saturates and ceases to increase, although multiplicity data indicate that the angular momentum input into ^{152}Dy continues to grow. (The curves for 168 and 184 MeV are omitted in Figure 9 for clarity since they overlap those for 160 and 176 MeV.) Notice that at saturation, ~90% of the feeding flows through the $I = 29$ state, an unusually high fraction at such high spins!

The population saturation implies that the γ deexcitation is diverted away from the yrast line at the highest spins and only feeds the yrast line between spins 30 and 40. Statistical γ rays should feed the yrast line directly even at the highest spins. Therefore, collective transitions are suggested which direct the flow more or less parallel to the yrast line.

The occurrence of a large E2 component in the continuum γ spectrum (see Figure 10) feeding the yrast states of ^{152}Dy is consistent with this picture. The continuum transitions in ^{154}Er also show similar E2 bumps.^{14,15}

Thus, although the yrast lines in ^{152}Dy and ^{154}Er is of single particle character up to the highest spin observed (38), it appears that a transition to collective character occurs at higher spins and/or higher excitation energy with respect to the yrast line. One of the exciting challenges awaiting us is to explore the nature of this transition.

Figure 10. Spectrum of γ rays from mainly ^{152}Dy observed in an NaI detector, showing both discrete yrast transitions and a continuum E2 component. The spectrum shown is the difference between two spectra associated with different sum energy slices of a sum spectrometer.

Acknowledgements

Many collaborators have contributed to different facets of this work. It is a pleasure to have worked with: I. Ahmad, J. Borggreen, P. Chowdhury, C. N. Davids, W. Kutschera, S. Levenson, R. E. Smither (Argonne); P. J. Daly, C. L. Dors, S. R. Faber, J. Wilson (Purdue University); B. Haas, H. R. Andrews, O. Häusser, D. Horn, J. F. Sharpey-Schafer, P. Taras,

W. Trautman and D. Ward (Chalk River). Experiments have been performed with beams from the Argonne superconducting linac and the Chalk River MP Tandem Accelerator. This work was performed under the auspices of the U.S. Department of Energy.

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