Paper given at the International Symposium on Collectivity of Medium and Heavy Nuclei, Tokyo, Japan, September 23-25, 1976.
MSUCL-222
MSUNC-194

ROTATION-ALIGNED AND DEFORMATION-ALIGNED YRAST STRUCTURES IN W, Os, AND Pt ISOTOPES*

F. M. Bernthal†

Michigan State University, East Lansing,

Michigan 48824, U.S.A.

1. Introduction

The discovery some five years ago of the backbending phenomenon in certain deformed rare-earth nuclei served to focus attention on the behavior of nuclei at high spins. The subsequent interpretation of backbending as a manifestation of the interplay between collective and intrinsic motion in the nucleus has led to a detailed exploration of such phenomena. Nuclei near the large-A limit of the rare-earth deformed region provide a particularly fertile ground for the study of high spin phenomena, influenced as they are by changing nuclear shapes, shell effects, and strong Coriolis forces. These are the general features expected to dominate nuclear structure at still higher spins, and they find their counterparts in the transition from prolate to oblate deformation in the Os and Pt isotopes, in the appearance of high-spin, multiquasiparticle yrast traps in certain Hf and W isotopes, and in the reappearance of strong rotation-alignment effects in Os and Pt isotopes with $106 \leq N \leq 110$.

2. Rotation-aligned Yrast Structure

A. Osmium and Platinum Isotopes

The general features of the yrast structures in even-A Os and Pt isotopes have been previously reported[1,2]; both isotopic series $^{182-188}$Os and $^{184-194}$Pt have their peculiar behavior. To place matters in perspective, fig.1 shows a conventional backbending-style plot of the yrast band data for the platinum isotopes 184, 186, and 188. The data show a transition

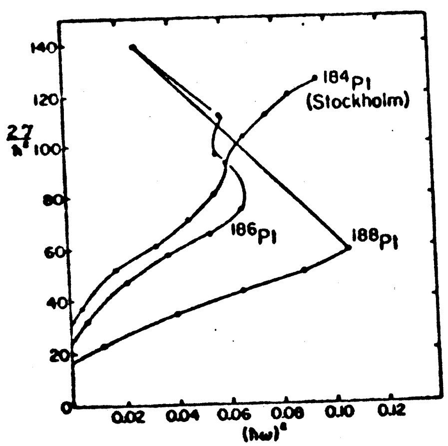

Fig.1. Yrast band behavior in platinum isotopes 184, 186, and 188. The data for ^{184}Pt are from ref.[3]).

from soft rotor behavior in ^{184}Pt to an exaggerated backbend in ^{188}Pt that anticipates the onset of clear band-intersection phenomena in 190 and 192 platinum[2,4]). An example of the latter is shown in fig.2. In the ^{190}Pt level scheme, the 12^+ isomer is interpreted as a $(\nu i_{13/2}^{-2})$ rotation-aligned structure, and the three closely-spaced 10^+ states below argue for intersecting band structures, probably with dominant g.r.b., $(\nu i_{13/2}^{-2})$, and $(\pi h_{11/2}^{-2})$ components. Similar data characterize the ^{192}Pt yrast and near-yrast levels[2,4]).

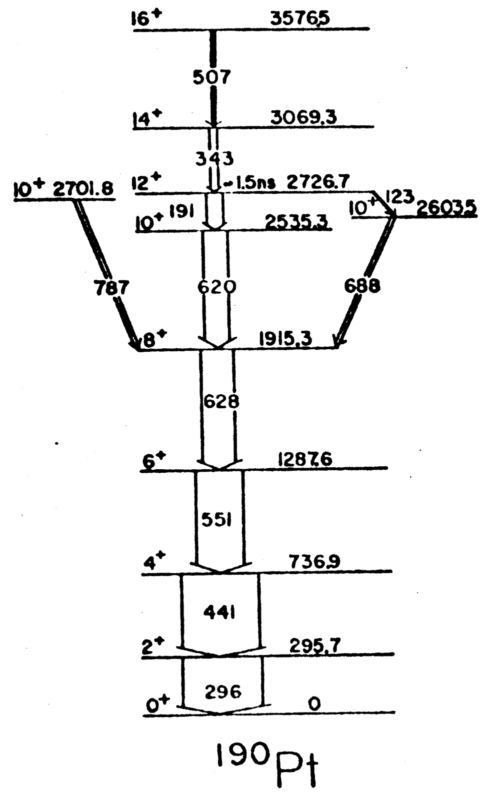

Fig.2. Partial level scheme of ^{190}Pt showing the yrast sequence (ref.2).

The osmium isotopes also show this progression from soft rotor, to backbending, to obvious band intersection as one progresses through the series $^{180-186}$Os[1]). In both ^{184}Os and ^{186}Os, the intruding yrast band structure appears to cross the ground band near spin 14 (fig.3), giving rise to sharp backbending behavior in the yrast sequence. The transition rates for decay of this crossing band into the g.r.b. have not been measured, but in ^{186}Os, the B(E2) value for the

16'→14 decay of the yrast state of the crossing band to the ground band is less than one-third of the corresponding intraband 16'→14' yrast transition. In ^{184}Os, the interband and intraband transition rates appear to be more comparable[5], and in ^{182}Os, of course, evidence for the intruding band is seen only in the backbending of the yrast sequence of states.

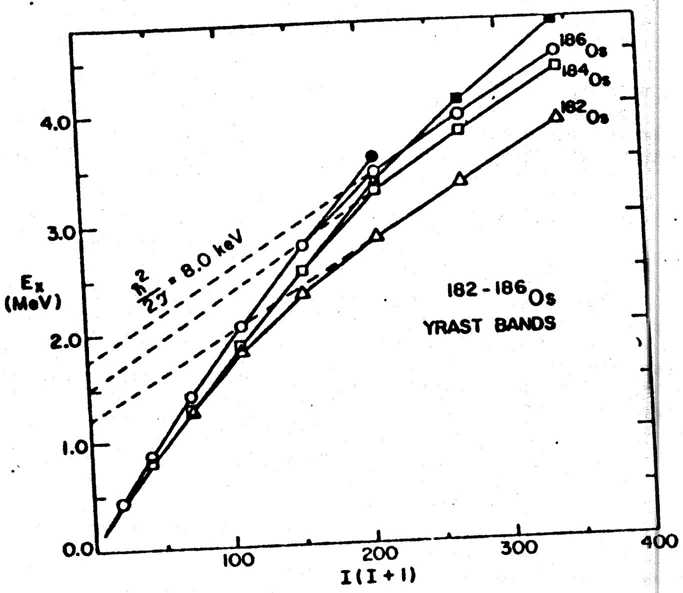

Fig.3. The yrast sequence of states in ^{182,184,186}Os. Non-yrast states presumed to be extensions of the g.r.b. are indicated by closed symbols. The moment of inertia for the higher-spin yrast states is approximately 70% of the rigid value. (Data from refs.1 and 5).

This general trend in the interaction between the g.r.b. and the crossing band reflects that seen in the platinum isotopes. It should be emphasized, the exact nature of the crossing bands has yet to be determined, but the experimental evidence argues strongly for associating them with rotation-aligned structures[2,4,5].

B. Tungsten Isotopes

The tungsten isotopes are of special interest in this context because they bridge the region between no backbending in the Hf isotopes, and the region of sharp backbending effects in Os and Pt isotopes. The general features of the yrast structures in the even-A tungsten isotopes might therefore be

expected to reflect both the rotation-alignment tendencies of their Os isotones and the deformation-aligned structures of their Hf isotones. As we shall see, this indeed seems to be the case.

We have most recently completed a study of the high-spin states in the more neutron-rich tungsten isotopes accessible by (α,xnγ) reactions[6]. Except as otherwise noted, the results described were obtained in conventional in-beam γ-ray spectroscopy experiments carried out using 26-50 MeV α-particles from the Michigan State University Cyclotron. The yrast band data for $^{177-182}$W are summarized in Fig.4.

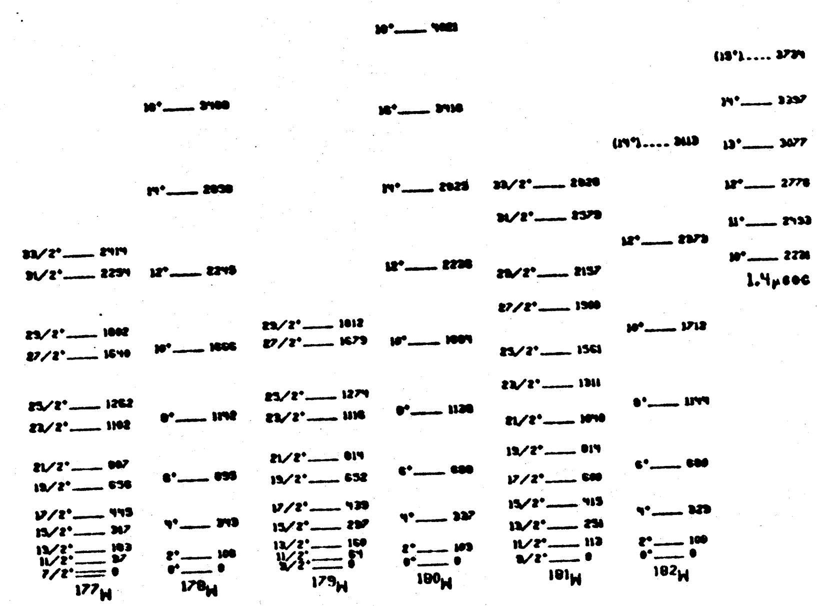

Fig.4. The yrast band structures in $^{177-182}$W (ref.6). In 177 and 179, the even parity sequence (here normalized to 0 keV) becomes yrast at spin 9/2 and 15/2, respectively. The 27/2 and 29/2 members in 179 are from ref.7.

There are two distinctive features of these systematics. The first is the ^{180}W yrast anomaly. The behavior of the ^{180}W yrast band very nearly qualifies that nucleus for the family of backbending nuclei, and it is at least as striking as the ^{170}Yb case[8]) which has recently received so much theoretical attention. Figure 5 shows a conventional backbending plot of the even-A tungsten data with the ^{170}Yb data also shown for comparison. The effect seen in ^{180}W is unique among all the even-A W isotopes with $98 \lesssim N \lesssim 108$, though some evidence for the

behavior persists in ^{178}W. No such backbending behavior is seen in the corresponding Hf or Yb isotones, with the important exception of ^{170}Yb.

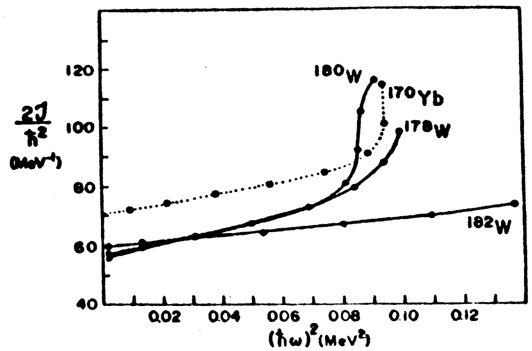

Fig.5. Backbending plot of the yrast bands in ^{178,180,182}W. The ^{170}Yb data of ref.8 are shown for comparison.

The second feature of interest in the tungsten data is our characterization (from γ-ray crossover/cascade ratios) of the 1.4-μsec, $K^\pi = 10^+$ isomer[9] in ^{182}W as a triplet coupling of the $9/2^+(624)$ and $11/2^+(615)$ neutrons. This provides the first experimental data on the location and behavior of a seniority-two, $i_{13/2}$ intrinsic configuration in the rare-earth deformed region, and is important for our discussion of yrast systematics in the tungsten isotopes.

Understanding the yrast behavior in ^{180}W within the framework of conventional explanations of backbending presents an intriguing problem. The recent experiments at Jülich would lead one to expect that the backbending-type behavior in ^{180}W may simply be an extension into the W isotopes of the $h_{9/2}$ proton-induced backbending proposed in the Os isotopes[5].

However, the data for the neighboring odd-A W isotopes, 177, 179, and 181, show a remarkable correlation between the degree of decoupling in the $i_{13/2}$ bands in those nuclei, and the behavior of the yrast band in their even-A neighbors. Specifically, the rotation-particle decoupling quantity $|\langle \vec{R}^2\rangle - \langle \vec{R}^2_{dec}\rangle|$ defined in ref.10 shows that the $i_{13/2}$ particle is substantially more decoupled from the core rotation in ^{179}W than in either ^{177}W or ^{181}W. Plots of the relevant data are shown in fig.6. Note that ^{170}Yb is clearly an exception to the general rule that backbending in even-A nuclei is reflected by the decoupling tendency of the $i_{13/2}$ bands in the (A-1) odd-mass neighbor[11]. It is noteworthy that the rule seems to hold in the W (and Os) isotopes also. The tendency toward particle-core decoupling at higher **spins in the $i_{13/2}$ rotational band in ^{179}W is qualitatively evident in fig.4 and is consistent with the ^{180}W anomalous ground band sequence. The more normal behavior of the ground bands in ^{178}W and ^{182}W should then find its counterpart in less decoupled**

$i_{13/2}$ structures in ^{177}W and ^{181}W, and this is indeed seen to be the case.

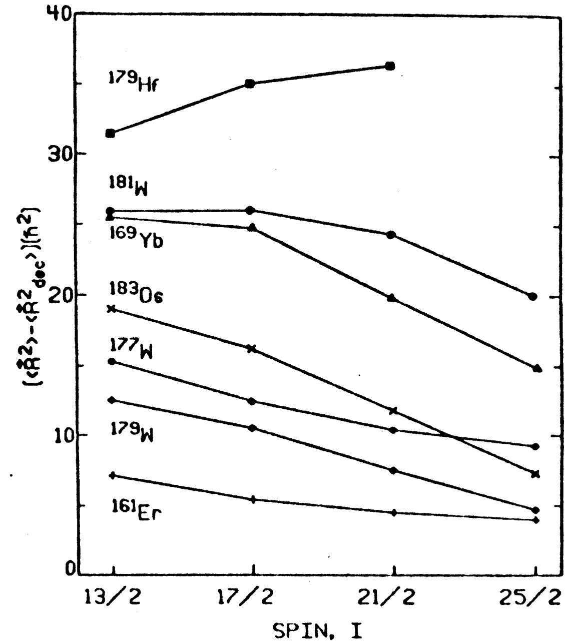

Fig.6. Rotation-particle decoupling for $i_{13/2}$ bands in odd-A tungsten isotopes. Several other cases are shown for comparison. The quantity plotted, $|\langle \vec{R}^2\rangle - \langle \vec{R}^2_{dec}\rangle|$ is defined in ref.10 and approaches zero in the decoupled $(\vec{I}=\vec{R}+\vec{J})$ limit.

Thus, there is evidence for the involvement of $i_{13/2}$ neutrons in the yrast behavior in even-A W isotopes, and one then asks what features in the $i_{13/2}$ single-particle spectrum would give rise to the special behavior in ^{180}W. A systematic and relatively rapid increase in hexadecapole deformation is expected to occur between ^{176}W and ^{182}W, and this will enhance the low-Ω components in the wave-functions of the low-energy $i_{13/2}$ states. This feature is probably responsible for the backbending tendency in ^{178}W and ^{180}W, but the effect is quickly quenched by the emergence of the Fermi surface into the large gap in the single-particle spectrum expected at N=108. One knows from experiment that the Fermi surface in ^{181}W has **moved substantially above the $7/2^+(633)$ orbit[12] quite in contrast to the situation in ^{179}W. This general interpretation is consistent with the appearance of the $|9/2^+(624);11/2^+(615)|$ isomer and its strongly-coupled band at 2231 keV in ^{182}W, and** suggests that other seniority-two $i_{13/2}$ configurations of corresponding spin must lie still higher in the spectrum. Thus, in ^{182}W backbending in the usual spin range (14-18ħ) cannot occur from intersection of the ground band with a rotation-aligned $i_{13/2}$ 2-quasiparticle structure.

The possible role of decoupled $h_{9/2}$ protons in the tungsten yrast band behavior remains a question, however. The data of the Jülich group[5] provide compelling evidence for the involvement of $h_{9/2}$ protons in the backbending in ^{182}Os, an isotone of ^{180}W. But the systematics of the location and extent of decoupling in the $1/2^-(541)$ bands in the (Z-1) isotones of ^{178}Hf, ^{180}W, and ^{182}Os do not argue strongly for the continued influence of proton decoupling in ^{180}W. Fig.7 shows that the $1/2^-(541)$ orbit is several hundred kilovolts nearer the ground state in both ^{177}Ta and ^{179}Re than in ^{179}Ta and ^{181}Re. If the $h_{9/2}$ protons were responsible for the backbending-type behavior in ^{180}W, one might then expect an even more pronounced effect in ^{178}W. The so-called "compression factor" proposed in ref.13 as a measure of particle-core decoupling is not very enlightening in this case, though one does note that the tendency toward $h_{9/2}$ proton decoupling increases with Z as one moves to smaller deformations.

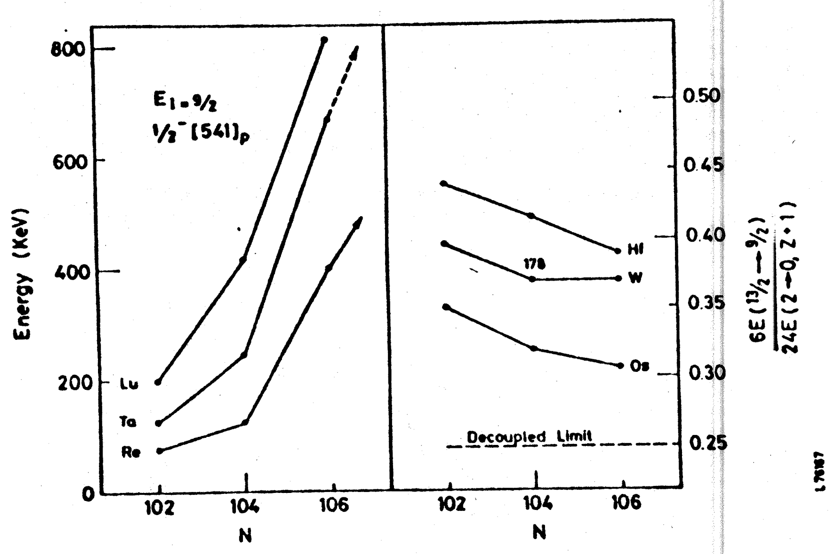

Fig.7. Energy of spin 9/2 member of $h_{9/2}$, $1/2^-(541)$ band in Lu, Ta, and Re isotopes (left); decoupling factor for 13/2→9/2 energy spacing (right). (Source: Nuclear Data Sheets and ref.5).

The data of figs.6 and 7 thus suggest that both proton and neutron rotation alignment can influence the yrast behavior in W and Os isotopes. In ^{180}W, the influence of $h_{9/2}$ protons in the yrast band behavior may be resolved in an experiment where substantially more angular momentum is brought into the odd-A neighbor, ^{179}W. If the ^{180}W backbending behavior does arise from decoupling of $h_{9/2}$ protons, the $i_{13/2}$ even-parity structure in ^{179}W should exhibit similar behavior at high spins.

Pedersen and coworkers at Risø[14] have very recently used the $^{170}Er(^{13}C,4n\gamma)$ reaction to populate high spins in ^{179}W. The results are tantalizing, but not conclusive. While the $7/2^-(514)$ band is observed to backbend (fig.8), the even-parity $i_{13/2}$ structure is weakly populated in the reaction, so that it is difficult to identify spins higher than the 29/2 shown in fig.4. This is surprising in view of the fact that the spin 29/2, $i_{13/2}$ band member is already yrast by over 320 keV. Moreover, a high-spin isomer is seen to decay directly into the backbending region of the $7/2^-(514)$band, probably at spin 35/2, but not into the even-parity band. All of this suggests the $i_{13/2}$ band in ^{179}W does not backbend, but further study is needed.

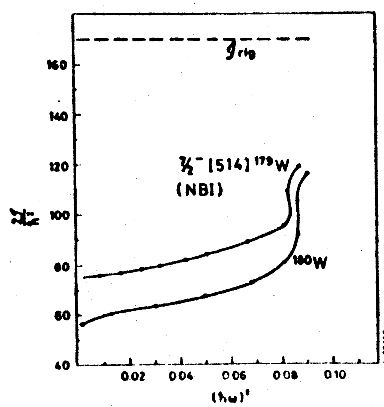

Fig.8. Backbending plot of $7/2^-(514)$ band in ^{179}W (ref.14). The ^{180}W yrast data are shown for comparison.

3. Deformation-Aligned Yrast Structure

In most regions of the nuclear chart, consideration of collective and rotation-aligned structures would complete a discussion of yrast structure, at least for the spins up to ∿ 24ħ so far identified. However, the single-particle spectrum in the region just below Z=78, N=108 is unique, because numerous high-Ω orbits are clustered near the Fermi surface. This special circumstance gives rise to a new and quite different type of yrast structure where angular momentum can be carried most "cheaply" not by collective rotation of the core, but rather by high-j, many-particle motion about the nuclear symmetry axis. Thus, in contrast to the rotation-aligned (RA) yrast structure where the particle angular momentum is approximately aligned with the axis of rotation, one now also finds deformation-aligned (DA) yrast structures, where the particle momentum is approximately aligned with the axis of symmetry (but strongly coupled to the core motion). The physical analogy between this situation in prolate nuclei at moderately high spins and that expected when some nuclei become oblate at very high spins has recently been discussed by Khoo et al.[15].

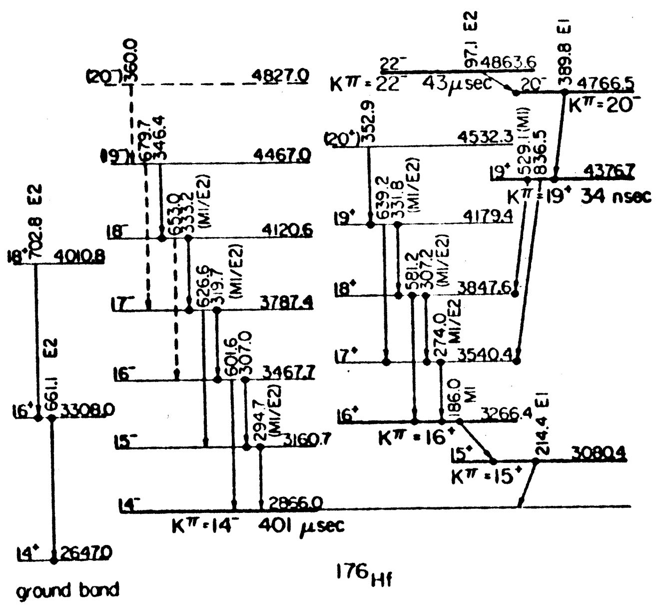

Fig.9. Partial level scheme of ^{176}Hf, showing $K^\pi = 16^+$ and $K^\pi = 22^-$ 4-q.p. and 6-q.p. deformation-aligned yrast states (ref.15).

The nuclei ^{176,177,178}Hf provided the earliest examples of such intrinsic, DA yrast structures[15,16,17]. Perhaps the most impressive example thus far encountered is that of ^{176}Hf, where a number of four quasiparticle and six-quasiparticle yrast states are identified (fig.9).

The tungsten isotopes offer similar, though less spectacular examples of DA yrast structure. In ^{182}W the strong-coupled $K^\pi = 10^+$ isomeric state is yrare, and as fig.10 shows, the band built on this unusual $\nu i_{13/2}$ configuration apparently becomes yrast above spin 16. The high-spin isomeric structure recently identified in ^{179}W by Pedersen et al.[14] appears to

represent another 5-q.p. yrast state, similar perhaps to that seen earlier in ^{177}Hf by Chu et al.[16].

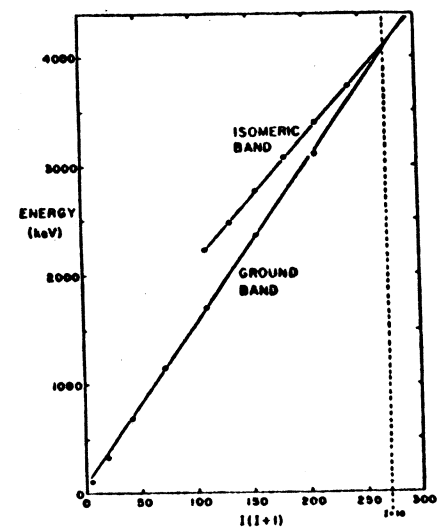

Fig.10. Energy vs. I(I+1) for ground and $K^\pi = 10^+$ bands in ^{182}W showing expected band crossing at 16ħ (ref.18).

It is interesting to note that in regions where such multi-particle DA structures may become yrast, backbending is not generally found, for the conditions which favor backbending, i.e. rotation alignment, are not favorable for producing DA yrast structures. (Coriolis forces and RA structures dominate in regions of low-Ω, high-j orbits, whereas high-Ω orbits are required for DA yrast structures). The W isotopes again are transitional between Hf isotopes where DA yrast structures seem to be most frequently found, and Os where RA structures reoccur. To date, no DA yrast states have been reported in the Os isotopes.

4. Conclusion

In summary, it seems that a reasonably coherent picture of yrast structure in the transitional region $72 \leq Z \leq 78$, $104 \leq N \leq 114$ is beginning to emerge. The experimental data suggest a rather smooth change in yrast behavior as one moves through the Os and Pt isotopes. The more neutron-deficient members of the two isotopic series behave as soft rotors. A rather conventional backbending-type behavior appears briefly in ^{182}Os and ^{186}Pt, and then the addition of still more neutrons brings the most distinctive and transparent manifestation of rotation alignment, where two or more crossing bands are seen to compete for the yrast position. As one moves downward in Z to the Hf isotopes, one enters a region distinguished primarily by the apparent absence of rotation-alignment effects. Instead, one encounters the added dimension of deformation-aligned yrast structures in certain favorable cases. The pivotal tungsten isotopes appear to reflect both RA and DA characteristics of the region.

Acknowledgements

The author wishes to thank the Niels Bohr Institute and the Risø Laboratory for their support in the preparation of this manuscript, and Dr. J. Pedersen for permission to quote his ^{179}W results prior to publication. The work of my many colleagues at Michigan State University and Purdue University has made this summary possible.

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* Research supported by the U.S. National Science Foundation.

† Address 1976-77: Niels Bohr Institute, Tandem Accelerator Laboratory, Risø, 4000 Roskilde, Denmark.

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