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Mass Dependence of the Yrast-Yrare Interaction and Backbending in the Light Osmium Isotopes

G. Dracoulis, C. Fahlander, and M. P. Fewell[(a)]
Department of Nuclear Physics, Research School of Physical Sciences, Australian National University, Canberra, Australian Capital Territory 2600, Australia
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Yrast states with spins up to about $22\hbar$ have been identified in ^{176}Os, ^{178}Os, ^{180}Os, and ^{182}Os. In each case anomalies are observed in the yrast sequence. The yrare extensions of the ground-state and Stockholm bands in ^{178}Os and ^{180}Os are also observed and the magnitude of the yrast-yrare interaction matrix elements extracted and discussed.

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In most deformed nuclei in which the yrast states have been identified to high spin, backbending phenomena are observed. Particularly pronounced anomalies are known in $^{182}_{76}$Os, $^{184}_{76}$Os, and $^{186}_{76}$Os,[1,2] and it is now accepted that a band crossing between the rotation-aligned $(i_{13/2})^2$ neutron configuration (the Stockholm or s band) and the ground-state band (gsb) is the cause of the backbending.[3] Although the neutron Fermi level in these heavy osmium isotopes is high among the $i_{13/2}$ orbitals, implying reduced Coriolis effects and therefore reduced rotation alignment, a critical role is played by the large hexadecapole deformation which enhances the Coriolis mixing.[1] Since the hexadecapole deformation is expected to vanish as the neutron number is decreased, a study of the high-spin states in the lighter osmium isotopes is of considerable interest. Systematic studies over a wide isotopic range are of crucial importance given the recent cranking-model predictions of an oscillating interaction strength between the s band and the gsb, as a function of neutron number.[4-6]

We have populated high-spin states in the osmium isotopes from $^{176}_{76}$Os to $^{182}_{76}$Os using (^{16}O, $4n$) and (^{16}O, $5n$) reactions on metallic erbium targets and ^{16}O beams from the Australian National University 14 UD Pelletron accelerator. For each osmium isotope, high-resolution γ-ray measurements included singles excitation functions, γ-γ time-coincidence experiments, and γ-ray angular distributions with a Compton-suppressed Ge(Li) spectrometer.

The partial level schemes showing states associated with the high-spin yrast cascades are shown in Fig. 1. The yrast sequence in $^{182}_{76}$Os, the only case previously studied to high spin, has been extended to spin $24\hbar$. In the other cases

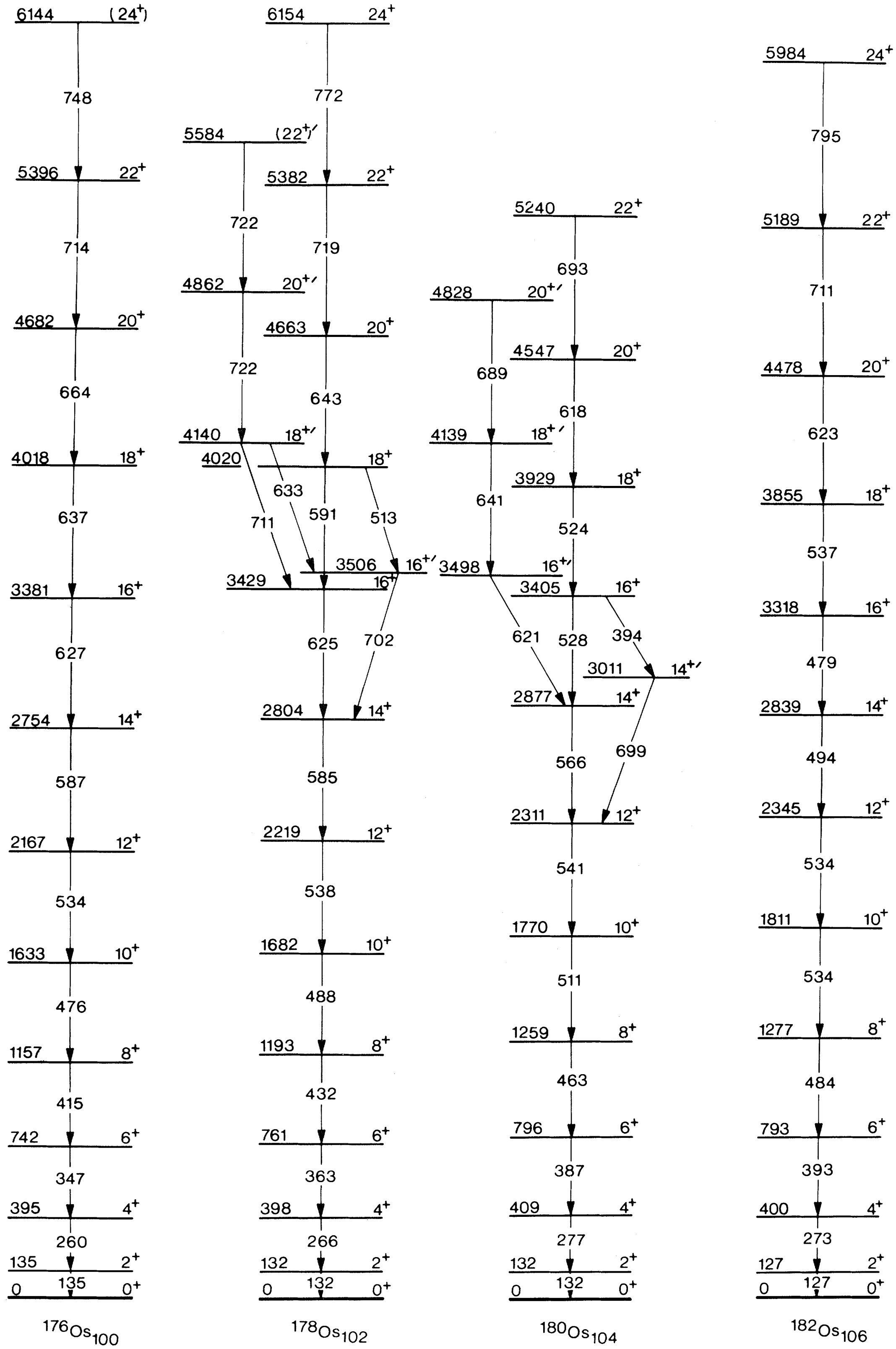

FIG. 1. Partial level schemes for the light even Os isotopes showing the γ decay of the yrast (and related) states.

states up to similar spins have been identified, including the yrare extensions of the gsb, and the s band in ${}^{178}_{76}$Os and ${}^{180}_{76}$Os. Anomalies in the yrast band spacings are observed in each nucleus. The results are shown in Fig. 2 in the plot of the angular momentum I_x against rotational frequency $\hbar\omega$.

Several features are apparent from Fig. 2. Firstly, the backbending anomaly changes smoothly from an S-shaped curve in ${}^{182}_{76}$Os to a weak, but well-defined up-bending in ${}^{176}_{76}$Os. Correlated with this trend, the anomaly occurs at progressively higher frequencies. Secondly, the yrast curves asymptote to a similar value at frequencies of about 0.35 MeV.

This second result is consistent with an equivalent observation for a range of tungsten isotopes[8] and argues for a common nature for the s band over this range of nuclei. That the s band is the aligned $(i_{13/2})^2$ neutron band is strongly supported by our results for the odd-neutron isotopes ${}^{177}_{76}$Os and ${}^{179}_{76}$Os in which blocking of the $i_{13/2}$ orbital inhibits the backbending. As well, the alignment in the $i_{13/2}$ orbital is similar for the isotopes ^{177,179,181}Os because the effect of the lowering of the Fermi level is balanced by the effect of the reduction in the hexadecapole deformation.

We suggest that the s band has a similar character from ${}^{176}_{76}$Os to ${}^{182}_{76}$Os, hence the asymptotic behavior of the alignment curves at high frequencies. Further, since the yrast states above the backbending anomaly are at similar excitation energies, and the gsb moment of inertia varies rapidly in this region; the bandcrossing, and hence the backbending anomaly, occurs at progressively higher frequencies with decreasing neutron number. The magnitude of the anomaly depends in detail on the difference between the s-band and the gsb moment of inertia, and on the strength of the interaction between the bands. We note that in a two-band–mixing case, increased interaction strength will lead to a smoothing of the backbending anomaly, but will not affect the frequency at which the anomaly occurs.[9]

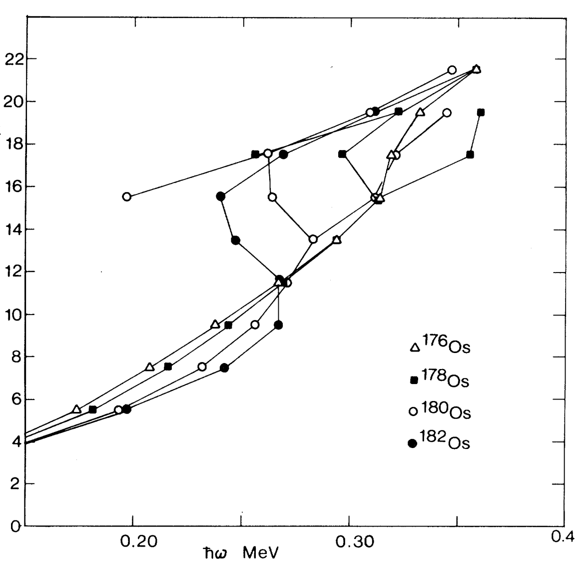

FIG. 2. Plot of the aligned angular momentum I_x, against the rotational frequency $\hbar\omega$ deduced from the experimental level schemes and the prescription of Bengtsson and Frauendorf (Ref. 7). Both yrast and yrare states are included.

To quantify this interpretation, and to estimate the interaction strength, we have simulated the experimental behavior using a two-band-mixing model with parameters for the unperturbed s band and gsb taken from experiment. The moment of inertia of the unperturbed s band was chosen to be consistent with the value in the yrast bands at the highest spin observed, and with the observed yrare states in ^{178}Os and ^{180}Os. The moment of inertia of the s band was assumed to be *the same for each isotope,* but its excitation energy was adjusted so that the final, spin-22, yrast-state excitation energy agreed with experiment. The unperturbed gsb was obtained by extrapolation of the experimental gsb from below the backbending anomaly, with the extrapolation constrained in the ^{178}Os and ^{180}Os cases to agree approximately with the observed gsb yrare extensions. The unperturbed bands were then mixed with use of matrix elements coarsely varied between 10 and 300 keV. No fitting procedure was carried out, but a value of the interaction energy which gave a reasonable reproduction of the data was chosen. A change of up to 25% in the interaction would not significantly alter the quality of the results.

The results are shown in Fig. 3(a). The shape of the I_x vs $\hbar\omega$ curve is reasonably well reproduced for all the isotopes, lending support to the contention that the main difference between the curves is due to the combination of a fixed s-band structure, and a variation in the gsb moments of inertia.

The interaction matrix elements used are compared with the theoretical predictions from the cranking-model calculations of Bengtsson and Frauendorf[6] in Fig. 3(b). The experimental values for ^{176}Os and ^{182}Os are in agreement with their predictions, but the small values obtained for ^{178}Os and ^{180}Os disagree with the large pre-

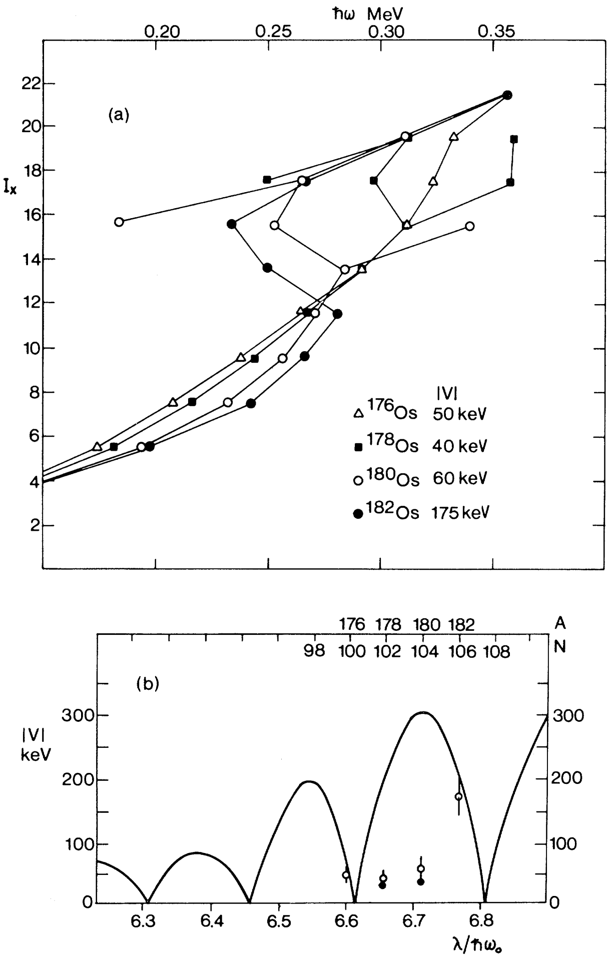

FIG. 3. (a) Calculated values of the aligned angular momentum I_x against rotational frequency $\hbar\omega$ from the two-band–mixing model described in the text. (b) Predicted values of the yrast/yrare interaction matrix elements given by Bengtsson and Frauendorf (Ref. 6), compared with the experimental values for the light Os isotopes. The open circles are the values used for the calculation of (a), the closed circles for the values derived from the yrast/yrare branching ratios.

dicted values. Bengtsson and Frauendorf also give a prescription for extracting the interaction matrix elements by fitting the shape of the I_x vs $\hbar\omega$ curves using a band-mixing model, with the assumption of a constant aligned angular momentum for the s band. Although the method of estimating the aligned angular momentum by use of the gsb as a reference band has been questioned,[10] and the suggested procedure is inherently inaccurate, application of their formulas to our experimental results gives values of the interaction in approximate agreement with the values used in our model, except for the ^{180}Os case.

TABLE I. Branching ratios of yrast states in ^{178}Os and ^{180}Os, and the deduced interaction matrix element, $|V|$.

	J_i [a]	J_f	E_γ (keV)	I_γ	$\lvert V \rvert$ (keV)
^{178}Os	18^+	16^+	591	63 ± 8	30^{+4}_{-3}
	18^+	$16^{+\prime}$	513	37 ± 8	
^{178}Os	$18^{+\prime}$	16^+	711	75 ± 8	24^{+7}_{-5}
	$18^{+\prime}$	$16^{+\prime}$	633	25 ± 8	
^{180}Os	16^+	14^+	528	73 ± 7	34 ± 4
	16^+	$14^{+\prime}$	394	27 ± 7	

[a]The primes refer to yrare states.

In any event, the interaction matrix elements in ^{176}Os and ^{180}Os can be extracted from experiment *independent* of fits to the shape of the I_x vs $\hbar\omega$ curve since we have identified the yrare states and measured the γ-ray branching ratios which are given in Table I. With the assumption that the intrinsic quadrupole moments of the g and s configuration are the same, the interaction matrix elements extracted, also given in Table I, are both about 30 keV, in agreement with the less accurate values discussed earlier. The measured branching ratios are also in agreement with those implied by our *model* wave functions, lending additional support to our earlier interpretation.

These interaction matrix elements for ^{178}Os and ^{180}Os are then in disagreement with the predicted values of about 200 and 300 keV. However, inclusion of a large and varying hexadecapole deformation in the calculations might alter the phase and magnitude of the predicted oscillations since the yrast-yrare interaction depends on the separation of the $i_{13/2}$ orbitals, which is significantly affected by the hexadecapole deformation. It depends as well on the position of the Fermi level and the level density, which also depend on the deformation. The experimental results could be interpreted as a shift in phase of the oscillations, given the relatively large interaction deduced for ^{182}Os compared to the lighter isotopes. Unfortunately that value is not determined from branching ratio measurements and therefore is less reliable. Whether inclusion of deformation effects in the calculations can account for the experimental results remains to be seen.

[(a)]Present address: Wright Nuclear Structure Lab-

oratory, Yale University, New Haven, Conn. 06520.
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g Factors of High-Spin States in ^{160}Dy and ^{170,174}Yb Measured by the Transient Magnetic Field Interaction

H. R. Andrews, O. Häusser, and D. Ward
Chalk River Nuclear Laboratories, Atomic Energy of Canada Limited, Chalk River, Ontario K0J 1J0, Canada

and

P. Taras
Laboratoire de Physique Nucléaire, Université de Montréal, Montréal, Quebec H3C 3J7, Canada

and

N. Rud
Physics Department, Aarhus University, DK-8000 Aarhus C, Denmark

and

B. Haas
Centre des Recherches Nucléaires, F-67037 Strasbourg, France

and

R. M. Diamond, D. Fossan, H. Kluge, M. Nieman, C. Roulet, and F. S. Stephens
Lawrence Berkeley Laboratories, Berkeley, California 94720
(Received 8 October 1980)

Ground-band states up to $16\hbar$ in ^{160}Dy and ^{170,174}Yb have been Coulomb excited by 350-MeV ^{86}Kr ions. The excited nuclei recoiled through magnetized iron where they experienced transient magnetic fields as high as ~3800 T. The nuclear precessions, determined from γ-ray time-integral perturbed angular correlations, suggest a small decrease of the g factors with increasing spin for all three nuclei.

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It is generally accepted that the breakdown of the pairing field and the alignment of nucleon pairs in high-j orbitals play a major role in phenomena observed in deformed nuclei at high angular momentum.[1-4] Mosel,[1] and others, have pointed out that g factors provide a unique measure of the relative contribution of protons and neutrons to the total angular momentum and are therefore very sensitive to pairing breakdown and alignment. Recent Hartree-Fock-Bogoliubov (HFB) cranking-model calculations[3-4] have shown that $g \sim 0$ for neutron alignment and $g \sim 1$ for proton alignment, and predict significant variations in different nuclei. In this Letter, we present the first results for g factors of high-spin discrete collective states.

The paucity of previous nuclear-moment information at high spin in deformed nuclei is a consequence of the very short ($\tau \lesssim 1$ ps) lifetimes of rotational states which makes it practically impossible to obtain measurable precession for even the largest static hyperfine fields. We have overcome this difficulty by taking advantage of the very large (several thousand teslas) transient

