Low-frequency anomaly in ^{172}Os moment of inertia

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An investigation of a low-frequency anomaly in the moments of inertia of the yrast sequence of ^{172}Os has been carried out via the ^{144}Nd(^{32}S,4n) reaction using a 162-MeV ^{32}S beam. Gamma-gamma coincidence information was obtained from a large array of Compton-suppressed Ge detectors. The ordering of the yrast sequence was deduced to be the same as had been previously proposed. Self-consistent cranked shell-model calculations and three-band-mixing calculations have been performed, but show only limited success in explaining the anomaly.

Our interest in ^{172}Os was first prompted through our efforts to document and understand the evolution of nuclear shapes at high spins by both γ-ray spectroscopy and Doppler-shift lifetime measurements. Lifetime measurements[1–3] of nuclei around $N \approx 90$ have shown that at high spins ($I > 12-14$) there is a loss in the nuclear collectivity which qualitatively is accounted for by both cranked shell-model[4,5] (CSM) and self-consistent[6,7] theories. These theories predict movement to triaxial shapes, with positive values for the γ deformation, at higher spins. Cranked shell-model predictions[4] also suggest that when the Fermi surface is raised to the middle of the $i_{13/2}$ neutron shell, the forces are such that the nucleus is driven in the direction of negative γ values, i.e., to triaxial shapes which at $\gamma = -60°$ become oblate with collective rotation. To test this latter prediction, we have turned to studies of osmium and tungsten nuclei having from 96 to 100 neutrons.

The nucleus ^{172}Os$_{96}$, whose Fermi surface is near the middle of the $i_{13/2}$ neutron shell, presents an interesting case. This nucleus was studied earlier by Durell *et al.*[8] who reported a very unusual pattern of behavior for the yrast sequence. This is displayed in the plot of the moment of inertia versus the rotational frequency shown in Fig. 1. The discontinuity at $\hbar\omega \approx 0.27$ MeV is presumably due to the rotation alignment of $i_{13/2}$ neutrons. In the isotone ^{170}W, this crossing occurs at $\hbar\omega \approx 0.25$ MeV. However, the discontinuity in ^{172}Os at $\hbar\omega \approx 0.24$ MeV is a surprising and interesting anomaly. An examination of the data of Durell *et al.*[8] presents an interesting possible alternate interpretation, viz., if the $8^+ \rightarrow 6^+$ transition at 471 keV were really misplaced and, instead, belonged at the $14^+ \rightarrow 12^+$ transition (with a part of the 471-keV intensity arising from an unassigned doublet), then the plot in Fig. 1 takes on the typically smooth *s* shape characteristic of most cases of $i_{13/2}$ neutron alignment.

Pursuant to the above discussion, we decided to remeasure the spectroscopy of the yrast sequence in ^{172}Os following the reaction ^{144}Nd(^{32}S,4n) which employed a 162-MeV ^{32}S beam from the Holifield Heavy Ion Research Facility (HHIRF) tandem accelerator. For the measurements, we used the Oak Ridge Compton Suppression Spectrometer System which, at that time, consisted of an array of 12 large volume Ge detectors, each suppressed by either a bismuth germanate (BGO) or a sodium iodide (NaI) shield. These shields, as well as two bare Ge detec-

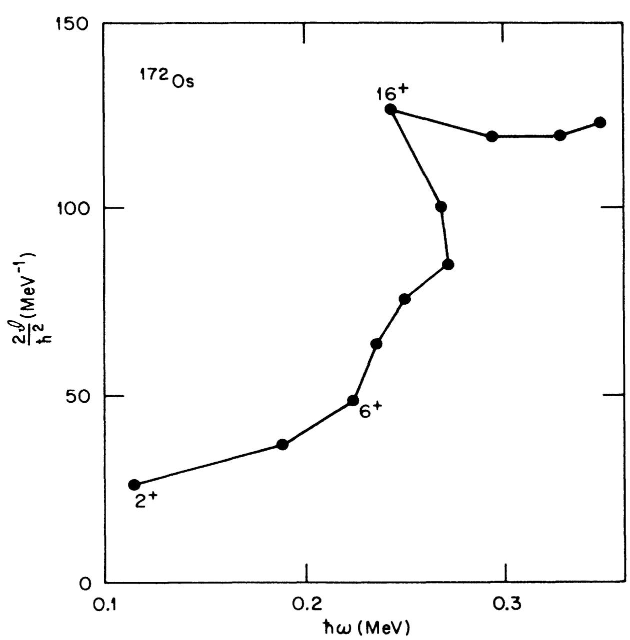

FIG. 1. Plot of the moment of inertia versus the rotational frequency for the yrast sequence of ^{172}Os. Discontinuities in this sequence are evident at $\hbar\omega \approx 0.24$ and 0.27 MeV.

tors, replaced solid NaI elements in the spin spectrometer, a 4π array of 71 detectors. With the combination of these two devices, we were able to collect γ-γ coincidence data between the 14 Ge detectors, while recording both the associated total energy and γ-ray fold (i.e., the number of detectors that fired) with the remaining elements of the ball.

The γ-ray spectra from these 14 Ge detectors were gain-matched and then maps of total energy versus fold were generated by gating on known γ rays associated with expected reaction channels. Once the optimum gating conditions for the 4n reaction channel (producing ^{172}Os) were determined, a $4K \times 4K$ coincidence matrix was produced by using coincidences between all possible pairs of detectors. The quality of the data is illustrated in Fig. 2, the spectrum obtained from the sum of gates on the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions, and in Fig. 3, the spectrum from the sum of gates on the higher yrast transitions ($10^+ \rightarrow 8^+$ and above).

Energies and intensities of the yrast transitions are tabulated in Table I. Intensities for transitions from the 10^+ state and above were obtained by using the sum of gates on the lowest four yrast transitions. Intensities for these lower transitions were obtained using sums of gates on transitions below them, with the $2^+ \rightarrow 0^+$ intensity being obtained from the total projection spectrum. These intensities were all normalized to the $4^+ \rightarrow 2^+$ intensity. The intensity of the $2^+ \rightarrow 0^+$ transition was not corrected for coincidence efficiency, and an estimate of this effect is included in its uncertainty. The 537-keV γ ray was found to be a doublet, with about 65% of its intensity being from the $14^+ \rightarrow 12^+$ transition. This can be clearly seen by observing that the relative heights of the 12^+ and 14^+ photopeaks are reversed in Fig. 2 and Fig. 3. The $14^+ \rightarrow 12^+$ transition intensity was determined from a gate on the $10^+ \rightarrow 8^+$ transition to be 0.71 times the $12^+ \rightarrow 10^+$ intensity, whereas the ratio of the intensity of the 537-keV γ ray to that of the 541-keV γ ray in the sum of $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ gates was 1.02. Using each of the yrast transitions in turn as a gate, the intensities of all other yrast transitions were measured in each of these gates, and these intensities were all consistent with the ordering of the transitions in Table I.

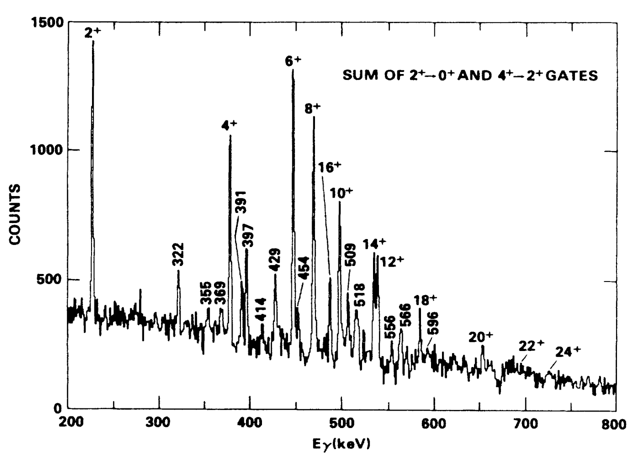

FIG. 2. Coincidence spectrum of ^{172}Os obtained from the sum of gates on $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions. Yrast transitions are labeled with initial spin. The other strong photopeaks, identified by energy (in keV), are deduced to arise from transitions in sidebands or from interband transitions.

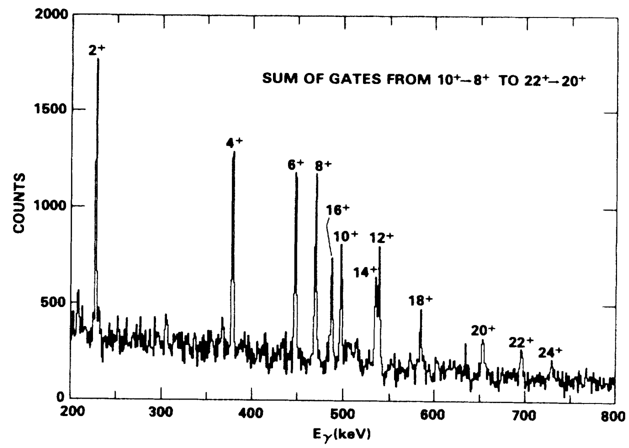

FIG. 3. Coincidence spectrum of ^{172}Os obtained from the sum of gates of yrast transitions above and including the $10^+ \rightarrow 8^+$ transition. Yrast transitions are labeled with initial spin.

A number of γ rays were found which were in coincidence with the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions, but which were deduced to not be part of the yrast sequence since none of them was in coincidence with the $10^+ \rightarrow 8^+$ or higher yrast transitions. These are identified by energy in Fig. 2 and tabulated in Table II. While it was not possible to place these γ rays uniquely in a level scheme, they appear to be either members of sidebands or interband transitions. Those showing coincidence relationships with each other, which are probably members of the same band, are indicated in Table II.

Based on the results from our measurements, we find no evidence that the yrast sequence of ^{172}Os is other than that presented by Durell *et al.*[8] Thus, it is necessary to

TABLE I. Energies and intensities of γ rays of the yrast band of ^{172}Os.

I_i^π	E_γ (keV)[a]	I
2^+	227.9	78 ± 8[b]
4^+	378.7	100 ± 6
6^+	448.8	81 ± 4
8^+	471.0	70 ± 4
10^+	499.4	49 ± 3
12^+	541.2	41 ± 2
14^+	537.0	29 ± 4
16^+	488.8	23 ± 2
18^+	587.5	22 ± 2
20^+	655.8	14 ± 1
22^+	697.9	9 ± 2
24^+	732.1	4 ± 1

[a]Uncertainty in energies is ±0.2 keV.
[b]Not corrected for coincidence efficiency.

TABLE II. Energies and intensities of nonyrast γ rays in coincidence with the $2^+ \to 0^+$ and $4^+ \to 2^+$ transitions.

E_γ (keV)[a]	I[b]	E_γ (keV)[a]	I[b]
322.0[c]	15±2	453.9[c]	15±3
354.5	10±2	508.5	d
368.9	12±2	518[c]	d
391.4[c]	18±3	537	16±4
396.5[c]	27±3	555.6	14±3
413.6	8±2	566.0[c]	23±3
429.1[c]	22±3	596.0[c]	11±3

[a]Uncertainty in energies (except 518 and 537 keV) is ±0.2 keV.
[b]Intensities normalized to 100 for the $4^+ \to 2^+$ transition.
[c]These γ rays show coincidence relationships with each other and are probably members of a sideband.
[d]Intensity not determined due to background difficulty.

search for an explanation for the anomalous behavior displayed in Fig. 1. In their paper, Durell *et al.*[8] suggest that the large change in moment of inertia at $I=8$ may be due to a change in the character of the s band from one dominated at low values of $\hbar\omega$ by the high-Ω components of the $i_{13/2}$ neutron orbitals to one which reflects the strong presence of low-Ω components at high frequencies. The implication is that there would be strong mixing at low frequencies with only a small anomaly, while at somewhat higher frequencies one would expect a weaker mixing accompanied by a more pronounced anomaly in the moment of inertia. They also suggested that ^{172}Os is bordering on γ instability and thus may undergo a significant jump in deformation at spin $I=8$ (a coexistence picture). Pursuing this possibility, we have carried out self-consistent cranked shell-model calculations of the quasiparticle configurations. In these calculations, the shape parameters β_2, β_4, and γ were determined for each rotational frequency by a self-consistent energy minimization procedure, and a frequency-dependent pairing gap was employed. (See, for example, Ref. 9.) However, we find no evidence for the shape coexistence. The calculations indicate a smooth, rather than sudden, increase of $\Delta\beta_2=0.02$ with increasing rotational frequency for the ground configuration.

Drawing on our recent work[10] on ^{172}W$_{98}$, we consider the possibility that the anomaly at $I=8$ arises from an additional band crossing. A sensitive indicator of band crossing is provided by the dynamical moment of inertia $\mathcal{J}^{(2)}$, which is defined as

$$\mathcal{J}^{(2)}=4/[E_\gamma(I+2\to I)-E_\gamma(I\to I-2)] \ . \quad (1)$$

In a plot of the dynamical moment of inertia $\mathcal{J}^{(2)}$ versus spin, a band crossing is generally indicated by the point at which the second derivative of this function becomes zero or changes sign. In Fig. 4 we show a plot of $\mathcal{J}^{(2)}$ for ^{168}Yb which has a single $i_{13/2}$ neutron band crossing below $I=20$, resulting in a single peak in its plot. The plot of ^{172}Os shown in this figure reveals one peak at low spin and another (which is actually a minimum off scale) at $I=12$. These experimental $\mathcal{J}^{(2)}$ results for ^{172}Os provide a rather strong suggestion of two band crossings at relatively low frequencies, although they do not unequivocally rule out the possibility of other explanations such as

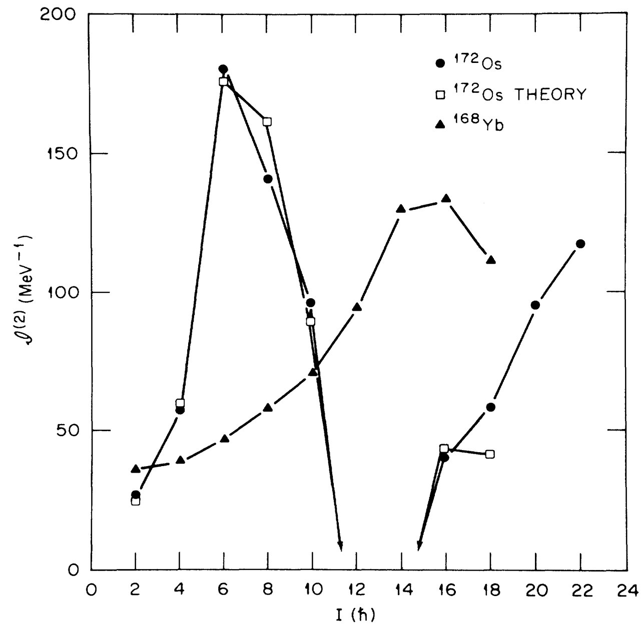

FIG. 4. Plot of dynamical moments of inertia $\mathcal{J}^{(2)}$ deduced from the present ^{172}Os experimental data, along with theoretical values for ^{172}Os calculated in the present work. Also shown are $\mathcal{J}^{(2)}$ values from ^{168}Yb data of Ref. 12.

coexisting collective structures analogous to those seen in the Hg region.[11]

Based on the systematic occurrence of the $h_{9/2}$ [541]1/2 protons as a ground or low-lying excited state in numerous nuclei in this region (see Ref. 10), there arises the suggestion that the lower-frequency anomaly in ^{172}Os at $\hbar\omega=0.24$ MeV may result from proton alignment. However, the rotational alignment of more than one pair of quasiparticles below $I\sim 18$ does not appear likely in light of the cranking calculations mentioned above. The $h_{9/2}$ proton alignment is predicted to occur only at much higher frequencies ($\hbar\omega=0.45$ MeV). Neither do the calculations give much support for early alignment of a second pair of quasineutrons. The calculated aligned angular momentum from two pairs of $i_{13/2}$ neutrons would be as large as the total angular momentum of the nucleus. One interesting aspect of the calculations is that rotational stretching of the prolate ground-band deformation is predicted.

Although the cranking calculations could not account for an additional band crossing at low rotational frequency in ^{172}Os, we feel that this possibility is not fully ruled out and, thus, have proceeded to perform a phenomenological three-band-mixing calculation by fitting the model parameters to the observed γ-ray energies. The unperturbed second and third bands are assumed to contain 4 and 12 units of intrinsic angular momentum, respectively, the same values we used[10] in the analysis of ^{172}W where $h_{9/2}$ protons and $i_{13/2}$ neutrons appear to align almost simultaneously. The resulting theoretical fit for ^{172}Os shown in Fig. 4 is quite good.

At this point we must conclude that there is insufficient evidence for selecting any one of the above discussed possibilities to account for the lower-frequency anomaly in the ^{172}Os moment-of-inertia plot in Fig. 1. Along with further theoretical calculations, there is a distinct need for lifetime and g-factor measurements in the yrast sequence of this nucleus in order to understand these very interesting structure effects.

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[1]M. P. Fewell, N. R. Johnson, F. K. McGowan, J. S. Hattula, I. Y. Lee, C. Baktash, Y. Schutz, J. C. Wells, L. L. Riedinger, M. W. Guidry, and S. C. Pancholi, Phys. Rev. C **31**, 1057 (1985).

[2]M. Oshima, N. R. Johnson, F. K. McGowan, C. Baktash, I. Y. Lee, Y. Schutz, R. V. Ribas, and J. C. Wells, Phys. Rev. C **33**, 1988 (1986).

[3]H. Emling, E. Grosse, R. Kulessa, D. Schwalm, and H. J. Wollersheim, Nucl. Phys. **A419**, 187 (1984).

[4]G. A. Leander, S. Frauendorf, and F. R. May, in *Proceedings of the Conference on High Angular Momentum Properties of Nuclei,* Vol. 4 of Nuclear Science Research Conference Series, edited by N. R. Johnson (Harwood-Academic, New York, 1983), p. 281.

[5]S. Frauendorf and F. R. May, Phys. Lett. **125B**, 245 (1983).

[6]R. Bengtsson, in *Proceedings of the Conference on High Angular Momentum Properties of Nuclei,* Vol. 4 of Nuclear Science Research Conference Series, edited by N. R. Johnson (Harwood-Academic, New York, 1983), p. 161.

[7]R. Bengtsson, Y-S. Chen, J-Y. Zhang, and S. Åberg, Nucl. Phys. **A405**, 221 (1983).

[8]J. L. Durell, G. D. Dracoulis, C. Fahlander, and A. P. Byrne, Phys. Lett. **115B**, 367 (1982).

[9]R. Bengtsson, T. Bengtsson, J. Dudek, G. Leander, W. Nazarewicz, and J-Y. Zhang, Phys. Lett. **183B**, 1 (1987).

[10]M. N. Rao, N. R. Johnson, F. K. McGowan, I. Y. Lee, C. Baktash, M. Oshima, J. W. McConnell, J. C. Wells, A. Larabee, L. L. Riedinger, R. Bengtsson, Z. Xing, Y. S. Chen, P. B. Semmes, and G. A. Leander, Phys. Rev. Lett. **57**, 667 (1986).

[11]J. H. Hamilton, P. G. Hansen, and E. F. Zganjar, Rep. Prog. Phys. **48**, 631 (1985).

[12]J. C. Bacelar, M. Diebel, C. Ellegaard, J. D. Garrett, G. B. Hagemann, B. Herskind, A. Holm, C-X. Yang, J-Y. Zhang, P. O. Tjøm, and J. C. Lisle, Nucl. Phys. **A442**, 509 (1985).