Multiphonon Vibrations at High Angular Momentum in ^{182}Os

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Evidence is presented for multiphonon excitations based on a high-spin ($25\hbar$) intrinsic state in the deformed nucleus ^{182}Os . Angular momentum generation by this mode competes with collective rotation. The experimental data are compared with tilted-axis cranking calculations, supporting the vibrational interpretation. However, the lower experimental energies provide evidence that more complex interactions of states are playing a role.

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The low-energy excitations of atomic nuclei can be understood as either being due to individual nucleonic (intrinsic) motions, or to collective rotations and vibrations of the bulk nuclear matter. In deformed nuclei, rotation typically dominates the high-angular-momentum structure, since it usually generates angular momentum with the lowest excitation energy. The lowest-energy state, at a given angular momentum, is called an *yrast* state, and such states have special status in nuclear-structure physics. Despite high level density at high excitation energy, the *yrast* states are readily identified experimentally, sometimes up to angular momenta in excess of $40\hbar$, and with excitation energies greater than 10 MeV. They therefore provide powerful probes of nuclear structure [1]. Notwithstanding the prevalence of rotational *yrast* states, there exists a small region of prolate deformed nuclei, centered on mass number $A \approx 180$, where few-nucleon, broken-pair excitations are found to be energetically favored [2]. In this Letter, the first evidence is provided that, in combination with few-nucleon excitations, the multiphonon vibrational mode can become the favored high-spin mode.

A key feature in the $A \approx 180$ region is that many of the individual nucleon orbits, close to the neutron and proton Fermi surfaces, have large angular-momentum projections on the symmetry axis (the long axis) of the prolate-deformed spheroidal nucleus. The individual projections sum up to give high- K , total projection values, and broken-pair excitations are then able to compete with collective rotation, which takes place about an axis perpendicular to the symmetry axis (i.e., with $K \approx 0$). In

some cases, the energetically favored states combine these two mutually perpendicular modes but, in accordance with the Bohr-Mottelson collective model [3], the addition of angular momentum by rotation requires more energy than it would in the absence of the high- K vector. That is, the rotational energy follows the strong-coupling formula, $E = [\hbar^2/(2\mathcal{I})][I(I+1) - K^2]$, where $\mathcal{I}$ is the moment of inertia, and I is the total angular momentum. This leaves open the possibility for a favorable orientation of quadrupole vibrations to play a role. The so-called γ vibration has angular momentum $I = 2$, oriented along the symmetry axis ($K = 2$). Such vibrations based on nuclear ground states are well known, but their energy of about 1 MeV cannot compete with typical $I = 2$ ($K = 0$) rotational energies of ≈ 100 keV. However, the situation may be radically different for γ vibrations based on high- K states, as we now report.

The present work focuses on the collective excitations of a $K^\pi = 25^+$, 130 ns isomeric state of the nuclide ^{182}Os . Previous studies of ^{182}Os [4–7] have established the six-quasiparticle (three-broken-pair) structure of this 7049-keV isomer, and given preliminary evidence [8] for a fragmented level structure above the isomer. The latter study was, however, unable to fully disentangle the transition sequences. The present work has exploited the large efficiency and resolving power of the Gammasphere γ -ray spectrometer [9], and the timing between beam pulses and γ rays, to establish the complex multiple structures above the 130-ns isomer. The most strongly observed sequence of γ rays incorporates twelve interlinked- $E2$ transitions, whose energies span a small range with

increasing spin. This suggests that the excitations may be of multiphonon vibrational character.

High-spin states were populated in ^{182}Os with the $^{150}\text{Nd}(^{36}\text{S}, 4n)$ reaction. The ^{36}S beam was supplied by the 88-inch cyclotron at the Lawrence Berkeley National Laboratory with a natural pulsing frequency of 14.2 MHz. A $1.0\text{-mg}/\text{cm}^2$ ^{150}Nd target (enriched to 89.9%) was used, with a $7.3\text{ mg}/\text{cm}^2$ backing of ^{197}Au to stop the nuclear recoils in the focus of the array. The γ - γ coincidence timing window was defined such that the maximum time difference between any two germanium-detector signals, considered to be part of the same event, was $\approx 1\text{ }\mu\text{s}$. More experimental details are given in Ref. [10].

The partial level scheme for the principal structure above the $K^\pi = 25^+$ isomeric state at 7049 keV is shown in Fig. 1, along with the extensions of the ground state and t bands in ^{182}Os [4,11]. [The t band is based on an $(i_{13/2})^2$ $K^\pi \approx 8^+$ band head with a strong rotational alignment [11].] In the present work, all structures with $K \leq 25$ were extended to higher spins, and the spin and parity of the isomer were firmly established to be $K^\pi = 25^+$ [12]. The time-coincidence information, with respect to the beam pulsing, enabled various prompt-delayed (across isomer) matrices to be created. In particular, a prompt-delayed matrix was constructed from gating on several delayed transitions (80–150 ns after the primary beam pulse) which lie below the 130 ns, $K^\pi = 25^+$ isomer, and selecting any prompt transitions (within 25 ns of the primary beam pulse) which were part of the same event. Gates were placed in these matrices and the γ -ray intensities and coincidence relationships were used to determine the ordering of the γ rays in the level scheme. Figure 2 shows a prompt spectrum of the $K^\pi = 25^+$ structure in coincidence with a prompt 757-keV transition from this matrix.

The structure built directly upon the $K^\pi = 25^+$ isomeric state consists of two irregular sequences of interlinked- $E2$ transitions (see Fig. 1). These sequences are unusual when compared with those of normal high- K rotational bands. For example, the γ -ray energy sequence is irregular, and the even-spin sequence is more strongly populated than the odd-spin sequence. In addition, the lack of a systematic increase in transition energy and the relatively small energy span, 157 keV (757–914 keV), for the six $E2$ transitions in each sequence are unexpected features. A sequence of six collective $K^\pi = 25^+$ transitions would be expected to have gradually increasing transition energies (proportional to spin) which would span a much larger energy range, such as those in the ground state and t bands. Finally, both sequences exhibit decays to other structures which lie above the $K^\pi = 25^+$ isomer [12]. This would not normally be associated with high- K rotational bands, where the band generally only decays out at the bandhead itself.

The anomalous aspects of the sequence above the $K^\pi = 25^+$ isomer may be interpreted as evidence for quadrupole vibrational excitations, in particular γ vibrations, whose angular momentum vector is in the same

FIG. 1. Partial level scheme for ^{182}Os showing the new structure above the 130 ns isomeric state, and the extensions to the $K \approx 0$ ground-state band (g) and the $K \approx 8$ band (t).

direction (along the symmetry axis) as the $K = 25$ intrinsic motion. Under these circumstances, harmonic multiphonon γ vibrations would be expected to have equal $E2$ transition energies, which is close to the observed behavior. A critical issue centers on the value of the phonon energy. The γ vibration based on the ground state of ^{182}Os has an energy of 891 keV [13], which is similar to the $E2$ energies in the structure above the $K^\pi = 25^+$ isomer. Indeed, due to the shallow potential-energy surface as a function of the γ deformation, calculated by Xu *et al.* [7], it might be expected that there would be even lower γ -vibrational energies based on the $K^\pi = 25^+$ isomer.

In competition with γ vibrations, the rotational energy would be expected to be similar to that in the extension of the ground-state band, e.g., 945 keV for the $28^+ \rightarrow 26^+$ transition [11]. This is only slightly greater than the observed value of 861 keV in the structure above the $K^\pi = 25^+$ isomer, leading to the possibility of admixture between rotational and vibrational excitations of the $K^\pi = 25^+$ configuration. This possibility is supported by the observation of strong $\Delta I = 1$ transitions: In the harmonic-vibration scenario, the vibrational angular momentum is in approximately the same direction as the magnetic-moment vector of the $K^\pi = 25^+$ structure, that is along the nuclear symmetry axis, and the $M1$ transitions would be very weak. Therefore, a rotational component, perpendicular to the symmetry axis, is implied, in order to account for the $\Delta I = 1$, $M1$ strength.

FIG. 2. A prompt spectrum showing the structure above the $K^\pi = 25^+$ state in ^{182}Os . The transitions labeled with a “●” are part of the main sequence above the $K^\pi = 25^+$ isomer; see Fig. 1. The other transitions (with given energies) are also placed above the isomer [12].

In the present work, a quantitative analysis has been undertaken with the shell-corrected tilted axis cranking (SCTAC) model [14]. The calculations, performed in the limit of zero pairing, show that the energy in the rotating frame, or Routhian, $E'(\omega_c, \theta, \gamma)$ is nearly constant, at a critical frequency (corresponding to half the $E2$ transition energy) of $\omega_c \approx 0.4$ MeV, along a path in $\theta - \gamma$ space, as the angular momentum increases. (Here, θ is the tilt angle between the angular-momentum vector and the long principal axis, and γ is the triaxiality parameter: $\gamma = 0^\circ$ for prolate shape, 30° for triaxial shape and 60° for oblate shape.) The quadrupole ($\epsilon_2 = 0.190$) and hexadecapole ($\epsilon_4 = 0.026$) deformations are also found to be almost constant. Since the energy $E(I) = E'(\omega_c) + \omega_c I$, increases linearly with I , then the transition energies are found to be constant and equal to ω_c . Table I compares the calculated and experimental excitation energies of the states, relative to the bandhead, and the $B(M1)/B(E2)$ values. The experimental energies (and the critical frequency) are reasonably well reproduced in the calcu-

lations. Figure 3 shows how the calculated and experimental excitation energies of the states progress with spin for the ground-state band, the t band, and the structure above the $K^\pi = 25^+$ isomer. The linear behavior of the latter contrasts with the quadratic behavior of the ground state and t bands.

The SCTAC calculations reveal that, as the spin increases up the band, both the orientation angle θ and the triaxiality parameter γ change, whereas the rotational frequency remains constant. In a normal rotational band, the angular momentum gain is due to the increasing angular frequency at an approximately constant shape. Thus, in this interpretation, the collective structure, based on the $K^\pi = 25^+$ isomer, is very different from a normal rotational band. It is more like a multiphonon band. A γ vibration appears similar to a static triaxial deformation in the frame of reference that rotates with the angular velocity ω_γ . The triaxiality parameter γ is proportional to $\sqrt{n}$, where n is the number of phonons. This is similar to the SCTAC result. The difference is that the phonons are not traveling waves with respect to the long axis but have a more complicated tilted geometry. The fact that the Routhian does not change along a $\theta - \gamma$ path, that combines changes of the angular momentum orientation and of the triaxiality of the shape, suggests that it is a similar path along which the high- K bands couple with the low- K bands. As discussed in Ref. [15], deviations from axial shape strongly enhance the coupling between different orientations. The resulting coupling appears to be strong enough to partially destroy the effect of the K -selection rule, which is an important issue in the $K^\pi = 25^+$ isomer decay in ^{182}Os [4].

The SCTAC calculations offer an explanation for the anomalous properties of the structure built upon the $K^\pi = 25^+$ isomeric state. The linear relation between the transition energy and spin is fairly well reproduced by the calculation [see Fig. 3(b)]. However, the calculations apparently underestimate the effects of other

TABLE I. Experimental and theoretical excitation energies relative to the $K^\pi = 25^+$ bandhead, and the $B(M1)/B(E2)$ ratios.

Spin ($\hbar$)	Excitation Energy (MeV)		$B(M1)/B(E2) (\mu_N/eb)^2$		Calculated	
	Calculated	Experiment	Calculated	Experiment	γ°	θ°
26.0	0.43	0.44	20.7	...	-7.4	19.0
27.0	0.83	0.88	16.4	92.5 ± 6.5	-9.7	23.7
28.0	1.25	1.30	13.4	22.6 ± 1.1	-12.2	26.8
29.0	1.67	1.65	11.1	1.6 ± 0.1	-15.0	28.5
30.0	2.12	2.05	9.6	1.7 ± 0.1	-17.6	29.2
31.0	2.59	2.55	8.0	64.8 ± 7.9	-20.4	30.7
32.0	3.10	2.89	7.0	3.4 ± 0.2	-22.9	31.9
33.0	3.69	3.46	6.3	7.0 ± 0.4	-25.1	33.3
34.0	4.26	3.73	5.6	2.1 ± 0.1	-27.2	34.8
35.0	4.81	4.26	5.0	4.1 ± 0.3	-29.0	36.3
36.0	5.35	4.51	4.3	1.2 ± 0.1	-31.1	37.3
37.0	5.90	5.05	3.6	3.4 ± 0.3	-33.4	37.4
38.0	6.44	5.32	3.0	5.3 ± 0.3	-35.0	36.0

FIG. 3. Comparison of the experimental and theoretical (SCTAC) excitation energies for (a) the $K^\pi = 0^+$ ground state and t bands, and (b) the $K^\pi = 0^+$ ground-state band and the structure above the $K^\pi = 25^+$ isomer in ^{182}Os .

degrees of freedom at higher spin where the solid line is observed to deviate from the experimental data. In addition, although the theoretical $B(M1, I \rightarrow I-1)/B(E2, I \rightarrow I-2)$ ratios fairly well reproduce the trend of the experimental data for many of the states, there are some discrepancies especially for the lower-spin values (see Table I). (The experimental $I \rightarrow I-1$ values assume that there is no $E2$ component.) These differences between the SCTAC model calculations and the experimental data can be taken as evidence for a complex interaction of states in several mixed bands. (The SCTAC calculation only follows the structure that gradually develops from the $K^\pi = 25^+$ bandhead state and, in particular, these calculations predict a $K = 32$ structure which may become important for spins $> 30\hbar$.)

In order to further investigate this effect, multiquasi-particle Nilsson-model calculations based on a fixed shape (with BCS pairing) have also been performed for ^{182}Os . These calculations use the method of Jain *et al.* [16], where the monopole pairing strengths ($G_n = 21 \text{ MeV/A}$ and $G_p = 22 \text{ MeV/A}$) were chosen to reproduce the one-quasiparticle states in the neighboring nuclei. Many intrinsic configurations are predicted to occur in the vicinity of the $K^\pi = 25^+$ isomeric state, each of which would be expected to have a γ -vibrational structure built upon it. All of these states can interact and perturb the states of the observed $K^\pi = 25^+$ structure and could thereby explain the fluctuations in the experimental $B(M1)/B(E2)$ values. Since there are uncertainties in the predicted

relative energies of the configurations, which are caused by the uncertainties of the theoretical single-particle levels, we have not attempted a full quantitative analysis in the present work. Although these bands cross each other in the $I \approx 30$ region (see Fig. 3), interband transitions have not been identified. A detailed report on the other complex structures observed above the $K^\pi = 25^+$ isomer, and the mixing calculations will be published in Ref. [12].

In summary, new structures have been established built upon the $K^\pi = 25^+$ isomeric state in ^{182}Os . Although these sequences appear somewhat irregular, the qualitative results suggest that the properties can be understood if the angular momentum is built up, to a large extent, from multiple phonons. Not only do the vibrations compete with rotations in generating angular momentum above the $K^\pi = 25^+$ isomer, but also, above $34\hbar$, the high- K vibrational structure becomes the yrast structure of ^{182}Os . We propose that, at high angular momentum, in a well-deformed nucleus, the γ -vibrational energy can become lower than the rotational energy, albeit with complex admixtures. It is hoped that the present results stimulate further investigations of multiphonon states built on high- K configurations. One important ingredient could be an extension of the RPA approach [17].

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