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New $K = 0$ Bands and Two-Phonon Gamma Vibrations in ^{188}Os and ^{190}Os†

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The level structure of ^{188}Os and ^{190}Os has been investigated by the (p,t) reaction at 19.0-MeV proton energy. New 0^+ states were seen at 1480 and 1705 keV in ^{188}Os and at 1551 and 1734 keV in ^{190}Os. Additional evidence is presented for describing the lowest excited $K=0$ and $K=4$ bands as two-phonon γ vibrations.

Important information has been obtained from (t,p) and (p,t) reactions for the soft nuclei around $N=88$ where there occurs a rapid change in the average nuclear shape from spherical to axially symmetric prolate as the neutron number increases. The most interesting experimental result is the strong population of excited 0^+ states in the residual nucleus which have average shapes similar to that of the target ground state. Thus deformed excited 0^+ states are seen in ^{148}Sm and ^{150}Sm in (p,t) reactions[1] and a spherical excited 0^+ state is seen in ^{152}Sm in the (t,p) reaction.[2] In the shape transition region, the usual tendency for pair correlations to force the two-particle transfer strength to the ground state is inhibited by the small shape overlap of the A and $A\pm 2$ ground states as has been calculated by Takemasa, Sakagami, and Sano.[3] This results in the excited 0^+ strength being a maximum ($\approx 100\%$ of the ground-state strength) between $N=88$ and 90 where the variation of the quadrupole deformation of the ground state (β) with neutron number is greatest, and where excited states of the residual nucleus exist which are similar in shape to the target ground state (shape isomeric states). In order to study this effect in the somewhat different and more gradual shape transition region around W, Os, and Pt, we have studied (p,t) reactions on ^{190}Os and ^{192}Os. For these nuclei the parameter β is changing much more slowly than around $N = 88$ but the nuclei are becoming very soft in the γ (axially asymmetric) direction, with a change in sign of the intrinsic quadrupole moment between Os and Pt.[4]

The experiments were performed with 19-MeV protons from the J. H. Williams Laboratory's MP-II tandem accelerator. Self-supporting, isotopically enriched targets were used.[5] The tritons were detected with photographic emulsions or position-sensitive detectors in the focal plane of an Enge split-pole spectrograph. The overall resolution was approximately 10 keV full width at half-maximum (FWHM). Excitation energies and peak yields were determined by using ground-state (p, t) Q values for the Os isotopes determined in this laboratory[6] and the calibration peak-fitting routine AUTOFIT.[7] The estimated accuracy of the excitation energies is ±10 keV. The relative intensities were calculated by summing cross sections over four angles (10, 25, 40, and 55 deg lab). The cross sections at each angle were measured with 3° angular resolution. At 19 MeV, $L = 0$ (p, t) angular distributions show strong and unique diffraction structure so that 0^+ assignments can be made unambiguously.[6] Unfortunately this is not the case for other L values and so assignments for these states are taken mostly from previous work. The energies of the $J^\pi = 0^+$ states which we see and their summed intensities in percent of the ground state (in parentheses) are: 913 (5.2), 1551 (2.4), and 1734 keV (8.2) in ^{190}Os and 1087 (6.6), 1480 (4.3), 1705 (1.2), and 1765 keV (2.0) in ^{188}Os. In ^{190}Os the only tentative 0^+ state known previously was at 912 keV.[8] In ^{188}Os, 0^+ states at 1087 and 1765 keV were known.[9] In addition, in ^{190}Os we see a state at 1115 keV, close to a recently reported[8] $J = 1, 2$ state at 1115 keV. Since only natural-parity states are populated with significant intensity in (p, t) reactions and our angular distribution is consistent with $L = 2$, we have assigned the state to be $J^\pi = 2^+$ and have associated it with the $K = 0$ band beginning at 912 keV. We also populate the known 4_3^+ state in ^{190}Os at 1168 keV with intensity comparable to the 0^+ (912 keV) and 2^+ (1115 keV) states.

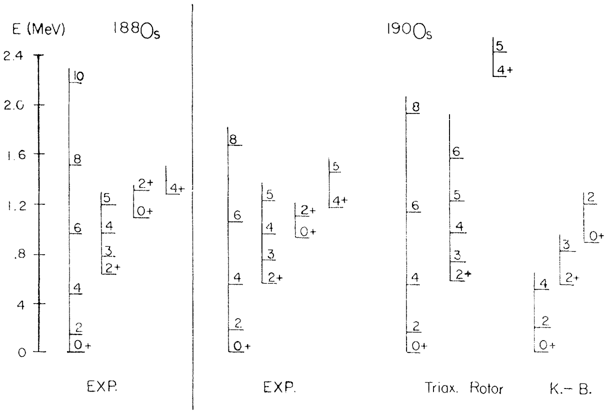

FIG. 1. Lowest even-parity bands in ^{188}Os and ^{190}Os. On the right are shown the levels predicted for ^{190}Os for a rigid triaxial rotor with $I_1/I_2/I_3 = 1/0.8/0.2$ and the predictions of Kumar and Baranger (Ref. 24).

The situation is strikingly similar in ^{188}Os. We see states at 1279 and 1306 keV with angular distribution consistent with either 2^+ or 4^+ for each state and with intensities close to that seen for the 2^+ (1115 keV) and 4^+ (1168 keV) states in ^{190}Os. Tentative J^π assignments have been made previously of 4^+ for the 1279-keV and 2^+ for the 1306-keV ^{188}Os states.[10,11] It now appears that the heavy Os isotopes have systematically occurring low-lying $K = 0$ and $K = 4$ bands at roughly twice the energy of the lowest $K = 2$ band. The known low-lying positive-parity levels for ^{188}Os and ^{190}Os are shown in Fig. 1. Although the $K = 0$ ground and $K = 2$ bands can be fitted by the rigid triaxial rotor model of Davydov and Filippov,[12] the 4_3^+ state in this model occurs at much too high an energy to explain the lowest $K = 4$ band observed. A number of sum rules exist for the energy of states of a rigid triaxial rotor.[13] In particular,

$$\sum_{i=3}^{3} E(4_i^+) = 5E(3^+), \tag{1}$$

independent of the three moments of inertia. This equation predicts the lowest 4_3^+ state at 2506 keV for ^{188}Os and 2276 keV for ^{190}Os. The levels predicted for a triaxial rotor with $I_1/I_2/I_3 = 1/0.8/0.2$ are shown in Fig. 1 for ^{190}Os along with the experimental ^{188}Os and ^{190}Os states.

It has been suggested previously[14,15] that the $K = 0$ and $K = 4$ bands can be described as two-phonon γ vibrations of an axially symmetric rotor. In this model the lowest $K = 2$ band is the one-phonon γ vibration. Additional evidence for this hypothesis can be seen in comparing the (p,t) intensities to these states with those for the excitation of the two-phonon multiplet in $^{108}\mathrm{Pd}(p,t)^{106}\mathrm{Pd}$[16] as shown in Fig. 2. In plotting Fig. 2 we have summed the 2^+ and 4^+ intensities of the $K = 2$ one-phonon γ bands in Os since the relevant comparison is with the total one- and two-phonon cross sections, which for deformed nuclei are spread among the rotational states in the band. The higher members of the $K = 2$ band are excited

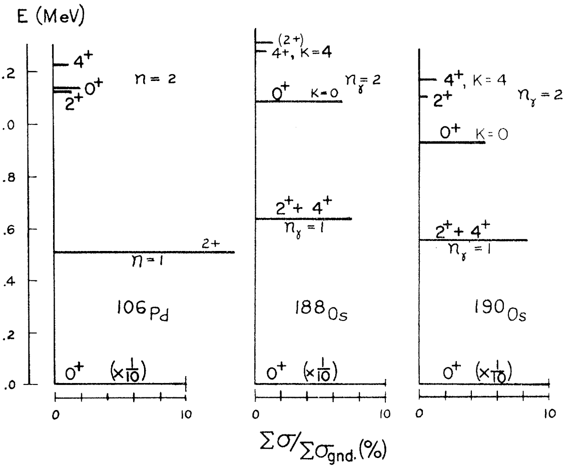

FIG. 2. Intensities for (p,t) transitions at 19 MeV to one- and two-phonon states in ^{106}Pd and to proposed one one- and two-phonon γ-vibrational states in ^{188,190}Os. The intensities were calculated by summing the cross sections over four angles (the maxima and minima of the $L=0$ cross sections).

only weakly and the 6^+ member of the $K=4$ band is not identified. The intensity patterns for Pd and Os are quite similar, the main difference being in the somewhat greater strength to the 0^+ states in Os, perhaps as a result of mixing with the pairing degrees of freedom.[6,17] In the pure phonon model, (p,t) transitions to the two-phonon states are forbidden in one-step processes. The population of two-phonon states can occur through anharmonic terms in the vibrational potential or by multistep processes involving inelastic excitation as well as transfer. Unfortunately, no calculations have been made for the excitation of two-phonon states in the deformed or transition region. The data seem to indicate somewhat more phonon mixing in Os than in Pd.

For a deformed vibrator, the two-phonon states will not occur at precisely twice the one-phonon energy because of the rotation-vibration interaction.[15,18] The energies of the two-phonon states are fitted remarkably well by a simple formula derived by Davydov[18] from an approximate treatment of the Bohr Hamiltonian for an axially symmetric rotor.[19] In the limit of $\mu \to 0$ ($\hbar\omega_\beta \to \infty$),

$$E_\lambda(I) = \hbar\omega_\gamma(2\lambda + \tfrac{1}{2}K) + A[I(I+1) - \tfrac{3}{4}K^2], \qquad (2)$$

where

$$\mu^2 = \frac{6A}{\hbar\omega_\beta} = \frac{E(2_1^+)}{E(0_\beta^+)}, \quad \lambda = 0, 1, 2, \ldots .$$

This equation has been derived by treating the γ dependence of the collective potential energy in an approximate way and by assuming the β and γ dependence of the moments of inertia to be given by the hydrodynamic model. Since we have taken the rotational and vibrational parameters from experiment, the effect of these approximations should be minimized.

TABLE I. Two-phonon states in ^{188,190}Os and comparison with theory.

	J^π	Expt. (keV)	$\mu=0$	Theory[a] $\mu=0.35$, ^{190}Os $\mu=0.30$, ^{188}Os
Os^{188}	0_2^+	1087	1120	1057
	(2_3^+)	1309	1274	1174
	(4_3^+)	1279	1325	1212
Os^{190}	0_2^+	913	927	868
	2_3^+	1115	1114	990
	4_3^+	1168	1177	1028

[a] Ref. 18

In Table I we show the experimental and calculated energies for the two-phonon 0^+, 2^+, and 4^+ states using Eq. (2). The value of A is taken from $E(2_1^+)$ and that of $\hbar\omega_\gamma$ from $E(2_2^+) = \hbar\omega_\gamma + 3A$. The fit is almost perfect for ^{190}Os and good for ^{188}Os, but the experimental 4_3^+ and 2_3^+ are in the wrong order for ^{188}Os. Definitive spin assignments for these states would be desirable. The simple Davydov equation predicts $E(0_2^+) = 2E(2_2^+) - E(2_1^+)$ which is satisfied to within 14 keV for ^{190}Os and 33 keV for ^{188}Os. Davydov also presents expressions for the energy for $\mu \neq 0$ but $\mu < \frac{1}{3}$ which then include the coupling to the β vibration. If the 0^+ states at 1551 keV in ^{190}Os and 1765 keV in ^{188}Os are used to fix μ, the fits to the $K=0$ and $K=4$ bands are not as good as is given by Eq. (2). Somewhat different approximations have been made by Belyak and Zaikin[15] in treating the Bohr Hamiltonian. In their work, if coupling to the β vibration is neglected, the results are the same as Davydov's. Including the coupling worsens the agreement with experiment as before. However, it is not clear that these states contain the main β-vibrational strength as the β- and pairing-vibrational states will be mixed.[20] The striking agreement with the Davydov prediction for $\mu=0$ indicates that the main β-vibrational strength may lie at higher energy.

The γ decay and Coulomb excitation[21,8,9] of the excited $K=0$ bands is consistent with the two-phonon interpretation of these states. The crossover ($n_\gamma = 2 \to n_\gamma = 0$) to stopover ($n_\gamma = 2 \to n_\gamma = 1$) ratio for the decay of the 0_2^+ is inhibited by about a factor of 5 for ^{188}Os and a factor of 17 for ^{190}Os, in fair agreement with factors of 16 and 12, respectively, calculated from the Belyak theory, especially considering the large errors in these measurements. Furthermore the Coulomb excitation of ^{188}Os gives $B(E2, 0_g \to 2_2) = 0.250e^2$ b^2 and $B(E2, 0_2 \to 2_1) = 0.0306e^2$ b^2. Using the above value of 5 for the ratio $(BE2, n_\gamma = 2 \to 1)/(BE2, n_\gamma = 2 \to 0)$, we get

$$\frac{B(E2, 0_2^+ \to 2_2^+)}{B(E2, 2_2^+ \to 0_1^+)} = \frac{B(E2, n_\gamma = 2 \to 1)}{B(E2, n_\gamma = 1 \to 0)} = 3.1$$

as compared to the value of 5 given by Belyak and Zaikin[15] for γ vibrations of a deformed nucleus. The two-phonon states in ^{190}Os are not seen in Coulomb excitation.

It appears that the situation in the Os transition region is quite different from that around $N = 88$ with respect to the existence of shape isomeric states populated in two-neutron transfer. In the Sm region the β values are changing very rapidly, with $\Delta\beta/\bar{\beta} = 0.46$ between ^{150}Sm and ^{152}Sm, giving rise to strong population of a 0^+ state in ^{152}Sm$(p,t)^{150}$Sm with a β deformation close to that of the ^{152}Sm ground state. For the Os nuclei, the maximum $\Delta\beta/\bar{\beta} = 0.13$ between ^{188}Os and ^{190}Os, as calculated from the $B(E2)$ values of Milner *et al.*[22] using the usual relation for an axially symmetric rotor,

$$\beta_2 = \frac{[B(E2, 0 \to 2)]^{1/2}}{(3/4\pi) Z R_0^{\,2}}, \text{ with } R_0 = 1.2A^{1/3} \text{ fm}. \quad (3)$$

However, for the Os nuclei, the static quadrupole moments of the first 2^+ states are changing very rapidly, with $\Delta Q/\bar{Q} = 0.32$ between 188 and 190 and 0.62 between 190 and 192. This indicates a rapid change of the average γ value, as can be seen from the expression for the quadrupole moment of the first 2^+ state for a triaxial nucleus[12]:

$$Q_2 = -\frac{3ZR^2}{5\pi}\beta\frac{6\cos(3\gamma)}{7[9 - 8\sin^2(3\gamma)]^{1/2}}. \quad (4)$$

For an excited γ shape isomer to exist in ^{188}Os, the nuclear potential energy surface must possess a secondary minimum in the γ direction as is the case for the β direction for ^{150}Sm. The lack of appreciable (p, t) strength to such a state in ^{188}Os indicates that the secondary γ minimum does not exist. This is in agreement with recent calculations of the potential-energy surface by Larsson[23] which give a very soft minimum in the γ direction, no secondary γ minimum, and a rather stable, stiff minimum in the β direction.

Finally, in contrast to the Yb isotopes where a rapid decrease in the pairing gap Δ with A gives rise to strongly populated excited 0^+ states in ^{176}Yb$(p,t)^{174}$Yb,[6,17] the gap parameter Δ is large and nearly constant for the Os isotopes, and thus no strong pairing vibrations are seen in (p,t).

In conclusion, it might be noted that the first excited $K = 0$ band heads in ^{188}Os and ^{190}Os are given at the correct energy in the dynamic-pairing-plus-quadrupole-force model of Kumar and Baranger,[24] but its phonon character is not evident in their papers and they do not calculate the position of the crucial 4_3^+ level.

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