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g bosons and the third 4^+ state in ^{192}Os

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Reduced matrix elements for excitation of the first three 4^+ states in ^{192}Os have been measured using inelastic scattering of 135 MeV polarized protons. These data, as well as the known quadrupole properties of ^{192}Os, are best described if the third 4^+ state is interpreted as a g-boson intruder state.

Recent years have seen significant advances in our understanding of heavy transitional nuclei ($180 \lesssim A \lesssim 200$). The advent of the interacting-boson model (IBM) has yielded a relatively clear picture of the nature of the transition: ^{196}Pt is a reasonably good example of an O(6) nucleus (i.e., γ unstable) and a generally smooth transition to SU(3)-like nuclei (i.e., axially symmetric rotors) occurs as one goes toward midshell. Warner and Casten[1] have suggested a particularly attractive parametrization of the Hamiltonian and the $E2$ transition operator:

$$H = \kappa Q \cdot Q + \kappa' L \cdot L \quad , \tag{1}$$

$$T(E2) = qQ \quad . \tag{2}$$

Here Q is the boson quadrupole operator,

$$Q = (d^\dagger s + s^\dagger \tilde{d})^{(2)} + \chi_{dd}(d^\dagger \tilde{d})^{(2)} \quad , \tag{3}$$

and L is the boson angular momentum operator. Since the same quadrupole operator is used in both H and $T(E2)$, this parametrization is referred to as the consistent-Q formalism (CQF). Two features make the CQF attractive. First, if $\chi_{dd} = 0$, H has purely O(6) eigenfunctions, and if $\chi_{dd} = -\sqrt{7}/2$, H has purely SU(3) eigenfunctions; therefore, the transition is described by a smooth variation of a single parameter. Second, relative $E2$ transition matrix elements depend *only* on χ_{dd}; κ and κ' determine only features of the eigenvalue spectrum. Warner and Casten have demonstrated that, with a smooth variation in χ_{dd} and a nearly constant q (boson $E2$ effective charge), virtually all known $E2$ properties of the broad range of even-A nuclei from Gd to Pt are well described.

Earlier work by Casten and Cizewski,[2] while less appealing in its parametrization, showed similar success in describing $E2$ properties of Pt and Os nuclei. Considerable emphasis was placed on the "emergence" of a "$K=4$" band in Os nuclei as evidence of the success of the calculations. Indeed, $E2$ branching ratios from this band to states in the ground and quasigamma bands are generally well described. The purpose of this Rapid Communication is to suggest that, based on $(\mathbf{p},p')$ excitation of the 4^+ bandhead of this band, this state is more likely to be a g-boson intruder state, not the third 4^+ state with only s- and d-boson configurations.

The experiment was performed at the Indiana University Cyclotron Facility. The proton energy was 135 MeV. Scattered protons were detected on the image surface of the QDDM spectrograph. Transition matrix elements (ME) for direct excitation of the first three 4^+ states (580, 910, 1070 keV) were deduced from coupled-channels analysis of the data; the analysis used either measured, if available, or predicted $E2$ ME's and dV/dr form factors for both $L=2$ and 4 transitions. Our deduced $E4$ ME are

$$M^4_{04_1}/M^4_{04_2}/M^4_{04_3} = -2000/\pm 1180/\pm 1100 \; e\text{fm}^4 \quad , \tag{4}$$

where

$$M^\lambda_{0J} \equiv i^\lambda \langle J^+ || T(E\lambda) || 0^+ \rangle \quad . \tag{5}$$

The magnitude of $M^4_{04_1}$ is in excellent agreement with recent (e, e′) results.[3] Signs of these ME are meaningful only in comparison to other ME. For example, the sign of $M^4_{04_1}$ is easily measured by observing interference between two-step $E2$ ($0^+ \to 2_1^+ \to 4_1^+$) and one-step $E4$ ($0^+ \to 4_1^+$) excitations such that

$$M^4_{04_1} M^2_{02_1} M^2_{2_1 4_1} < 0 \quad . \tag{6}$$

The $(\mathbf{p}, p')$ experiment could not determine phases for ME for the second and third 4^+ states; there are therefore four possible solutions for the three ME. Additional details of the experiment and the coupled-channels analysis will be published elsewhere.

In the usual IBM the $E4$ transition operator is

$$T(E4) = h(d^\dagger \tilde{d})^{(4)} \quad . \tag{7}$$

The $E4$ boson effective charge h is the only parameter available to fit $E4$ properties once the parameter χ_{dd} has been fixed by $E2$ properties. For ^{192}Os$\chi_{dd} = -0.205$, determined by $B(E2, 2_2^+ \to 2_1^+)/B(E2, 2_2^+ \to 0^+)$, and $q = 15$ $e$fm^2, determined by $B(E2, 2_1^+ \to 0^+)$. If one then chooses $h = -520$ $e$fm^4 to fit $M^4_{04_1}$, all other $E4$ ME's are predicted, in particular,

$$M^4_{04_1}/M^4_{04_2}/M^4_{04_3} = -2000/+363/+18 \ . \quad (8)$$

This prediction is clearly in poor agreement with Eq. (4), particularly for the 4_3^+ state. It is not surprising that $M^4_{04_3}$ is predicted to be very small. The third 4^+ state is the state which, in the SU(3) limit, becomes the state analogous to the two-phonon gamma vibration $K=4$ bandhead; one would naturally expect this state to be only weakly connected to the ground state. Thus, one does not expect to improve the IBM prediction by merely readjusting parameters or modifying the form of H. Recent analysis of the ^{196}Pt(e, e′) experiment[4] also failed to successfully reproduce measured $E4$ properties; Ref. 4 used IBM2 in the analysis, indicating that the failure of our IBM1 calculation is not due to treating proton and neutron bosons as indistinguishable.

We have investigated the possibility that the $E4$ collectivity of the 4_3^+ state might be attributed to g bosons which are normally truncated from the usual IBM space. The versions of PHINT and FBEM (Ref. 5) modified by Van Isacker[6] have been used to perform all calculations; in these calculations a configuration may have at most a single g boson. We have chosen to simply extend the CQF. A single-g-boson energy term is added to H,

$$H = \kappa Q\cdot Q + \kappa' L\cdot L + \epsilon_g \hat{n}_g \ , \quad (9)$$

the transition operator retains the form given in Eq. (2), and Q is generalized to be

$$Q = (d^\dagger s + s^\dagger \tilde{d})^{(2)} + \chi_{dd}(d^\dagger \tilde{d})^{(2)} + \chi_{gd}(g^\dagger \tilde{d} + d^\dagger \tilde{g})^{(2)} + \chi_{gg}(g^\dagger \tilde{g})^{(2)} \ . \quad (10)$$

Similarly, $T(E4)$ is generalized:

$$T(E4) = h[(d^\dagger \tilde{d})^{(4)} + \eta_{gs}(g^\dagger s + s^\dagger \tilde{g})^{(4)} + \eta_{gd}(g^\dagger \tilde{d} + d^\dagger \tilde{g})^{(4)} + \eta_{gg}(g^\dagger \tilde{g})^{(4)}] \ . \quad (11)$$

Although H is certainly not of the most general form possible, retaining the CQF is a reasonable way of keeping the number of new parameters to a minimum; this is necessary because of the restricted $E4$ data base. The parameter ϵ_g is held fixed at 1.5 MeV, the appropriate pairing gap in this region, since such a value is reasonable and physically motivated. The parameter χ_{gg} causes no mixing of g-boson configurations into pure s-d states, but causes splitting of the degenerate pure s-d-g states; this causes bands to emerge,[7] the lowest of which is a $K=4$ band built on the lowest s-d-g state which has a configuration of a g boson coupled to the ground state of the seven s-d boson system (^{192}Os has eight bosons). The parameter χ_{gd} is the only parameter in H which does cause mixing. We now vary χ_{gd} and seek a "reasonable" solution; we consider a reasonable solution one in which the effective charge parameters $|q|$ and $|h|$ are not very far from their values without g bosons (15 $e$fm^2 and 520 e fm^4) and in which the relative effective charge parameters χ and η are not extremely large in magnitude, e.g., in the general range

$$-10 \lesssim \eta, \ \chi \lesssim 10 \ . \quad (12)$$

χ_{gg} is initially held fixed at 1.0 such that there is a band built on the lowest g-boson 4^+ state but that this state is at rather high excitation energy (near 2.0 meV; see Fig. 2). The operator $(g^\dagger \tilde{g})^{(4)}$ was found to be very ineffective at causing $0^+ \rightarrow 4^+$ transitions, and so the parameter η_{gg} was set equal to zero (the calculations are quite insensitive to its value). There are, finally, four parameters to be varied: χ_{gd}, which causes the mixing, and the $E4$ effective charge parameters h, η_{gs}, η_{gd}. There being three data, the effective charges required to fit the data can be studied as a function of the mixing.

Shown in Fig. 1 are the results of such a calculation for the solution where all three ME are negative. For values of $|\chi_{gd}|$ up to 3.0 (corresponding to approximately 24% g-boson configurations in the 4_3^+ state) the values $|\eta_{gs}|$ and $|\eta_{gd}|$ are reasonable, but the values of $h > 10^4$ $e$fm^4 are not. Solutions for the other three possibilities of the relative signs of the three ME show similar behavior. Qualitatively, the origin of the unreasonable solutions is that what is required to reasonably explain our data is for g-boson configurations to be preferentially mixed into the 4_3^+ state; instead, approximately equal percentages of g-boson configurations are mixed into 4_1^+, 4_2^+, and 4_3^+ for each χ_{gd}. Although we studied changing the mechanism for mixing by altering H (e.g., by including a hexadecapole-hexadecapole term), the only way found to induce this preferential mixing was to lower the energy of the g-boson 4^+ until it was quite close to the 4_3^+; this can be easily done by either increasing χ_{gg} or decreasing ϵ_g. This could yield reasonable results but raises a problem: The g-boson state should be strongly excited in inelastic scattering and, if it is in the vicinity of 1.0 MeV excitation energy, should have been observed experimentally.

The above arguments have led us to the following conclusion: The state at 1070 keV in ^{192}Os is not the 4_3^+ state of the s-d IBM, but is, mainly, the lowest g-boson state. It is quite possible to explain both $E4$ and $E2$ properties of the $K=4$ band with this hypothesis. If one chooses the parameters $\chi_{gg}=3.6$, $\chi_{gd}=-0.5$, and $\epsilon_g=1.5$ MeV, then the $E4$ effective charge parameters shown in Table I are ob-

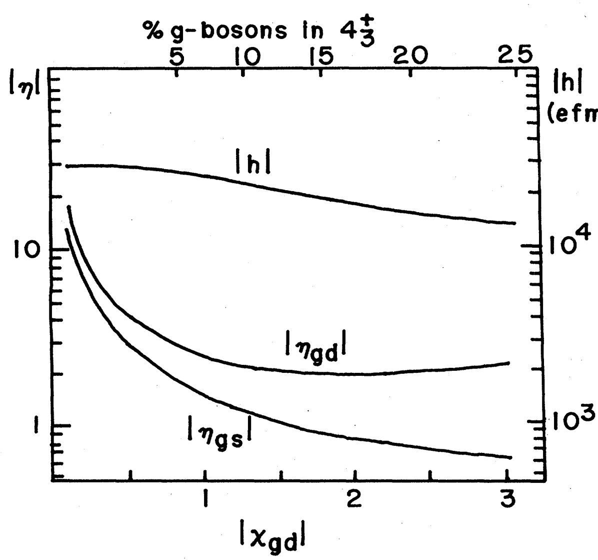

FIG. 1. Dependence of $E4$ effective charge parameters h, η_{gs}, η_{gd} on χ_{gd}. Also shown is the percentage of g-boson configurations in the 4_3^+ state which is controlled by χ_{gd}. Note the different scales for $|h|$ and for $|\eta|$.

TABLE I. Solutions for $E4$ effective charge parameters for $\chi_{gd}=-0.5$, $\chi_{gg}=3.6$.

$s_1/s_2/s_3$[a]	h ($e$fm^4)	η_{gs}	η_{gd}
−/−/−	1535	4.8	−9.5
−/−/+	411	7.8	−18.0
−/+/−	−737	0.9	−3.0
−/+/+	−1860	2.5	−5.1

[a] s_i is the sign of the reduced matrix element $M^4_{04_i}$.

tained; these, for the most part, constitute reasonable solutions. Changing the sign of χ_{gd} merely changes the signs of η_{gs} and η_{gd}.

It should be noted that the $K=4$ s-d state, now the 4_4^+ rather than the 4_3^+ state, has not been identified experimentally. However, many levels have been observed between 1 and 2 MeV for which definite J^π values have not been determined.

Figure 2 shows that $E2$ branching ratios are as well described as they are for the standard interpretation of the $K=4$ band. It should be noted, however, that the agreement for branching ratios from the $K=4$ band 5^+ state should be considered fortuitous. Mixing is quite sensitive to how close states of the same J^π are and correct relative placements of the 4^+ states do not ensure the correct placements of the 5^+ states. Indeed, in our calculations the transition from the J, $K^\pi=5$, 4^+ state to the J, $K^\pi=3$, 2^+ state is predicted to be strong, but is known experimentally to be weak.

It is important to note that our calculations have determined *no* parameters. Rather, we have shown that with reasonable parameters our calculations successfully describe both $E2$ and $E4$ properties of ^{192}Os.

Finally, it should be noted that our conclusion (that the 4_3^+ state is mainly a g-boson state) is not a completely new and novel interpretation of the nature of this state; earlier workers[8,9] have noted that properties of this state suggest that it is a "hexadecapole vibration." This would be, in the standard Bohr-Mottelson model, a very collective $J=4$ state which is exactly what a g-boson configuration would represent in the IBM. We have shown that this (often ignored) interpretation of the 4_3^+ state can be incorporated into the IBM by the inclusion of a g boson and that a reasonable IBM calculation reproduces known $E2$ properties as well as does a calculation without the g boson.

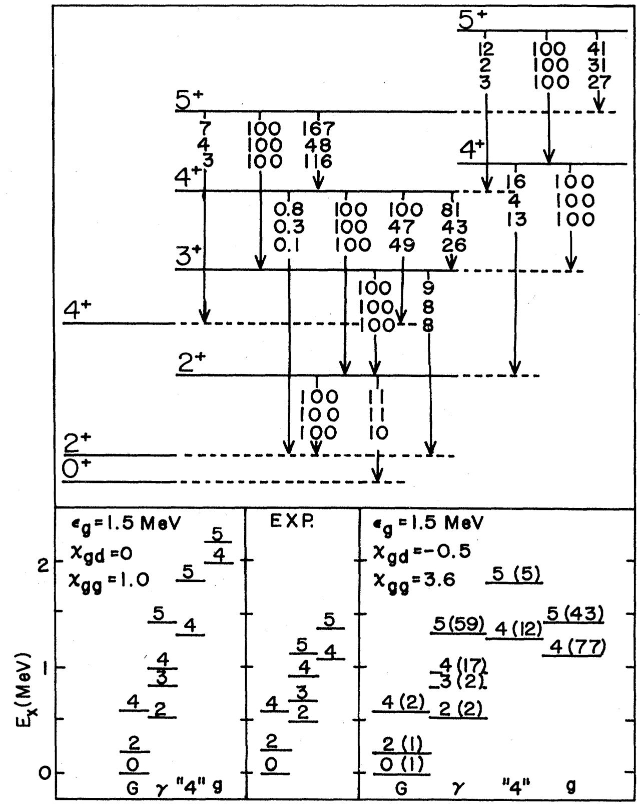

FIG. 2. The lower part of the figure compares the experimental band structure of ^{192}Os with calculations including a g boson. The leftmost spectrum is for no mixing, so the bands labeled G, γ, and "4" are the bands which appear in the usual interacting-boson approximation; the band labeled g is the g-boson band. The rightmost spectrum has mixing and a lowered g-boson band; also shown, in parentheses, are the percentages of g-boson configurations in each state. The energy scale is 0.5 MeV/division. The upper portion shows $E2$ branching ratios for experiment (first number), for the calculation without mixing (second number), and for the calculation with mixing (third number).

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