# EXPERIMENTAL TESTS OF RECENT PAIRING-PLUS-QUADRUPOLE MODEL CALCULATIONS IN THE OSMIUM NUCLEI*

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(Received 10 March 1967)

It has been evident in recent years that, although the existing phenomenological and microscopic descriptions of collective motion in nuclei have succeeded in correlating many of the gross aspects of a large body of experimental information related to collective phenomena, there have remained a number of longstanding problems in reproducing many of the detailed experimental data on electromagnetic transition rates, excitation spectra, and static moments. One of the more important of these problems concerns the effect of the couplings between the rotational motion, $\beta$ vibrations, and $\gamma$ vibrations on the above quantities. These effects have usually been taken into account by assuming that the interactions were weak and that various approximation schemes could be used in their evaluation.[1] Although the approximate separation of rotations, $\beta$ vibrations, and $\gamma$ vibrations may be valid for very nearly spherical nuclei and for very strongly deformed nuclei, it is clear from the existing experimental information that the majority of nuclei fall between these two extremes and that a more general treatment of the coupling is required. This is particularly the case for the transition nuclei at both extremities of the rare-earth region. The inadequacy of the traditional models and approximations has been further emphasized recently[2] by the conflict between the vibrational model and measurements of large spectroscopic quadrupole moments of $2^+$ states in nuclei heretofore considered spherical.

A calculation which is free from some of the above assumptions and which treats the coupling among the three motions exactly, within the framework of the Bohr Hamiltonian,[3] has recently been carried out by Kumar and Baranger[4] for the transitional osmium nuclei. In this calculation the seven functions which enter the Bohr Hamiltonian, and which determine the couplings, are derived microscopically from the pairing-plus-quadrupole model for the residual interactions; the strengths of the two forces are obtained by fitting the existing data on the odd-even mass differences and the experimental intrinsic quadrupole moments for the entire region $Z=50$-$82$, and $N=82$-$126$. Although the pairing-plus-quadrupole model may only provide a gross representation of the realistic residual forces, these calculations at least may establish a starting point for further even more detailed attempts at reproducing the experimental observations. The calculations[4] not only bear out the "soft" character of the osmium nuclei as evidenced by the shallow minima in the calculated potential energy as a function of $\beta$ and $\gamma$, but also reproduce the slow variation in properties from nucleus to nucleus exhibited by the experimental excitation spectra. Agreement with the experimental spectra is good.[4]

In view of the encouraging aspects of these calculations and of their possible consequences for the understanding of collective nuclear phenomena, it is important that they be subjected to a variety of experimental tests including the measurement of the dynamic as well as the static quantities. In this Letter we report a comparison of the predicted $E2$ transition rates with new experimental results; this comparison is particularly sensitive to the detailed structure of the calculated wave functions. The discussion is confined presently to states with spins of 4 or less for which there exist calculated values.[4,5]

Transition probabilities and branching ratios for $Os^{186,188,190,192}$ were obtained via Coulomb excitation induced by $O^{16}$ ions with incident laboratory energies of 48.3, 62.1, and 70.3 MeV from the High Voltage Engineering Corporation Model MP tandem Van de Graaff accelerator at Yale. The experiments were carried out with both thick and thin self-supporting targets of separated isotopes in pure metallic form. De-excitation gamma radiation was observed with Ge(Li) and NaI(Tl) detectors. Coincidence experiments were performed between gamma rays and backscattered ions, and between gamma rays from the transitions $2^+\to 0^+$ and $4^+\to 2^+$ and gamma rays feeding the $2^+$ and $4^+$ states. Gamma-ray angular distributions were measured in all cases and were employed in arriving at the reduced transition probabilities. These were calculated using almost exclusively the gamma–backscattered-ion coincidence data. Experiments performed with the Ge(Li) detector and the gamma-gamma coincidence data were used to examine the complex character of lines seen with the NaI(Tl) detector and to establish the placement of the gamma-ray transitions in the level spectra. The gamma-gamma coincidence data did not add significantly to the information for the states presently under discussion but were valuable in the investigation of higher lying states not discussed here. Figures 1(a) and 1(b) show representative gamma–backscattered-ion coincidence data and the Ge(Li) detector data for 70.3-MeV $O^{16}$ ions incident on $Os^{188}$. Data taken at other bombarding energies and for the other three nuclei are similar.

The lower lying states which were Coulomb excited, in the four osmium nuclei, are shown in the energy-level diagram of Fig. 1(c). Levels usually associated with the ground-state band and with the $\gamma$-vibrational band are readily populated in excitations by $O^{16}$ ions. Conspicuous in the data is the general absence of the excitation of $0^{+\prime}$ states associated with $\beta$-vibrational bands. It should be noted that coincidence experiments with backscattered ions would enhance the population of these states relative to that of the $2^{+\prime\prime}$ beta-band state. The Kumar and Baranger calculations predict $0^{+\prime}$ states in all four even-even osmium nuclei at approximately 800-keV excitation energy. We see no evidence thus far for such an excitation below about 1100 keV, except in $Os^{188}$ where the well-known 1086-keV state is weakly populated. However, barring an energy degeneracy of the de-excitation gamma rays from the $0^{+\prime}$ states with other stronger transitions, these measurements imply an upper limit on the $B(E2)$ values associated with the excitation of the $0^{+\prime}$ states which is not inconsistent with the calculations. Furthermore, mixing of collective and quasiparticle excitations, which is not included in the calculations, would tend to reduce further the $B(E2)$ values to the $0^{+\prime}$ states and render the observation of these states even more improbable. An attempt is presently being made to pursue this part of the investigation using heavier bombarding projectiles.

The measured reduced transition probabilities and branching ratios for ground-state band and $\gamma$-vibrational band states are shown in Table I.[6] The errors quoted include statistical errors, counter efficiency and dead-time errors, uncertainties in internal conversion co-

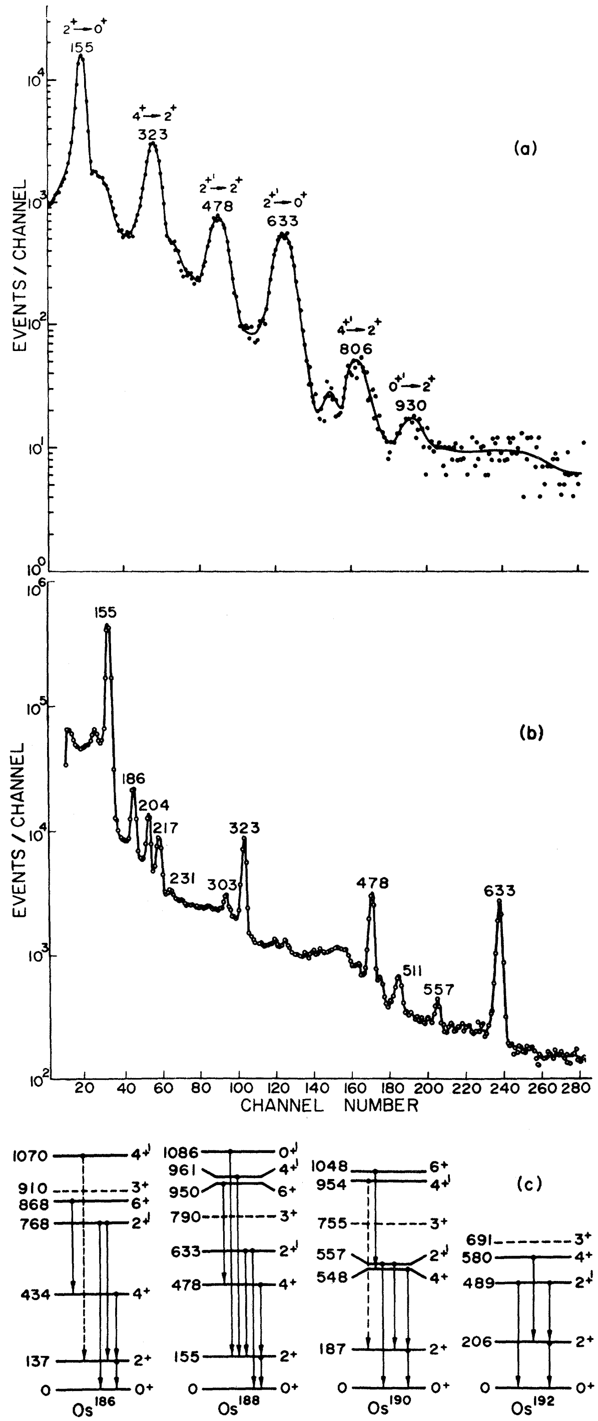


FIG. 1. Gamma-ray spectra for 70.3-MeV $O^{16}$ ions on $Os^{188}$: (a) NaI(Tl) spectrum taken in coincidence with backscattered $O^{16}$ ions, (b) direct singles spectrum taken with a 7.7-cc Ge(Li) counter, and (c) levels excited in $Os^{186,188,190,192}$.

Table I. $B(E2)$ values for $Os^{186,188,190,192}$ in units of $e^2 \times 10^{-48}$ cm$^4$. The effects of static quadrupole moments on the transition probabilities have not been included in calculating the $B(E2)$ values. For the $B(E2{:}0^+ \rightarrow 2^{+\prime})$ values, the positive sign for the interference term has been chosen (see text).

| | $B(E2{:}0^+ \rightarrow 2^+)$ | $B(E2{:}2^+ \rightarrow 4^+)$ | $B(E2{:}0^+ \rightarrow 2^{+\prime})$ | $B(E2{:}2^+ \rightarrow 2^{+\prime})$ | $\frac{B(E2{:}2^{+\prime} \rightarrow 2^+)}{B(E2{:}2^{+\prime} \rightarrow 0^+)}$ |
|---|---|---|---|---|---|
| $Os^{186}$ | $3.10 \pm 0.40$ | $1.54 \pm 0.30$ | $0.215 \pm 0.040$ | $0.137 \pm 0.026$ | $3.18 \pm 0.22$ |
| $Os^{188}$ | $2.70 \pm 0.40$ | $1.36 \pm 0.20$ | $0.211 \pm 0.030$ | $0.164 \pm 0.024$ | $3.88 \pm 0.27$ |
| $Os^{190}$ | $2.50 \pm 0.37$ | $1.07 \pm 0.15$ | $0.244 \pm 0.036$ | $0.370 \pm 0.055$ | $7.58 \pm 0.53$ |
| $Os^{192}$ | $2.22 \pm 0.34$ | $0.93 \pm 0.14$ | $0.184 \pm 0.027$ | $0.423 \pm 0.063$ | $11.50 \pm 0.84$ |

efficients, and uncertainties in choosing the low-energy cut-off point for the thick-target integrations. They do not include any other error introduced in the theoretical calculations of the Coulomb-excitation probabilities, such as the omission of the effect of the static quadrupole moments on the excitation probabilities. Measured values for these static moments are presently not available. However, based on moments predicted by the rotational model or the smaller moments from the Kumar and Baranger calculations,[4] these effects are generally estimated to be the order of 10% or less; therefore, they are not a significant consideration at the present stage of the comparison of the calculations with experimental values for the reduced transition probabilities. The $B(E2{:}0^+ \rightarrow 2^{+\prime})$ values quoted in Table I are calculated using a positive sign for the term in the transition probability arising from the interference between the amplitude for the direct transition from the ground state to the $2^{+\prime}$ state and the amplitude for the excitation of the $2^{+\prime}$ level which occurs via the $2^+$ state. This choice of sign is favored by the measured energy dependence of the excitation probability.[7]

Figure 2 presents a comparison of the experimental results with the Kumar and Baranger calculations. The calculations follow the general trends of the experimental results quite well. The largest disagreement occurs in the ratio $B(E2{:}2^{+\prime} \rightarrow 2^+)/B(E2{:}2^{+\prime} \rightarrow 0^+)$ which depends sensitively on the details of the wave function. For the phonon model this ratio would be infinite, while, at the other extreme, for a "hard" rotator it would be 1.43. Therefore, it is not surprising that large fluctuations in this ratio can result from small changes in wave-function admixtures between the two bands in these intermediate "soft" nuclei. For $Os^{186}$, where the calculations predict a well-deformed prolate nucleus, the agreement between the cal-

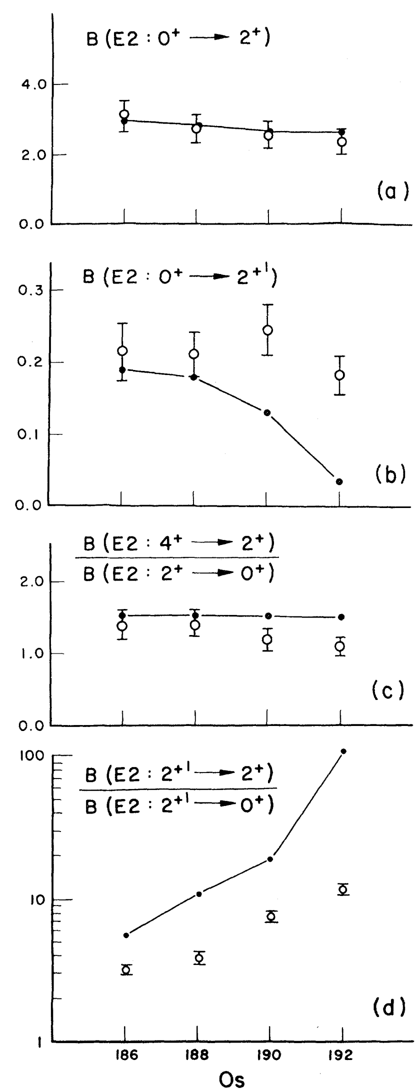


FIG. 2. Comparison of the Kumar and Baranger calculations with the measured reduced transition probabilities for (a) the $0^+ \rightarrow 2^+$ transitions, and (b) the $0^+ \rightarrow 2^{+\prime}$ transitions, and with the ratios (c) $B(E2{:}4^+ \rightarrow 2^+)/B(E2{:}2^+ \rightarrow 0^+)$, and (d) $B(E2{:}2^{+\prime} \rightarrow 2^+)/B(E2{:}2^{+\prime} \rightarrow 0^+)$. The solid lines join points predicted by the Kumar and Baranger calculations.

culated ratio and the data is within a factor of 2. For $Os^{192}$, where an asymmetric but "soft" shape is expected, with the wave function smeared over many possible shapes, the calculated ratio is approximately a factor of 10 larger than measured. It is clear that the pairing-plus-quadrupole model calculations, with the strengths of the forces as used, lead to potential wells that are somewhat shallower in the $\gamma$ coordinate than are needed to fit the experimental data on transition rates. A modification towards the rotational limit would produce a better over-all fit to the data. It will be of interest to make similar comparisons with the Nd, Gd, and Sm nuclei in the lower mass transition region as soon as the numerical calculations become available.

We thank Dr. Krishna Kumar and Dr. Joseph Weneser for informative discussions concerning this work. We would like to express our appreciation to the operating staff of the A. W. Wright Nuclear Structure Laboratory for their assistance in carrying out the measurements.

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*Work supported by the U. S. Atomic Energy Commission.

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[7]Although the data are consistent with a positive value for the sign of the interference term in all four nuclei, the accuracy of the measurements does not completely exclude the choice of a negative sign. If the negative sign is used, the following $B(E2{:}0^+ \rightarrow 2^{+\prime})$ values are obtained for $Os^{186,188,190,192}$, respectively: $0.295 \pm 0.060$, $0.284 \pm 0.042$, $0.303 \pm 0.045$, and $0.206 \pm 0.030$.

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# VECTOR POLARIZATION IN $d$-$\alpha$ SCATTERING

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(Received 10 April 1967)

A beam of polarized deuterons has been scattered from a helium target. The results show that $d$-$\alpha$ scattering is a useful analyzer for deuteron vector polarization for most deuteron energies between 2.5 and 10 MeV. It is also observed that the $d$-$\alpha$ break-up reaction is strongly dependent on deuteron spin.

Experiments with polarized protons have led to a detailed knowledge of the spin dependence of the proton-nucleus interaction. Very little is known, by comparison, about the interaction of deuterons with nuclei. Polarization experiments are indispensable if one wishes to determine the strength of the deuteron spin-orbit interaction with any degree of accuracy but progress has been hindered by the lack of suitable polarization analyzers. In a number of recent experiments the reaction $He^3(d,p)He^4$ has been used as a polarization analyzer, following a proposal by Galonsky, Willard, and Welton.[1] The deuterons have to be slowed down to an energy of a few hundred keV because the method depends on the assumption that the reaction takes place only with $s$-wave deuterons. However, the reaction mentioned above only permits the determination of the tensor polarization (alignment parameters) of the deutrons. The reaction is completely insensitive to the vector polarization because the deuteron orbital angular momentum is zero. The vector polarization of the deuterons can in principle be