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Evidence for a New Symmetry in Nuclei: The Structure of ^{196}Pt and the O(6) Limit

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^{196}Pt has been investigated with numerous (n,γ) techniques. The structure of the low-spin positive-parity states below the pairing gap shows excellent agreement with the predictions of the O(6) limit of the interacting boson approximation model of Arima and Iachello.

The pure harmonic vibrator and the quadrupole-deformed rotor have long provided two elegant nuclear-structure symmetries or limiting cases. Though few nuclei attain the idealized extremes, these limits are useful in part because their simple energy-level and branching-ratio predictions offer a framework from which deviations, and thereby the forces or interactions that produce them, are more easily identified. A class of nuclei exists toward the end of major shells for which neither limit is applicable. These nuclei are characterized, for example, by low-lying 2_2^+ states and missing or much higher-lying excited 0^+ levels. (The triaxial-rotor model has sometimes been invoked for such cases, but with varying success.) Our purpose here is to summarize a third limiting symmetry, recently proposed,[1] which may characterize such nuclei and, in particular, to propose that ^{196}Pt may be an excellent empirical manifestation of it.

Recently Iachello and Arima have developed an interacting-boson approximation (IBA)[1-3] model in which the Hamiltonian is written in terms of interactions between bosons which can occupy $L=0$ and $L=2$ (s and d) states. This model can be phrased in the group theoretical language of SU(6) in terms of which three natural limits arise for which analytical solutions are obtainable. These limits correspond to three subgroups of SU(6), namely SU(5),[2] SU(3),[3] and O(6).[1,3] The first two correspond to an (anharmonic) vibrator and the quadrupole-deformed rotor (with degenerate "2_β^+" and "2_γ^+" levels), respectively. Many examples of nuclei close to these two limits are well known. The third limit and its application to ^{196}Pt is the subject of this Letter.

In the O(6) limit the energies of collective states are given by[1]

$$E(\sigma,\tau,J)=\tfrac{1}{4}A(N-\sigma)(N+\sigma+4)+B\tau(\tau+3)+CJ(J+1), \qquad (1)$$

where N is the number of bosons, defined as half the sum of the number of protons plus the number of neutrons away from the nearest respective closed shells (for ^{196}Pt, $N=6$); $\sigma=N,N-2,N-4,\ldots,0$, and $\tau=0,1,\ldots,\sigma$. J takes on the values 2λ, $2\lambda-2$, $2\lambda-3$, $\ldots$, $\lambda+1$, λ, where λ is a nonnegative integer defined by $\lambda=\tau-3\nu_\Delta$ for $\nu_\Delta=0,1,2,\ldots$. An example of a level scheme with $N=6$ is shown in Fig. 1. Each level can be uniquely identified by the quantum numbers $J^\pi(\sigma,\tau,\nu_\Delta)$.

The wave functions of the collective levels may be expanded[1-3] in basis states characterized by their spin, d-boson number n_d, and the numbers of pairs and triplets of bosons coupled to spin zero. In this representation, states with identical J and τ but different σ are composed of identical nonvanishing basis states whose amplitudes are distributed in different (orthogonal) ways. States differing only in τ consist of basis states differing in n_d. Electromagnetic transitions follow the $E2$ selection rules[1] $\Delta\sigma=0$, $\Delta\tau=\pm1$.

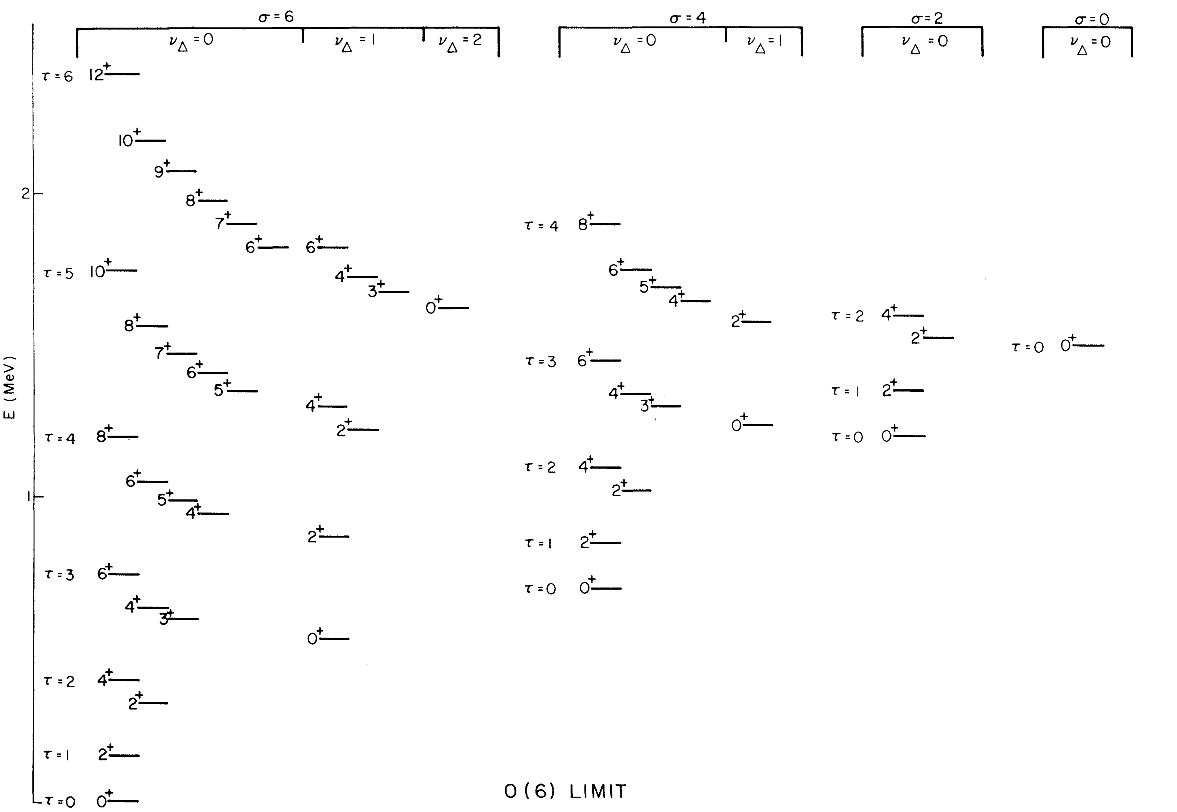

FIG. 1. A typical spectrum for a nucleus exhibiting the O(6) symmetry (see Ref. 1). The energy levels are given by Eq. (1) with $N=6$, $A=100$ keV, $B=30$ keV, and $C=5$ keV.

The levels fall into groups characterized by a σ value. Energy spacings and level spins are repeated for each group, but with different cutoffs given by $\tau=\sigma$. The quantum number ν_Δ further subdivides levels of the same σ. A characteristic feature of the level scheme is, therefore, a recurring 0^+-2^+-2^+ pattern of levels with the $E2$ selection rules predicting strong cascade γ-ray transitions within the sequence.

Within each σ grouping itself, the level spacing somewhat resembles a vibrational model but with certain states missing and an energy spacing proportional to $\tau(\tau+3)$ rather than to τ. This gives rise, for example, to large energy differences between states of high τ. Further, the vibrational-phonon-model degeneracies, branching ratios, and absolute $B(E2)$ values are not maintained.

In some ways the O(6) limit also resembles phenomenological triaxial models with their characteristic low-lying 2_2^+ level and a "missing" 0^+ state. However, again certain γ-ray branching ratios differ in the two models, and many more levels occur naturally in the O(6) limit because of the recurring pattern for $\sigma<\sigma_{max}$.

The O(6) limit (especially for large N) seems to resemble most closely the γ-unstable model which exhibits a $\tau(\tau+3)$ energy dependence and the same allowed spin values for each τ, and which can give rise to states corresponding to the $\sigma<\sigma_{max}$ group of the O(6) limit. However, the O(6) limit differs from the γ-unstable case in certain respects; for example, in the occurrence of broken degeneracies [last term in Eq. (1)] and spin cutoffs.

The experiments performed in this study consisted of measuring the reaction $^{195}Pt(n,\gamma)^{196}Pt$ with a variety of (n,γ) techniques. As previously reported,[4] singles spectra of secondary and primary transitions at 11.9 eV, 19.6 eV, 2 keV, and thermal neutron energies have been recorded with Ge(Li) detectors at the Brookhaven National Laboratory high-flux beam reactor and γ-γ coincidence measurements have been made. To these data have been added very high-resolution spectra of secondary transitions taken at the Institut Laue-Langevin reactor with the highly sensitive GAMS1 and GAMS23 bent-crystal spectrometers[5] which viewed an internal ^{195}Pt (97.28% enriched)

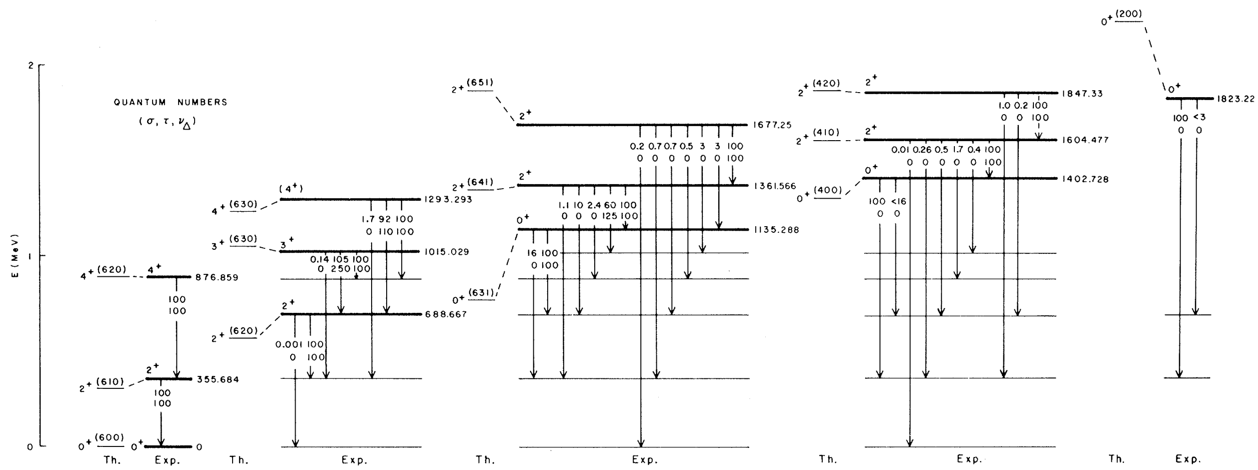

FIG. 2. Level scheme for positive-parity states in ^{196}Pt. Level energies are based on precise Ritz combinations. Their uncertainties range from 2 to 20 eV for levels below 1650 keV and from 40 to 80 eV for higher-lying states. The theoretical levels are obtained from Eq. (1) for $A = 185$ keV, $B = 43$ keV, $C = 23$ keV; in parentheses on the theoretical levels are the quantum numbers $(\sigma, \tau, \nu_\Delta)$. The upper (lower) number on the transition arrows is the measured [O(6)-limit predicted] relative $B(E2)$ value. Uncertainties on the observed γ-ray intensities range from 7 to 30% except for values of ±43% on the 589- and 242-keV γ rays, respectively. The empirical $B(E2)$ values were obtained assuming pure $E2$ multipolarities, a reasonable assumption in this mass region (see Ref. 10).

target.

Our experimental results are summarized in Fig. 2. The 2-keV neutron beam averaged over a sufficient number of resonances[4] to ensure that *all* 0^+, 1^+, and 2^+ levels below 2.5 MeV have been identified. The present results, thanks primarily to the high sensitivity and precision of the GAMS spectrometers, significantly extend earlier work. In particular, a number of crucial low-energy transitions are placed; though weak in intensity, they represent the largest deexcitation $B(E2)$ values from their respective levels. Intensity limits on unobserved transitions have also been improved.

The γ-ray decay and spin and parity of the lowest three states and the excited 0^+ levels were previously known from β-decay and (p,t) studies.[6,7] For the 1015-keV level, the nonobservance of population by a primary transition in 2-keV capture restricts the previosly allowed[6] J^π values of 2^+ and 3^+ to a unique 3^+ assignment. The transition to the 4^+ level at 876 keV is newly placed. The 1293-keV level was observed in (p,t) studies[7] and assigned as (4^+), although 3^- and 5^- assignments could not be ruled out. Its deexcitation identified here eliminates 5^-: 4^+ is strongly preferred over 3^- on the basis of regional systematics. The decay of the 1361-keV level differs considerably from that in earlier work. A ground-state transition has been eliminated and three low-energy deexcitation transitions placed. The 1604- and 1847-keV levels were identified in the present study[4] and in concurrent (p,t) work.[7] The 1604-keV level, and the newly discovered 1677-keV level, are assigned as 2^+ on the basis of transitions to 0^+ and 4^+ levels. The (2^+) assignment from the (p,t) data for the 1847-keV state is made definite because of population by an $E1$ primary transition in 2-keV capture.

The correspondence shown in Fig. 2 between predicted levels of the O(6) limit and those observed in ^{196}Pt is based on level energies, J^π values, and relative $B(E2)$ values. For most levels only one transition is permitted by the $\Delta\sigma = 0$, $\Delta\tau = \pm 1$ selection rules; experimentally for most levels one transition does dominate. It should be noted that the predicted $B(E2)$ values are characteristic of the O(6) limit itself and independent of the specific choices for A, B, and C.

The $0^+(631)$ level should decay only to the $2^+(620)$ state; the 1135-keV state decays predominantly in this manner and has been assigned as such. Associated with this 0^+ state are the 2^+ states at 1361 [$2^+(641)$] and 1677 [$2^+(651)$] keV. The pure O(6) limit forbids all γ-ray decay of the lowest 0^+ states with $\sigma = 4$ and $\sigma = 2$. However, a perturbation of the boson energy breaks the σ selection rule, preserving the $\Delta\tau = \pm 1$ rule, by simply redistributing the amplitudes of the nonzero basis components of the wave functions (τ breaking requires a perturbation, such as a quadrupole force between bosons, that changes the d-boson number by 1). Therefore, one expects the $0^+(400)$ and $0^+(200)$ states to decay only to the $2^+(610)$ state, as is observed for the 0^+ states at 1402 and 1823 keV. The 2^+ states associated with the 1402-keV level are those at 1604 $[2^+(410)]$ and 1847 $[2^+(420)]$ keV.

The agreement between experiment and the O(6) limit is remarkable. First, *all* predicted low-spin levels have been identified. Second, *all* low-spin positive-parity states below the pairing gap[4] can be interpreted in terms of the O(6) limit: That is, the empirical levels in Fig. 2 have not been selected from a larger set of states. Third, *all* predicted γ-ray transitions have been observed and, fourth, *all* those that are forbidden are weak or unobserved. The only exception to this is for the higher 0^+ states where, as explained above, some (formally, only infinitesimal) σ breaking is required. We have also performed calculations[8] involving deviations from O(6) by the introduction of a τ-symmetry-breaking quadrupole force. The results show that the empirical branching ratios limit the permissible size of such a force to a very small contribution.

The calculated and observed energies are also in reasonable accord in view of the many different intrinsic excitation modes involved. The major discrepancy is in the spacings in the $\nu_\Delta = 1$, $\sigma = 6$ group which are considerably compressed compared with the calculations. As mentioned earlier, large theoretical spacings here are characteristic, stemming from the τ dependence in Eq. (1). The $J(J+1)$ term in Eq. (1) is responsible for the $0^+(631)$ state's being predicted lower in energy than the $3^+(630)$, contrary to experiment. Arima, Iachello, and co-workers[9] are currently investigating the effect on these states of an explicit proton-neutron interaction between bosons. Preliminary results[9] show a considerable improvement in the predicted energies without disturbing the agreement with empirical branching ratios.

In summary, the predictive power of the O(6) limit of the IBA model of Arima and Iachello appears to be remarkable in ^{196}Pt. No other existing model provides as extensive agreement. It would now be interesting to study whether the systematics of the Os–Pt transition region (or that near Te–Ba) can be successfully interpreted from a new viewpoint in terms of progressively larger departures from this limit. Such work is currently in progress.

We are very much indebted to F. Iachello for extensive and continuing consultation and discussion both of the IBA model and its limiting symmetries and the relationship of these to the empirical level scheme of ^{196}Pt. We also are grateful to P. T. Deason and C. H. King for access to their (p,t) results prior to publication. This work was supported in part by the U. S. Department of Energy under Contract No. EY-76-C-02-0016.

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