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Simple interpretation of shape evolution in Pt isotopes without intruder states

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The most commonly accepted interpretation of the light Pt isotopes invokes the coexistence and mixing with proton intruder states from above the $Z = 82$ shell gap. Using an alternative description, interacting boson model (IBA) calculations are performed for the Pt isotopes with a simple, single configuration, two-parameter Hamiltonian. Excellent agreement is obtained for energies and electromagnetic transition strengths over the entire isotopic chain, spanning a wide variety of structures, and suggesting that these nuclei can be described more simply without the introduction of an intruder configuration. The Pt nuclei close to midshell are found to lie close to a region of phase/shape coexistence.

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The phenomenon of coexisting shapes in nuclei has been studied for decades and continues to be an active topic of current research. Traditionally, shape coexistence in regions near magic shells has been linked to particle-hole excitations across a closed shell, referred to as intruder excitations [1,2]. In the Pb region, the increased quadrupole collectivity of proton p-h excitations results in the appearance of a deformed band on top of the near-spherical ground state band. Moving down from the $N = 126$ closed shell, the proton-neutron monopole and quadrupole forces lower the excitation energy of these intruder states [3,4]. This phenomenon is clearly seen in the light Pb and Hg isotopes [1,2,5,6], where a more strongly deformed configuration is observed to approach the spherical ground state, with the 0^+ intruder state even coming below the 2_1^+ state near midshell.

An analogous interpretation with an intruding deformed configuration has been extended to the light Pt isotopes [1]. Figure 1 illustrates a common description [1,7–9] of the Pt isotopes in terms of weakly deformed (open symbols) and strongly deformed (solid symbols) configurations. Here, the picture differs from the Pb and Hg isotopes in that it has been suggested that the 2p-6h intruder configuration crosses the normal configuration, becoming the ground state for the Pt nuclei around midshell. This crossing is explicitly shown in Fig. 1.

Several different approaches have been employed to understand this behavior in the Pt isotopes. Deformed mean field calculations [10] predict two coexisting minima (prolate and near-spherical) lying close in energy near midshell. Yrast states in this region have been studied in numerous band-mixing calculations (see, for example, [11–13]), and recently, more detailed three-band mixing [14] has been applied to yrast and nonyrast states in the Pt nuclei below midshell. Particle-hole excitations have been incorporated [15] into the algebraic framework of the IBA model [16] by applying a Hamiltonian made up of a regular configuration composed of pure valence excitations (N_B bosons), a deformed 2p-2h excitation involving $N_B + 2$ bosons, and a mixing between the two. This approach has been shown [7,8] to reproduce the Pt energy systematics shown in Fig. 1. In addition, earlier IBA-2 calculations for the heavier Pt isotopes ($A \geqslant 186$) have also been reported [17].

Both the band mixing and the IBA-mixing calculations, however, generally require many parameters (as many as 6–13) embodying a priori assumptions about the structure of the observed bands. In particular, it is assumed that the excited band in the Pt isotopes away from midshell (making the analogy with the Pb and Hg isotopes) is more deformed than the ground state structure. However, in these nuclei, only the excited 0_2^+ state (and in some a tentatively associated 2^+ state) is known, and therefore, experimentally, the structure of the excited bands is uncertain.

The concept of cross shell-gap excitations is one way to describe the emergence of different shapes within a nucleus. An alternative interpretation of phase/shape coexistence, however, has been established in terms of phase transitions within the IBA. In this approach, the ground state and low-lying valence excitations are considered in a single configuration Hamiltonian. With this simple Hamiltonian, some isotopic chains are well described in terms of a transition from a spherical phase to a more deformed phase, with some nuclei lying in or close to a phase transitional region where the two phases coexist. Detailed experimental and theoretical studies have established this behavior in the $N = 90$ region for Nd, Sm, and Gd [18,19], as well as the vibrational to γ-soft region of Ru and Pd [20,21]. An analysis of the different forms of shape change is described in Ref. [22]. With two approaches to describing shape changes and coexisting structures, the question is which is most applicable to the Pt isotopes.

The purpose of this rapid communication is to present an alternative description of the structural evolution of the Pt isotopes using a *single configuration* IBA-1 Hamiltonian. This simple approach will be shown to reproduce the evolution of both energies and electromagnetic transition strengths across the Pt isotopic chain at least as well as more complicated approaches involving several times the number of parameters. It offers a straightforward interpretation of the actual empirical systematics which does not involve *a priori* assumptions concerning the structure of different levels.

As our starting point, we plot the excitation energies of low-lying states in the Pt isotopes in Fig. 2 (top) *without* presumptions concerning structure. Figure 2 portrays a very different picture than Fig. 1. While the way the levels are

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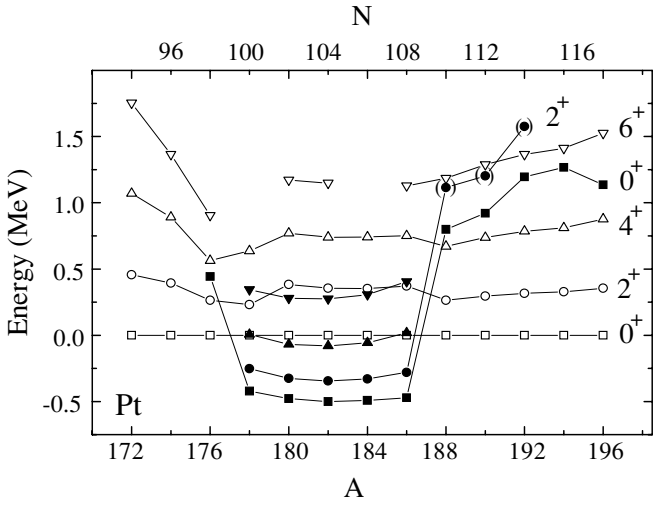

FIG. 1. Common interpretation [1,7–9] of the systematics of low-lying states in the light Pt isotopes based on an intruder state ansatz, in which solid (open) symbols label states interpreted as strongly (weakly) deformed.

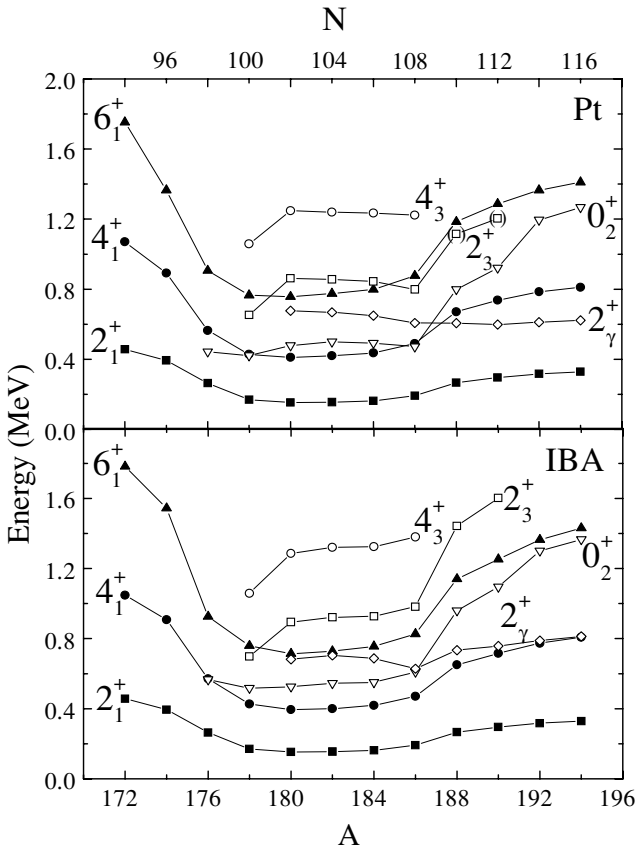

FIG. 2. Systematics of low-lying states in the Pt isotopes: experimental energies (top) and results of the IBA calculations in the present work (bottom). Levels in different isotopes are connected according to their ordered appearance in energy. Here the solid (open) symbols label the yrast (nonyrast) states.

assumed to be connected across the Pt isotopes in Fig. 1 *seems* to suggest an interpretation in terms of intruder states, the data themselves, given in Fig. 2 (top), show a smooth evolution which presents no obvious need to invoke an intruder configuration crossing a less deformed ground state. The yrast band energies behave as expected, decreasing in energy as midshell is approached. The 2^+_γ state evolves extremely smoothly with a gradual decrease in energy with increasing neutron number. The 0^+_2 state exhibits a decrease in energy moving from ^{194}Pt towards midshell and then remains rather constant around midshell.

Given these data, the traditional reconstruction in Fig. 1, inspired by interpretations of the Pb and Hg isotopes, would seem unnecessary. Nevertheless, the data do present significant challenges for a single-space interpretation since the level spacings (e.g., the respective $R_{4/2}$ ratios) can be quite different in the ground and excited 0^+-band sequences. The picture presented in Fig. 2 (top) thus prompts the present investigation into the Pt isotopes to test whether a successful description can emerge without the introduction of an intruder configuration.

To do this, we use the simple, single-space IBA Hamiltonian discussed above. We apply the extended [23] consistent Q formalism [24] (ECQF) of the IBA in which the Hamiltonian can be written as [19,25]

$$H(\zeta) = c\left[(1-\zeta)\hat{n}_d - \frac{\zeta}{4N_B}\hat{Q}^\chi \cdot \hat{Q}^\chi\right], \qquad (1)$$

where $\hat{n}_d = d^\dagger \cdot \tilde{d}$, $\hat{Q}^\chi = (s^\dagger \tilde{d} + d^\dagger s) + \chi(d^\dagger \tilde{d})^{(2)}$, and N_B is the number of valence bosons.

The Hamiltonian of Eq. (1) involves only two parameters ζ and χ, plus an overall scaling factor c, and can describe the entire IBA symmetry triangle by variation of ζ between 0 and 1, and χ from 0 to -1.32. The three dynamical symmetries are given by limiting values of these parameters: $\zeta = 0$, any χ for U(5); $\zeta = 1$, $\chi = -1.32$ for SU(3); and $\zeta = 1$, $\chi = 0$ for O(6).

We performed IBA calculations for the Pt isotopes ranging from ^{172}Pt to ^{194}Pt. Parameters were obtained by placing an equal emphasis on reproducing three structurally important energy ratios: $R_{4/2} \equiv E(4^+_1)/E(2^+_1)$, $E(2^+_\gamma)/E(2^+_1)$, and $E(0^+_2)/E(2^+_1)$. The results of the calculations for the low-lying states are given in Fig. 2 (bottom). Comparison of the data (Fig. 2, top) with the calculations (Fig. 2, bottom) shows that the IBA can nicely reproduce the systematics of the low-lying levels in Pt with a smooth evolution of the parameters (see discussion below). Energies of the yrast band and excited 0^+_2 states are described very well. The overall constant energy of the 2^+_γ level is also given by the calculations.

A more challenging test of the quality of the fits is illustrated in Fig. 3 for ^{180}Pt, ^{186}Pt, and ^{194}Pt. The calculations for both ^{180}Pt and ^{186}Pt show remarkable agreement with the known experimental data (with a similar level of agreement for ^{178,182,184}Pt). Note that the different $R_{4/2}$ values and spacings within the yrast levels and the excited 0^+_2 sequence result naturally from the calculations. Also well described is the staggering within the γ band. The calculations for branching ratios from excited states in the $K = 0^+$ excited sequence and the γ band are in near perfect agreement with

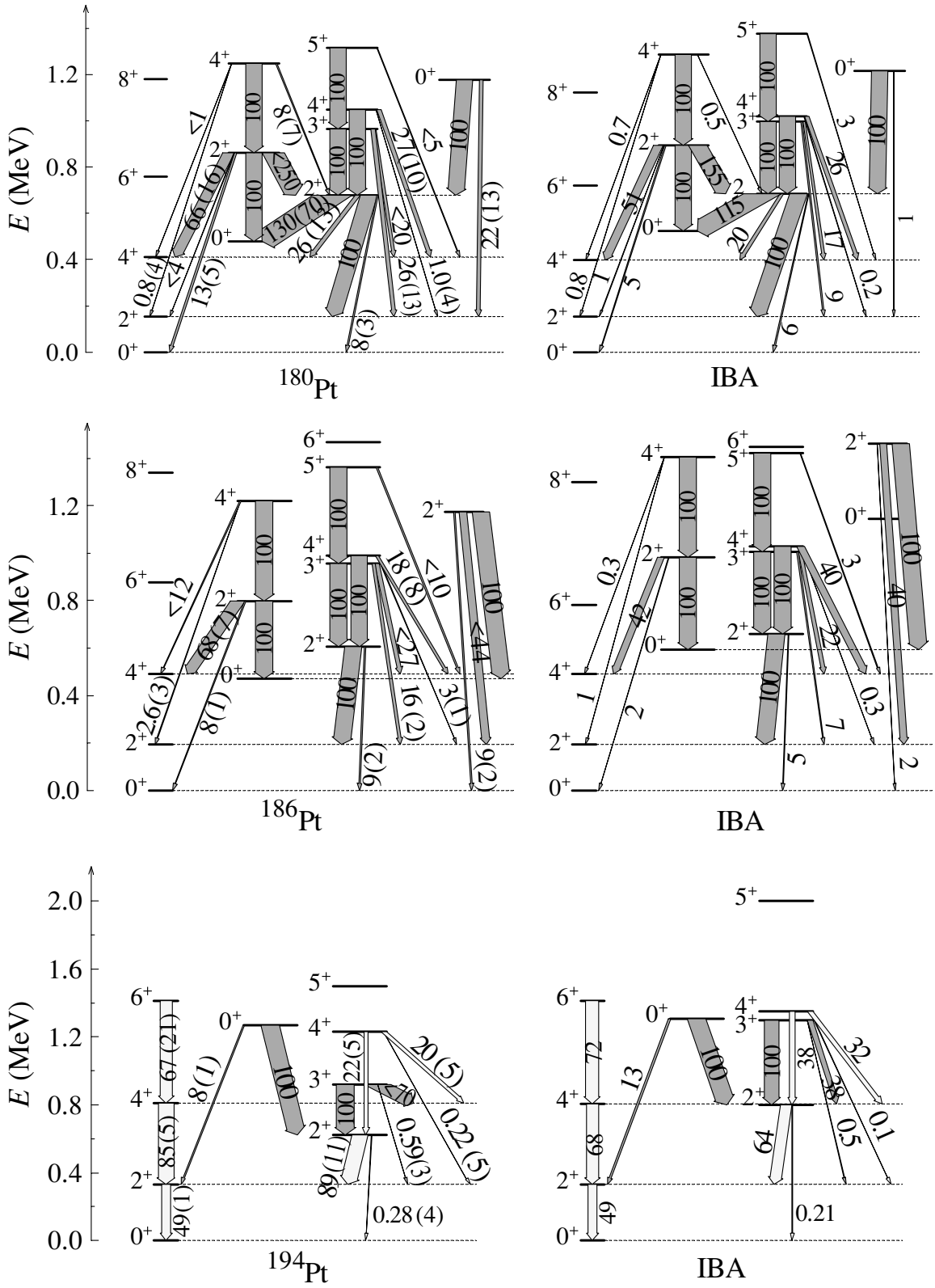

FIG. 3. Comparison of experimental (left) and IBA calculations (right) for energy levels and electromagnetic transition strengths in ^{180}Pt (top), ^{186}Pt (middle), and ^{194}Pt (bottom). The thickness of the arrows indicates the relative and/or absolute $B(E2)$ strengths, which are also labeled by their values. In ^{180,186}Pt, only relative branching ratios are known. In ^{194}Pt, relative (gray arrows) and absolute (white arrows) $B(E2)$ strengths are shown where the absolute $B(E2)$ strengths in the IBA calculations are normalized to the experimental $B(E2; 2_1^+ \rightarrow 0_1^+)$ value. Experimental data are taken from Refs. [14,26–28]. Only the ground, 0_2^+, and γ band sequences are included for ^{194}Pt since multiple states with the same spins and similar energies make the identification of the corresponding states in the IBA difficult.

the measured experimental values. Beyond the states assigned to a particular band structure, there are other known states in these nuclei which can be compared to the calculations. Below 1200 keV, the only states not assigned to the ground, 0_2^+, or 2_γ^+ sequence are a 0_3^+ state in ^{180}Pt and a 2^+ state in ^{186}Pt. These states, whose incorporation would add additional parameters into band-mixing calculations, appear naturally in the IBA and are in good agreement with the data. In addition, the calculations predict a second excited 0^+ state in ^{186}Pt, whose observation would serve as a test of these calculations.

In ^{194}Pt (with similar results for ^{188,190,192}Pt), good agreement is obtained for both absolute $B(E2)$ strengths (white arrows) and relative branching ratios (gray arrows) where absolute $B(E2)$ values are calculated by normalizing the calculations to the experimental $B(E2; 2_1^+ \rightarrow 0_1^+)$ value. For the heavier Pt isotopes ($A \geqslant 190$), the one obvious discrepancy between the data and calculations is in the description of the energies of the γ band. The simple Hamiltonian of Eq. (1) is not suited to generate a 2_γ^+ energy below that of the 4_1^+ state, and thus the IBA overpredicts the energy of the 2_γ^+ state for the heavier Pt nuclei. In terms of the spacings within the γ band, the IBA predicts an exaggerated staggering while the data show a much more equal spacing with increasing spin. These discrepancies relate to the fact that the potential energy surfaces for these nuclei are not completely flat in γ. Previous studies [29,30] have found that by introducing a very weak γ dependence in the potential (by including a cubic term in the Hamiltonian), the energy of the 2_γ^+ state can be predicted below the 4_1^+ state, and the experimental γ band spacings can be better reproduced.

The parameters ζ and χ obtained for each nucleus are plotted [31] in the IBA symmetry triangle in Fig. 4. We omit the parameters for ^{172,174}Pt since, while ζ can be fixed from the known yrast states, the lack of knowledge of any nonyrast states places no constraint on the parameter χ. The overall evolution is quite smooth, with a cluster of near-midshell nuclei just beyond the phase transition region. The parameter ζ, which gives a measure of the deformation and is represented in the triangle by the radial distance from the U(5) vertex, is quite constant for almost all the nuclei, representative of the small variation in yrast $R_{4/2}$ values (2.5–2.7) across most of the isotopic chain. A small increase in ζ is required to describe the transition from a more spherical ground state to a more deformed one in moving from ^{176}Pt to ^{178}Pt. The parameter χ is given by the angle of the radial vector of length ζ from the U(5)-SU(3) axis to the γ-soft U(5)-O(6) axis. The absolute value of χ is large for the lighter Pt isotopes ($\sim$1.0) and smoothly decreases with increasing neutron number as the nuclei evolve towards a γ-soft O(6) structure. The decrease in χ is dictated by the decreasing $E(2_\gamma^+)/E(2_1^+)$ energy ratio seen in Fig. 2 (top). As shown above, with this smooth evolution of the parameters, the IBA is able to reproduce the energy systematics of the low-lying levels (including the increase in 0_2^+ energy which occurs around $A = 188$), as well as absolute and relative branching ratios from low-lying states.

In order to further study the structural evolution, we investigate the wave functions for a sample of nuclei across the isotopic chain in Fig. 5, focusing on the 0_1^+ and 0_2^+ states.

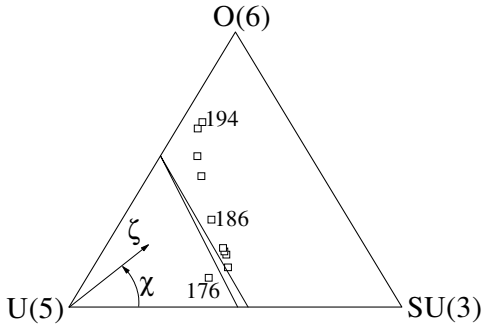

FIG. 4. Trajectory in the IBA symmetry triangle for the Pt isotopic chain. The slanting lines enclose the region of phase coexistence in the IBA model. The significance of the parameters ζ and χ is indicated. $\chi = -1.32$ along the bottom axis of the triangle and goes to zero along the U(5)-O(6) leg.

(Similar results apply for levels of higher angular momenta). Those nuclei at either end of the trajectory exhibit 0_1^+ wave function distributions close to the expected dynamical symmetry limits. The ground state of ^{176}Pt contains a large amplitude for $n_d = 0$, typical of the ground state of a spherical [U(5)] wave function distribution. The wave function of the ground state of ^{194}Pt is typical of a γ-soft [O(6)-like] distribution [32] with finite n_d components in $n_d = 0, 2, 4$. In moving from ^{176}Pt to ^{180}Pt, the structure of the 0^+ states reverses. The ground state of ^{180}Pt shows a wide distribution in the number of d bosons, typical of a deformed [SU(3)] wave function distribution, in contrast with a large amplitude for $n_d = 0$ in the 0_2^+ state, suggesting a spherical structure.

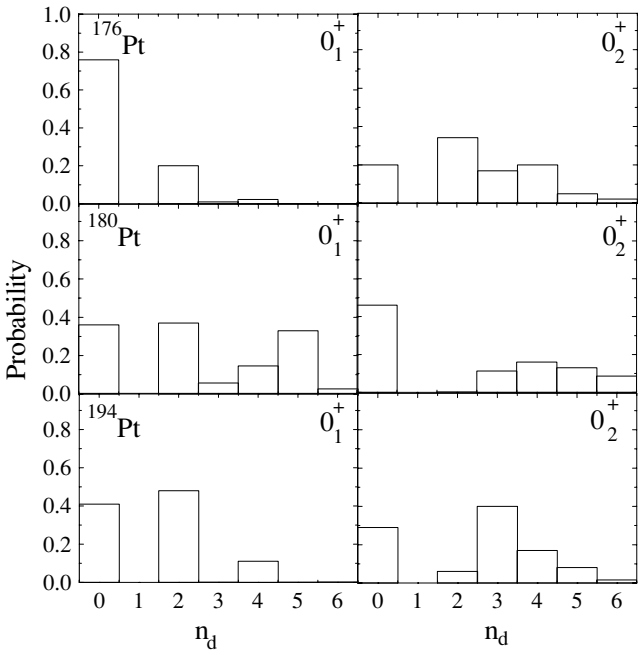

FIG. 5. Distribution of squared wave function amplitudes for 0_1^+ and 0_2^+ states as a function of n_d for ^{176,180,194}Pt. Amplitudes up to $n_d = 6$ are given.

The wave functions of ^{180}Pt hint at the existence of states with different deformations. Using the coherent state formalism, it has been shown that the spherical to deformed transition in the IBA undergoes a first order phase transition [33] for $\chi \neq 0$, and that near the transition point, different shapes can coexist in a soft potential. Inspection of Fig. 4 finds that the Pt nuclei near midshell lie quite close to this phase/shape transition region of the IBA. Evidence for states with different deformations is seen in both the data and calculations for ^{180}Pt and ^{186}Pt. Figure 3 shows that both the 0^+-2^+ spacings and $R_{4/2}$ values are quite different [e.g., $R_{4/2} = 2.7$ (g.s.) and $R_{4/2} = 2.1$ (0_2^+ sequence)] in the two sets of levels. Indeed, the calculations shown in Figs. 2 and 3 predict quadrupole moments which also indicate that different deformations emerge naturally from the calculations. In the region $^{178-186}$Pt, the intrinsic quadrupole moments for the 2_1^+ and 2^+ ($K = 0_2^+$) states have typical values of $\sim 3\,e$ b and $\sim 1.5\,e$ b, respectively, showing that the excited 0_2^+-band sequence is somewhat less deformed than the equilibrium structure. This feature would suggest that the nuclei lie on the deformed side of the spherical-deformed phase transition which is, in fact, consistent with their location in Fig. 4.

In conclusion, we have applied a single-configuration simple IBA-1 Hamiltonian to the Pt isotopic chain. The excellent agreement obtained for both energies and a large number of electromagnetic transition strengths suggests that these nuclei can be described *without* the need for intruder configurations. Instead, with a smooth variation in parameters within a single space Hamiltonian, the Pt nuclei are described in terms of a transition from spherical nuclei with soft energy surfaces to deformed nuclei with increasingly γ-soft surfaces as N increases. In contrast, the light Pb and Hg isotopes (in particular their low-lying 0_2^+ energies) cannot be fit with such an approach and seem to require a two-space interpretation. Thus, while the concept of cross shell-gap excitations descending into the low-lying spectrum of nuclei due to the p-n interaction is well founded and closely related to the development of collectivity in nuclei [3,34], the application of this concept to particular nuclei needs to be carefully confronted with, and validated by, the data for such nuclei.

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[1] J. L. Wood, K. Heyde, W. Nazarewicz, M. Huyse, and P. van Duppen, Phys. Rep. **215**, 101 (1992).
[2] K. Heyde, P. Van Isacker, M. Waroquier, J. L. Wood, and R. A. Meyer, Phys. Rep. **102**, 291 (1983).
[3] K. Heyde, P. Van Isacker, R. F. Casten, and J. L. Wood, Phys. Lett. **B155**, 303 (1985).
[4] K. Heyde, J. Jolie, J. Moreau, J. Ryckebusch, M. Waroquier, P. van Duppen, M. Huyse, and J. L. Wood, Nucl. Phys. **A466**, 189 (1987).
[5] A. N. Andreyev *et al*., Nature (London) **405**, 430 (2000).
[6] R. Julin, K. Helariutta, and M. Muikku, J. Phys. G: Nucl. Part. Phys. **27**, 109(R) (2001).
[7] M. K. Harder, K. T. Tang, and P. Van Isacker, Phys. Lett. **B405**, 25 (1997).
[8] S. L. King *et al*., Phys. Lett. **B443**, 82 (1998).
[9] K. Heyde, J. De Beule, B. Decroix, and C. De Coster, Hyperfine Interact. **127**, 65 (2000).
[10] R. Bengtsson, T. Bengtsson, J. Dudek, G. Leander, W. Nazarewicz, and Jing-Ye Zhang, Phys. Lett. **B183**, 1 (1987).
[11] G. D. Dracoulis, Phys. Rev. C **49**, 3324 (1994).
[12] G. D. Dracoulis, A. E. Stuchbery, A. P. Byrne, A. R. Poletti, S. J. Poletti, J. Gerl, and R. A. Bark, J. Phys. G **12**, L97 (1986).
[13] D. Seweryniak *et al*., Phys. Rev. C **58**, 2710 (1998).
[14] P. M. Davidson, G. D. Dracoulis, T. Kibédi, A. P. Byrne, S. S. Anderssen, A. M. Baxter, B. Fabricius, G. J. Lane, and A. E. Stuchbery, Nucl. Phys. **A657**, 219 (1999).
[15] P. D. Duval and B. R. Barrett, Phys. Lett. **B100**, 223 (1981).
[16] F. Iachello and A. Arima, *The Interacting Boson Model* (Cambridge University Press, Cambridge, England, 1987).
[17] R. Bijker, A. E. L. Dieperink, O. Scholten, and R. Spanhoff, Nucl. Phys. **A344**, 207 (1980).
[18] F. Iachello, N. V. Zamfir, and R. F. Casten, Phys. Rev. Lett. **81**, 1191 (1998).
[19] N. V. Zamfir, P. von Brentano, R. F. Casten, and J. Jolie, Phys. Rev. C **66**, 021304(R) (2002).
[20] A. Frank, C. E. Alonso, and J. M. Arias, Phys. Rev. C **65**, 014301 (2001).
[21] N. V. Zamfir *et al*., Phys. Rev. C **65**, 044325 (2002).
[22] K. Heyde, J. Jolie, R. Fossion, S. De Baerdemacker, and V. Hellemans, Phys. Rev. C **69**, 054304 (2004).
[23] P. O. Lipas, P. Toivonen, and D. D. Warner, Phys. Lett. **B155**, 295 (1985).
[24] D. D. Warner and R. F. Casten, Phys. Rev. Lett. **48**, 1385 (1982).
[25] V. Werner, P. von Brentano, R. F. Casten, and J. Jolie, Phys. Lett. **B527**, 55 (2002).
[26] S.-C. Wu and H. Niu, Nucl. Data Sheets **100**, 483 (2003).
[27] C. M. Baglin, Nucl. Data Sheets **99**, 1 (2003).
[28] E. Browne and B. Singh, Nucl. Data Sheets **79**, 277 (1996).
[29] R. F. Casten and P. von Brentano, Phys. Lett. **152**, 22 (1985).
[30] N. V. Zamfir and R. F. Casten, Phys. Lett. **B260**, 265 (1991).
[31] E. A. McCutchan, N. V. Zamfir, and R. F. Casten, Phys. Rev. C **69**, 064306 (2004).
[32] R. F. Casten, *Nuclear Structure from a Simple Perspective* (Oxford University Press, New York, 2000).
[33] A. E. L. Dieperink, O. Scholten, and F. Iachello, Phys. Rev. Lett. **44**, 1747 (1980).
[34] P. Federman and S. Pittel, Phys. Lett. **B69**, 385 (1977).