THE GROUND STATES OF $^{176-186}$Pt: AN EXAMPLE OF A SHELL MODEL INTRUDER STATE CONFIGURATION*

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Abstract

The systematics of excited states in the neutron-deficient even-mass Pt isotopes are shown to provide evidence that a strongly deformed configuration is present in the ground states of these isotopes. This configuration is proposed to be due to $(\pi h_{9/2})^2$, based on proton intruder state systematics and the importance of valence neutrons and protons in producing deformation. It is suggested that this phenomenon is unprecedented and, for the present, unique to the neutron-deficient even-mass Pt isotopes. A simple test of this picture using the blocking effect of an $h_{9/2}$ proton coupled to the ^{186}Pt core, as observed in ^{187}Au, is discussed. The consequences of this intruder state structure in the neutron-deficient Pt isotopes on other observable quantities in this region are considered.

1. Introduction

Historically, the properties of nuclear ground states have provided the first view of the frontiers of the nuclear mass surface. This continues, as is evident from the new results presented at this conference. The reason for this is simple. It is the ground state (or sometimes also a low-energy isomeric state) of a nucleus that lives long enough for the species to be isolated for study, and to be subjected to external fields as a means of study. These fields can be due either to the natural atomic electron environment giving rise to atomic hyperfine studies (e.g. laser spectroscopy); or, to a man-made environment, giving rise to e.g. direct mass measurements.

The most pronounced feature among nuclear ground states, beyond nuclear shell structure, is unquestionably the universal occurrence of 0^+ spin-parity for the ground states of doubly-even nuclei. This is due to the dominance of a residual pairing force between like nucleons throughout the mass surface. This, together with a weaker residual quadrupole force, appears to control the structure of most nuclei to a very fine level of detail. The residual pairing and quadrupole forces give rise to very smoothly varying collective properties in a given shell region, as can be illustrated by e.g. two-nucleon separation energies and first excited 2^+ state energies, respectively. It is the departure from these smooth properties that has produced some of the greatest excitement and stimulation to further work in studies far from stability. Historically, none of these "exotic" regions of nuclear structure (e.g. the neutron-rich Na and Zr isotopes, the neutron-deficient Hg isotopes) have been predicted by existing theories. Specific predictions of exotic behaviour for yet-to-be-studied nuclei should be of great interest to experimentalists: the prediction of nuclear properties far from stability was widely discussed recently at the Nashville Symposium[1]. A critical aspect of 0^+ states in nuclei, and therefore of the ground states of all doubly-even nuclei, is that excited 0^+ states in nuclei are often very poorly understood (see ref.[2]) and the discussion below). This suggests that even the calculation of ground-state properties of doubly-even nuclei is not always reliable: a point often obscured by the familiarity of these states !

The neutron-deficient Hg isotopes form a classic illustration of a totally unexpected phenomenon: the sudden appearance of strong deformation in the ground states of ^{185,183}Hg, as first seen in optical pumping studies of the atomic hyperfine structure of these nuclides at ISOLDE by Otten and coworkers[3]. Following this discovery, a large amount of experimental and theoretical work ensued (see below). Recent studies include the demonstration of shape isomerism in ^{185}Hg by laser hyperfine spectroscopy[4], and the extension of the phenomenon to the neutron-deficient Pt isotopes by α-decay measurements[5] on the Hg isotopes. Despite numerous theoretical investigations of this shape isomerism in the neutron-deficient Hg isotopes, there were no predictions of the similar behaviour in the neutron-deficient Pt isotopes !

The present investigation provides a new way of looking at the shape isomerism in the neutron-deficient Hg and Pt isotopes. The approach taken emphasizes the importance of shell and subshell gaps in nuclei, together with the role played by orbitals that intrude across these gaps, in producing shape coexistence and exotic structures. This approach has its conceptual origin in the proton-neutron interacting boson approximation (IBA 2), and preliminary details have been reported already by the author[2]. Independently, the concept has been introduced by Duval and Barrett[6] in an explicit IBA 2 formalism for the neutron-deficient Hg isotopes. Although the IBA 2 is ideally suited to formulating the concept theoretically, the picture is not dependent on the IBA, and independently of the boson picture, it leads to the prediction of simple phenomena.

2. 0^+ States in Nuclei

Excited 0^+ states are probably the most poorly understood modes of excitation below the pairing gap in doubly-even nuclei. This was illustrated drastically by the recent

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discovery that the lowest excited 0^+ state in $^{112-118}$Sn is strongly deformed with a well-defined rotational band built on it[7]. Consequently, it is now believed that the excitation of nuclear pairs across closed shells can give rise to fairly low-lying excited 0^+ states which are much more deformed than the ground state[8]. Although less dramatic, the lowest excited 0^+ state in a number of Ra, Th, U and Pu isotopes is still the subject of considerable debate (see e.g. refs. [9,10,11] and references therein). The lack of understanding of actinide states was emphasized even further by the very recent observation that they are strongly populated in α-transfer reactions[12]. (They have been shown previously to possess anomalous α-decay feeding hindrance factors[13].)

Despite the generally widespread lack of understanding of excited 0^+ states, there are some cases which appear to be at least partially understood. These cases can be characterized roughly into (a) excitations of pairs of nucleons across subshell gaps, (b) excitations of pairs of nucleons across major shell gaps and (c) coupling of bosons to $J^\pi = 0^+$ in the IBA. The best example of (a) is probably the first excited 0^+ state in ^{90}Zr and of (b) are the first excited 0^+ states in the Sn isotopes: these are discussed in some detail in ref.[2]. Case (c) has been widely illustrated: e.g. the lowest excited 0^+ states in the Sm isotopes[14], and the complete spectrum of excited 0^+ states below the pairing gap in ^{196}Pt (ref.[15]) and ^{168}Er (ref.[16]).

The pairing structure of 0^+ states is naturally probed by two-neutron, two-proton and alpha transfer reactions. Two-neutron transfer reactions have been used widely to explore neutron pairing correlations throughout the mass surface[17]. Two-proton transfer reactions have been used far less due to experimental difficulties (see e.g. ref.[18]). Alpha transfer reactions can probe proton pair-neutron pair correlations; but, it is only very recently that this kind of spectroscopy has come into use (see e.g. ref.[12] and references therein). Information on pairing structure can also be obtained from the blocking effect, i.e. the Pauli exclusion principle, and results in a loss of pairing correlation energy. The effect is universally manifested in the odd-even mass difference of nuclear ground states. The rates of α decay also offer some information analogous to α-transfer reaction data (see the comment on the actinide 0^+ states above). (At present, the systematic behaviour of E0 transition probabilities is not understood well enough to be of use.) However, all probes of 0^+ state structure using transfer reactions require stable or long-lived targets and thus are confined to studies of nuclear structure near the line of stability. Only odd-particle blocking and α-decay rates can provide information on the pairing structure of 0^+ states far from stability. Odd-particle blocking as a probe of pairing correlations in excited 0^+ states has not been used widely as a tool. The best examples (which have been investigated by blocking and transfer reaction studies) are probably the studies of the first excited 0^+ states in ^{72}Ge and ^{234,236}U. In ^{72}Ge and ^{73}As (see e.g. refs.[19,20]), the odd proton evidently blocks the excited 0^+ configuration strongly and it has not been observed as a core configuration in ^{73}As. In ^{232,233,234}U, the odd neutron partially blocks the ground-state 0^+ configuration and does not significantly block the excited 0^+ configuration[21]. These cases illustrate strong and weak blocking of the excited state and ground state configurations, respectively.

3. The 0^+ States in the Neutron-Deficient Pt and Hg Isotopes and Intruder Configurations

The essential features of the neutron-deficient Pt and Hg isotopes for this discussion are shown in Figs. 1 and 2. These figures are taken from ref.[2], and the reader is referred there for further details. The most puzzling feature of Figs. 1 and 2 is: where are the strongly deformed states in the odd-Pt and even- and odd-Hg isotopes ? The work of Hagberg et al.[6] shows that the moment of inertia parameter is e.g. 14.7 keV for ^{181}Pt and 25.8 keV for ^{182}Pt. The answer to this puzzle is illustrated by Fig. 3, which shows the systematics of the yrast bands in the N=106 isotones and the deformed band in ^{186}Hg. Evidently the yrast band in ^{184}Pt increases in deformation with increasing spin, as seen from the rotational parameter extracted from the transition energies. A consideration of the low-spin excited states in ^{184}Pt (see Fig. 1) suggests that the 0^+ ground state and 0^+ excited state mix strongly and the ground state energy is lowered. To a lesser extent, the $2_1{}^+$ and $2_3{}^+$ states similarly must mix and repel. The E0 transition between these two states supports this. A similar systematic behaviour is found for the other even-Pt isotopes with A=176-186 (see refs.[2,5]). Thus, the ^{184}Pt ground state contains the major component of a strongly deformed 0^+ configuration. Fig. 3 shows that this configuration does not contribute to the ground state in ^{182}Os.

In the proton-neutron interacting boson approximation (IBA 2) nuclear deformation comes about through a proton-neutron quadrupole interaction (between bosons). This requires the valence configuration for a nucleus to contain a number of each kind of nucleons before deformation results, and nuclei with a closed or near-closed shell (e.g. Pb, Hg isotopes) will be spherical or weakly deformed. This suggests that the valence space for proton configurations in the neutron-deficient Hg isotopes (and for the neutron-deficient Pt isotopes) is increased for the deformed excited 0^+ states: this can be achieved most simply by promoting a pair of protons across the Z=82 closed shell. It is in just this region that proton intruder orbitals come very low in energy[8]: the most notable strucutre being the $h_{9/2}$ states in the odd-Tl and -Au isotopes[22]. Thus, it is proposed that the configuration $(\pi h_{9/2})^2$ plays a major role in the first excited 0^+ state of the neutron-deficient Hg isotopes and in the ground state of the neutron-deficient Pt isotopes.

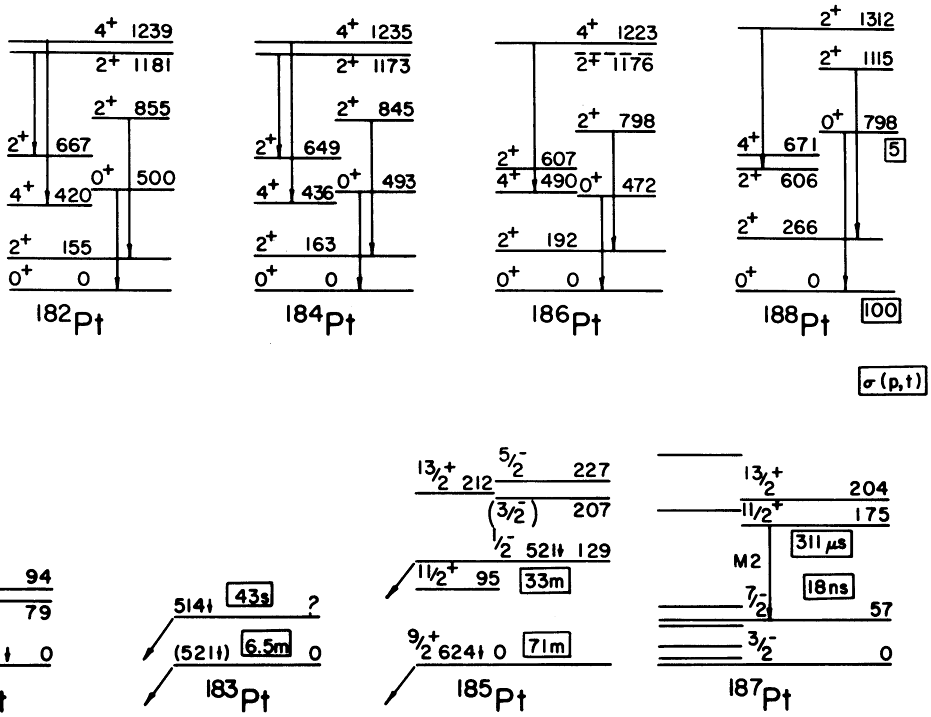

Fig. 1 A schematic summary of the structure of $^{181-188}$Pt. The deformed states in ^{181,183,185}Pt are labelled by the Nilsson quantum numbers $Nn_z\Lambda\Sigma$. EO transitions in the even-Pt isotopes are shown by arrows.

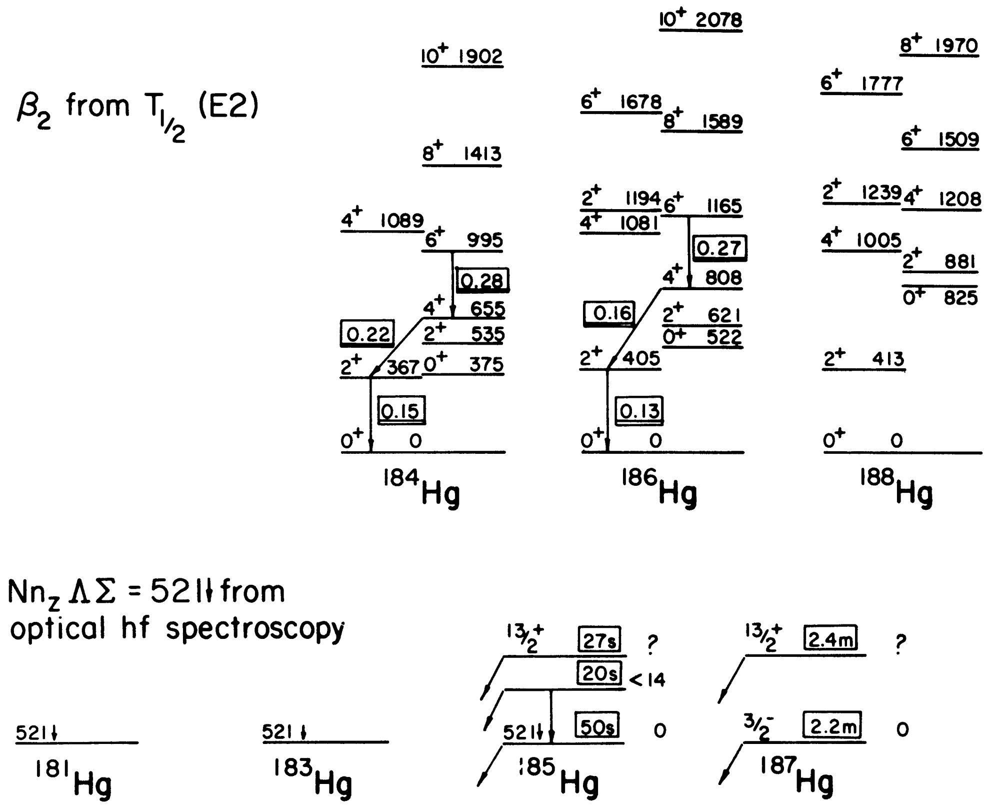

Fig. 2 A schematic summary of the structure of $^{181,183-188}$Hg. The β_2 values are deduced from $T_{1/2}$(E2) measurements.

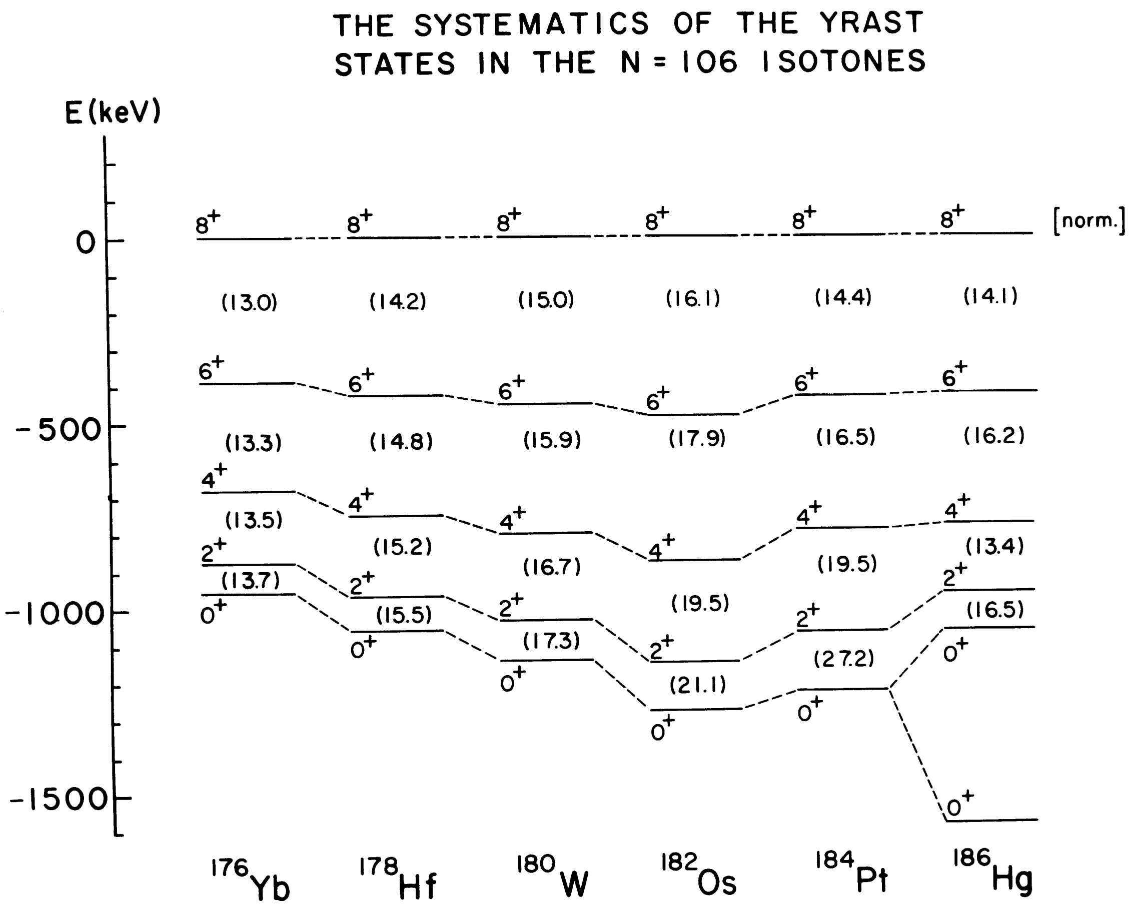

Fig. 3 The 0_1^+, 2_1^+, 4_1^+, 6_1^+ and 8_1^+ states in the N=106 isotones and the 0_1^+, 0_2^+, 2_2^+, 4_1^+, 6_1^+ and 8_1^+ states in ^{186}Hg (see also Fig. 2). The rotational parameter $\hbar^2/2I = (E_J - E_{J-2})/(4J-2)$ is shown in parentheses between the levels. Energies are shown relative to the 8_1^+ states.

Further, this configuration does not lie at low energy in the neutron-deficient Os isotopes. This bears some resemblance to the Sn and Cd isotopes, where a proton pair excitation across the Z=50 closed shell[8,18] gives rise to deformed excited 0^+ states[2,3,8] below the pairing gap. However, the assertion that this configuration plays a major role in the ground states of the neutron-deficient Pt isotopes and not in the ground states of neighbouring doubly-even isotopes is believed to be unprecedented.

This picture leads to a number of simple tests: Such a pairing excitation will be strongly populated in two-proton transfer reactions, and will be blocked by an odd proton occupying the $\pi h_{9/2}$ orbital. Unfortunately, the first test is not widely applicable because there are few targets suitable for studying this region by two-proton transfer (see below). However, the second test is readily applicable and it has been carried out[23] for $^{187}Au\{^{186}Pt \otimes \pi h_{9/2}\}$ and $^{189}Pt\{^{188}Hg \otimes \pi h_{9/2}\}$: From the above discussion we can predict that an $h_{9/2}$ proton coupling to a Pt core in the neutron-deficient Au isotopes will block the 0^+ ground state (0_1^+) more than the first 0^+ excited state (0_2^+), and the converse will be true for $Hg \otimes \pi h_{9/2}$ coupling in the neutron-deficient Tl isotopes. In ^{187}Au, the separation of the $9/2^-$ states due to the couplings $^{186}Pt(0_1^+) \otimes \pi_{9/2}$, $9/2^-$, and $^{186}Pt(0_2^+) \otimes \pi h_{9/2}$, $9/2^-$, is observed to be 323 keV, which is to be compared with the 0_1^+-0_2^+ core separation energy of 471 keV. This alone is insufficient to demonstrate that an unpaired proton in the $\pi h_{9/2}$ orbital blocks the 0_1^+ core configuration more than the 0_2^+ core configuration. The 0_1^+ and 0_2^+ configurations are unlikely to have equal quadrupole moments and thus, since the coupling of a particle to the core is strongly affected by $Q_{core} \cdot q_{particle}$ (see e.g. ref.[24]), the $9/2^- - 9/2^{-\prime}$ separation energy is not a direct reflection of the blocking effect. It is asserted that this problem can be circumvented by considering the bands of states with $9/2^-$, $5/2^-$, $7/2^-$, $9/2^-$, $11/2^-$, $13/2^-$ and $9/2^{-\prime}$, $5/2^{-\prime}$, $7/2^{-\prime}$, $9/2^{-\prime}$, $11/2^{-\prime}$, $13/2^{-\prime}$ formed by the couplings to the 0_1^+ and 0_2^+ configurations and their respective 2^+ excitations. The difference in energy of the centroids of the two groups is then considered to reflect a particle-core coupling energy that is relatively independent of $Q_{core} \cdot q_{particle}$, i.e. that reflects particle-core blocking effects. All of these states (except $9/2_2^-$, $9/2_2^{-\prime}$) have been found[23] in ^{187}Au and the difference in energy of the centroids of the two groups of five states is 320 keV. It is thus concluded that indeed the $^{186}Pt(0_1^+)$ configuration is blocked more than the $^{186}Pt(0_2^+)$ configuration by an $h_{9/2}$ proton and hence $(\pi h_{9/2})^2$ plays an important role in the $^{186}Pt(0_1^+)$ configuration. The non-observation[23] of an E0 transition in ^{189}Tl below 1 MeV is also consistent with this picture, since the $\pi h_{9/2}$ blocking will affect the excited 0^+ state in ^{188}Hg and result in a raising of the E0 transition energy.

4. Implications and Future Work

The unique structure proposed here for the ground states of the even-Pt isotopes with A=176-186 leads to a number of unusual predictions. The involvement of the $(\pi h_{9/2})^2$ configuration in the ground states of just the even-Pt isotopes with $A \leq 186$, and not in the neighbouring even-mass Os and Hg isotopes and the even-Pt isotopes with $A \geq 188$, implies that an island of discontinuous behaviour in ground state properties exists for these isotopes. For example, ground state masses should show a discontinuity: a preliminary report of decay energies in the A=182 decay chain[25] is consistent with this. The reduced widths for ground state-to-ground state α decay between even-mass Hg and Pt isotopes and Pt and Os isotopes also should be anomalous: although some discrepancies still exist between experimental reduced α widths in this region[26,27], it can safely be stated that anomalous behaviour is seen[5,26,27]. Evidently, both decay energies and reduced widths for α decay in this region need detailed study in order to test the structures proposed here.

The most direct test available is the $^{184,186}Os(^3He,n)$ reactions. This should show strong population of the 0_1^+ and 0_2^+ states in $^{186,188}Pt$. Unfortunately, the natural abundance of $^{184,186}Os$ is 0.02% and 1.6%, respectively. In addition, the $(^3He,n)$ reaction would be difficult to study with the high resolution required for the high final state density involved in the Pt isotopes. Possibly, a $(^{16}O,^{14}C)$ reaction study would overcome this.

Recently, a successful prescription for the shape isomerism in the even Hg isotopes, involving a mixing of boson states with proton boson numbers $N_\pi=1$ and $N_\pi=3$, was reported[6]. The structure proposed here for the even-Pt isotopes would involve $N_\pi=2$ and $N_\pi=4$ proton boson states and would form an exacting test of this prescription. (The IBA2 calculations of Bijker et al.[28] are recoginzed to have some shortcomings[29]: primarily, the calculations used too large a quadrupole interaction between neutron bosons.)

Similar odd-proton blocking experiments to the ones described here need to be done for neighbouring odd-mass Tl and Au isotopes. These are either in progress or will soon begin at UNISOR.

Perhaps the most interesting questions to be answered are: how widespread is the occurrence of such low-lying structures ? And, do multi-particle-multi-hole structures appear at low-energy ? Some progress in answering these questions can be found in a forthcoming review article[8]. It would be particularly interesting to locate the $(\pi h_{9/2})^2$ configuration in the even-Os isotopes.

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DISCUSSION

R.A. Sheline: You did not talk about beta vibrations and pairing vibrations.

J.L. Wood: The beta vibrations are manifested in the Sm example where the vibrational → rotational transition gives rise to softness and low beta vibrational energies. Pairing vibrations are another name for the example of excitation of pairs across shell or subshell gaps: I avoided the use of the term vibration since the dynamical degree of freedom is not in a physical space and is thus difficult to visualize.

A. Gelberg: Could this Duval-Barrett mechanism in which two configurations with different N's are mixed play a role in the case of states with $I \neq 0$?

J.L. Wood: Possibly. But such a state would almost certainly lie above an $I = 0$ state with a similar structure; this might play an important role in yrast structures.

J.H. Hamilton: I had not seen your abstract prior to this conference. It is very interesting to see the similarity of these light Pt isotopes to ^{74,76}Kr which I presented this morning where the depression of the 0^+ ground state energies make these nuclei look less deformed than they really are, when only the 2-0 energies are considered. Also I note in a little-known review program 0^+ states at the Delhi Conference in 1974, we presented lifetime states and suggested shape-coexistence where the 0_2^+ expected level in ^{116}Sn was deformed. Of course, the beautiful Amsterdam work more clearly establishes the deformation of these 0_2^+ states and shape coexistence in the Sn isotopes.