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THE STRUCTURE OF NEUTRON DEFICIENT ODD-PROTON NUCLEI NEAR THE SHELL CLOSURE AT Z=82

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The experimental data on neutron deficient odd-proton isotopes of Au(Z=79), Tℓ(Z=81), and Bi(Z=83) relevant to core-particle coupling schemes and the shell model intruder state phenomenon are presented. The data show that near the Z=82 closed proton shell, the unpaired nucleon can be used to probe the structure of the core. It is demonstrated that the description of this process in terms of core-particle coupling models enables one to quantify and systematize a large body of experimental data and consequently, to provide new insights into the relevant nuclear structure. The purity of the particle/hole configurations is discussed. Information on the mechanisms responsible for the disappearance of the Z=82 shell model gap as the neutron number decreases is obtained from the spectrum of states which result from the coupling of the intruder particle and the even-even core. The observed band structure indicates that the intrusion of the extra shell proton (or proton hole) into the low energy structure of the neutron deficient odd-A Au, Tℓ, and Bi isotopes is not strongly related to the deformation of the core.

INTRODUCTION

Recent developments in experimental techniques, particularly in the field of heavy-ion interactions, have lead to an extremely rapid expansion of the available spectroscopic data on isotopic and isotonic sequences of nuclei on the neutron deficient side of beta stability. This has enabled one to examine very large sequences of nuclei while varying only a few nuclear parameters. These experimental results not only help to provide more thorough tests of the relevant nuclear models, but they have also, because of the broad systematics, led to the elucidation of new and unexpected nuclear phonomena.

The radioactive sources used in measurements performed at UNISOR† were produced by the continuous bombardment of an appropriate target with a heavy-ion beam from the Oak Ridge Isochronous Cyclotron and the continuous extraction of the products of that reaction to the UNISOR isotope separator. The separated beam of interest (the selected mass number) was collected on a continuous tape which moved after a preset collection time to an array of particle and photon detectors. The reader is refered to the previous paper by J. L. Wood for a thorough discussion of the types of measurements and the experimental philosophy developed and implemented at UNISOR.

Among other studies, we have investigated the systematic features of the neutron deficient odd-proton isotopes of Au(Z=79), Tℓ(Z=81), and Bi(Z=83) which are relevant to core-particle coupling schemes and the shell model intruder state phenomenon. The experimental data covering the 19 nuclei involved has come from our own work at UNISOR, from a number of other scientists working at UNISOR (see acknowledgments) and from the available literature. The basic theoretical picture utilized is that of a proton particle or hole coupled to a slightly deformed and possibly triaxial even-even core which is not appreciably polarized by the extra nucleon or hole. The triaxial rotor model of Meyer ter Vehn [1] was used to extract the relevant nuclear parameters. The results demonstrate the applicability of core-particle coupling to the odd-proton nuclei near Z=82, and indicate that triaxial shapes are a common feature of these transitional nuclei. The resulting systematic features also enable one to investigate possible mechanisms which give rise to shell model intruder states which in this region results in the disapppearance of the energy gap at the Z=82 shell closure. The results indicate that deformation is not the mechanism responsible for the observed intruder phenomenon in the neutron deficient odd-A Au, Tℓ, and Bi isotopes.

Although these nuclei exhibit a rich variety of interesting nuclear phenomena, the present discussion is limited to an examination of the excitations based on the $h_{11/2}$ proton hole and $h_{9/2}$ proton particle in the odd-A isotopes of Au, to excitations based on the $h_{11/2}$ proton hole and $h_{9/2}$ proton particle in the odd-A Tℓ isotopes, and to the intruder state phenomenon. The latter manifests itself in this region by the intrusion of the $h_{9/2}$ and $i_{13/2}$ proton excitations from above the closed shell at Z=82 into the low-energy structure of the neutron deficient Au and Tℓ isotopes and the intrusion of the $s_{1/2}$ state from below the closed shell at Z=82 into the low-energy structure of the neutron deficient Bi nuclei.

Since the discovery by Stephens [2] of decoupled and strongly coupled bands in transitional nuclei and their explanation in terms of the coupling of a particle (or hole) to a rigid rotor, a great deal of theoretical and experimental effort has been devoted to the study of such phenomena. In this picture the rigid deformation and the Coriolis force gives rise to high-spin states which are grouped into decoupled or strongly-coupled bands. A more complete description of these states, which readily includes prolate as well as oblate deformation was formulated by Meyer ter Vehn [1] through the introduction of triaxiality of the core nucleus. Although it is not possible at this time to differentiate between the various theoretical pictures which deal with the structure of these odd-proton transitional nuclei, it is necessary to at least mention the more prominent work. The triaxial rotor model of Meyer ter Vehn [1] differs from the very early core-particle coupling model of Hecht and Satchler [3] in that only a single j-shell is used in the single-particle configuration space and Coriolis effects are included. It also differs from the early model of Pashkevich and Sardaryan [4] in that it includes pairing correlations by treating the odd-nucleon as a quasiparticle. This basic picture [1] was extended by Toki and Faessler [5,6] to include the variable moment of inertia and the coupling of two j-shells. A semi-microscopic model describing the $h_{11/2}$ system in ^{195}Au was developed by Hecht [6]. This was done in the framework of a shell model description based on the coupling of an $h_{11/2}$ proton hole to core proton states which are approximated in the pseudo SU_3 coupling scheme. Paar _et al_. [7] use a spherical representation in which a cluster of three proton holes is coupled to quadrupole vibrations and described the $h_{11/2}$ and the positive parity band structures in the ^{193,195}Au nuclei. This results simultaneously in both a weak coupling pattern for the positive parity states and a decoupled pattern for the negative parity $h_{11/2}$ states. To describe the $h_{9/2}$ band structure, they [8] couple one j=9/2 particle to the quadrupole vibrations of the neighboring even-even Pt nuclei rather than resort to a four-hole one-particle cluster. Leander [9], Tanaka and Sheline [10], and Dönau and Frauendorf [11] apply a generalized core-quasiparticle coupling model to the odd-proton transitional nuclei in the Z=82 region. Leander [9] couples the odd nucleon to core states obtained from a numerical diagonalization of the Bohr collective Hamiltonian in order to describe the ^{187}Ir and ^{197}Tℓ nuclei. In this picture the odd particle can have a large polarizing effect on the core and it is then possible for the core to assume various shapes for different states in the same nucleus because of the shallowness of the minima in the γ-degree of freedom. It is interesting that the results of calculations with this γ-soft model are very similar to the results from the γ-rigid model calculations of the Meyer ter Vehn model. Tanaka and Sheline [10] extend the core-particle coupling model of de-Shalit [12], which is based on a quadrupole interaction between the particle and the core, by including the excited states of the core. They apply the picture to $^{191-199}$Tℓ, $^{189-191}$Au, and ^{187}Ir. Dönau and Frauendorf [11] apply a generalized core-quasiparticle formalism to the coupling of a quasiparticle to a triaxial rotor (γ=30°) and to a γ-unstable core. They investigate the coupling of an $h_{11/2}$ quasiparticle to both types of cores in ^{191}Pt and find a similar behavior for each, thus concluding that the odd particle is not sensitive enough to distinguish between these two types of cores. The Hecht-Satchler model has also recently been extended by Larsson et al. [13] to include an arbitrary number of Nilsson orbitals simultaneously and has been applied by Vieu et al. to the positive parity states in $^{193-199}$Au [14] and $^{187-193}$Ir [15] and to the $h_{11/2}$ system in ^{189,193,195}Au. The above are by no means a complete list of the relevant theoretical work related to odd-proton transitional nuclei in the Z=82 region, but they do provide a representative sample.

The first evidence for the existence of shell model intruder states in the light Tℓ nuclei came from the very early work of Diamond and Stephens [17]. They identified low lying $9/2^-$ isomeric states having excitation energies which varied systematically with mass number. The interpretation of these states was uncertain for some time since the only candidate for low-lying high-spin negative parity states in these nuclei, provided by the simple spherical shell model, are states arising from the $h_{11/2}$ orbital. Newton et al. [18] later found the systematic occurence of $11/2^-$, $13/2^-$, and $15/2^-$ states above the $9/2^-$ isomers in $^{191-197}$Tℓ and interpreted the structure as a rotational band based on the $9/2^-$ [505] state arising from the $h_{9/2}$ orbital. They [18] combined the blocking effect with shape isomerism in order to explain the appearance of the $h_{9/2}$ states at low energies (≈500 keV) rather than at ≈4 MeV as predicted by the shell model. Shape isomerism, where the ground state is spherical and the $9/2^-$ excited state is oblate, has also been suggested by Heyde et al. [19]. In this picture, as in the former, the deformation of the $h_{9/2}$ state would lower this level closer to the ground state. Wieclawik et al. [20] have also suggested that the mass dependence of the nuclear shape might be responsible for the lowering of the level. They [20] perform a microscopic calculation of the potential energy surface of several odd-A Tℓ, Au, Ir, and Re isotopes as a function of the quadrupole deformation. Dionisio et al. [21] employ a semi-emperical method based on Blomqvist's [22] calculation of the $9/2^-$ excitation energy in ^{201}Tℓ. They [21] apply it to the odd-A Tℓ, Au, and Ir isotopes and find that the semi-emperical predictions, which are in reasonable agreement with the experimental values, also agree with the results of a single particle potential energy surface calculation [20]. Dionisio et al. [21] and Goodman [23] compute the $h_{9/2}$ energy with a spherical HF model, but of these calculations only that of Goodman is successful in accounting for the experimental observations, in particular the subsequent rise of the $h_{9/2}$ intruder at the very light Tℓ isotopes (see Fig. 4, ahead). Goodman and Borysowicz [24] have extended this work in a more general discussion of the spin-orbit splitting [24]. Wood [25] has accounted for the systematic behavior of these intruders by treating them as isomeric pairing phases due to a residual quadrupole pairing force. As in the case of the core-particle models, we will not attempt to differentiate between these pictures apart from the fact that the data clearly demonstrate that deformation is not responsible for the disappearance of the Z=82 shell model gap in the neutron deficient odd-proton Au, Tℓ, and Bi isotopes.

THE ODD-A Au NUCLEI

In addition to a rich spectrum of positive parity levels based on s and d states, the study of the odd-A neutron deficient Au isotopes has revealed the existence of collective excitations based on the negative parity high-j $h_{11/2}$ proton hole states and $h_{9/2}$ and $i_{13/2}$ proton particle states. These separate sets of excitations have been interpreted within the framework of the rotation-aligned model [2] as decoupled rational bands [1,5]. The relevant experimental work on these excitations include references 26-31 for general systematics and references 32(^{195}Au), 33-35(^{189}Au), 36-38(^{187}Au), and 39-41(^{185}Au) for specific isotopes. In addition, the atomic beam measurements of Ekström et al. [42,43] provide definitive ground and isomeric-state spin assignments. In the decay work at UNISOR, beams of ^{14}N and ^{16}O were used in various combinations with targets of ^{181}Ta, ^{180}W, and ^{182}W. The in-beam work on ^{185}Au [39] utilized the ^{169}Tm(^{20}Ne, 4nγ) and ^{175}Lu(^{16}O, 6nγ) reactions. A considerable amount of work on these odd-A Au isotopes has also been done at Orsay [28,33,34,36,37,40].

The experimental spectrum of states observed in the odd-A Au nuclei can be divided into three distinct and essentially independent structures which can be grouped into bands based upon excited $11/2^-$ and $9/2^-$ states and into a system of levels built upon the positive parity states which lie near the Fermi surface. This discussion is confined to the particle-core coupling aspects of the $h_{9/2}$ and $h_{11/2}$ states. In Au (Z=79) the proton Fermi energy lies between the $h_{11/2}$ - $h_{9/2}$ doublet whose spin-orbit splitting gives rise to the closed shell at Z=82. In the framework of the core-particle picture these structures are viewed as an $h_{9/2}$ proton particle coupled to an even-even $^{A-1}$Pt core, and an $h_{11/2}$ proton hole coupled to a $^{A+1}$Hg core. In the rotation-alignment model [2] they arise from the decoupling of the odd particle (or hole) from the core under the action of the Coriolis force. The degree of decoupling then depends upon the deformation of the core, and has been expressed [1,5] in terms of the deformation parameter β and the asymmetry parameter γ. In this picture an $h_{9/2}$ particle will give rise to a strongly coupled band ($\Delta I=1$) for $\gamma > 30^o$. An $h_{11/2}$ hole will give rise to a strongly coupled band for $\gamma < 30^o$ and a decoupled band for $\gamma > 30^o$. The $h_{11/2}$ band structure in the odd-A Au isotopes provided one of the early tests of the various models which attempted to deal with such structures (see for example, refs. 1,5,7,8,10,14,16). The $h_{11/2}$ band structure for $^{185-195}$Au are presented in Fig.1. A number of $h_{11/2}$ states have been left off Fig.1 for reasons of clarity (see ref. 31 for additional details). It is immediately observed from Fig.1 that the $h_{11/2}$ structure is decoupled ($\Delta I=2$). In the region below about 1.5 MeV, in beam-spectroscopy reveals [26] the yrast sequence $9/2^- \rightarrow 15/2^- \rightarrow 11/2^-$ which corresponds to the $4^+ \rightarrow 2^+ \rightarrow 0^+$ sequence in the even-even Hg cores. The yrast members of these bands are relatively insensitive to the shape of the core and can only distinguish between rotation-aligned and deformation-aligned coupling. The locations of the low-spin members, which can be obtained from decay spectroscopy, are, on the other hand, very sensitive to the shape parameters β and γ [1,5]. Note also from Fig.1 the high degree of stability of the entire $h_{11/2}$ structure. This is expected within the context of core-particle coupling since the even-even Hg isotopes have a stable sequence of 2^+, 4^+, and 2^+_2 levels (Fig.1). The values for the shape parameters taken from ^{196}Hg (2^+ = 426 keV, 2^+_2 = 1037 keV, 4^+ = 1062 keV), are β = 0.13 and γ = 37^o. In the framework of the triaxial rotor model [1] these values can quite adequately account for the entire $h_{11/2}$ structure from ^{195}Au (core ^{196}Hg) to ^{185}Au (core ^{186}Hg), and are consistent with these Hg isotopes having a small asymmetric-

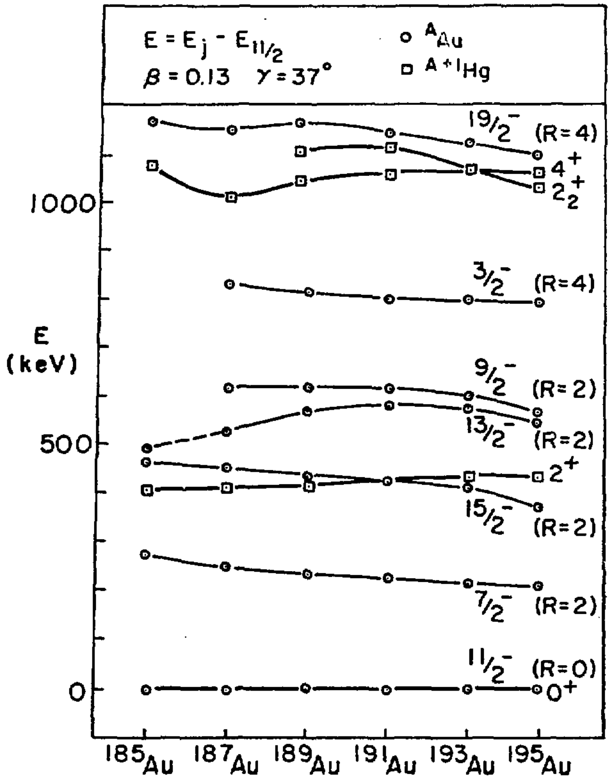

Fig. 1

The structure of states based on the $h_{11/2}$ excitation in $^{185-195}$Au. The energy of the $11/2^-$ band head has been normalized to zero. Shown also in heavy lines are the 2^+, 2^+_2, and 4^+ excited states for the neighboring A+1 Hg isotopes. The shape parameters β=0.13 and γ=37^o are computed from the 2^+ and 2^+_2 energy of ^{196}Hg and are the same values deduced from the experimental band structure [27,31, 35] and the triaxial rotor model [1].

oblate deformation. It should be pointed out that a band of low-lying 0^+, 2^+, and 4^+ states appear below the 2_2^+ states in ^{186,188}Hg. These states, which are not displayed in Fig.1, have been shown [44] to be members of a prolate deformed band which first appears at these low energies in ^{188}Hg and continue to drop in energy as one proceeds away from stability. Core-particle coupling involving a core based upon this deformed configuration is considered later (see Discussion).

The $h_{9/2}$ band structure for $^{185-195}$Au is presented in Fig.2 along with the 2^+, 2_2^+, and 4^+ states of the even-even $^{A-1}$Pt isotopes. Several states have been omitted for clarity (full details appear in ref. 31). One notes, in contrast to the $h_{11/2}$ structure, that the $h_{9/2}$ system is more deformation-aligned at ^{195}Au (the $11/2^-$ is below the $13/2^-$), which corresponds to a slightly oblate ^{194}Pt core of moderate deformation, and then becomes a decoupled structure beyond ^{190}Au. This latter situation corresponds to prolate deformed cores. This qualitative trend is born out quantitatively by using the energy of the very γ sensitive low-spin states obtained from the decay measurements in conjunction with an asymmetric rotor model [1] to compute shape parameters. The resulting "good fit" values are presented at the bottom of Fig.2. The trend from a moderately triaxial-oblate deformation to a more severe triaxial-prolate structure in going from ^{195}Au to ^{185}Au is consistent with the changes in deformation between ^{194}Pt and ^{184}Pt examplified by the 2^+, 2_2^+, and 4^+ levels. Note also (Fig.2) the similarity of the 2_2^+ and the second $13/2^-$ systematics. The $(13/2^-)_2$ state arises from the coupling of the $h_{9/2}$ proton to the 2_2^+ state of the Pt core and corresponds to a rotation about an axis perpendicular to that of the 2^+ and 4^+ states.

While the $h_{11/2}$ system remains relatively stable between ^{195}Au and ^{185}Au, the $h_{9/2}$ system undergoes a change from oblate to prolate shape. This produced a unique situation in ^{189}Au where the corresponding γ-parameters of 37° ($h_{11/2}$) and 23° ($h_{9/2}$) are particle-hole analogues (γ ranges between 0° and 60°). They should, in the triaxial rotor picture, display similar decoupled rotational-aligned bands which differ in spin by one unit. The $h_{11/2}$ bands are then triaxial-oblate and the $h_{9/2}$ triaxial-prolate, and since they appear near the same energy, one can use the terminology of shape coexistence. Actually, the positive parity states, being relatively flat on a

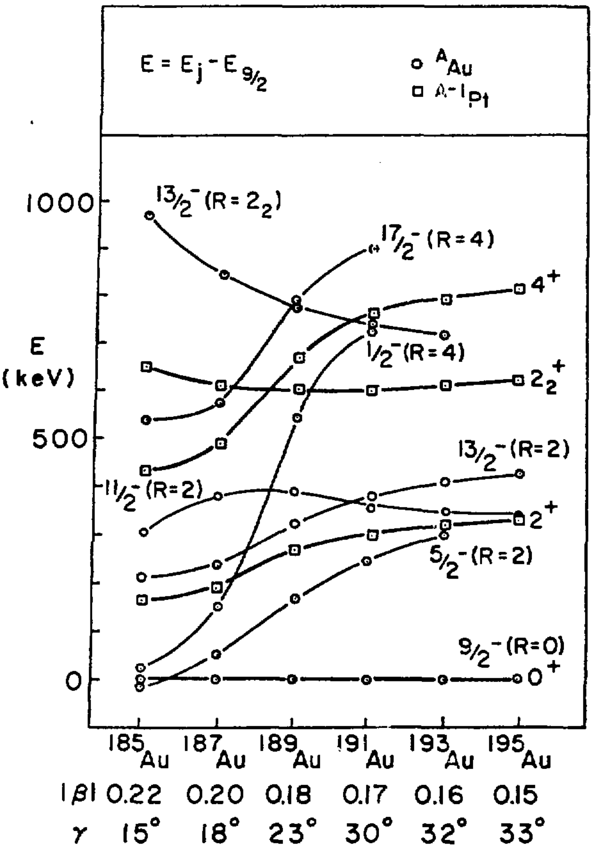

Fig. 2

The structure of states based on the $h_{9/2}$ excitation in $^{185-195}$Au. The energy of the $9/2^-$ band head has been normalized to zero. Shown also in heavy lines are the 2^+, 2_2^+, and 4^+ excited states for the neighboring A-1 Pt isotopes. The shape parameters (β,γ) appropriate to each odd-A Au isotope are also indicated. They were deduced from the experimental band structure [31,35] and the triaxial rotor model [1].

Nilsson diagram, require different shape parameters than either of the negative parity bands [27,37,40]. The implications of this are that the $h_{9/2}$ proton does have a slight polarizing effect on the Pt cores.

The systematics of the shell model states observed in the odd-A Au isotopes are presented in Fig.3. One immediately notes the steeply sloping $h_{9/2}$ and $i_{13/2}$ "intruders". That these states belong to the same structure and can be connected as shown in Fig.3 is born out by the experimental band structure built on the states as well as lifetime measurements [28] on the $h_{9/2}$ band. Also, the in-beam work, [39,40] on ^{185}Au has revealed a decoupled band structure based on an $i_{13/2}$ proton particle (above the Fermi energy) coupled to a prolate deformed ^{184}Pt core. In addition, Ekström et al. [42,43] have measured the ground state spin in ^{185}Au to be 5/2. The decay work [41] clearly indicates that the parity of this state must be negative. It is apparent from Fig.3 then that the $h_{9/2}$ particle state has become part of the ground state structure in ^{185}Au. Coriolis mixing can account for the $5/2^-$ state lying lower in energy than the $9/2^-$. The data [39,40,41] indicate that the energy difference is less than 2 keV, however. A remaining and as yet unresolved question is the applicability of the rotation-aligned scheme to ^{185}Au and even lighter Au isotopes because of the ever increasing deformation.

In terms of the technique of using the odd-proton particle and proton hole in the Au isotopes to probe the even-even Pt and Hg cores, the important question is whether or not the cores are stable enough to be used in this way. The systematics of Fig.1 clearly show this to be true for an $h_{11/2}$ proton hole on an even-even Hg core. Although the data of Fig.2 indicate that the $h_{9/2}$ proton particle may have a small deforming effect on the even-even Pt cores (probably the same for $i_{13/2}$), other data indicate that the core-particle picture is quite valid for that case as well. For example, the very large retardation of the $h_{9/2}$ to $h_{11/2}$ transition in ^{189}Au (15000, ref. 34) comes from the purity of the hole/particle configurations. To further substantiate this core-particle purity, Gono et al. [30] measured the sign of the E2/M1 mixing ratio for the $I + 1 \rightarrow I$ transitions in the $h_{11/2}$ and $h_{9/2}$ bands in $^{189-193}$Au and attribute the opposite sign observed for the mixing ratios of the two bands to be a consequence of the particle/hole symmetry.

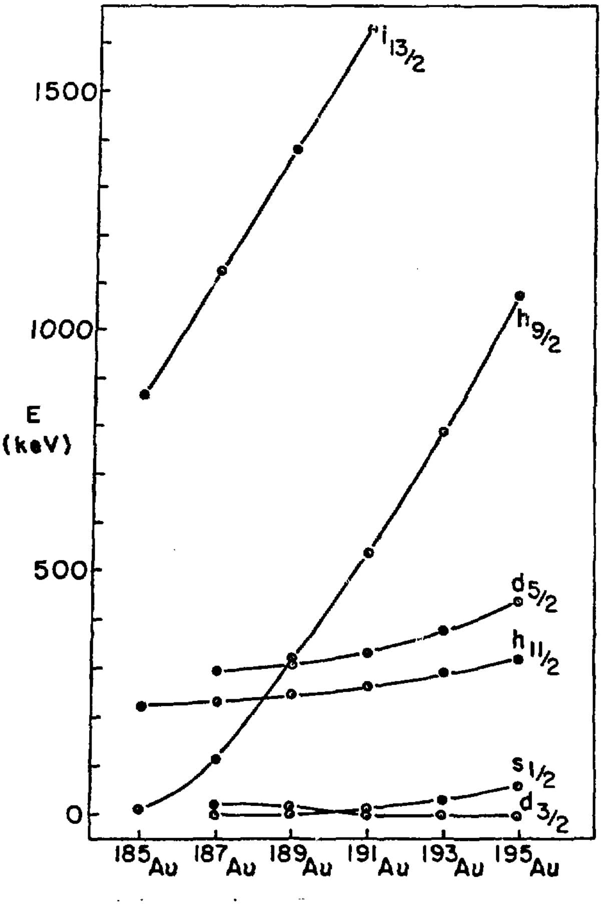

Fig. 3

Shell model states in $^{185-195}$Au. The $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, and $h_{11/2}$ excitations are proton hole states coupled to even-even Hg cores. The $h_{9/2}$ and $i_{13/2}$ excitations are proton particle states coupled to even-even Pt cores.

THE ODD-A Tℓ NUCLEI

The existence of rotational bands, based on the $h_{9/2}$ isomeric state in the odd-A Tℓ nuclei was first clearly established by Newton, Diamond, Stephens [45]. The relevant experimental work on these excitations include references 17,25,45,46, and 47 for general systematics and references 48-49 (^{201}Tℓ), 50-52 (^{197}Tℓ), 51,53 (^{195}Tℓ), 53,54 (^{193}Tℓ), and 55 ($^{185-191}$Tℓ) for specific isotopes. The majority of these investigations involved in-beam γ-ray spectroscopy studies. However, references 46, 47,52, and 53 refer to the UNISOR work on the decay of $^{197-193}$Pb and references 25 and 55 to the UNISOR work on the decay of $^{185-191}$Tℓ in which the location of the $9/2^-$ isomer was determined for $^{185-187}$Tℓ [55] and estimated for $^{189-191}$Tℓ [25]. The latter studies were done using beams of ^{14}N and ^{16}O ions in various combinations with targets of ^{181}Ta, ^{180}W, and ^{182}W. The former were done using ^{16}O beams on ^{185}Re and ^{187}Re targets. As in the case of the neutron deficient odd-A Au discussed above, the odd-A $^{197-193}$Tℓ experimental level schemes separate [52,53] into three distinct subgroups (excluding the $i_{13/2}$) consisting of the proton particle $h_{9/2}$ structure, the proton hole $h_{11/2}$ structure and a system of positive parity states based on the s and d orbitals which lie near the Fermi surface. These shell model states are shown in Fig.4. Again, as for the odd-A Au isotopes, the $h_{9/2}$ and $i_{13/2}$ proton "intruder" states drop quite rapidly as A decreases, achieving for the $h_{9/2}$ state a minimum at $^{189-191}$Tℓ. For the odd-A Au the minimum lies at or beyond ^{185}Au which was the lightest Au isotope investigated. Studies [25,55] on $^{189-185}$Tℓ, however, indicate that the $h_{9/2}$ intruder turns back up beyond $^{189-191}$Tℓ. Since the $i_{13/2}$ has a similar particle-core structure, its mass dependence should be nearly the same as that of the $h_{9/2}$ with about a 1 MeV offset. The intruder state phenomenon will be discussed further in the final section.

The Proton Fermi energy in Tℓ (Z=81) is somewhat higher than in Au (Z=79), but still lies between the $h_{11/2}$ - $h_{9/2}$ spin-orbit doublet. The corresponding cores for the odd-A Tℓ are $^{A-1}$Hg for the $h_{9/2}$ and $i_{13/2}$ proton particle and $^{A+1}$Pb for the $h_{11/2}$ proton hole. The $h_{9/2}$ band should show strong coupling for γ > 30° and decoupling for γ < 30°. Since it was shown in the previous section that the $^{A-1}$Hg cores are oblate (γ = 37°) one should expect, in the framework of the triaxial rotor models, strong coupling (ΔI=1) in the $h_{9/2}$ band of Tℓ. This is indeed found to be the case as is shown

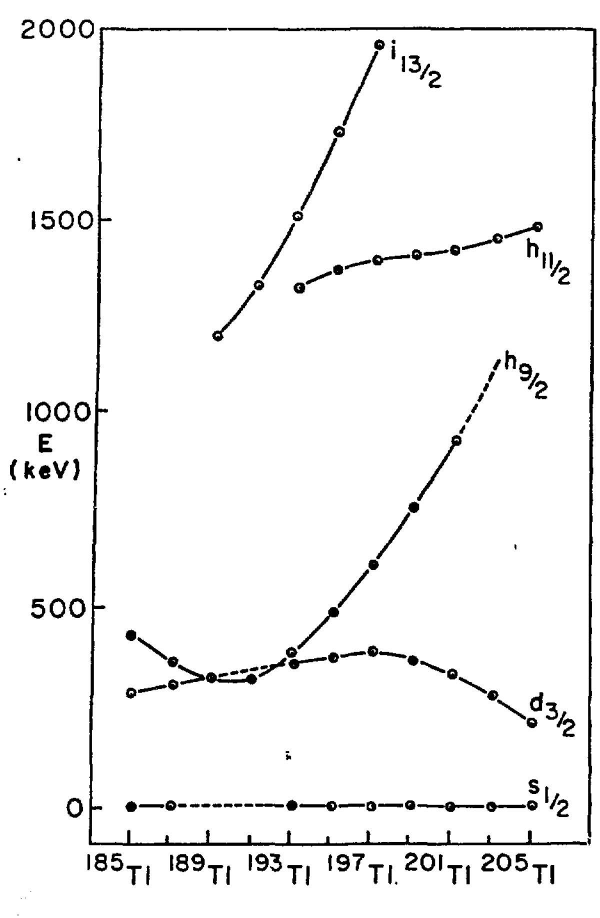

Fig. 4

Shell model states in $^{205-185}$Tℓ. The $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ excitations are proton hole states coupled to even-even Pb cores. The $h_{9/2}$ and $i_{13/2}$ excitations are proton particle states coupled to even-even Hg cores.

in Fig.5. The $\Delta I = 1$ sequence of yrast states and the close correlation between the $11/2^-$ and $15/2^-$ with the $^{A-1}$Hg 2^+ and 4^+ states (shown by full circles in the lower part of the figure) is quite apparent. The energy of the Hg 2_2^+ state is indicated by a light continuous line in Fig.5. As shown above for the $h_{11/2}$ band in the odd-A Au isotopes, the energy of this 2_2^+ level yields $\gamma = 37^\circ$ for essentially all the isotopes shown. This value is also successful in explaining the observed yrast structure in the odd-A Tℓ isotopes, but these levels are not very sensitive to the asymmetry parameter γ. The non-yrast levels are far more sensitive to variations in γ. The recently observed second $13/2^-$ state [47,50-53], and $5/2^-$ state [47,52,53], shown for $^{193-197}$Tℓ in Fig.5, are examples of such levels. The fact that they exhibit a marked mass dependence (see Fig.5) is indicative of this sensitivity. While it was demonstrated that $\beta = 0.13$, determined from the Hg 2^+ energies, was appropriate to the $h_{11/2}$ band structure in the odd-A Au isotopes, $\beta = 0.16$ works better in explaining the experimental $h_{9/2}$ band structure in $^{193-197}$Tℓ [47]. Although this change in β is not large, it is similar to the

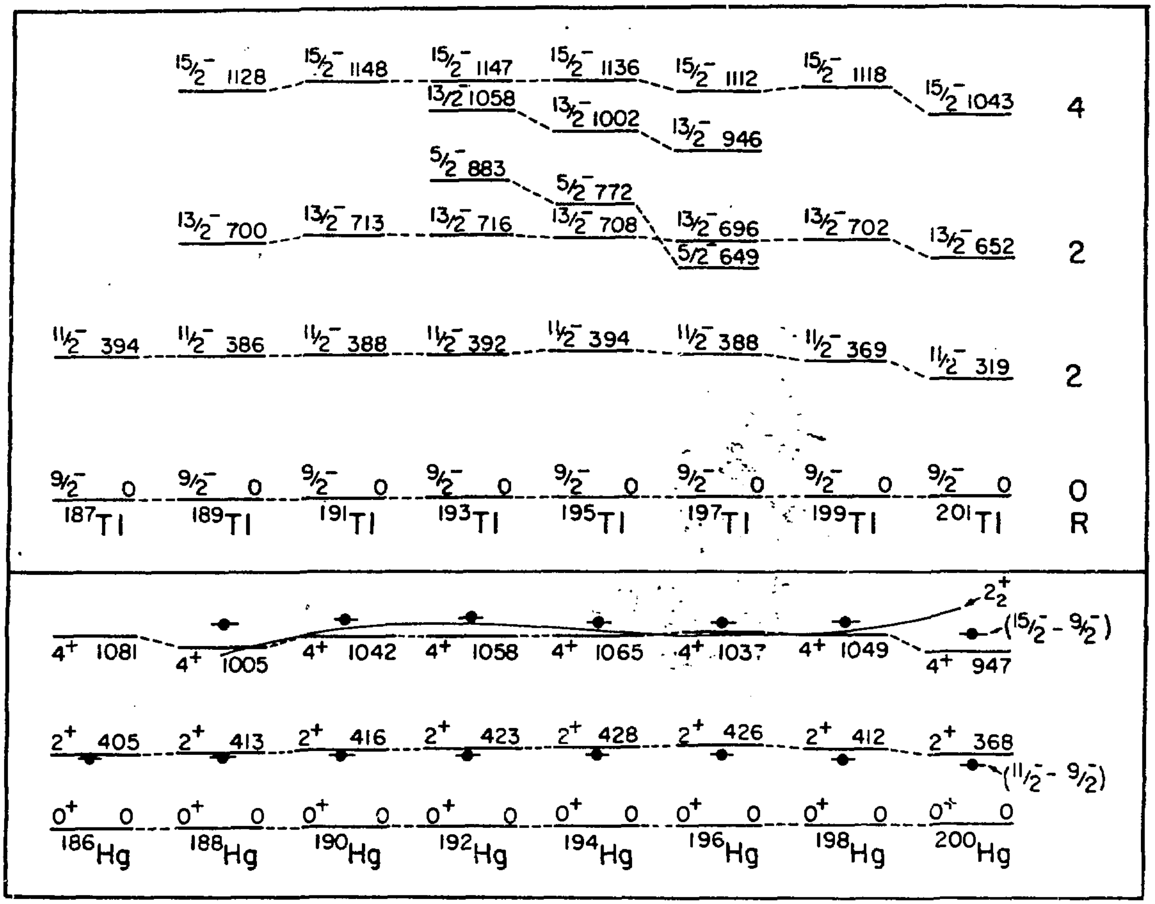

Fig. 5

The structure of states based on the $h_{9/2}$ excitation in $^{187-201}$Tℓ. The energy of the $9/2^-$ band head has been normalized to zero. Shown in the lower part of the figure are the 2^+, 2_2^+, and 4^+ excitations of the even-even A-1 Hg isotopes. The shape parameters $\beta = 0.16$ and $\gamma = 37^\circ$ deduced from the experimental band structure in $^{193-197}$Tℓ [47,52,53] and the triaxial rotor model [1] are approximately applicable to all the odd-A Tℓ isotopes. A comparison of the $11/2^-$ and $15/2^-$ energies relative to the 2^+ and 4^+ core states is also shown in the lower part of the figure (full circles). The 2_2^+ energy is indicated by a continuous light line.

earlier situation for the $h_{9/2}$ band structure in the odd-A Au isotopes and probably arises from a slight polarizing effect of the "extra" high-j proton from above the closed shell.

While the yrast levels are sensitive to β, it is quite apparent that the $5/2^-$ and $13/2^-)_2$ states are stongly γ dependent. A correlated fit [47] of both the energies and the branching ratios associated with these states to the parameters of the triaxial rotor model of Meyer ter Vehn [1] yield $\gamma = 38^\circ$, 39°, and 40° for ^{197}Tℓ, ^{195}Tℓ, and ^{193}Tℓ respectively. If the idea of rigid triaxial shapes is valid, it appears that the $h_{9/2}$ proton particle is a most sensitive probe of the nuclear shape. As mentioned earlier, there is a reluctance to accept the idea that nuclei in this region have rigid triaxial shapes. Leander [9] assumes dynamical rather than rigid asymmetries in a calculation for ^{197}Tℓ based on a numerical diagonalization of the Bohr Hamiltonian. In this picture the minimum in the γ-degree of freedom is quite shallow. There appears, however, to be no major difference in the predictions of these γ-rigid [1] and γ-soft [9] models for the odd-A Tℓ isotopes [47]. This similarity is not surprising since the minimum [9] in the γ-soft potential energy surface occurs at 37°, in excellent agreement with both the γ-rigid picture and the value obtained from the even Hg cores.

While the $h_{11/2}$ shell model state lies quite low in the Au nuclei, it appears considerably higher in Tℓ (compare Figs.3 and 4) and was not known prior to the recent UNISOR work [47,52,53]. The structure built on this excitation is quite different from that of the $h_{9/2}$ excitation and, as expected in the core-particle picture, indicates weak coupling to the nearly spherical Pb cores. The coupling of the $h_{11/2}$ hole and the first 2^+ of the Pb core (at $\approx$ 1 MeV) produces a cluster of states approximately 1 MeV above the $h_{11/2}$ state. The great difference in structure of the bands built on the $h_{9/2}$ and $h_{11/2}$ states and the rather complete separability of their structures (no interband transitions) again demonstrates the importance of the core in determining the structure of these states. It is, of course, the difference in the core-particle structure of these two excitations that retards the spin-allowed transitions. This same effect is present in the odd-A Au nuclei discussed earlier, and in the odd-A Bi isotopes which are discussed next.

THE ODD-A Bi NUCLEI

If the concepts of core-particle stability and shell model intruder states apply to nuclei with one or two protons less than shell closure at Z=82, one might also expect similar phonomena above the shell. This does occur in Bi (Z=83) where a low-lying $1/2^+$ state has been observed in $^{201-207}$Bi and interpreted [56-58] as $s_{1/2}$ proton hole states on even-even $^{A+1}$Po cores. The relevant experimental work on this excitation include refs. 56 and 59 (^{207}Bi), 56 and 57 (^{205,203}Bi), 56,58,60, and 61 (^{201}Bi), and 58 (^{199}Bi). The UNISOR work [58,60] was done using beams of ^{14}N on targets of Ir. The $^{205-199}$Bi $s_{1/2}$ shell model systematics and other low-energy positive parity states are shown in Fig.6. One notes immediately the drop in the $1/2^+$ energy as neutrons are removed, reminiscent of the $h_{9/2}$ states in the odd-A Au and Tℓ isotopes. The $s_{1/2}$ energy in ^{207}Bi is 1902 keV [56]. Since Alpha decay work has established [62] isomerism in the odd-A Bi isotopes down to ^{191}Bi, the $s_{1/2}$ state probably continues to drop toward a minimum somewhere near the center of the N = 82 – 126 closed neutron shell as is observed in Tℓ and Au. In this core-particle interpretation then the cores are the nearly spherical $^{A-1}$Pb for the $h_{9/2}$ ground state and the $^{A+1}$Po for the $s_{1/2}$ isomeric state. A check of the 2^+ and 4^+ energies of the $^{200-208}$Po isotopes reveals a relatively stable structure with the 2^+ energy ranging between extremes of 668 to 700 keV and the 4^+ between extremes of 1177 and 1279 keV. This is consistent with the mass independent structure of the states which populate the $s_{1/2}$ isomer (see Fig.6), even though it is not clear at this time as to the nature of those excitations. The $s_{1/2} \rightarrow h_{9/2}$ isomeric transition takes on a special importance then since it connects a hole state with a particle state.

In a recent study at UNISOR [58], a careful investigation was made of the α_K and K/L ratio of the 846 keV transition in ^{201}Bi. The results are consistent with pure M4 multipolarity. From this fact, and the measured half-life and α branching ratio of the 846 keV state, it was shown [58] that the 846 keV transition is hindered by a factor of 2200. The M4 transition in ^{201}Bi is ℓ-forbidden, but that alone cannot account for the observed retardation since E5 is not ℓ-forbidden and no measurable [58] E5 contribution was noted. Supporting this is the fact that this is the slowest (by a factor of 2000) M4 transition observed in any odd-A nucleus [58]. In the case of ^{189}Au (discussed earlier) the $h_{11/2} \rightarrow h_{9/2}$ hole-particle transition, which is not ℓ-forbidden, is also greatly hindered. The very different core-particle structure between these states can account for the retardation.

DISCUSSION

The experimental data on the odd-proton Au Tℓ and Bi isotopes has been discussed in the context of core-particle coupling and the relevant nuclear shape parameters determined in the framework of the triaxial rotor model [1]. The data support the contention that excitations in the odd-proton nuclei near the Z=82 shell closure can be described in terms of a relatively pure proton particle or proton hole coupled to an even-even nuclear core which is not appreciably affected by the extra particle or hole. For example, compare Figs.1 and 5. The first represents an $h_{11/2}$ proton hole coupled to even-even Hg cores. The second represents an $h_{9/2}$ proton particle coupled to the same even-even Hg cores. The band structures of

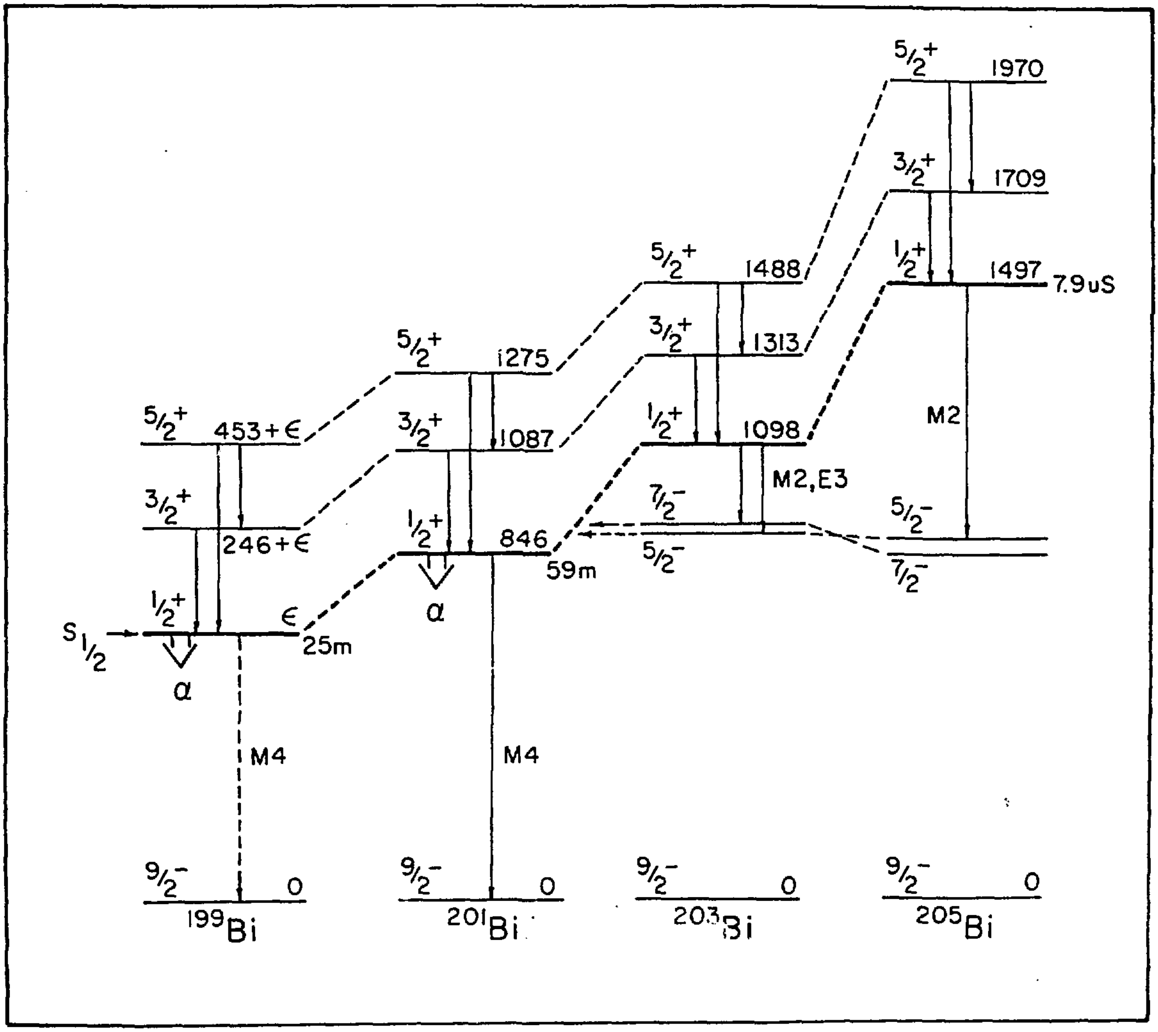

Fig. 6

The $s_{1/2}$ shell model state and the structure of related positive parity levels in $^{199-205}$Bi.

these excitations are quite different. The first is decoupled and the second strongly coupled. Yet, they are each consistent with $\beta = 0.13$ and $\gamma \approx 37^{\circ}$, the same values obtained from the 2^+, 2_2^+, and 4^+ energies of the Hg core. The rather complete separability of the $h_{9/2}$ and $h_{11/2}$ structures in both Au and Tℓ are also indicative of the very great difference in the corresponding core-particle and core-hole structures. In ^{189}Au, for example the $9/2^- \rightarrow 11/2^-$ transition is retarded by a factor of 15000, and in $^{189-195}$Au the E2/M1 mixing ratio, δ, for the $h_{9/2}$ and $h_{11/2}$ $I + 1 \rightarrow I$ intraband transitions have opposite signs. It is demonstrated that the hindrance of the $s_{1/2} \rightarrow h_{9/2}$ M4 transition in ^{201}Bi is not due to ℓ-forbiddeness and that it, like the analogous cases in Au and Tℓ, arises from the particle-hole nature of the transition. These experimental facts support the relative purity of the particle/hole configurations in these nuclei.

The $5/2^-$ and $(13/2^-)_2$ members of the $h_{9/2}$ band in $^{193-197}$Tℓ (Fig.5) demonstrate the sensitivity of the non-yrast states to the shape of the core, and suggest that a γ-rigid picture best explains the $h_{9/2}$ bands in $^{193-197}$Tℓ. As discussed in the introduction, other theoretical pictures (for example, the multiparticle vibrator, ref. 9), which have been quite successful in explaining the observed states in the odd-A Au isotopes, should also be applicable to the $h_{9/2}$ bands in the odd-A Tℓ nuclei, which are only one proton removed from shell closure. To date such calculations have not appeared in the literature. These types of theoretical questions, including the question of the rigidity of γ, are still open, but the use of an unpaired nucleon or hole to probe the structure of the core and the description of the process in terms of core-particle models appears to work exceptionally well near the Z=82 closed shell. In order to further test these ideas a search is underway for states in odd-A Hg and Tℓ which are indicative of coupling to the excited prolate deformed bands ($\beta \approx 0.25$) observed [44] in ^{188}Hg. By observing both the oblate and prolate structures in the same odd-A nucleus one can determine if the features which support asymmetry are unique to the slightly deformed nuclei in the region. A joint GSI/UNISOR experiment on ^{189}Tℓ from ^{189}Pb decay to search for such states is in progress.

The $i_{13/2}$ and $h_{9/2}$ states in the neutron deficient odd-A Au and Tℓ isotopes (Figs.3 and 4) and the $s_{1/2}$ state in the neutron deficient odd-A Bi isotopes (Fig.6) fall rapidly in energy as one proceeds to the lighter isotopes. The $h_{9/2}$ intruder becomes the first excited state in ^{189,191}Tℓ and actually becomes the ground state in ^{185}Au. That these are properly identified particle states was not easily accepted in view of the fact that the $s_{1/2} - h_{9/2}$ gap expected from the shell model is on the order of 4 MeV (4.23 MeV in ^{208}Pb). The preponderence of evidence (including that presented here) indicates, however, that these intruder excitations are indeed $h_{9/2}$ and $i_{13/2}$ proton particles and $s_{1/2}$ proton holes.

Various theoretical mechanisms to account for the reduction of the shell model gap were presented in the Introduction. In most of these, an increasing deformation was required, over and above any other mechanism, to account for the drop in the $h_{9/2}$ and $i_{13/2}$ energy with decreasing neutron number. The data presented above, in particular that for the $h_{9/2}$ intruder, quite clearly eliminates deformation as the major mechanism. Compare Figs.4 and 5 for example. The odd-A Tℓ yrast structure based on this $h_{9/2}$ excitation (Fig.5) indicates an unchanging core structure from ^{201}Tℓ to ^{187}Tℓ. The lower part of Fig.5 clearly shows that the slightly oblate ($\beta = 0.13$, $\gamma = 37^{\circ}$) but quite stable even-even Hg cores are not appreciably affected by the "extra core" $h_{9/2}$ proton. In contrast the $h_{9/2}$ excitation energy drops approximately 600 keV between ^{201}Tℓ and ^{191}Tℓ (Fig.4) before rising again. As discussed in the Introduction, Goodman [23] uses a spherical HFB prescription to compute the $h_{9/2}$ energy. In this picture the depression of the $h_{9/2}$ energy is not a collective effect resulting from the changing deformation, but rather a single particle effect. The calculations [23,24] demonstrate that the proton spherical single-particle energies around Z=82 are very dependent on the occupancy of the neutron orbitals, and that the neutron-proton interaction quite properly accounts for the drop and subsequent rise in the energy of the $h_{9/2}$ excitation. Wood views the proton-neutron interaction in a somewhat different way. He suggests [25,63] that because of quadrupole pairing, excitation of the odd proton into the $h_{9/2}$ intruder orbital removes the blocking effect for proton pairing correlations, thus permitting proton pair/neutron pair correlations to occur. Neither of these pictures require a changing deformation to account for the trends displayed by the shell model intruder states at Z=82.

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FOOTNOTES

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