PHYSICAL REVIEW C **67**, 014312 (2003)

In-beam γ-ray spectroscopy of ^{172}Pt

M. Danchev,[1,*] D. J. Hartley,[1,†] F. G. Kondev,[2] M. P. Carpenter,[3] R. V. F. Janssens,[3] L. L. Riedinger,[1] K. H. Abu Saleem,[3]
I. Ahmad,[3] H. Amro,[4] D. L. Balabanski,[1,*] J. A. Cizewski,[5] C. N. Davids,[3] A. Heinz,[3] T. L. Khoo,[3] T. Lauritsen,[3]
C. J. Lister,[3] W. C. Ma,[4] G. L. Poli,[3] J. Ressler,[3] W. Reviol,[6] M. B. Smith,[5] D. Seweryniak,[3] and I. Wiedenhöver[3,‡]
[1]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996*
[2]*Technology Development Division, Argonne National Laboratory, Argonne, Illinois 60439*
[3]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439*
[4]*Department of Physics, Mississippi State University, Mississippi State, Mississippi 39762*
[5]*Department of Physics and Astronomy, Rutgers University, New Brunswick, New Jersey 08903*
[6]*Chemistry Department, Washington University, St. Louis, Missouri 63130*
(Received 11 July 2002; published 22 January 2003)

Collective structures in ^{172}Pt have been investigated by measuring in-beam γ rays with mass selection and the recoil-decay tagging technique. The discrepancy in the ground-state band from previous studies has been resolved, and a new collective structure that is likely based on an octupole vibration has been identified. A band mixing model is used to determine the properties of the competing near-spherical and deformed ground-state sequences in the light Os-Pt-Hg-Pb region. Evidence for a reduction of deformation in the deformed vacuum structure below $N=98$ is presented.

DOI: 10.1103/PhysRevC.67.014312 PACS number(s): 21.10.Re, 23.20.Lv, 21.10.Tg

I. INTRODUCTION

Nuclei with $Z\approx 82$ are well known for displaying textbook examples of shape coexistence. In nearly all instances, this competition has been between prolate and spherical shapes or prolate and oblate shapes. Recently, competition between three shapes (prolate, oblate, and spherical) has been observed. This was first identified in ^{186}Pb [1], where in addition to the spherical ground state, excited 0^+ states associated with prolate and oblate shapes were observed at low energy ($\leqslant 650$ keV). Similar examples from in-beam γ-ray spectroscopy have recently been presented for ^{175}Au [2] and ^{179}Hg [3]. In the light even-even Os, Pt, Hg, and Pb nuclei, a low-spin interaction in the yrast sequence is observed, which has been interpreted as the result of the crossing of a weakly deformed/spherical structure by a deformed vacuum configuration originating from a multi-particle-hole excitation across the $Z=82$ gap [4–7]. The ramifications of this shape coexistence may not be limited to perturbed yrast even-even sequences. For example, shape coexistence may also have an effect on proton decay rates in neighboring proton unbound nuclei since these depend on deformation in both the parent and daughter nuclei [8,9].

Observing high-spin states in the very neutron-deficient Os-Pt-Hg-Pb region is rather difficult, due to high fission yields following the formation of a compound nucleus in fusion-evaporation reactions. This experimental difficulty can be overcome by coupling a large γ-ray array with a recoil mass separator. While the direct detection of the residue nuclei eliminates the fission background, it is still difficult to identify the most proton-rich isotopes due to their low production cross sections relative to the other fusion-evaporation products. This second difficulty can be overcome in the Os-Pb region due to the fact that all proton-rich isotopes decay either by proton or alpha emission. This allows for the utilization of the recoil-decay tagging (RDT) technique [10], which correlates charged-particle decay with in-beam γ rays produced at the target. Thus, direct nuclide identification of the detected γ rays on an event-by-event basis can be made. The power of recoil-decay tagging in this mass region was first demonstrated by Carpenter *et al.* in the study of ^{176,178}Hg [11]. We have employed this technique to investigate high-spin states in ^{172}Pt. In two previous in-beam studies of ^{172}Pt by Seweryniak *et al.* [12] and Cederwall *et al.* [13], the yrast band was delineated up to tentative spins of $14\hbar$ and $8\hbar$, respectively. Our results resolve a discrepancy in the ordering of the yrast sequence between these two works, and establishes a new sideband. In addition, an investigation of the moments of inertia for the deformed vacuum sequences was performed for this region. A band-mixing model (as described in Ref. [14], for example) facilitated this analysis and a trend of decreasing deformation was observed below $N=98$ in Pt and Hg nuclei.

II. EXPERIMENTAL DETAILS

The experiment was performed with the ATLAS superconducting linear accelerator at the Argonne National Laboratory. The main emphasis of this experiment was to study high-spin states in the proton unbound systems ^{173,175,177}Au, and a paper reporting the results on these nuclei has been published recently [2]. High-spin states in ^{172}Pt were weakly

---

[*] Permanent address: Faculty of Physics, St. Kliment Ohridski University of Sofia, BG-1164 Sofia, Bulgaria.

[†] Present address: Department of Physics, United States Naval Academy, Annapolis, Maryland 21402.

[‡] Present address: Department of Physics, Florida State University, Tallahassee, Florida 32306.

populated in the $2p2n$ channel of the ^{84}Sr$+^{92}$Mo reaction. Two energies, 390 and 395 MeV, were used to bombard the 0.774-mg/cm^2- and 0.449-mg/cm^2-thick, self-supporting, isotopically enriched, ^{92}Mo targets. Prompt γ rays were detected with 101 Ge detectors in the Gammasphere array [15]. The recoiling products were separated by the Argonne fragment mass analyzer [16] according to their mass-to-charge (m/q) ratio. A multiwired parallel grid avalanche counter (PGAC) situated at the focal plane provided the m/q information as well as the time of arrival and energy loss of the residues. These recoiling nuclei were implanted in a 40×40 double-sided silicon strip detector (DSSD) located 40 cm behind the PGAC where subsequent alpha decays were measured. A 47-bit, 1-MHz clock time stamped each event and allowed for a measure of the time correlation between implanted recoils and alpha decays, thus enabling a "tagging" of the detected prompt γ rays at the target position with the characteristic alpha decay energies. The background introduced by scattered projectiles, which have much higher velocities than the evaporation residue, was removed in the off-line analysis by placing coincidence gates on (i) the time of flight of the evaporation residues from the target to the focal plane of the PGAC, and (ii) the two-dimensional histogram of the energy of recoils measured in the DSSD versus the time of flight from the PGAC to the DSSD. The γ rays were Doppler corrected (with $v/c\sim 0.045$) and then two γ-γ matrices were created where one required a coincidence with the characteristic ^{172}Pt alpha line and the other simply contained all γ rays associated with $A=172$ recoils. An energy of 6316(5) keV and a half life of 97.6(13) ms were measured for the ^{172}Pt α decay. These characteristics are consistent with previous observations [17]. Unfortunately, the low statistics prevented a meaningful angular correlation analysis and, therefore, a determination of the multipolarities of the γ rays was not possible.

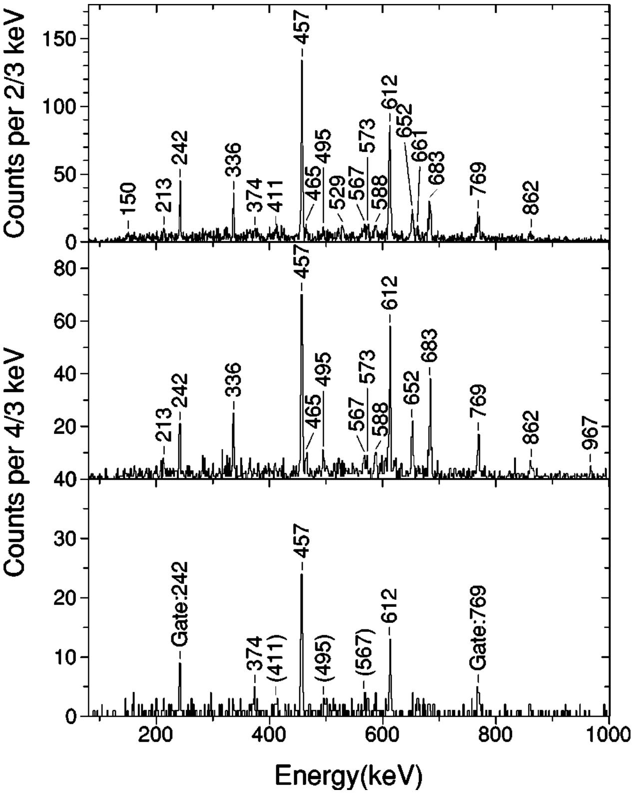

FIG. 1. Upper panel: Gamma-ray spectrum associated with the alpha decay of ^{172}Pt. Middle panel: Sum of gates on the 457-, 612-, 683-, and 652-keV transitions from the RDT-gated γ-γ matrix. Lower panel: Sum of gates on the 242- and 769-keV transitions from the same matrix noted above.

III. RESULTS

In a previous study, Seweryniak *et al.* [12] identified excited states in ^{172}Pt through the RDT technique. An array of ten Compton-suppressed Ge detectors was used, but a γ-γ coincidence analysis was not possible. Nevertheless, a level scheme was proposed (up to a spin of $I=14\hbar$) on the basis of the gated RDT singles data. A parallel work, by Cederwall *et al.* [13], applied the same RDT method with an array of 25 Ge detectors to observe levels in this nucleus. The larger array allowed for a γ-γ coincidence analysis, where the ground-state band was reported up to $I=8\hbar$ and a side level was tentatively placed at 1838 keV. A discrepancy in the ordering of the $8^+\rightarrow 6^+\rightarrow 4^+$ transitions resulted between the two studies. In the present work, the use of Gammasphere provides coincidence information with better accuracy, and the ordering was reevaluated. In addition, new states were placed in the level scheme.

The γ rays correlated with the ^{172}Pt alpha decay are presented in the upper panel of Fig. 1. All the transitions reported by Cederwall *et al.* [13] were confirmed, except for six of the weakest γ rays. Transitions with established coincidence relations were placed in the level scheme shown in Fig. 2. Their placement is based on the relative intensities of the transitions as presented in Table I, while the spin assignment of the ground-state band levels assumes that the transitions all have stretched $E2$ character. Cederwall *et al.* [13] suggested that the 652-keV γ ray corresponds to the $8^+\rightarrow 6^+$ transition and is followed by the 683-keV γ ray in the decay sequence $(6^+\rightarrow 4^+)$, whereas this ordering was inverted in Ref. [12]. The 683-keV line was observed to be more intense than the 652-keV γ ray from the RDT spectrum (see Fig. 1 and Table I). In addition, the middle panel of Fig. 1 displays the summed spectrum of γ rays in coincidence with the 457-, 612-, 683-, and 652-keV transitions. As one may observe, the 683-keV line is the third most intense transition in the spectrum, followed by the 652-keV γ ray. Therefore, the coincidence data are in agreement with the ordering suggested by Cederwall *et al.* [13]. The 588- and 573-keV γ rays were found to be in coincidence with the four previously mentioned ground-state transitions with successively decreasing intensities with respect to the 652-keV line (see Table I). Thus, they were placed above the $I=8$ state in the ground-state band, as shown in Fig. 2, and this sequence is now established up to $I=(10)$ [tentatively $I=(12)$] based on coincidence relations.

It should be noted that a 567-keV γ ray was found to be in coincidence with the 457-, 612-, and 769-keV lines (see

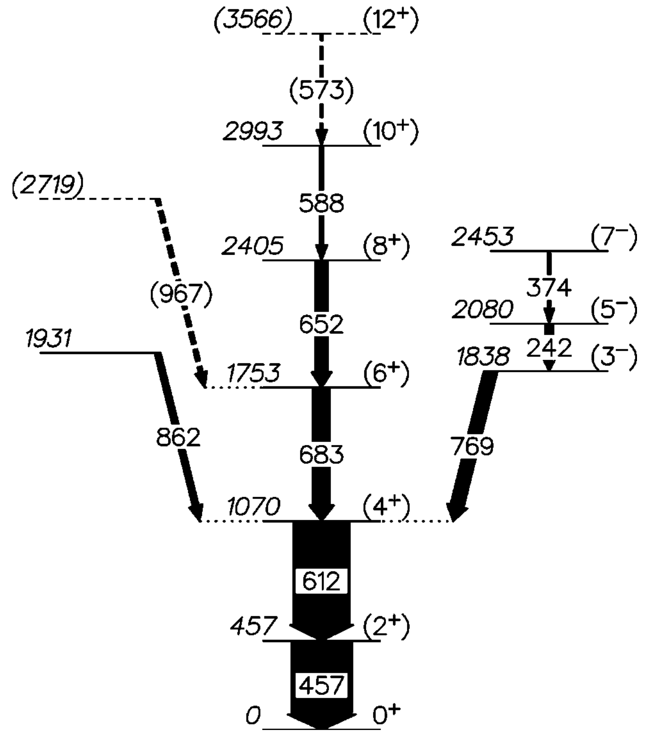

FIG. 2. Level scheme of ^{172}Pt deduced from the present work.

bottom panel of Fig. 1), indicating that it most likely results from a decay from a level in a sideband. In Ref. [12], a 564-keV transition was associated with the decay of the 10^+ yrast level. Our coincidence data do not support this conclusion, and it is likely that the 564-keV γ ray of Ref. [12] is the same transition we report as 567 keV. New side levels have been observed at 1931 and (2719) keV from the observed coincidences of the 862- and 967-keV transitions, respectively. The relatively strong 336-keV γ ray (see Fig. 1) was also found to be in coincidence with the ground-state sequence up to the $I=(8)$ state. However, it is not clear whether this is a linking transition or an in-band member of a sideband.

TABLE I. Energies and relative intensities of γ-ray transitions assigned to ^{172}Pt from the RDT spectrum. All γ-ray intensities were corrected for detector efficiency.

Energy (keV)	Intensity
150.1(5)	30(10)
213.3(3)	36(6)
241.7(2)	149(21)
336.4(2)	158(23)
374.1(3)	43(10)
411.4(3)	60(13)
457.3(2)	1000(50)
465.1(3)	69(13)
495.0(3)	56(12)
529.4(4)	63(14)
567.2(3)	68(14)
573.0(3)	70(14)
588.0(4)	88(15)
612.4(2)	818(49)
652.3(2)	271(25)
661.4(4)	83(14)
683.2(2)	374(30)
768.5(2)	280(31)
861.9(5)	100(15)
967	<10

The tentative placement of a side level at 1838 keV by Cederwall *et al.* [13] was confirmed by the Gammasphere data. The bottom panel of Fig. 1 displays transitions that are in coincidence with the 769- and 242-keV transitions (which are mutually coincident). Only the 457- and 612-keV lines from the ground-state sequence are observed in the spectrum, which implies a feeding into the $I=(4)\hbar$ state. A larger intensity was observed for the 769-keV γ ray, as compared with the 242-keV transition (see Table I), therefore the former has been assumed to be a linking transition, as shown in Fig. 2 and as suggested in Ref. [13]. In addition, a 374-keV transition is observed in the lower panel of Fig. 1, with a lower intensity than the 242-keV line. Therefore, the former is assumed to feed the 2080-keV level, as shown in Fig. 2. Two other tentative peaks at 411 and 495 keV are found in the lower panel of Fig. 1. Either could correspond to the third transition in the sequence, but the intensities of these lines were found to be larger than the 374-keV line (see Table I). Thus, their placement into the level scheme cannot be confidently made at this time. A spin of $5\hbar$ or higher for the 1838-keV level would make the 2453-keV state yrast with respect to the $I=8\hbar$ state in the ground-state band. Since the measured intensities do not support this assignment, a spin of $I<5\hbar$ appears to be more appropriate for the former state. An $I=4\hbar$ assignment is possible, however, this would result in the 2453-keV level being nearly yrast. Thus, a spin of $I=(3)\hbar$ has been assigned to the 1838-keV state. This argument is based on the assumption that the low-energy transitions in the sideband are stretched $E2$, rather than dipole, in nature (since no crossover transition was observed and strongly coupled sidebands have not been observed in neighboring nuclei), and therefore, the assignment must be regarded as tentative.

The lowest excited band that has been observed in light Os and Pt isotopes has negative parity and odd spins [18–27]. Thus, the proposed spin assignment is consistent with these systematics and an odd parity is tentatively proposed for the sideband. These sidebands in neighboring Os and Pt nuclei are generally described as possessing strong octupole correlations [18–23]. The presence of a strong $I\rightarrow I+1$ linking transition (the 769-keV γ ray) and the unobserved $I\rightarrow I-1$ transition (which would normally be favored) from the 1838-keV state may indicate that octupole correlations are also involved in the sideband. As discussed in Refs. [18,28], $K=0$ octupole bands (which only have odd spins) can favor the $I\rightarrow I+1$ decay over $I\rightarrow I-1$. However, a two-quasiparticle assignment [likely based on a $\nu(i_{13/2},h_{9/2})$ excitation, similar to that suggested by Dracoulis *et al.* [29] for the sideband in $^{170}_{76}$Os] cannot be ruled out.

TABLE II. Properties of the unperturbed bands determined in the band-mixing calculations described in the text.

Nucleus	Band [a]	Moment of inertia ($\times10^{-2}$keV^{-1})	E_0 [b] (keV)	V [c] (keV)	$E(2^+\rightarrow0^+)$ (keV)	Experiment (Reference)
^{168}Os	*g*	0.574	19	181	337	[36]
	d	3.253	1884		91	
^{170}Os	*g*	0.752	25	161	290	[29]
	d	3.318	1201		90	
^{170}Pt	*g*	0.076	17	180	518	[37]
	d	1.5	1850		139	
^{172}Pt	*g*	0.142	16	141	468	this work
	d	1.609	1179		163	
^{174}Pt	*g*	0.219	33	142	413	[38]
	d	2.469	721		117	
^{176}Pt	*g*	0.225	66	147	323	[26]
	d	2.985	339		98	
^{176}Hg	*g*	0.86×10^{-1}	15	132	623	[11,39]
	d	2.300	1223		124	
^{178}Hg	*g*	0.786×10^{-1}	15	101	620	[40]
	d	2.719	704		106	
^{182}Pb	*g*	0.966×10^{-4}	2	38	962	[39]
	d	3.046	811		97	
^{184}Pb	*g*	0.998×10^{-2}	5	29	772	[39]
	d	2.972	614		99	

[a] The *g* band represents the near-spherical ground-state band, while the *d* band denotes the deformed vacuum sequence.

[b] Excitation energy of band.

[c] Interaction strength between *g* and *d* bands.

IV. DISCUSSION

Evidence of the aforementioned shape coexistence leading to perturbations in the ground-state bands of several light Os-Pt-Hg-Pb nuclei has been demonstrated in Figs. 5, 1, and 2 in Refs. [12,14,30], respectively. A band crossing is seen at low spin ($I\sim6$), which is unlikely to result from an alignment since the excitation energy is not sufficient to overcome the influence of pairing. In several studies (e.g., Refs. [11,12,14,30–33]) this interaction has been discussed in terms of a deformed vacuum configuration (*d* band) crossing the near-spherical ground-state sequence (*g* band). A phenomenological band-mixing model was used in these works, where the observed yrast sequence is described as mixing of two or three unperturbed bands which interact via spin independent interactions. The details of this approach are outlined in Ref. [14]. The parameters of such band-mixing calculations are the variable moment of inertia parameters [34] (moment of inertia and restoring force constant), the excitation energies, alignments, K values, and interaction strengths between the g, d, and s unperturbed bands. A fit of these parameters is performed such that the experimental energy levels are reproduced. In this way we can examine the properties of the unperturbed bands resulting from the fit. Indeed, systematic studies of these sequences in the Pt nuclei were performed within this framework [12,31,33]. A nearly constant moment of inertia for the *d* band was observed in $N\geqslant96$ Pt nuclei [31,33] and, thus, it was assumed in Ref. [12] that this same value could be applied to the lighter ^{172}Pt nucleus in order to investigate the excitation energy of the *d* band. However, the recent observation of the first excited states in the neighboring $N=94-98$ Au nuclei [2] indicates a different conclusion pertaining to the moment of inertia of the *d* band. The prolate deformed $\pi i_{13/2}$ band in ^{173,175,177}Au was observed to be characterized by decreasing deformation as N decreased. It is likely that the *d* band in even-even Pt nuclei has a structure similar to the band based on the deformation driving $\pi i_{13/2}$ orbital. Therefore, it can be conjectured that the moment of inertia of the *d* band begins to decrease below $N=98$ as well.

In order to investigate this possibility, an extension of the systematic studies in Refs. [12,30] has been performed in the light Os-Pt-Hg-Pb region with the same band-mixing model. Dracoulis [30] presented calculations in this region previously, and we have adopted his values for the heavier nuclei. At the time, the lightest known isotopes were ^{172}Os, ^{174}Pt, ^{180}Hg, and ^{186}Pb, whereas now the lightest nuclei with well developed yrast sequences are ^{168}Os, ^{170}Pt, ^{176}Hg, and ^{182}Pb. A summary of the parameters for unperturbed bands, best describing experimental level energies for these lighter nuclei, is given in Table II.

For most of the nuclei listed in Table II a two-band calculation was performed. However, for ^{174,176}Pt, where the yrast band is observed through the $\nu i_{13/2}$ crossing, a three-band mixing calculation was carried out in order to include

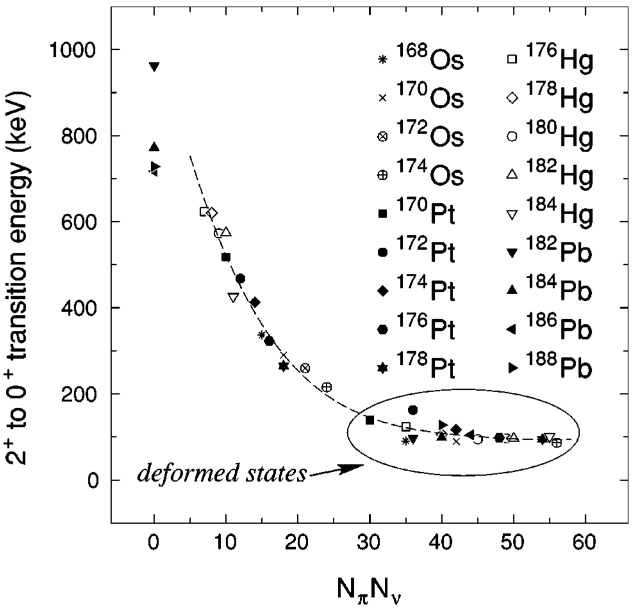

FIG. 3. Unperturbed 2^+ energies for both near-spherical and deformed bands. The deformed states are enclosed in the oval. The dashed line is provided as a guide for the eye.

the aligned s band. The alignment and K values were fixed to $0\hbar$ for the g and d bands, which left many free parameters (e.g., the moments of inertia, excitation energies, and interaction strength between the g and d bands) in the fit to the experimental data. In order to construct a meaningful analysis the unperturbed 2^+ energies, the energy difference between the 0^+ states of the g and d bands, and the moment of inertia of the g band, were compared with previously established trends [12,30] (as discussed below) to verify the appropriateness of the resulting fits. Dracoulis [30] plotted the unperturbed 2^+ energies of both the g and d bands deduced from the model in the Os-Pt-Hg-Pb region as a function of $N_\pi N_\nu$, where N_π and N_ν are the number of valence bosons for protons and neutrons counted from the nearest shell. The g band in ^{182}Pb has $N_\pi = 0$, while $N_\pi = 4$ for the d band, where a 4-particle, 4-hole excitation is assumed with an equivalent treatment of particles and holes. In both cases, $N_\nu = (100-82)/2 = 9$ giving products of $N_\pi N_\nu = 0$ and 36 for the g and d bands, respectively. Dracoulis observed a monotonic dependence of the 2^+ energies when considering a 4-particle, 4-hole excitation for the deformed band. This same plot is presented in Fig. 3 with the inclusion of our calculated energies for the lighter nuclei. One may observe that our new values fall reasonably well along the line obtained by Dracoulis, indicating a satisfactory consistency between the two sets. It should also be noted that Seweryniak *et al.* [12] reproduced the experimental $E(2^+)$ trends in Os and Pt using the $N_\pi N_\nu/(N_\pi + N_\nu)$ scheme assuming a transition to a 2-particle, 2-hole excitation of the core between ^{170}Pt and ^{180}Pt.

The energy difference between the 0^+ states belonging to the near-spherical and deformed configurations were also monitored. Dracoulis [30] and Seweryniak *et al.* [12] observed that the d band lies increasingly higher in excitation energy above the g band as N decreases. Our results, along with those of Dracoulis, are shown in the upper panel of Fig. 4, where it is seen that the previously defined trends of increasing energy with decreasing N are reproduced. The calculated moment of inertia of the g band by Davidson *et al.* [33] indicated that this quantity systematically decreases with lower N. Once again, this trend is reproduced with the new calculations. The interaction strengths between the g and d bands are similar to those used by Dracoulis; however, to estimate how much influence the interaction strength (V) has on the moment of inertia of the d band, calculations were performed with different fixed V values. We found that altering V by 30% generally produces less than a 10% change in the moment of inertia for the d band that is shown in Table II.

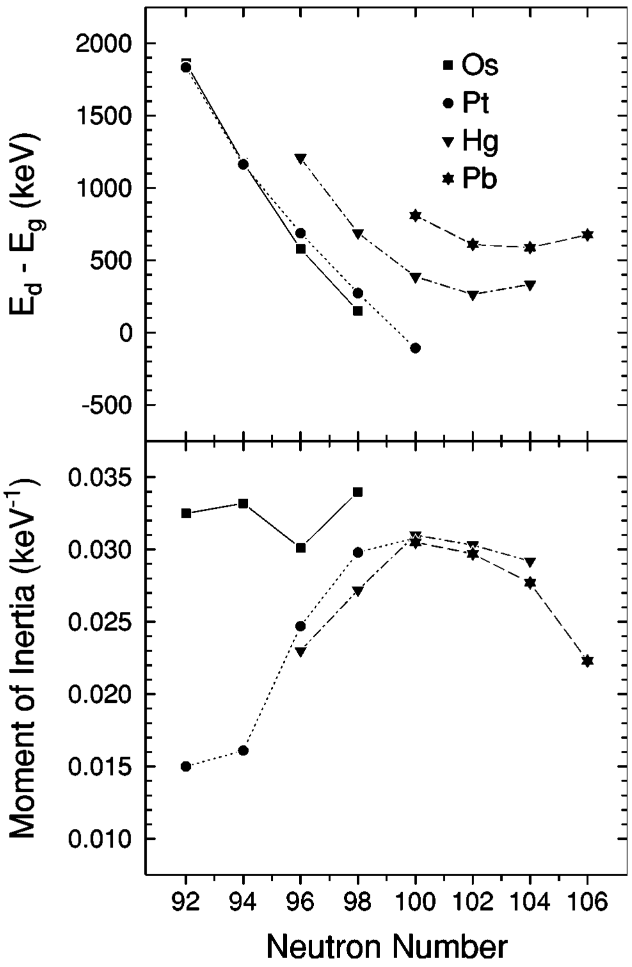

FIG. 4. Upper panel: Relative energies of the deformed band (E_d) with respect to the near-spherical band (E_g). Lower panel: Moments of inertia for the deformed band as determined in the band-mixing model.

Once all of these factors have been taken into consideration, a comparative analysis for the moment of inertia of the d band can be performed. The calculated moments for the d band (from both the present and Dracoulis study) are displayed in Fig. 4 versus neutron number. For $N = 100-104$, a large and nearly constant moment of inertia is observed. This is consistent with the findings of Lane *et al.* [35], where total Routhian surface (TRS) calculations were found to suggest a rise in the deformation of the deformed vacuum configuration near $N=106$ for Hg nuclei, followed by large and similar deformations between $N=100-104$. However, at $N=98$ and below, the moments decrease in the Pt and Hg nuclei. Therefore, the *d* band not only increases in energy as the neutron Fermi surface moves away from midshell, but it also becomes less deformed. Thus, these calculations are consistent with the observations of decreasing deformation in the $\pi i_{13/2}$ bands of the lightest Au nuclei [2] mentioned above.

The rise in deformation as N approaches midshell from $N>106$ was suggested to result from an increased occupation probability of $h_{9/2}$, $f_{7/2}$, and $i_{13/2}$ protons [35]. The lower panel of Fig. 4 establishes a mirror image of this trend below midshell. Therefore, it is likely that the occupation probabilities of these same orbitals are decreasing as N is reduced from 98. In fact, Kondev *et al.* [2] calculated the occupation probabilities of the proton orbitals discussed above as well as of the $i_{13/2}$ neutron orbitals for the $N=94-98$ ^{173,175,177}Au nuclei and found a stepwise decrease in all of these states as N was reduced. It is also interesting to note that the moments of the Os nuclei change little as a function of N (see Fig. 4). However, the lightest Os nuclei show little, if any, effect of shape coexistence since a disturbance is difficult to observe in their yrast sequences [36].

V. SUMMARY

In summary, excited states of ^{172}Pt have been observed using the recoil-decay tagging technique. A new sideband has been identified with parity and spin assignments based on the systematics in light Os and Pt nuclei. The moments of inertia of the deformed vacuum sequence were investigated using a band-mixing model for many nuclei in the Os-Pt-Hg-Pb region. Care was taken to ensure that previously established trends in relative excitation energy and $E(2^+)$ states of the near-spherical and deformed states were reproduced by these calculations. A decreasing trend in the moments for the deformed bands was observed below $N=98$, which is consistent with the recent findings for the $\pi i_{13/2}$ bands in light Au nuclei.

ACKNOWLEDGMENTS

The authors would like to thank the staff of the ATLAS accelerator facility and the Physics Support Group for their assistance in various phases of the experiment. Discussions with G. D. Dracoulis are gratefully acknowledged. The software support by D. C. Radford and H. Q. Jin is greatly appreciated. We would like also to thank R. A. Bark for his help with the band-mixing code. This work was supported by U.S. Department of Energy under Contract Nos. DE-FG02-96R40983 (University of Tennessee), W-31-109-ENG-38 (Argonne National Laboratory), DE-FG02-95ER40939 (Mississippi State University), DE-FG05-88ER40406 (Washington University), and the National Science Foundation (Rutgers University).

[1] A. N. Andreyev *et al.*, Nature (London) **405**, 430 (2000).
[2] F. G. Kondev *et al.*, Phys. Lett. B **512**, 268 (2001).
[3] F. G. Kondev *et al.*, Phys. Lett. B **528**, 221 (2002).
[4] K. Heyde, P. Van Isacker, M. Waroquier, J. L. Wood, and R. A. Meyer, Phys. Rep. **102**, 291 (1983).
[5] R. Bengtsson and W. Nazarewicz, Z. Phys. A **334**, 269 (1989).
[6] J. L. Wood, K. Heyde, W. Nazarewicz, M. Huyse, and P. Van Duppen, Phys. Rep. **215**, 101 (1992).
[7] W. Nazarewicz, Phys. Lett. B **305**, 195 (1993).
[8] P. J. Woods and C. N. Davids, Annu. Rev. Nucl. Part. Sci. **47**, 541 (1997).
[9] C. N. Davids *et al.*, Phys. Rev. Lett. **80**, 1849 (1998).
[10] E. S. Paul *et al.*, Phys. Rev. C **51**, 78 (1995).
[11] M. P. Carpenter *et al.*, Phys. Rev. Lett. **78**, 3650 (1997).
[12] D. Seweryniak *et al.*, Phys. Rev. C **58**, 2710 (1998).
[13] B. Cederwall *et al.*, Phys. Lett. B **443**, 69 (1998).
[14] R. A. Bark, J. Phys. G **17**, 1209 (1991).
[15] I. Y. Lee, Nucl. Phys. **A520**, 641c (1990).
[16] C. N. Davids *et al.*, Nucl. Instrum. Methods Phys. Res. B **70**, 358 (1992).
[17] R. D. Page, P. J. Woods, R. A. Cunningham, T. Davinson, N. J. Davis, A. N. James, K. Livingston, P. J. Sellin, and A. C. Shotter, Phys. Rev. C **53**, 660 (1996).
[18] G. D. Dracoulis, C. Fahlander, and M. P. Fewell, Nucl. Phys. **A383**, 119 (1982).
[19] C. Fahlander and G. D. Dracoulis, Nucl. Phys. **A375**, 263 (1982).
[20] R. A. Bark, G. D. Dracoulis, and A. E. Stuchbery, Nucl. Phys. **A514**, 503 (1990).
[21] L. Hildingsson *et al.*, Nucl. Phys. **A545**, 871 (1992).
[22] M. J. A. de Voigt *et al.*, Nucl. Phys. **A507**, 472 (1990).
[23] F. G. Kondev *et al.*, Phys. Rev. C **61**, 044323 (2000).
[24] B. Fabricius, G. D. Dracoulis, R. A. Bark, A. E. Stuchbery, T. Kibédi, and A. M. Baxter, Nucl. Phys. **A511**, 345 (1990).
[25] R. M. Lieder *et al.*, Nucl. Phys. **A645**, 465 (1999).
[26] B. Cederwall *et al.*, Z. Phys. A **337**, 283 (1990).
[27] D. G. Popescu *et al.*, Phys. Rev. C **55**, 1175 (1997).
[28] F. W. N. de Boer, P. Koldewijn, R. Beetz, J. L. Maarleveld, J. Konijn, R. Janssens, and J. Vervier, Nucl. Phys. **A290**, 173 (1977).
[29] G. D. Dracoulis, R. A. Bark, A. E. Stuchbery, A. P. Byrne, A. M. Baxter, and F. Riess, Nucl. Phys. **A486**, 414 (1988).
[30] G. D. Dracoulis, Phys. Rev. C **49**, 3324 (1994).
[31] 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).
[32] 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. **A568**, 90 (1994).
[33] 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).
[34] M. A. J. Mariscotti, G. Scharff-Goldhaber, and B. Buck, Phys. Rev. **178**, 1864 (1969).
[35] G. J. Lane, G. D. Dracoulis, A. P. Byrne, P. M. Walker, A. M. Baxter, J. A. Sheikh, and W. Nazarewicz, Nucl. Phys. **A586**, 316 (1995).
[36] D. T. Joss *et al.*, Nucl. Phys. **A689**, 631 (2001).
[37] S. L. King *et al.*, Phys. Lett. B **443**, 82 (1998).
[38] J. Goon (private communication).
[39] R. Julin, K. Helariutta, and M. Muikku, J. Phys. G **27**, R109 (2001).
[40] F. G. Kondev *et al.*, Phys. Rev. C **62**, 044305 (2000).