In-beam γ-ray spectroscopy of Pt isotopes located at the proton drip line

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In-beam γ rays have been observed in the neutron-deficient isotopes ^{170,171,172}Pt using the recoil-decay tagging technique. The yrast transition sequence proposed for ^{172}Pt indicates that the 0^+ bandhead of the deformed intruder band is situated about 900 keV above the weakly deformed ground state, i.e., its excitation energy has risen by about 300 keV compared to ^{174}Pt. The measured energy of the $2^+ \rightarrow 0^+$ transition in ^{170}Pt supports an even larger increase in the excitation energy of the intruder configuration with the departure from the middle of the 82–126 major neutron shell. Furthermore, a band with transition energies almost identical to those found in ^{172}Pt has been assigned to ^{171}Pt and was interpreted as corresponding to a rotationally aligned $i_{13/2}$ neutron orbital coupled to the core excitations. [S0556-2813(98)02311-5]

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I. INTRODUCTION

One of the interesting facets of the structure of nuclei around the $Z=82$ proton shell closure is the phenomenon of shape coexistence. In light Hg isotopes, rotational bands based on low-lying well-deformed prolate 0^+ states have been known for quite some time [1]. These bands coexist with slightly oblate ground-state bands and the interaction between coexisting excitations leads to notable distortions in the measured yrast transition sequences. It has been proposed that the strongly deformed structures are due, at least in part, to the presence of intruder configurations formed by promoting two protons across the $Z=82$ shell gap into the $h_{9/2}$ orbital, which exploits the strong attractive interaction between valence neutrons and protons [2]. The presence of the prolate intruder band was inferred from the data in the light Hg isotopes up to ^{178}Hg where the unperturbed excitation energy of its bandhead was deduced to be about 700 keV [3]. In Ref. [3] no evidence was found at low spin for the intruder configuration in ^{176}Hg.

The shape coexistence phenomenon has also been observed in light Pt and Os isotopes. In Ref. [4], the yrast transition sequences observed in ^{176,178}Pt were interpreted as resulting from the interaction and crossing of two bands; one weakly deformed and another having larger deformation. The moments of inertia of the two bands were deduced to be 0.009 and 0.036 keV^{-1}, respectively. From the data, the interaction matrix element between the two configurations was estimated to be about 200 keV in both nuclei, similar to the values obtained for heavier Pt isotopes, $^{180-184}$Pt. In $^{178-184}$Pt, the unperturbed bandhead of the strongly deformed band was found to be the ground state, while in ^{176}Pt it was pushed up in energy with respect to the less deformed band by about 300 keV. This increase in excitation energy continues with decreasing neutron number: in ^{174}Pt, the lightest Pt isotope with known excited states [5], the position of the second 0^+ state was deduced to be around 700 keV. Remarkably, the interaction matrix element required to fit the data was only 82 keV, about one half the value for ^{176}Pt.

Excited states in odd Pt isotopes are known thus far down to ^{175}Pt. Two bands interpreted as signature partners built on the $i_{13/2}$ neutron orbital have been reported in Ref. [6]. Both bands exhibit irregularities in the energy spectrum at low spin, suggesting a change in deformation, possibly due to an intruder configuration similar to the one proposed to play a role in light even-even Pt isotopes.

Prior to the present work, nothing was known about excited states in the light Pt isotopes with $A \leq 173$. Light Pt isotopes have a strong α decay branch and their decay properties are known down to ^{166}Pt. The energy of α particles emitted from the ground state of ^{172}Pt is 6314(4) keV, the associated half-life is 98(3) ms, and the α decay branch is larger than 60% [7]. The ground states of ^{171}Pt and ^{170}Pt decay predominantly by α emission with $E_\alpha=6453(3)$ keV, $T_{1/2}=40(3)$ ms [7] and $E_\alpha=6545(8)$ keV, $T_{1/2}=6(+5-2)$ ms [8], respectively.

It is clearly of interest to extend our knowledge of the yrast sequences of light Pt isotopes toward lower neutron numbers; i.e., toward the proton drip line, to see whether the observed trends in the excitation energy and interaction strength of the intruder bands persist. This paper reports on the in-beam γ-ray spectroscopic study of the neutron-deficient ^{170,171,172}Pt isotopes.

II. EXPERIMENT

Two experiments were performed with the ATLAS superconducting linac accelerator at the Argonne National Laboratory to study light Pt isotopes. In the first one a 345-MeV ^{78}Kr beam was used to bombard a 0.7 mg/cm^2 thick, self-supporting, isotopically enriched ^{96}Mo target. The average beam intensity was about 3 pnA for a period of about 8 h. The beam energy was optimized for the production of the ^{171}Pt and ^{172}Pt nuclei via the $3n$ and $2n$ evaporation channels, respectively. In the second measurement the ^{96}Ru(^{78}Kr,$xpyn$) reaction at 385 MeV was used to produce

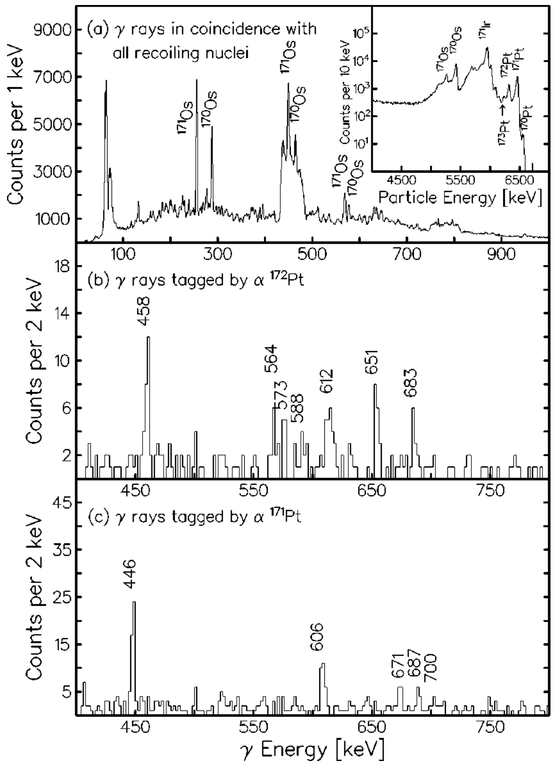

FIG. 1. Energy spectra of γ rays detected in coincidence with (a) recoiling nuclei and tagged (b) on the ground-state ^{172}Pt α decay and (c) on the ground-state ^{171}Pt α decay using the ^{96}Mo(^{78}Kr,$xpyn$) reaction. The measured α-decay spectrum is shown as an inset in the topmost panel.

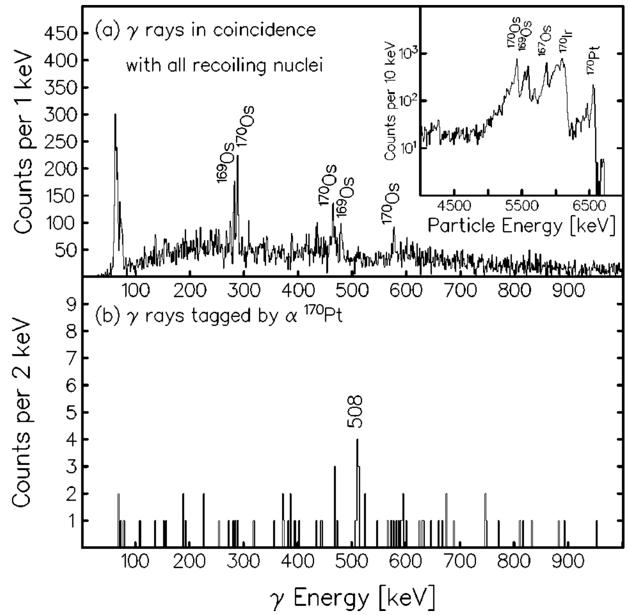

FIG. 2. Energy spectra of γ rays detected in coincidence with (a) recoiling nuclei and tagged on (b) the ground-state ^{170}Pt α decay using the ^{96}Ru(^{78}Kr,$xpyn$) reaction. The measured α-decay spectrum is shown as an inset in the topmost panel.

^{170}Pt via the $2p2n$ evaporation channel. A 0.4 mg/cm^2 thick layer of isotopically enriched ^{96}Ru material was deposited on a 0.7 mg/cm^2 thick Al foil. The Al foil was placed upstream in order to minimize the straggling of recoiling nuclei in the target. The second experiment lasted about 19 h and the average beam intensity throughout the experiment was again 3 pnA.

The reaction channels leading to ^{170,171,172}Pt are very weak and γ rays emitted from these nuclei are buried in the strong background from many other more strongly populated residues and from prompt γ decay of fission products. Hence, a highly efficient and selective experimental setup is required. Since all of the Pt isotopes under study are ground-state α emitters, the recoil-decay tagging (RDT) method [9] was chosen to extract and identify the γ-ray transitions of interest.

In-beam γ rays were detected by the Argonne-Notre Dame array of 10 Compton-suppressed HP-Ge detectors. The photopeak efficiency of the array was about 0.5% at a γ-ray energy of 1.3 MeV. After leaving the target, recoiling nuclei were analyzed according to their mass to charge-state ratio with the fragment mass analyzer (FMA) [10] and implanted into a double-sided silicon strip detector (DSSD) placed behind the focal plane of the FMA. The implants subsequently decayed in the DSSD emitting α particles and/or protons with characteristic energies and half-lives. Using coincidence relationships between prompt γ rays and recoiling nuclei, together with the space and time correlations between implants and decays, the γ rays detected at the target position could be associated with α and/or proton radiation observed at the focal plane of the FMA and an assignment to a particular reaction channel followed.

In the first experiment, the mass spectrum of recoiling nuclei measured at the focal plane of the FMA was dominated by $A=170$ and $A=171$ residues, but a peak corresponding to $A=172$ could also be seen. γ-ray spectra detected in coincidence with $A=170$–172 residues contained mainly lines assigned previously to the light Os isotopes ^{170,171,172}Os [11–13] as can be seen in Fig. 1(a). The measured α particle spectrum is given as an inset in Fig. 1(a). The strongest line in this spectrum corresponds to ^{171}Ir. The group of α lines at higher energies was assigned to the light Pt isotopes ^{170,171,172,173}Pt. α lines corresponding to ^{170,171}Os are weak because of their very low α-decay branch. Singles γ-ray spectra correlated with the ground-state α decay of ^{171,172}Pt are presented in Fig. 1(b) and (c), respectively (correlation times of 1.1 s and 400 ms were used for ^{172}Pt and ^{171}Pt, respectively). Despite low statistics, several γ-ray lines can be clearly seen between 400 and 700 keV in both spectra along with x-ray lines characteristic of the Pt isotopes.

In the second reaction, mostly residues with masses 169 and 170 were produced. As illustrated in Fig. 2(a), γ-ray lines associated with ^{169}Os [14] and ^{170}Os [11] dominate the in-beam γ-ray spectra measured in coincidence with recoils detected at the focal plane of the FMA. The two strongest α lines in the DSSD spectrum (see inset in Fig. 2) correspond to ^{167}Os and ^{170}Ir. α lines associated with ^{169,170}Os are weak because of their low α-decay branches. A single γ-ray line at 508 keV is present in the spectrum correlated with the ground-state α decay of ^{170}Pt shown in Fig. 1(b) (correlation time of 110 ms was used).

III. RESULTS

Because the statistics of the data was not sufficient to obtain information from γ-γ coincidence relationships, only singles γ-ray spectra were used in the data analysis. Tables I

TABLE I. Energies and intensities of γ rays obtained from singles γ-ray spectra correlated with the ground-state α decay of ^{171}Pt.

Energy (keV)	Intensity	Assignment
446	100(15)	$17/2^+ \rightarrow 13/2^+$
606	58(10)	$21/2^+ \rightarrow 17/2^+$
671	25(8)	$25/2^+ \rightarrow 21/2^+$
687	17(8)	$29/2^+ \rightarrow 25/2^+$
700	8(4)	$33/2^+ \rightarrow 29/2^+$

and II contain energies, relative intensities, and proposed spin and parity assignments for the lines associated with ^{171}Pt and ^{172}Pt, respectively. The level schemes constructed for ^{171}Pt and ^{172}Pt are shown in Fig. 3. The 508-keV transition assigned to ^{170}Pt is suggested to be the $2^+ \rightarrow 0^+$ transition. Figure 4 contains the systematics of the yrast 0^+, 2^+, 4^+, 6^+, 8^+, 10^+ states in light even Pt isotopes, including states proposed in this paper for ^{170}Pt and ^{172}Pt. The transitions were ordered based solely on intensity considerations and were assumed to form cascades of stretched $E2$ transitions. Because the intensities obtained for the 564 and 573 keV transitions in ^{172}Pt are identical the order proposed here is arbitrary. Reversing the order does not change the conclusions presented in this paper. In view of the low statistics, the levels at the top of the proposed bands must be considered as tentative and are marked with dashed lines in Fig. 3. It can be seen from Fig. 4 that these assignments are in line with expectations based on the systematics of light Pt nuclei.

IV. DISCUSSION

The same approach as used in Refs. [4,5] can also be applied here to interpret the ground-state band in ^{172}Pt. Namely, this band can be viewed as based on a weakly deformed ground state which interacts with a band based on an excited well deformed intruder configuration. To estimate the excitation energy of the intruder configuration, band-mixing calculations were performed. Since the data obtained for ^{172}Pt are not very extensive some simplifying assumptions were made. The moments of inertia obtained for ^{174}Pt and ^{176}Pt in Refs. [4,5], i.e., 0.009 and 0.036 keV^{-1}, were assumed to describe also the weakly deformed and well-deformed band in ^{172}Pt. A spin-independent interaction between the bands of 100 keV was used in the calculations,

TABLE II. Energies and intensities of γ rays obtained from singles γ-ray spectra correlated with the ground-state α decay of ^{172}Pt.

Energy (keV)	Intensity	Assignment
458	100(19)	$2^+ \rightarrow 0^+$
564	34(12)	$10^+ \rightarrow 8^+$
573	34(12)	$12^+ \rightarrow 10^+$
588	27(12)	$14^+ \rightarrow 12^+$
612	85(19)	$4^+ \rightarrow 2^+$
651	58(15)	$6^+ \rightarrow 4^+$
683	46(15)	$8^+ \rightarrow 6^+$

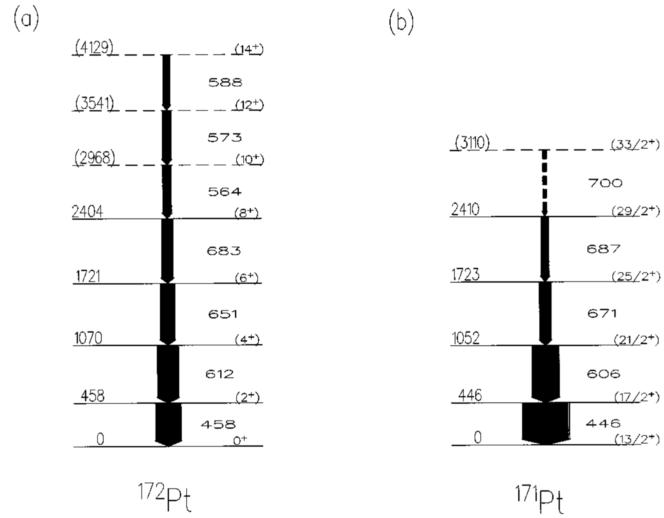

FIG. 3. Level schemes proposed for (a) ^{172}Pt and (b) ^{171}Pt. The widths of the arrows represent transition intensities including the calculated contribution from the electron conversion (white portion).

which is close to the value of 82 keV obtained for ^{174}Pt in Ref. [5]. The results of the calculations are compared with the data in Fig. 5. The kinematic moments of inertia, J_1, derived from the level schemes of heavier Pt isotopes $^{176-184}$Pt are shown in Fig. 5(a). Figure 5(b) presents J_1 deduced for ^{172}Pt and ^{174}Pt. From Figs. 5(a) and 5(b) it can be seen that the dependence of J_1 on rotational frequency is smooth in the heavier Pt isotopes, while for ^{172}Pt and ^{174}Pt pronounced irregularities appear at low spin. This sudden change can be associated with a weaker interaction between the bands. Calculated kinematic moments of inertia for different excitation energies of the intruder band are presented in Fig. 5(c). It can be seen from Fig. 5(c) that the intruder band is situated at about 800–1000 keV above the ground state. By the same token, it can be concluded that in ^{174}Pt the

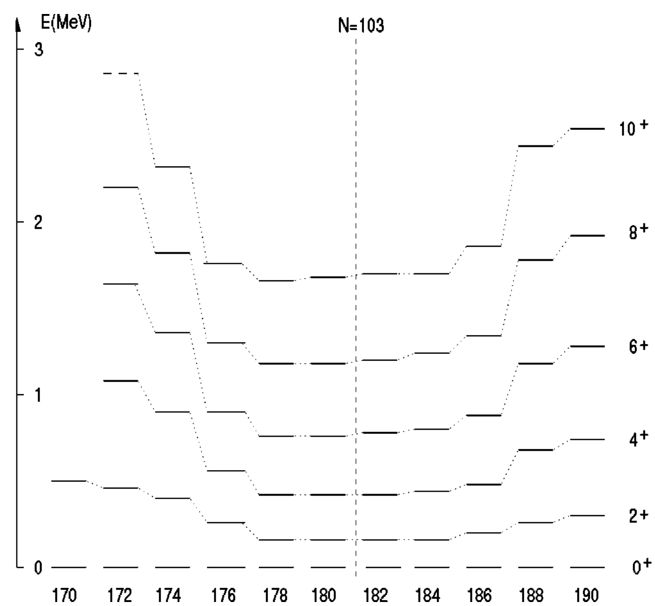

FIG. 4. The systematics of positive-parity states in light even-even Pt isotopes. The data were taken from Ref. [17] and from the present measurement.

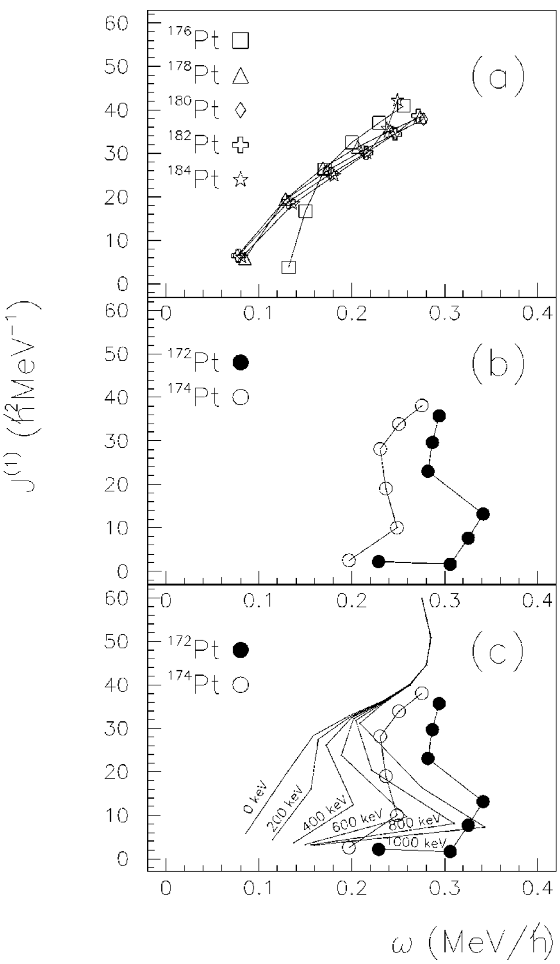

FIG. 5. Kinematic moments of inertia, J_1, for light even-even Pt isotopes (a) $^{176–184}$Pt and (b) ^{172,174}Pt. The data for ^{172}Pt were obtained from this work. In panel (c) the curves labeled with numbers represent results of band-mixing calculations with the unperturbed excitation energy of the well-deformed intruder band varying between 0 and 1000 keV. Moments of inertia of 0.009 and 0.036 keV^{-1}, for the weakly deformed and well-deformed bands, respectively, and a spin-independent interaction between the bands of 100 keV were used in the calculations (see text for details).

excitation energy of the intruder band is about 600–700 keV, which agrees with the value of 700 keV deduced in Ref. [5].

As mentioned above, only a single γ-ray line was assigned to ^{170}Pt. However, as it defines the energy of the first 2^+ state it can provide a hint about the deformation of ^{170}Pt and about a possible admixture of the intruder state. The 2_1^+ energies in even-even nuclei from Dy to W have been successfully described using a linear function of the so-called P factor [15], defined as $P = N_\pi \cdot N_\nu/(N_\pi + N_\nu)$, where N_π and N_ν are valence numbers of protons and neutrons, respectively. The above prescription fails, however, to reproduce data on Pt and Os isotopes with $N<104$. To remedy this problem a generalization of the P-factor definition was proposed in Ref. [16] which takes into account possible admixtures of intruder states. The intruder states in light Pt (Os) isotopes are due to $2p$-$6h$ ($2p$-$8h$) proton excitations across the $Z=82$ gap and, as such, contain four more valence quasiparticles than normal states. In Ref. [16] this effect was simulated by adding four extra valence protons for N

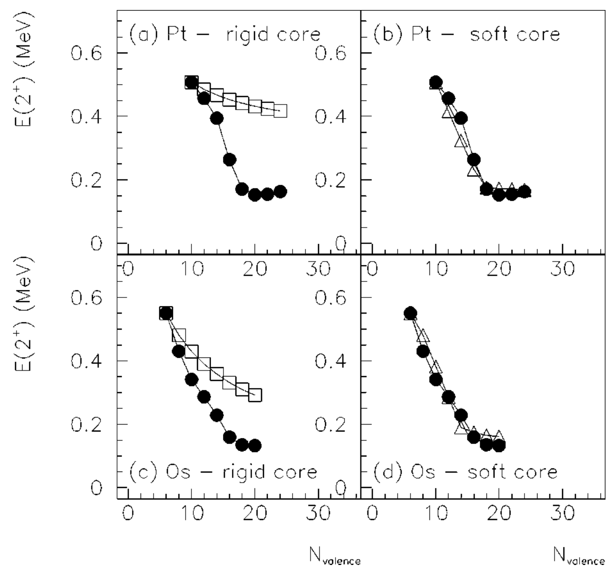

FIG. 6. Comparison of the observed (filled symbols) and calculated (open symbols) energies of the first 2^+ states in light (a),(b) Pt and (c),(d) Os isotopes as a function of the number of valence neutrons. The calculations are based on Refs. [15,16] and assume the linear dependence: $E(2^+) = a - bP$, where P is the P factor (see text), b is the slope parameter obtained from a fit to $E(2^+)$ energies in Dy-Er-Yb-Hf-W isotopes, and a is the offset, which was adjusted to the lightest isotope in each isotopic chain. Squares mark energies obtained using a rigid $Z=82$ shell closure, whereas triangles were calculated using an effective number of valence protons. Experimental values for ^{170,172}Pt were obtained from this work. Data on ^{164,166,168}Os were taken from Ref. [14].

$=102-108$ nuclei and gradually decreasing the number of extra valence protons from 4 to 0 between $N=100$ and $N=90$. Much better agreement was found between the measured 2_1^+ energies in light even-even Pt and Os isotopes and

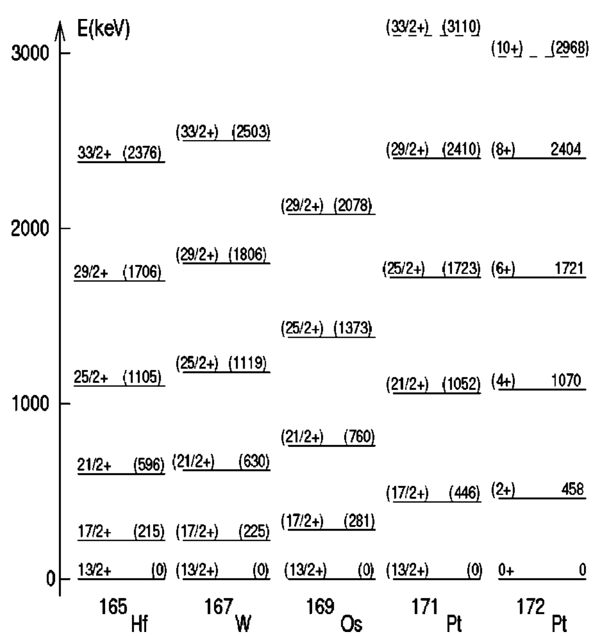

FIG. 7. The favored-signature $i_{13/2}$ bands observed in the heavy $N=93$ isotones ^{165}Hf [18], ^{167}W [19], ^{169}Os [14] and ^{171}Pt. For comparison, the ground-state band in ^{172}Pt is also shown. The data on ^{171}Pt and ^{172}Pt were obtained in this work. In the odd-A isotopes the excitation energies of the $13/2^+$ states were set to 0.

those calculated using the effective P factor defined as: $P_{\mathrm{eff}}=N_{\pi}^{\mathrm{eff}}\cdot N_{\nu}/(N_{\pi}^{\mathrm{eff}}+N_{\nu})$ where N_{π}^{eff} is the effective number of valence protons. In Figs. 6(a) and 6(b), the results obtained using the two formulas above for light Pt isotopes are compared with the data, including the 2_1^+ energies measured for ^{170}Pt and ^{172}Pt in the present work. The comparison indicates that the simple model proposed in Ref. [16] can be extended to the lighter even-even Pt isotopes observed in the present work. As illustrated in Figs. 6(c) and 6(d), good agreement is also found for light Os isotopes, including the 2_1^+ energies in ^{164,166,168}Os measured using the present setup [14]. However, there are some notable differences between the data and the calculations. In the Pt isotopes, the transition between the normal and the intruder states seems to be more rapid than predicted, whereas the Os isotopes change character more gradually. It is plausible that already the ground state in ^{170}Pt does not have a significant admixture from the intruder state.

In the case of the odd-A Pt isotopes, two bands were assigned to ^{175}Pt in Ref. [6] and they were interpreted as two signature partners based on the $i_{13/2}$ neutron orbital. The $\nu i_{13/2}$ bands are populated quite strongly by the heavy-ion-induced fusion-evaporation reactions in this region. Figure 7 shows the systematics of the favored-signature $\nu i_{13/2}$ bands in light $N=93$ isotones, including the level scheme of ^{171}Pt proposed in the present work. The energies of the states within the bands increase gradually with increasing proton number, indicating a decrease in deformation when approaching the $Z=82$ shell closure. Figure 7 also contains the level scheme of ^{172}Pt, an even-even neighbor of ^{171}Pt. Remarkably, the energies of the first four transitions in both nuclei do not differ by more than 20 keV. In view of the above, we suggest that the states observed in ^{171}Pt correspond to the rotationally aligned $i_{13/2}$ neutron coupled to the 0^+, 2^+, 4^+, 6^+, 8^+, 10^+ excitations of the core, as is also observed in other $N=93$ isotones.

V. SUMMARY

Excited states in three light Pt isotopes ^{170,171,172}Pt have been observed using the recoil-decay tagging technique. The energies in the ground-state band in ^{172}Pt suggest that the 0^+ intruder bandhead is situated at about 900 keV above the ground state. The energy of the only transition found in ^{170}Pt, which is most likely the $2^+\rightarrow0^+$ transition, suggests that the intruder band has an even higher energy in this nucleus. The band found in ^{171}Pt resembles very closely the band in ^{172}Pt and is, thus, proposed to be due to a rotationally aligned $i_{13/2}$ neutron coupled to the corresponding core excitations.

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