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Delayed backbending in the $\pi h_{9/2}$ band of ^{187}Ir

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High-spin states of ^{187}Ir have been populated in the ^{176}Yb(^{15}N, $4n$) reaction and measured with the YRAST Ball spectrometer. The $\pi h_{9/2}$ rotational band has been extended beyond the first alignment crossing, which was found at rotational frequency $\hbar\omega_c \approx 0.39$ MeV. Two different scenarios for describing this crossing are considered: the alignment of an $h_{9/2}$ proton or $i_{13/2}$ neutron pair and it is concluded that a proton band crossing is more likely. A systematic study of the rotational alignment crossings in the $\pi h_{9/2}$ bands in the N=104, 106, 108 isotopes of $_{73}$Ta, $_{75}$Re, $_{77}$Ir, and $_{79}$Au is presented.

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I. INTRODUCTION

The origin of the band crossings observed in the $N \approx 106$ nuclei is still debated, despite the fact that many studies on the high-spin structure of different isotopes have been carried out in this region [1–11]. To explain the first crossing in these nuclei, investigators have invoked the rotational alignment of a pair of both $h_{9/2}$ quasiprotons and $i_{13/2}$ quasineutrons. References [3–7] provide arguments in support of the alignment of a $\pi h_{9/2}$ pair below $\hbar\omega$=0.30 MeV. On the other hand, it is quite difficult to theoretically reproduce this $\pi h_{9/2}$ crossing at such a low frequency using a standard set of Nilsson-model parameters, as discussed in Ref. [8]. For the N=106 nucleus ^{184}Pt, two successive crossings have been observed in the ground-state band at nearly degenerate frequencies [8], while for the N=108 ^{186}Pt a single band crossing was observed [6] at the same frequency as in ^{184}Pt. Studying the $\pi h_{9/2}$ bands in the odd-Z nuclei in this region should lead to a better understanding of the origin of this low-frequency crossing.

In the analysis of band-crossing trends, one must realize that changes in the deformation of different configurations can significantly influence observables such as aligned angular momentum, dynamic moment of inertia, etc. It is well known that the nuclei close to the $Z \approx 82$ shell gap exhibit coexistence between different excitations associated with single-particle or collective motions, which are built on spherical, prolate, and oblate shapes [12,13]. This shape coexistence is an indication that the cores of these nuclei are "soft" with respect to deformation. As a consequence, excitations based on intruder orbitals can polarize the core in different ways, leading to sizable shape variations. Direct experimental evidence for the existence of different shapes in Ir nuclei was presented by Seewald *et al.* [14], who measured the spectroscopic quadrupole moments for a number of Ir isotopes using a nuclear magnetic resonance technique. They extracted different quadrupole moments for the 2^- isomeric state and the 5^+ ground state of ^{186}Ir, which are built on a normal and an intruder excitation, respectively. Deformation changes and their influence on the band-crossing pattern have been considered for these nuclei [8].

This paper reports a study of high-spin states in the $\pi h_{9/2}$ band in ^{187}Ir. We observe a band crossing at a rotational frequency $\hbar\omega_c \approx 0.39$ MeV and compare this with the previously observed crossings in the $\pi h_{9/2}$ bands in ^{181,183,185}Ir. The lighter ^{181,183}Ir align at a lower rotational frequency $\hbar\omega_c$ and gain more angular momentum Δi_x compared to ^{185,187}Ir.

II. EXPERIMENTAL DETAILS AND RESULTS

The experiment was performed at the ESTU Tandem Van de Graaff accelerator at the Wright Nuclear Structure Laboratory at Yale University. High-spin states of ^{187}Ir were populated in the $4n$ channel of the fusion-evaporation reaction induced by a ^{15}N beam at 82 MeV energy. A 6.65 mg/cm^2 ^{176}Yb foil was used as a target. Gamma rays were detected with the YRAST Ball spectrometer [15], which for this experiment consisted of seven clover detectors, 16 single-crystal Ge detectors, and three Low-Energy Photon Spectrometers (LEPS) detectors. The trigger condition required a minimum of three coincident γ rays to deposit their energy in

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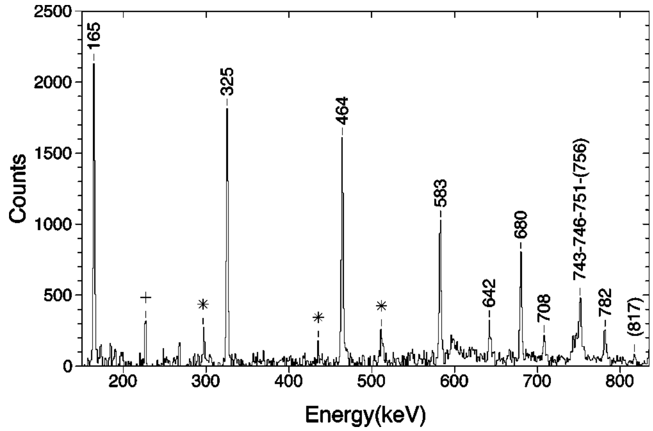

FIG. 1. A spectrum displaying the transitions belonging to the $\pi h_{9/2}$ band in ^{187}Ir. It results from the summing of all double-gated coincidence spectra, obtained by gating on the 165-, 325-, 464-, 583-, 680-, 751-, and 782-keV transitions. Contaminated peaks labeled with + belong to ^{186}Ir and those labeled with $*$ belong to ^{186}Os. The energies of the uncertain transitions are put in brackets.

a clover or a single Ge detector. The γ-γ-γ coincidence events were sorted into a three-dimensional histogram (cube) using the incub8r code from the RADWARE package [16]. A sample spectrum of summed double gates on transitions belonging to the $\pi h_{9/2}$ sequence is shown in Fig. 1.

In a previous study the $\pi h_{9/2}$ band in ^{187}Ir was established up to I^{π}=33/2^{-} for the favored signature (α=+1/2) and up to a tentative spin (27/2^{-}) for the unfavored signature (α=−1/2) [17]; the signature quantum number α is defined by the relation $r \equiv \exp(-i\pi\alpha)$, where r is the eigenvalue of the operator $\mathcal{R}_x = \exp(-i\pi J_x)$, which describes rotation at an angle π around an axis perpendicular to the symmetry axis.

In the present work these sequences were extended up to spins of (45/2^{-}) and (31/2^{-}), respectively. In this way, the favored sequence has been established through the first band crossing. The level scheme for the $\pi h_{9/2}$ band, as deduced in the present study, is shown in Fig. 2. Transitions were ordered on the basis of their coincidence relationship and relative intensities. The spin and parity of the new levels were assigned assuming that the rotational behavior of the band persists, i.e., the in-band transitions are stretched electric quadrupoles ($E2$) and the transitions between the signatures of the band are magnetic dipole ($M1$) transitions. In the level scheme the spin/parity labels of these states are shown in parentheses. The tentative transitions were only observed after summing coincidence spectra gated on the known transitions in the band.

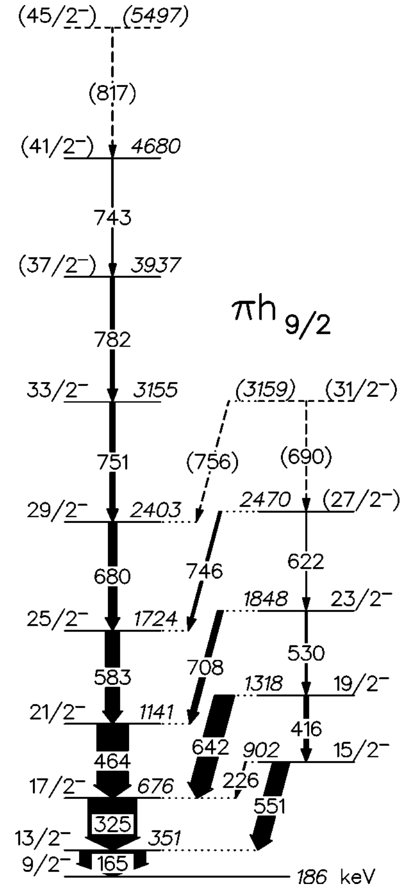

FIG. 2. A partial level scheme showing the $\pi h_{9/2}$ band in ^{187}Ir as deduced from the present study. The arrow widths are proportional to the intensities of the corresponding transitions. Tentative transitions are shown with dashed lines and uncertain spin and parity assignments are shown in parentheses.

III. DISCUSSION

The aligned angular momenta i_x of the favorite signatures of the $\pi h_{9/2}$ bands in ^{181,183,185,187}Ir nuclei are presented in Fig. 3. The reference parameters have been selected in such a way that i_x takes a constant value before and after the band crossing. It should be noted that although the value of aligned angular momentum depends on the choice of the reference parameters, the alignment gain Δi_x at the crossing point remains essentially unchanged. For the lighter ^{181,183}Ir isotopes ($N<108$), the $\pi h_{9/2}$ bands undergo a crossing at a rotational frequency $\hbar\omega_c \approx 0.29$ MeV with a gain of alignment $\Delta i_x \approx 7\hbar$, while for the heavier ^{185,187}Ir isotopes a crossing is observed at $\hbar\omega_c \approx 0.39$ MeV with an alignment gain of $\Delta i_x \approx 5\hbar$. New data for ^{185}Ir [18] have been included in Fig. 3. The last data point for ^{187}Ir, although uncertain (see Sec. II), allows an estimate for the alignment gain for ^{187}Ir. These results demonstrate that *an abrupt change* of the crossing frequency and the alignment gain takes place for $N \geqslant 108$ in the $\pi h_{9/2}$ bands in the $_{77}$Ir isotopes.

The origin of backbending in the $\pi h_{9/2}$ bands in the $_{77}$Ir nuclei can be due to the rotational alignment of either $\nu i_{13/2}$ or $\pi h_{9/2}$ quasiparticles. If we follow the quasiparticle notations of Ref. [8], the first neutron crossing is labeled AB and the first proton crossing is ef. If the AB crossing is blocked by a quasiparticle occupying an A (B) level, then the secondary BC (AD) crossing is expected at a somewhat higher frequency than the AB crossing. Similarly, the secondary proton band crossing in a $\pi h_{9/2}$ band can be labeled eh or fg and is expected to occur at a higher rotational frequency than the ef crossing. Since the ef crossing is blocked in an $\pi h_{9/2}$ band, the first crossing can be either AB or eh.

It is well known that the rotational alignment of a quasineutron (quasiproton) pair is related to both the neutron

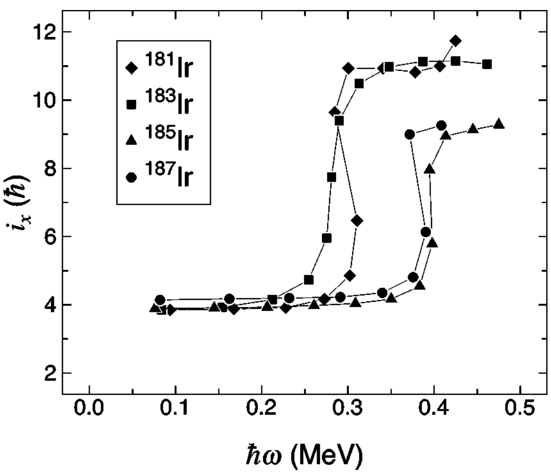

FIG. 3. Aligned angular momenta for $\pi h_{9/2}$ bands in $^{181-187}$Ir. The reference parameters and data used for the plot are ^{181}Ir $\Im_0=22$, $\Im_1=90$ [9]; ^{183}Ir $\Im_0=25$, $\Im_1=55$ [4]; ^{185}Ir $\Im_0=27$, $\Im_1=55$ [5,18]; ^{187}Ir $\Im_0=22$ MeV $^{-1}\hbar^2$, $\Im_1=55$ MeV $^{-3}\hbar^4$.

(proton) pairing gap Δ_ν (Δ_π) and the position of the neutron (proton) Fermi level, λ_ν (λ_π), relative to the corresponding intruder subshell, e.g., $\nu i_{13/2}$ ($\pi h_{9/2}$) for the Ir isotopes. Since both Δ and λ depend on the shape parameters, any deformation differences can influence the alignment pattern of the bands.

The band crossings in the $N\approx106$ nuclei have been debated for a long time and no definite conclusion has been reached. The Tennessee group has investigated the aligned angular momenta of $N=106, 107, 108$ isotopes of Ir ($Z=77$), Pt ($Z=78$), and Au ($Z=79$); see Ref. [8], and the references therein. The authors have discussed that the observed band crossings can be explained in a consistent way using two different approaches: using blocking arguments or defining the deformation and the corresponding band-crossing frequency theoretically for each individual band.

In terms of the former approach, the band crossings in ^{181,183}Ir were interpreted as *AB* crossings [4,9]. The low-frequency (0.24 MeV) band crossing in the ground-state band in ^{186}Pt was interpreted as an *ef* crossing [6], since this crossing is blocked in the $\pi h_{9/2}$ band of ^{185}Ir. The ground-state band of ^{186}Pt is known up to a $\hbar\omega=0.45$ MeV and no second crossing is observed near the 0.39 MeV crossing we see in ^{185,187}Ir. This fits with the interpretation of the $\hbar\omega_c\approx0.24$ MeV crossing in ^{186}Pt as $\pi h_{9/2}$ (*ef*) and the 0.39 MeV crossing in ^{185}Ir as the *eh* alignment, since the latter would not occur in the *ef* band of ^{186}Pt [5]. The *AB* crossing is expected to be delayed due to the existence of a significant gap in the neutron single-particle levels at $N=108$ [5]. The aligned angular momenta of the $\pi h_{9/2}$ bands in ^{187}Ir and ^{185}Ir (Fig. 3) show a very similar pattern, thus suggesting a common interpretation of the band crossings in these nuclei. Therefore, the band crossing in ^{187}Ir is interpreted as an *eh* alignment in this line of argumentation.

Additional support for this assignment can be acquired from investigation of the $\pi h_{9/2}$ bands in ^{181,183}Ir and the $\pi h_{9/2}\otimes\nu i_{13/2}$ band in ^{186}Ir. As the alignment of $h_{9/2}$ protons should not depend on the neutron number N, one would then expect that an *eh* crossing in ^{181,183}Ir would take place at approximately the same frequency as for ^{185,187}Ir. If this were not the case, then the possibility of an *eh* crossing in ^{185,187}Ir is called into question. The last two transitions which have been added at the top of the $\pi h_{9/2}$ band in ^{181}Ir (see Fig. 3) indicate the beginning of an upbend at a frequency similar to that of the crossing seen in ^{185,187}Ir [9]. However, the last transition in ^{183}Ir does not show this pattern [4]. Each of the top transitions in these bands are uncertain [4,9], and thus firm conclusions cannot be reached based on these observations.

In the $\pi h_{9/2}\otimes\nu i_{13/2}$ band (fA) of ^{186}Ir [19] one expects to see the same *eh* crossing observed at $\hbar\omega\approx0.39$ MeV in ^{185,187}Ir. The fA band is observed up to a frequency of 0.40 MeV in ^{186}Ir and no crossing has occurred, although there is a hint of an upbend in alignment and perhaps the beginning of a crossing.

In the second approach, the deformation of each band was determined from cranking calculations with the Woods-Saxon potential, where the deformation parameters were determined from total routhian surfaces (TRS) calculations [8]. The band crossings in ^{181,183}Ir and ^{185}Ir were interpreted as *AB* crossings [8], despite the large change of frequency $\hbar\omega_c$ at $N=108$ ($\Delta\hbar\omega_c=0.10$ MeV). We now realize that there is a difference in the gain of aligned angular momentum in this crossing of the $\pi h_{9/2}$ band: $2\hbar$ larger in the lighter ($N<108$) compared to the heavier ($N\geqslant108$)Ir isotopes (see Fig. 3).

It is possible that the observed difference of the alignment gain in the crossings in the $\pi h_{9/2}$ bands in ^{181,183}Ir compared to ^{185,187}Ir is related to the position of the Fermi level for neutrons, λ_ν, relative to the $\nu i_{13/2}$ intruder subshell. As discussed in Ref. [20], the gain in angular momentum of the high-j levels lying immediately above the Fermi surface λ_ν decreases when the Fermi surface moves from the bottom to the top of the $\nu i_{13/2}$ subshell. The reverse dependency is true for the crossing frequency, i.e., when the Fermi surface moves from the bottom to the top of the subshell, $\hbar\omega_c$ increases. The reason for these trends is that the orbitals with a large angular momentum component along the rotation axis are dominated by components that have small angular momentum projection along the symmetry axis (low Ω value) and which are situated at the lower part of the $\nu i_{13/2}$ subshell (see Fig. 4). In the diagram of the single-particle neutron levels (Fig. 4), one can see that the Fermi levels for ^{181,183}Ir are located at the middle of the $i_{13/2}$ subshell, while for ^{185,187}Ir they are in the upper part of the subshell. However, these arguments should be accepted with caution, because one would expect to observe smooth changes of the crossing frequency $\hbar\omega_c$ and the alignment gain Δi_x with the increase of the neutron number from ^{181}Ir to ^{187}Ir, instead of the abrupt changes that are found.

As noted above, Carpenter *et al.* [8] observed in the ground-state band of ^{184}Pt two successive band crossings at nearly degenerate rotational frequencies which match the crossing frequencies in the $\pi h_{9/2}$ bands in ^{181,183}Ir. These crossings in ^{184}Pt were interpreted either as two successive neutron crossings (*AB* and *CD*; in this case it is necessary to explain why the two neutron pairs align simultaneously) or as successive neutron and proton crossings (*AB* and *ef*) [8]. Recently, average g factors of high-spin states were mea-

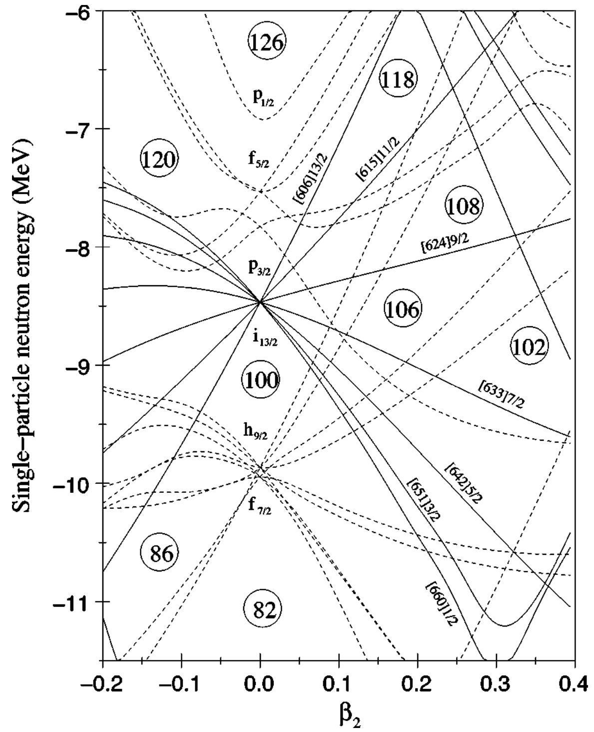

FIG. 4. Single-particle neutron levels calculated with a Woods-Saxon potential as a function of deformation parameter β_2 and $\beta_4=\gamma=0$.

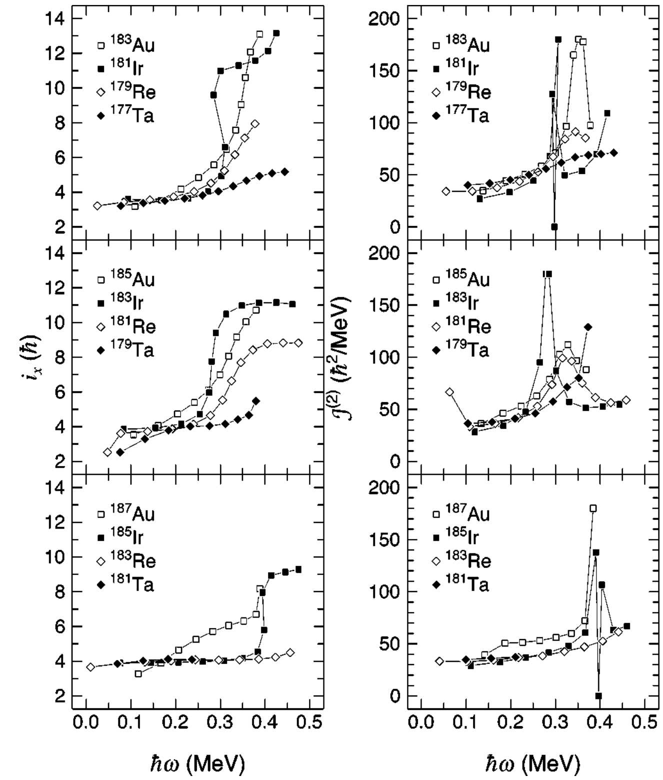

FIG. 5. Aligned angular momenta (left-hand side) and second moments of inertia (right-hand side) for $\pi h_{9/2}$ bands in the Au, Ir, Re, and Ta isotones. Data are shown relative to a reference configuration parametrized by different sets of Harris parameters, which provide constant aligned angular momentum before and after a band crossing. Experimental data are taken from Ref. [25]. The graphs on the top refer to the $N=104$ isotones, middle 106, and bottom 108.

sured for ^{180,182,184}Pt at an angular momentum of $\approx 20\hbar$ [21]. These results indicate that $h_{9/2}$ proton pairs align along with the $i_{13/2}$ neutrons at a rotational frequency $\hbar\omega_c \approx 0.3$ MeV in ^{184}Pt, which supports the existence of an ef crossing.

A different interpretation of the band crossings in this region can be attempted in terms of the recently developed E-GOS plot (E_γ over spin vs spin) analysis [22]. Regan *et al.* explain the band crossings in even-even $A \sim 110$ nuclei as a vibrational-to-rotational transition instead of a result of aligned quasiparticles. TRS calculations presented in Ref. [8] demonstrate that the energy-surface minimum is very shallow with respect to the γ deformation. For Os, Ir, and Pt nuclei it is clear that vibrational degrees of freedom are important, since the deformation here is smaller than that of the well-deformed rare-earth nuclei. This was demonstrated by Davidson *et al.* [23], who applied a three-band mixing model to the ground-state collective structures of ^{176,178,180,182}Pt by mixing two bands with different deformations along with γ vibrational states. An E-GOS analysis would be more complicated for odd-A nuclei and is not attempted here. It is likely that a regular rotational analysis of these bands may be in order, since the occupation of the $h_{9/2}$ orbit tends to stabilize the deformation for the observed bands in the odd-A Ir nuclei. Of course, incorporation of vibrational degrees of freedom needs to be considered also.

The difference in crossing frequencies and the alignment gains in the $\pi h_{9/2}$ band are observed not only in odd Ir nuclei but also in the odd $_{79}$Au, $_{75}$Re, and $_{73}$Ta nuclei. In Fig. 5 the aligned angular momenta (left-hand side) and the second moments of inertia (right-hand side) are plotted as a function of rotational frequency for the existing data for the $\pi h_{9/2}$ bands in the previously mentioned elements for $N=104, 106$, and 108.

Two observations can be made concerning the data for the $N=106$ isotones shown in the middle of Fig. 5. (i) The frequency of the observed crossing varies for different Z and (ii) the alignment gain in the crossing decreases as the atomic number Z decreases (the alignment gain in ^{179}Ta cannot be estimated, but the existence of a band crossing at a higher frequency is clear). These trends seem to also be present for the $N=104$ isotones (the upper panel of Fig. 5) and with caution in the bottom panel (the $N=108$ isotones). The plots for the second moment of inertia demonstrate the existence of at least three groups of band-crossing frequencies: $\hbar\omega_c=0.29$–0.30 MeV for the $N<108$ Ir isotopes; $\hbar\omega_c=0.33$–0.35 MeV for the $N<108$ Re and Au isotopes; and $\hbar\omega_c=0.39$–0.40 MeV for $N=108$ ^{185}Ir and ^{187}Au and $N=106$ ^{179}Ta (there is an indication for a second band crossing at this frequency in ^{181}Ir as well). For $N=108$ ^{183}Re the backbending is delayed beyond $\hbar\omega_c>0.45$ MeV.

The first and the last group of band-crossing frequencies reflect the picture that has been observed for the Ir isotopes for $N\leqslant 110$. The third group of frequencies may be due to considerable γ deformation of the $\pi h_{9/2}$ band in the corresponding nuclei. It will be interesting to observe the evolution of the first band crossing in the $\pi h_{9/2}$ structure of ^{189,191}Ir.

The rather complicated picture that emerges from these data is an indication that the fingerprints of different phenomena mix together. The observed changes in band crossings might not be entirely related to deformation variations. Similar effects could emerge also from higher multipole orders of residual proton-neutron (or neutron-neutron) interactions involving particles in the $\pi h_{9/2}$ (or $\nu i_{13/2}$) orbital. This has been discussed for the $\pi h_{9/2}$ bands in the N=98 $_{75}$Re, $_{73}$Ta, $_{71}$Lu, and $_{69}$Tm isotones [24].

IV. CONCLUSIONS

Various arguments have been used to explain the pattern of crossings in rotational bands built on the proton $h_{9/2}$ orbital in odd-A Ta through Au nuclei. In this work we have assigned new high-spin states to the $\pi h_{9/2}$ band in ^{187}Ir and observed the first crossing at a rotational frequency $\hbar\omega_c \approx 0.39$ MeV. There are two important characteristics of the band crossing in this N=108 $_{77}$Ir isotope: the crossing is delayed and the alignment gain is $2\hbar$ smaller in ^{185,187}Ir compared to the lighter isotopes. If this is consistently a neutron $i_{13/2}$ crossing, rather substantial deformation changes would have to be invoked to try to reproduce this trend of frequency and alignment gain changes in the Ir isotopes from N=104 to 110. It is more logical to attribute this trend to a switch from a neutron $i_{13/2}$ crossing in the $\pi h_{9/2}$ band for N=104 and 106 Ir to a proton $h_{9/2}$ crossing at N=108 and above. The increase in the frequency and the reduced gain in quasiparticle alignment for this crossing in ^{185,187}Ir lead to the indication that this is a blocked proton $h_{9/2}$ band crossing.

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