Properties of the $\pi h_{11/2}$ band in the stable nucleus ^{193}Ir

Y. D. Fang,[1] Y. Shi,[2] Y. H. Zhang,[1,*] B. S. Gao,[1,3] S. C. Wang,[1,3] X. H. Zhou,[1] M. L. Liu,[1] J. G. Wang,[1] F. Ma,[1] Y. X. Guo,[1] X. G. Wu,[4] C. Y. He,[4] Y. Zheng,[4] Z. M. Wang,[4] S. C. Li,[1,3] X. L. Yan,[1,3] L. He,[1,3] Z. G. Wang,[1,3] F. Fang,[1] and F. R. Xu[2]

[1]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China*

[2]*Department of Technical Physics and MOE Key Laboratory, Peking University, Beijing 100871, People's Republic of China*

[3]*Graduate University of Chinese Academy of Sciences, Beijing 000049, People's Republic of China*

[4]*China Institute of Atomic Energy, Beijing 102413, People's Republic of China*

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Excited states in the stable nucleus ^{193}Ir have been investigated through an in-beam γ-ray spectroscopic technique following the ^{192}Os(^{7}Li, $\alpha 2n$) reaction at a beam energy of 44 MeV. A level scheme built on the $\pi h_{11/2}$ isomer has been extended to high-spin states using eleven newly observed γ transitions. The $\pi h_{11/2}$ band is proposed to be formed by coupling an $h_{11/2}$ proton to a core with large triaxial deformation. Three-quasiparticle states are suggested in ^{193}Ir on referring to the similar states in ^{187}Ir. The features of signature splitting in the $\pi h_{11/2}$ bands of $^{187-193}$Ir are discussed with the help of total Routhian surface calculations.

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I. INTRODUCTION

Osmium and iridium isotopes locate in the transitional region between the well-deformed rare-earth nuclei and the spherical lead isotopes. These transitional nuclei show a rich variety of structures associated with different shapes and deformations. The osmium nuclei in the $A = 190$ mass region are believed to be γ-soft [1–3], and the γ degree of freedom plays an important role in describing these nuclei. When adding one more proton to the γ-soft even-even osmium nuclei, the shape-polarizing effects of the single particle in the high-j orbitals can be effectively reflected in the nuclear structure properties in the odd-A iridium nuclei.

An interesting phenomenon observed in the odd-A iridium nuclei is the signature splitting in the rotational bands built on the high-K Nilsson orbitals originating from the $\pi h_{11/2}$ spherical parentage. For the odd-A $^{175-181}$Ir isotopes [4–7], the small signature splitting was observed; this is consistent with a near-prolate configuration. With the decrease of neutron number, the signature splitting increases gradually from ^{175}Ir to ^{169}Ir [4,8–10]. This has been interpreted as the result of increasing the shape asymmetry when approaching the $N = 82$ neutron shell closure [8]. A similar trend has also been observed in the heavier iridium isotopes from ^{185}Ir to ^{191}Ir [11–13].

The $\pi h_{11/2}$ bands in the stable or neutron-rich iridium isotopes are usually difficult to study because no proper heavy-ion-induced fusion-evaporation reactions are available to populate the high-spin states. The excited states of the stable nucleus ^{193}Ir were studied previously using different techniques including β decay of ^{193}Os [14], (n,γ) reactions [15,16], coulomb excitation [17], and the ^{192}Os(d, $n\gamma$)^{193}Ir reaction [16]. However, one only observed the rotational bands built on the low-j $3/2^+$[402] and $1/2^+$[400] configurations [13–17], and the band structure built on the high-j $\pi h_{11/2}$ intrinsic states (i.e., the $11/2^-$ isomer) has not yet been established. Recently, high-spin states of nuclei in this mass region have been investigated by employing multinucleon transfer reactions, such as in the ^{82}Se + ^{192}Os collision system [18]. In this article we report on the $\pi h_{11/2}$ band structure observed in ^{193}Ir using a ^{7}Li-induced incomplete fusion reaction [19]. Total Routhian surface calculations have been made in order to understand the shape variations of odd-A iridium isotopes from ^{187}Ir to ^{193}Ir.

II. EXPERIMENT AND RESULTS

A. Measurements

The nucleus ^{193}Ir was produced in the ^{192}Os(^{7}Li,$\alpha 2n$) reaction. The ^{7}Li beam was provided by the HI-13 Tandem Accelerator at the China Institute of Atomic Energy in Beijing (CIAE). The target was an isotopically enriched ^{192}Os metallic foil 1.7 mg/cm^2 thick with a 1.1 mg/cm^2 carbon backing to stop the recoiling nuclei. An excitation function was measured at beam energies of 34, 38, 42, 44, and 46 MeV to choose the optimum beam energy for the production of ^{194,195}Au. X-γ-t and γ-γ-t coincidence measurements were performed at a beam energy of 44 MeV with an array of 14 Compton-suppressed HPGe detectors. The energy and efficiency calibrations were made using ^{60}Co, ^{133}Ba, and ^{152}Eu standard sources. Typical energy resolutions were about 2.0 ∼ 2.5 keV at full width at half maximum for the 1332.5-keV line. A total of 9×10^7 γ-γ-t events were accumulated and sorted into a $4k \times 4k$ matrix for offline analysis.

To obtain the multipolarity information of the emitting γ rays, the detectors were divided into three groups. Two asymmetric matrices were constructed from the coincidence data: one matrix with detectors at $\theta_2 = 90^\circ$ and another one with $\theta_1 = 40^\circ$ and 152° (the averaged angle is about 35°) against those at all angles. From these two matrices, the angular distribution asymmetry ratios, defined as $R_{\mathrm{ADO}}(\gamma) = I_\gamma(35^\circ)/I_\gamma(90^\circ)$, were extracted from the γ-ray intensities $I_\gamma(35^\circ)$ and $I_\gamma(90^\circ)$ in the coincidence spectra gated by the

*yhzhang@impcas.ac.cn

γ transitions (on the y axis) of any multipolarities. The intensities of the γ rays are corrected for the detection efficiency of the corresponding group of detectors. In the present geometry, stretched quadrupole transitions are adopted if $R_{\mathrm{ADO}}(\gamma)$ values are larger than unity [an average value of $R_{\mathrm{ADO}}(\gamma) = 1.20 \pm 0.15$ is obtained for the known $E2$ transitions in ^{194,195}Au and ^{194}Pt], and dipole transitions are assumed if $R_{\mathrm{ADO}}(\gamma)$ values are less than 1.0.

B. Level scheme

Prior to this work, three rotational sequences were identified with the highest spin state of $I^\pi = 21/2^+$ [16]. All of those bands are confirmed in the present study. For the negative-parity levels, the 399-keV $15/2^- \to 11/2^-$ and 389-keV $13/2^- \to 11/2^-$ transitions were proposed to directly feed the $11/2^-$ isomer by Prokofev *et al.* [15], which was confirmed later by Drissi [16] and Fotiades *et al.* [20]. This information is used as a starting point for assigning the new transitions to ^{193}Ir on the basis of γ-γ coincidences. Figure 1 presents coincidence spectra by setting gates on (a) 398.9- and (b) 545.7-keV transitions. The Ir K x-ray and the new transitions can be clearly identified in Fig. 1. The assignment of the new γ rays, as indicated in Fig. 1, to ^{193}Ir are cross-checked by analyzing the γ-γ coincidence relationships in the ^{82}Se $+^{192}$ Os reaction [18]; the 398.9-, 449.3-, 545.7-, and 566.3-keV lines are found to be in strong coincidence with the $(5/2)^- \to 3/2^-$, 336-keV transition in ^{81}As [13]. In the ^{82}Se $+^{192}$ Os colliding system, a proton transfer reaction populated the excited states of the reaction partners ^{193}Ir and ^{81}As. The γ rays from the excited states of ^{193}Ir and ^{81}As are simultaneously emitted and detected in coincidence.

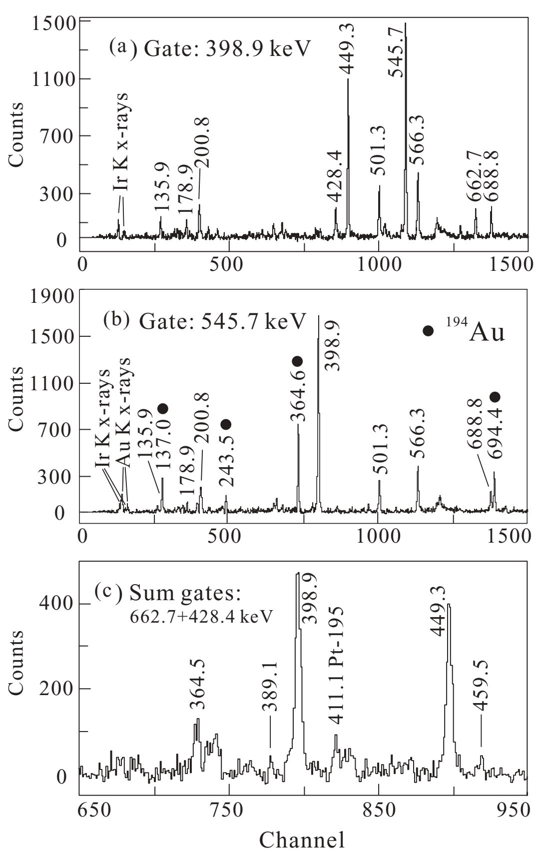

FIG. 1. γ-ray coincidence spectra by setting a gate on (a) 398.9-keV, (b) 545.7-keV, and (c) the summed gates of 662.7- and 428.4-keV transitions.

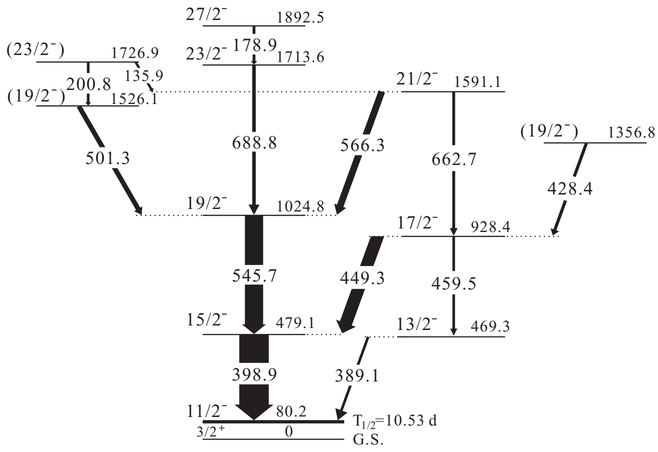

FIG. 2. Partial level scheme of ^{193}Ir deduced from the present work. The widths of the arrows indicate the relative transition intensities.

Coincidence relationships have been analyzed yielding a new level scheme as shown in Fig. 2. Eleven new transitions and eight new levels are added to the level scheme of ^{193}Ir. The γ-transition energies in the level scheme are within an uncertainty of 0.5 keV, and the ordering of the transitions in the band are established on the basis of γ-γ coincidence relationships, the sum of the γ-ray energies, and their relative intensities. The relative spins in the level scheme are proposed on the basis of the measured ADO ratios. The measured γ-ray energies, relative intensities, ADO ratios, and suggested spin and parity assignments are summarized in Table I.

We note that the previously reported [16] 451- and 461-keV γ rays deexciting the $(17/2^-)$ level correspond to the 449.3- and 459.5-keV transitions in this work. In Fig. 1(c) we show a summed coincidence spectrum from which the 449.3- and 459.5-keV transitions are clearly seen. Checking carefully the known γ rays from ^{194,195}Au and ^{194}Pt observed in this experiment, we found that their energies as determined in our work are consistent with the previously published values within an uncertainty of 0.5 keV.

III. DISCUSSION

In order to justify the present spin-parity assignments, the level scheme of ^{193}Ir is compared with those of its neighboring odd-A iridium isotopes. We have performed the total Routhian surface (TRS) calculations for the negative-parity bands in $^{187-193}$Ir and the ground-state bands in $^{186-192}$Os which may provide important information for understanding the band properties in ^{193}Ir and the single-particle polarizing effect of the $h_{11/2}$ proton.

TABLE I. γ-ray transition energies, relative intensities, ADO ratios, and their assignments in ^{193}Ir.

E_γ(keV)[a]	I_γ[b]	R_{ADO}	$E_i \to E_f$(keV)[c]	$J_i^\pi \to J_f^\pi$[d]
135.9	5(1)		1726.9 → 1591.1	$(23/2^-) \to (21/2^-)$
178.9	6(1)	1.14(24)	1892.5 → 1713.6	$(27/2^-) \to 23/2^-$
200.8	9(1)	1.10(17)	1726.9 → 1526.1	$(23/2^-) \to (19/2^-)$
389.1			469.3 → 80.2	$13/2^- \to 11/2^-$
398.9	100(7)	1.17(11)	479.1 → 80.2	$15/2^- \to 11/2^-$
428.4	11(1)	0.89(22)	1356.8 → 928.4	$(19/2^-) \to 17/2^-$
449.3	43(3)	0.98(8)	928.4 → 479.1	$17/2^- \to 15/2^-$
459.5			928.4 → 469.3	$17/2^- \to 13/2^-$
501.3	16(2)	1.13(13)	1526.1 → 1024.8	$(19/2^-) \to 19/2^-$
545.7	62(5)	1.18(12)	1024.8 → 479.1	$19/2^- \to 15/2^-$
566.3	23(2)	0.92(11)	1591.1 → 1024.8	$21/2^- \to 19/2^-$
662.7	10(1)	1.10(23)	1591.1 → 928.4	$21/2^- \to 17/2^-$
688.8	12(1)	1.10(16)	1713.6 → 1024.8	$23/2^- \to 19/2^-$

[a]Uncertainties are within 0.5 keV.
[b]Uncertainties are within 30%.
[c]Excitation energies of initial E_i and final E_f states.
[d]Proposed spin and parity assignments for the initial J_i^π and final J_f^π levels.

A. Systematics of negative-parity level structures in $^{187-193}$Ir

The excitation energies of the $\pi h_{11/2}$ bands in $^{187-193}$Ir [13] are shown in Fig. 3, from which one can see that the energy levels of the bands decrease with the increase of neutron number. The excitation energies of the $\pi h_{11/2}$ band in ^{193}Ir fit well into the systematics if the proposed I^π values are accepted. In addition, the relative excitation energies of the $\pi h_{11/2}$ band heads decrease smoothly with increasing neutron number. This can be attributed to a decrease in quadrupole deformation while increasing the neutron number. This is supported in the TRS calculations and will be discussed in Sec. III C.

The energy difference between the $27/2^-$ and $23/2^-$ states in the $\pi h_{11/2}$ band (as shown in Fig. 2) is small, indicating a structure change most likely associated with the breaking of an $h_{11/2}$ proton pair. This energy difference is similar to those observed in ^{187}Ir and in ^{187,193}Au [11,21,22]. Modamio *et al.* [11] have interpreted the $27/2^-$ state at $E_x = 2491$ keV in ^{187}Ir as a three-quasiproton state. Such three-quasiproton states have also been observed in ^{187,193}Au isotopes, and the total aligned spin of $27/2^-$ was interpreted as an $h_{11/2}$ proton-hole coupled to the $\pi h^2_{11/2}$ state in the Hg core [21,22]. Analogous to the cases in ^{187}Ir and ^{187,193}Au, the $27/2^-$ state in ^{193}Ir could be understood as the coupling of a $\pi h_{11/2}$ hole to the 10^+ isomer in the core nucleus ^{194}Pt [23].

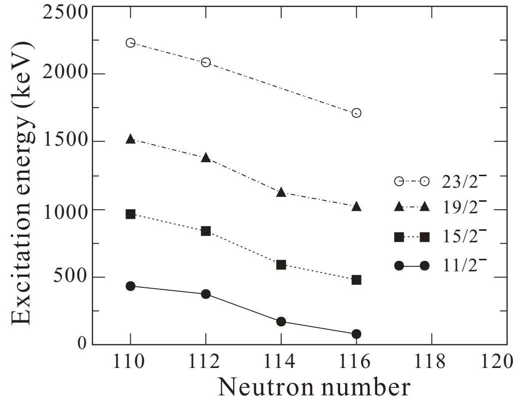

FIG. 3. Energy systematics of the $\pi h_{11/2}$ bands in odd-A iridium isotopes $^{187-193}$Ir. Data are taken from Ref. [13] and the present work.

We turn now to the states at excitation energies of 1526.1 and 1726.9 keV. These two levels decay via the 501.3- and 135.9-keV transitions to the $19/2^-$ and $21/2^-$ states. ADO ratios for the 501.3- and 200.8-keV lines were measured to be 1.13(13) and 1.10(17), respectively. These values are consistent with stretched $\Delta I = 2$ or nonstretched $\Delta I = 0$ transitions. We assigned the former to be a nonstretched $\Delta I = 0$ transition, and the latter to be a stretched $E2$ transition by comparing the level structure of ^{193}Ir with that of ^{187}Ir [11]. The $(23/2^-)$ assignment for the 1726.9-keV level is supported by the observation of the 135.9-keV transition. The energies of the $(19/2^-)$ and $(23/2^-)$ states relative to the $\pi h_{11/2}$ band head are 1445.9 and 1646.7 keV, respectively, which are consistent with the energies needed for a two-quasiparticle excitation [24,25]. Therefore, it is probable that these two states are formed by a three-quasiparticle configuration. In the recent work of Modamio *et al.* [11], a number of three- and even five-quasiparticle states in ^{187}Ir have been identified. We notice that the 200.8-keV, $(23/2^-) \to (19/2^-)$ and 501.3-keV, $(19/2^-) \to 19/2^-$ transitions (see Fig. 2) are similar to those (226- and 511-keV transitions) in ^{187}Ir (see Fig. 3 in Ref. [11]). In Ref. [11], the $\pi 11/2^-[505] \otimes \nu\{9/2^-[505], 3/2^-[512]\}$ configuration was tentatively assigned to the 2261-keV $23/2^-$ level in ^{187}Ir, and a strongly mixed configuration to the $19/2^-$ state at 2034 keV (see Table III in Ref. [11]). Given the similar level structure of ^{193}Ir with that of ^{187}Ir, the same configurations could be assigned to the $(23/2^-)$ and $(19/2^-)$ states in ^{193}Ir.

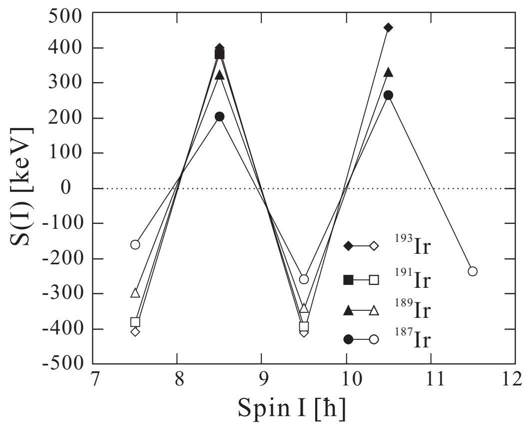

FIG. 4. Staggering parameter $S(I)$ as a function of spin I for the $\pi h_{11/2}$ bands in the odd-A iridium isotopes $^{187-193}$Ir. The filled (open) symbols represent the $\alpha = +1/2$ ($\alpha = -1/2$) signature. Data are taken from Ref. [13] and the present work.

B. Signature splitting of the $\pi h_{11/2}$ bands in $^{187-193}$Ir

The observed $\pi h_{11/2}$ band in ^{193}Ir shows a large signature splitting of $\simeq$200 keV. Figure 4 compares the signature splitting of the $\pi h_{11/2}$ band in ^{193}Ir with those in the lighter isotopes ^{187}Ir [11], ^{189}Ir [12], and ^{191}Ir [13] using the energy-staggering parameter $S(I)$, defined as

$$S(I) = [E(I) - E(I-1)] - 1/2[E(I+1) - E(I) + E(I-1) - E(I-2)]. \quad (1)$$

This quantity, $S(I)$, is directly proportional to the energy difference of the two signatures, but magnified by approximately a factor of 2. As can be seen in Fig. 4, each isotope exhibits a large signature splitting. The signature splitting can be interpreted as arising from mixing of a $K = 1/2$ component into the high-K $h_{11/2}$ proton configuration. However, in the iridium isotopes with a proton number of 77, the proton Fermi surface locates at the upper part of the $h_{11/2}$ subshell, the normal Coriolis mixing of the $K = 1/2$ component into the wave function is expected to be small for an axially symmetric nucleus. In order to reproduce the large signature splitting observed in the high-K $h_{11/2}$ band, one has to introduce a mechanism which can lead to an enhanced mixing with the $K = 1/2$ orbital. In fact, large signature splitting has been observed in the lighter ^{169}Ir [8], ^{171}Ir [9], and ^{173}Ir [10] isotopes, which has been interpreted as resulting from a triaxial deformation generated by the core polarization of the high-K $h_{11/2}$ proton.

C. TRS calculations and polarizing effects of the $h_{11/2}$ proton

We have performed total Routhian surface (TRS) calculations for the vacuum configurations of even-even $^{186-192}$Os and for the lowest negative-parity bands in $^{187-193}$Ir using the nonaxial deformed Woods-Saxon potential [26]. Collective rotation was investigated in the frame of the cranked shell model in the three-dimensional deformation space (β_2, β_4, and γ) [27,28]. At a given frequency, the deformation of a state is determined by minimizing the resulting total

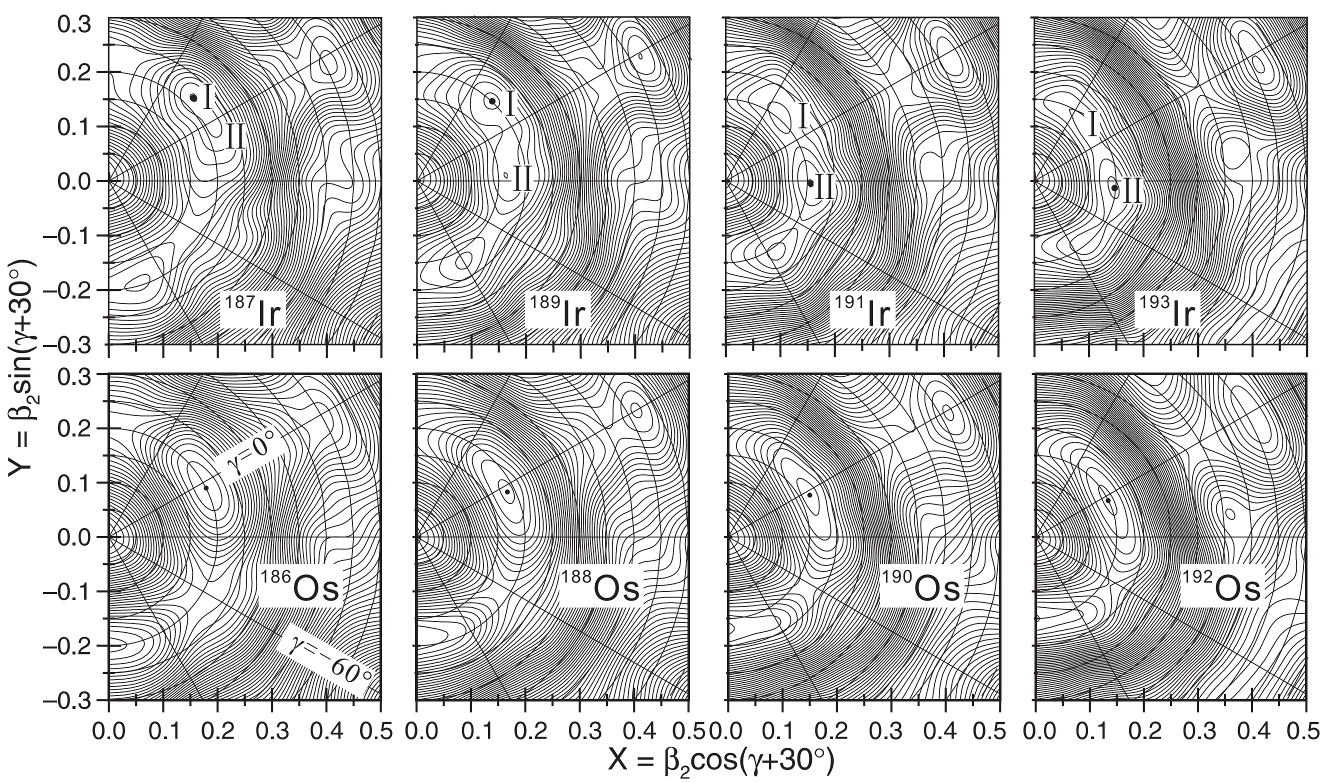

FIG. 5. Total Routhian surfaces at $\hbar\omega = 0.15$ MeV calculated for the lowest $(\pi, \alpha) = (-, +1/2)$ configuration in $^{187-193}$Ir (top panel), and for the ground-state configuration in $^{186-192}$Os (bottom panel). The energy difference between neighboring contours is 100 keV.

Routhian surfaces. Figure 5 presents the results for the vacuum configurations of even-even $^{186-192}$Os and for the lowest $(\pi, \alpha) = (-, +1/2)$ configurations in $^{187-193}$Ir at a rotational frequency of $\hbar\omega = 0.15$ MeV.

These calculations yield an almost axially symmetric prolate shape with pronounced γ softness in even-even osmium (see the lower panel of Fig. 5). The negative-parity surfaces of $^{187-193}$Ir are very soft against γ deformation, and two shallow minima can be identified at moderate deformations for each isotope. These shallow minima are susceptible to the rotational frequencies, especially, for the $(\pi, \alpha) = (-, -1/2)$ configuration. In the upper panel of Fig. 5, we present the calculated TRSs for the $(\pi, \alpha) = (-, +1/2)$ configuration; the two minima within 300 keV energy difference can be found in the region of $-40^\circ < \gamma < 30^\circ$ and $0.15 < \beta_2 < 0.25$. Our TRS calculations show that the minimum with positive γ deformation [labeled as (I)] has a low-K value, and the minimum with negative γ [labeled as (II)] has a high-K value. Considering the negative-parity orbitals closest to the proton Fermi surface, the former corresponds presumably to the intruder $1/2[541](\pi h_{9/2})$ configuration, and the latter to the high-K $\pi h_{11/2}$ configuration. Experimentally, the $1/2[541](\pi h_{9/2})$ band-head energy in ^{187}Ir [11] has been observed to be slightly lower than that of the $\pi h_{11/2}$ configuration, while only the $\pi h_{11/2}$ bands are observed in ^{191,193}Ir. This is consistent with our TRS calculations where the minima with positive γ deformations are favored in ^{187,189}Ir, while the minima with negative γ and smaller β_2 deformations are slightly deeper in ^{191,193}Ir.

An inspection of Fig. 5 reveals that adding a high-j, $h_{11/2}$ proton to the Os core will drive the nucleus from almost axially symmetric ($\gamma \sim -3^\circ$) to a shape with pronounced γ deformation (or pronounced γ softness). The polarizing effect depends on the γ softness of the even-even Os core. This is reflected in our TRS calculations in that the increasing γ deformation for the odd-A iridium isotopes is parallel to the tendency toward larger γ softness in the corresponding Os cores. The negative-γ driving effect of the high-K, $h_{11/2}$ proton has been discussed extensively in Ref. [29]. Finally, it is interesting to point out that a prolate super-deformed minimum seems to exist in the TRS of Os isotopes of interest (see Fig. 5). This supper-deformed minimum is enhanced by the polarizing effects of an odd proton. This theoretical prediction needs further investigations.

Our TRS calculations may also be used to interpret, at least qualitatively, the evolution behaviors of signature splitting from ^{187}Ir to ^{193}Ir. One can see in Fig. 4 that the amplitude of signature splitting increases gradually from ^{187}Ir to ^{193}Ir. This trend may be understood by considering the variations of β_2 and γ deformations from the TRS calculations. The deformation parameters for Os isotopes and those results with negative γ for Ir isotopes at the corresponding TRS minima are extracted and summarized in Table II. The gradual decrease of β_2 and increase of negative γ deformations are evident from ^{187}Ir to ^{193}Ir; this trend of shape variations could be associated with the gradual increase of signature splitting from ^{187}Ir to ^{193}Ir. The increasing signature splitting is thus a consequence of increased shape asymmetry as the position of the neutron Fermi level moves away from the neutron midshell ($N = 104$) to the shell closure at $N = 126$. In this context, we would mention that the $h_{11/2}$ bands in $^{169-175}$Ir [8] exhibit the same trend of increasing signature splitting but with decreasing neutron number; this has been interpreted as due to an increased shape asymmetry when the closed neutron shell $N = 82$ is approached [8].

TABLE II. Calculated equilibrium deformations β_2 and γ for the minima II of Fig. 5 and for the vacuum configurations in even-even $^{186-192}$Os at $\hbar\omega = 0.15$ MeV.

Nucleus	γ	β_2
^{187}Ir	$>-13^\circ$	$\sim$0.200
^{189}Ir	-26°	0.164
^{191}Ir	-32°	0.156
^{193}Ir	-35°	0.147
^{186}Os	-3°	0.200
^{188}Os	-3°	0.186
^{190}Os	-3°	0.169
^{192}Os	-3°	0.150

IV. SUMMARY

The high-spin states of ^{193}Ir have been studied using the ^{192}Os(^{7}Li,$\alpha 2n$)^{193}Ir reaction at a beam energy of 44 MeV. A level scheme built on the $\pi h_{11/2}$, $11/2^-$ isomer has been established. This result extends our knowledge of negative-parity band structures to a neutron-rich iridium isotope. The $\pi h_{11/2}$ band exhibits a larger signature splitting among the $\pi h_{11/2}$ bands in odd-A $^{187-193}$Ir. Total Routhian surface calculations have been made for the negative-parity bands in $^{187-193}$Ir and for the ground-state bands in the corresponding even-even $^{186-192}$Os. It has been shown that the triaxial shapes in odd-A $^{187-193}$Ir are owed to the strong core polarization of the high-j $h_{11/2}$ proton. The signature splitting in the $\pi h_{11/2}$ bands of $^{187-193}$Ir has been discussed with the help of TRS calculations. It seems that the increasing signature splitting from ^{187}Ir to ^{193}Ir could be understood, at least qualitatively, as due to the decrease of quadrupole deformation and the increase of shape asymmetry. This increased shape asymmetry may occur when the position of the neutron Fermi level moves away from the neutron midshell ($N = 104$).

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