Identification of high-spin states in the stable nucleus ^{195}Pt

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Excited states of the stable nucleus ^{195}Pt have been studied using an in-beam γ-ray spectroscopic technique following the incomplete fusion of ^{7}Li on an ^{192}Os target at 44 MeV. A level scheme built on the $I^{\pi} = 13/2^{+}$ isomer has been established up to $I^{\pi} = 33/2^{-}$ at an excitation energy of about 2.6 MeV. Spin and parity values of these states have been assigned from an analysis of anisotropy ratios of γ rays and by analogy with the neighboring nuclei. A comparison of the observed structures with the yrast states in the neighboring even-even ^{196}Pt core indicates that the identified levels may be regarded as arising from the weak coupling of a $\nu i_{13/2}$ neutron hole to the core states.

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As is commonly encountered in many stable nuclei, spectroscopic information on high-spin states in the stable nucleus ^{195}Pt is limited. This is because the high-spin states of ^{195}Pt cannot be populated via conventional heavy-ion fusion-evaporation reactions with a stable beam-target combination. Spectroscopic data of ^{195}Pt exist mainly for the low-spin states, which were obtained from the studies of β decay [1], neutron transfer (p, d) [2] and (^{3}He,α) [3] reactions, and the Coulomb excitation [4]. A number of low-lying negative-parity levels based on Nilsson configurations, such as $1/2^{-}[530]$, $3/2^{-}[532]$, and $5/2^{-}[532]$, were reported [2,5], and the properties of the levels below 700 keV have been interpreted as a case of the U(6/12) supersymmetry [2]. In this mass region, the decoupled bands associated with the $\nu i_{13/2}$ configuration have been observed systematically in odd-A $^{187-193}$Pt isotopes [6–9]. Although the $\nu i_{13/2}$, $13/2^{+}$ isomer in ^{195}Pt is known to exist at an excitation energy of 259.3 keV [10], the high spin level structure above this isomer remains unknown. Identification of the rotational band based on this isomer would extend our experimental knowledge further toward neutron-rich platinum isotopes.

An alternative way to populate high-spin states of ^{195}Pt in a fusion-evaporation reaction would be the use of a neutron-rich radioactive ion beam. However, such beams are currently not available with sufficient intensities. In recent years, the ^{7}Li-induced incomplete-fusion reaction has been proved to be effective for populating high-spin states of nuclei near the line of stability [11,12]. As mentioned in Ref. [12], the weakly bound ^{7}Li nucleus can break up into either a proton, a deuteron, or a triton while the remaining He-like fragments (^{4,5,6}He) fuse with the target. These reactions are, in effect, the fusion-evaporation reactions using a radioactive beams of ^{4,5,6}He from the breakup of ^{7}Li.

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 [13]. In this Brief Report, we report the first observation of high-spin states in ^{195}Pt through the ^{7}Li+^{192}Os incomplete-fusion reaction.

The nucleus ^{195}Pt was produced in the ^{7}Li + ^{192}Os reaction via the (^{7}Li,$p3n$), (^{7}Li,$d2n$) and (^{7}Li,tn) channels. 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 a 1.7-mg/cm^{2}-thick isotopically enriched ^{192}Os metallic foil with a 1.1-mg/cm^{2} carbon backing to stop the recoiling nuclei. X-γ-t and γ-γ-t coincidence measurements were performed at a beam energy of 44 MeV with an array consisting of 12 Compton-suppressed HPGe detectors and two planar detectors for low-energy photon detection. 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 multipole orders 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 $\theta_1 = 90^{\circ}$ and another one with $\theta_2 = 40^{\circ}$ or 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 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 $R_{\mathrm{ADO}}(\gamma) = 1.20 \pm 0.15$ was obtained for the known $E2$ transitions in ^{194,195}Au and ^{194}Pt], and dipole transitions are assumed if $R_{\mathrm{ADO}}(\gamma)$s are less than 1.0.

In the ^{7}Li + ^{192}Os collision system, a number of Pt isotopes have been produced at high-spin states with different probabilities via the pxn, $d(x-1)n$, and $t(x-2)n$ reaction channels. Gamma-ray transitions can be assigned unambiguously to platinum through coincidences with characteristic x rays. However, it is difficult to assign the observed γ rays to a specific Pt nucleus in the absence of charged-particle detections. Given the fact that the level schemes of ^{191,193}Pt [8,9], ^{194}Pt [13], and ^{196}Pt [14] had been well known from previous studies, we have looked into the Pt K x-ray gated spectra; in addition to the known transitions emitted from the excited states of ^{193}Pt [9], ^{194}Pt [13], and ^{196}Pt [14], two strong transitions at energies of 368.8 and 578.1 keV have been clearly observed. These two transitions are mutually coincident, but they are not in coincidence with any of the known transitions in ^{193,194,196}Pt. Thus they are most likely the candidate transitions in ^{195}Pt.

The candidate transitions (368.8- and 578.1-keV lines) in ^{195}Pt are cross-checked by analyzing the γ-γ coincidence relationships in the ^{82}Se + ^{192}Os reaction [13]; the 368.8- and 578.1-keV lines are found to be in strong coincidence with the $2^+ \rightarrow 0^+$, 619-keV and $4^+ \rightarrow 2^+$, 951-keV transitions in ^{78}Ge [15]. In the ^{82}Se + ^{192}Os multinucleon transfer reaction, there are always multiple pairs of binary partners associated with a given nucleus. The corresponding partners of ^{78}Ge are $A \leqslant 196$ Pt isotopes in the ^{82}Se + ^{192}Os collision system. By double gating on the known γ rays in ^{78}Ge, one can identify the transitions belonging to its Pt partner.

To go further, we have then analyzed the relative cross sections for the different production of Pt isotopes. Usually, the relative cross sections for populating the different Pt nuclei can be estimated from the measured γ-ray flux into the ground states of the corresponding Pt isotopes [16]. In the case of odd-A Pt nuclei, it is not possible to determine the relative cross sections from the γ-ray flux to the ground states since the decay schemes of these nuclei involve a long-lived $13/2^+$ isomer. However, the γ-ray flux can be estimated qualitatively by extracting the γ-ray intensity using the lowest transition as a gate in each of Pt isotopes. Spectra gated on the 341.0-keV $17/2^+ \rightarrow 13/2^+$ (^{193}Pt), 328.5-keV $2^+ \rightarrow 0^+$ (^{194}Pt), 368.8- keV (candidate transition in ^{195}Pt), and 355.6-keV $2^+ \rightarrow 0^+$ (^{196}Pt) transitions are shown in Figs. 1(a), 1(b), 1(c), and 1(d), respectively. [Note that all the transitions in Fig. 1(c) were previously unknown.] We can clearly see that ^{194}Pt is the most strongly populated nucleus among the Pt isotopes. Also, as indicated in Fig. 1, the relative γ-ray yields in the 368.8-keV gated spectrum [Fig. 1(c)] are larger than those in the 341-keV gated spectrum [Fig. 1(a) for ^{193}Pt] and 355.6-keV gated spectrum [Fig. 1(d) for ^{196}Pt]. Thus the 368.8- keV transition as well as the other transitions in Fig. 1(c) should belong to ^{195}Pt; its population is expected in the present reaction since ^{194}Pt and ^{196}Pt are both populated. This analysis ruled out also the possibility of the 368.8-keV γ ray belonging to ^{197}Pt, which would be less populated in the (^{7}Li, pn) and (^{7}Li, d) channels at a beam energy of 44 MeV. Moreover, the assignment of these γ rays to ^{197}Pt is contrary to the fact that the binary partners of ^{78}Ge should have $A \leqslant 196$ in the ^{82}Se + ^{192}Os multinucleon transfer reaction. Accordingly, we propose that the 368.8-keV γ ray

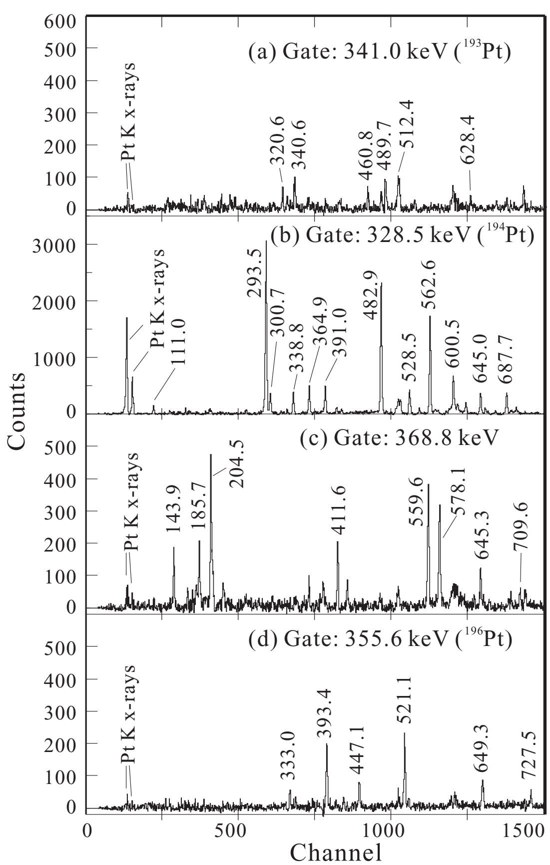

FIG. 1. The γ-ray coincidence spectra by setting a gate on (a) 341.0-keV $17/2^+ \rightarrow 13/2^+$ transition in ^{193}Pt, (b) 328.5-keV $2^+ \rightarrow 0^+$ transition in ^{194}Pt, (c) 368.8-keV transition, and (d) 355.6-keV $2^+ \rightarrow 0^+$ transition in ^{196}Pt.

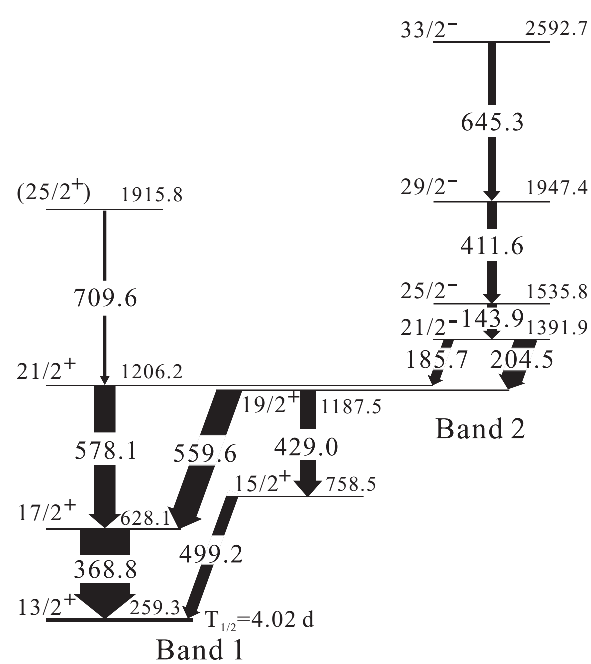

FIG. 2. Level scheme of ^{195}Pt deduced from this work. The widths of the arrows indicate the relative transition intensities.

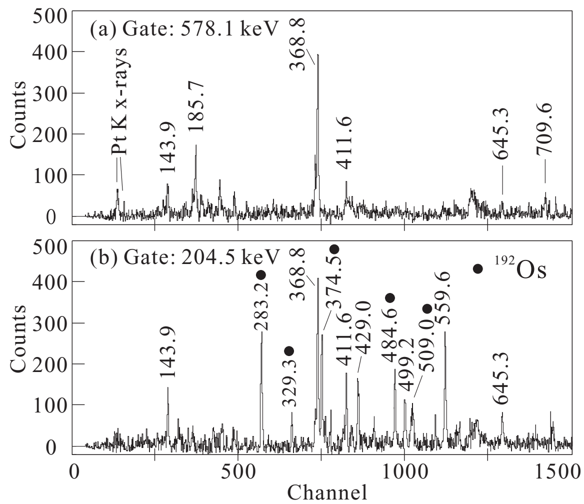

FIG. 3. The γ-ray coincidence spectra gated on (a) the 578.1-keV transition and (b) the 204.5-keV transition. Contaminant lines indicated by solid circles arise from ^{192}Os, which are in coincidence with 205.8-keV $2^+ \rightarrow 0^+$ transition [19].

corresponds to the $17/2^+ \rightarrow 13/2^+$ transition in ^{195}Pt, taking into account the similar $17/2^+ \rightarrow 13/2^+$ transitions (E_γ is about 300–400 keV) observed in odd-A $^{187-193}$Pt isotopes [6–9], while the other transitions in Fig. 1(c) should belong to the rotational bands above the $13/2^+$ state. These assignments are further supported from comparisons with the excited states in the neighboring ^{191,193}Pt nuclei, as will be discussed later.

Accepting the assignment of the 368.8-keV transition to ^{195}Pt, we have then analyzed the spectra in coincidence with this transition and, when possible, with the K x rays of Pt. The level scheme established from all the analyzed coincidence relationships is shown in Fig. 2, including 11 transitions and 9 levels. Typical γ-γ coincidence spectra gated on the 578.1- and 204.5-keV transitions are given in Fig. 3. We have gathered in Table I all the properties of the transitions assigned

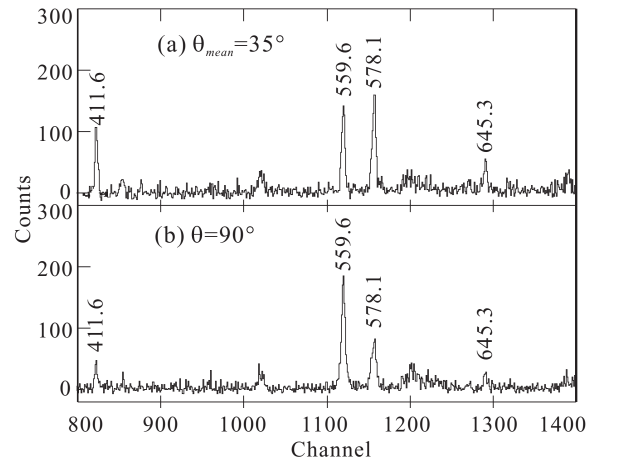

FIG. 4. Projected spectra at a mean angle of (a) 35° and (b) 90° by setting a gate on the 368.8-keV transition at all angles.

to ^{195}Pt from this work. In particular, the third column gives the $R_{\rm ADO}$ values, which allow us to determine the relative spins in the level scheme. As an example, we present the 368.8-keV gated spectra in Fig. 4. The contrasting behavior between the 559.6-keV $\Delta I = 1$ and 578.1-keV $\Delta I = 2$ (411.6- and 645.3-keV) transitions is clearly demonstrated in Fig. 4; the relative intensity of 578.1-keV $\Delta I = 2$ transition is large at a detection angle of $\theta_{\rm mean} = 35°$ [Fig. 4(a)] , while the 559.6-keV $\Delta I = 1$ transition is much enhanced at a detection angle of $\theta = 90°$ [Fig. 4(b)].

The weak 709.6-keV transition is in coincidence with the 368.8- and 578.1-keV lines [see Figs. 1(c) and 3(a)] but not in coincidence with other transitions in ^{195}Pt. A lack of sufficient statistics prevents a determination of its multipolarity. As this transition continues the rotational sequence of band 1, we could assume that it is the next $\Delta I = 2$ transition, and a tentative $I^\pi = (25/2^+)$ spin-parity value is proposed to the state at 1915.8 keV. It should be noted that only one transition

TABLE I. γ-ray transition energies, relative intensities, ADO ratios, and their assignments in ^{195}Pt.

E_γ (keV)[a]	I_γ[b]	$R_{\rm ADO}$	E_i (keV)[c]	E_f (keV)[c]	J_i^π[d]	J_f^π[d]
143.9	27(4)		1535.8	1391.9	$25/2^-$	$21/2^-$
185.7	29(3)	1.29(17)	1391.9	1206.2	$21/2^-$	$21/2^+$
204.5	47(6)	0.76(8)	1391.9	1187.5	$21/2^-$	$19/2^+$
368.8	100(8)	1.26(13)	628.1	259.3	$17/2^+$	$13/2^+$
411.6	30(4)	1.32(15)	1947.4	1535.8	$29/2^-$	$25/2^-$
429.0	47(6)	1.40(27)	1187.5	758.5	$19/2^+$	$15/2^+$
499.2	35(4)	0.61(11)	758.5	259.3	$15/2^+$	$13/2^+$
559.6	74(6)	0.50(6)	1187.5	628.1	$19/2^+$	$17/2^+$
578.1	64(5)	1.49(20)	1206.2	628.1	$21/2^+$	$17/2^+$
645.3	23(3)	1.34(37)	2592.7	1947.4	$33/2^-$	$29/2^-$
709.6	12(2)		1915.8	1206.2	$(25/2^+)$	$21/2^+$

[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.

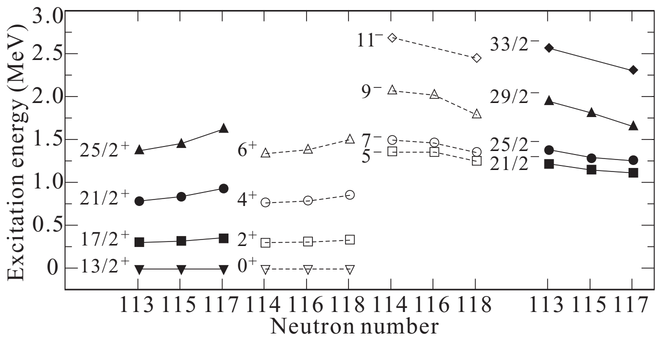

FIG. 5. Energy systematics of excited states in $^{191-196}$Pt. The excitation energies of the $13/2^+$ states in odd-A ^{191,193,195}Pt have all been normalized to the yrast levels of 0^+ in even-even ^{192,194,196}Pt for comparison. Solid (empty) symbols denote the excited states of odd-A (even-even) Pt isotopes. Data are taken from Ref. [19] and the present work.

(429.0-keV line) has been observed in the unfavored signature of band 1, as indicated in Fig. 3(b).

Two linking transitions, 185.7- and 204.5-keV lines, are observed between bands 1 and 2 (see Fig. 2). Figure 3 shows the members of band 2. The order of the γ rays in this band is determined by their relative intensities. The ADO ratio for the 204.5-keV line is measured to be 0.76(8). This value is consistent with a dipole $\Delta I = 1$ transition, leading to either an $I^\pi = 21/2^+$ or $21/2^-$ for the 1391.9 keV state. Based on the systematic observation of a $21/2^-$ state at similar excitation energy in the neighboring odd-A Pt nuclei [17], we propose spin and parity of $21/2^-$ for this level. As regards the 143.9-keV transition, we have extracted its internal conversion coefficient using its intensity imbalances measured from gating on the 645.3-keV transition. We have obtained a value of $\alpha_{\text{tot}} = 1.02(10)$ for the 143.6-keV transition. Using BRICC [18], theoretical total internal conversion coefficients have been calculated, yielding $\alpha_{\text{tot}}(E_\gamma = 143.6\text{ keV})$ values of 2.36, 0.16, 1.17, and 15.14 for the $M1$, $E1$, $E2$, and $M2$ multipolarities, respectively. The measured value of 1.02(10) is only consistent with an $E2$ transition.

We propose that band 1 in ^{195}Pt is associated with $\nu i_{13/2}^{-1}$ configuration, while band 2 is based on the $\nu i_{13/2}^{-2} \nu j^{-1} (j = p_{3/2}$ or $f_{5/2})$ configuration. These assignments are consistent with investigations of odd-$A^{187-193}$Pt nuclei in which two bands with the same configurations have all been identified [6–9]. Energy systematics of the $\nu i_{13/2}^{-1}$ and $\nu i_{13/2}^{-2} \nu j^{-1}$ (built on the $21/2^-$ state) bands in odd-A $^{191-195}$Pt are shown in Fig. 5 as a function of neutron number. Indeed, the energy level spacing of bands 1 and 2 in ^{195}Pt fits well into the systematics (see Fig. 5).

The excitation energies of the ground state and the $\nu i_{13/2}^{-1} \nu j^{-1}$ (built on the 5^- state) bands in ^{192,194,196}Pt are also presented in Fig. 5. As can be seen in Fig. 5, a close energy level spacing and parallel trends in excitation energy can be found between the bands in odd-A and those of even-even $A+1$ Pt isotopes. This behavior suggests that the excited states of bands in odd-A Pt nuclei can be understood as an $i_{13/2}$ neutron hole weakly coupled to the corresponding bandsin $A+1$ Pt cores. In Ref. [9], the particle-plus-triaxial-rotor (PTR) model was employed to describe the energy levels of the $\nu i_{13/2}^{-1}$ bands in ^{191,193}Pt. It has been shown [9] that the complex level spectra in ^{191,193}Pt could be well reproduced by the coupling of the $i_{13/2}$ neutron hole to a triaxially deformed even-even Pt core. In addition, the experimental $B(E2)$ values support the interpretation of the $\nu i_{13/2}^{-2} \nu j^{-1}$ bands in ^{191,193}Pt as arising from the coupling of the $i_{13/2}$ neutron hole with the $\nu i_{13/2}^{-1} \nu j^{-1}$ bands in the corresponding even-even Pt core [9].

In summary, high-spin states in the stable nucleus ^{195}Pt have been observed using the ^{7}Li + ^{192}Os incomplete-fusion reaction. The assignment of the transitions to ^{195}Pt is based on coincidences with Pt characteristic x rays and on an understanding of the [^{7}Li, $(p, d, t)xn$] cross sections. A level scheme built on the $\nu i_{13/2}$ isomer has been established. This result extends our knowledge of high-spin level structure to the most neutron-rich odd-A platinum isotope. The two bands have been assigned to be built on the $\nu i_{13/2}^{-1}$ and $\nu i_{13/2}^{-2} \nu j^{-1}$ configurations on referring to the similarity with the analogous bands in odd-A $^{187-193}$Pt, which can be interpreted as the coupling of a $\nu i_{13/2}$ neutron hole to the ground state and $\nu i_{13/2}^{-1} \nu j^{-1}$ bands in the ^{196}Pt core.

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