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Identification of the $K^{\pi} = 11/2^{+}$ isomer in neutron-rich ^{187}W

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Excited states in neutron-rich ^{187}W have been populated via deep inelastic collisions of a 630-MeV ^{82}Se beam on a ^{186}W target. Projectilelike fragments were measured by an annular Si detector for reaction channel selection. Delayed γ rays from target residues were detected by means of the so-called recoil shadow technique. A new isomer at 411 keV, based on the $11/2^{+}[615]$ Nilsson configuration, has been identified with a half-life of 1.55(13) μs. The decay rates of the isomers are discussed in terms of the K quantum number by comparison with the systematics from neighboring nuclei.

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The nucleus ^{187}W lies at the neutron-rich side of the nuclear valley of stability and thus cannot easily be produced in standard heavy-ion fusion-evaporation reactions with a stable beam and target combination. Energy levels of this nucleus have been studied to date via neutron capture [1–3] and (d, p) transfer reactions [3–6]. Although a number of low-spin negative-parity ($I^{\pi} = 1/2^{-}, 3/2^{-}$) levels, based on Nilsson configurations such as $1/2^{-}[510]$, $1/2^{-}[501]$, and $3/2^{-}[512]$, were predominantly populated in neutron capture on ^{186}W, higher spin ($5/2 \leqslant I \leqslant 9/2$) levels were observed in the ^{186}W(d, p) transfer reactions. In this mass region, low-lying one-quasiparticle isomers, in part resulting from the K selection for electromagnetic transitions, where K is defined as the projected component of the total angular momentum on the symmetry axis in deformed nuclei, are systematically observed. For example, in ^{183}W and ^{185}W, the $K^{\pi} = 11/2^{+}$ isomer based on the $11/2^{+}[615]$ Nilsson configuration is known to exist at excitation energies of 309 and 197 keV, respectively [7]. Although the $K^{\pi} = 11/2^{+}$ isomer in ^{187}W is expected at low excitation energy and much effort to search for this isomer has been made, no evidence has been found yet [3,5]. In this brief report, we report on new results, including identification of the $K^{\pi} = 11/2^{+}$ isomer, from a γ-ray spectroscopic experiment on ^{187}W produced by one-neutron transfer in deep inelastic collisions (DICs) between ^{82}Se and ^{186}W. This type of reaction has been proven to be effective for populating high-spin states through multinucleon transfer [8–11].

The experiment was performed at the tandem booster facility [12] of the Japan Atomic Energy Research Institute (JAERI). A 0.3-particle-nA ^{82}Se beam at an energy of 630 MeV was incident on a self-supporting target of ^{186}W enriched to 98.2%. The target was made of two stacked 450-μg/cm^2 foils. Both projectilelike fragments (PLFs) and targetlike fragments (TLFs) produced in DICs can recoil out from the target material into a vacuum. For the reaction channel selection, total kinematic energies of PLFs were measured by an annular Si detector [13], covering the scattering angles of $25^{\circ} \lesssim \theta \lesssim 50^{\circ}$ and $225^{\circ} \lesssim \phi \lesssim 315^{\circ}$. A tantalum catcher foil, with thickness of 100 μm was placed across the Si detector, approximately 40 mm from the target, to collect TLFs. The foil covered the solid angle of $60^{\circ} \lesssim \theta \lesssim 80^{\circ}$ and $45^{\circ} \lesssim \phi \lesssim 135^{\circ}$. Delayed γ rays from the TLFs emitted at the catcher foil were detected by three HP-Ge detectors with a relative efficiency of 60%. These detectors were arranged horizontally (one detector) and vertically (two detectors) at an angle of 90° with respect to the beam direction. Prompt γ-ray radiation at the target position was shielded by a lead absorber placed between the target and the Ge detectors. The time difference (Δt) between PLF and γ-ray signals was measured by time-to-amplitude conversion (TAC). The TAC range was set to 2 μs. Energy and time information on PLFs and γ rays was recorded event by event on magnetic tape. A total of 1.6×10^{8} and 3.9×10^{7} events for PLF-γ and PLF-$\gamma\gamma$ coincidences, respectively, were collected. Energy and efficiency calibration of the Ge detectors was made by using ^{133}Ba, ^{152}Eu, and ^{241}Am standard γ-ray sources.

An energy spectrum of PLFs in coincidence with γ rays is shown in Fig. 1. The energy spectra of γ rays gated on different energy ranges of PLFs, indicated by A and B in this figure, are shown in Fig. 2. The previously known γ rays from the isomers in ^{187}W [7], ^{187}Re [14], and ^{185}Re [15] populated in DICs can be clearly seen in the spectrum of gate B, but they are hardly observed in that of gate A. Thus, imposing the condition that the PLF energy be in the range of gate B, the experimental data were sorted into (E_{γ}, E_{γ}) two-dimensional matrices with various PLF-γ time (Δt) windows.

Figure 3 shows a partial level scheme of ^{187}W deduced from the present experimental data. The ground state based on

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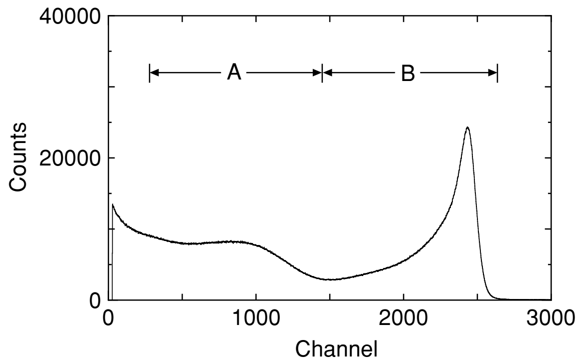

FIG. 1. A PLF energy spectrum measured with the Si detector.

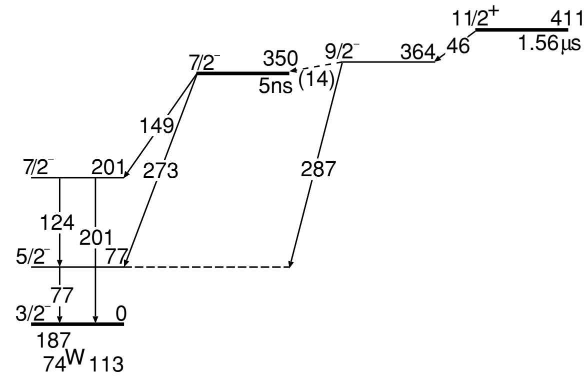

FIG. 3. A partial level scheme of ^{187}W deduced from the present data. Levels below the 364-keV state are known from previous work [3,5]. The 14-keV transition is unobserved but deduced from the γ-ray coincidence relation.

the $3/2^-[512]$ Nilsson configuration and its rotational band members are known from previous work [3]. The 5-ns isomer at 350 keV [16], based on the $7/2^-[503]$ Nilsson configuration, is depopulated by the 149- and 273-keV γ-ray transitions into the ground-state rotational band. Above the 5-ns isomer, the $K^\pi = 9/2^-$ state at 364 keV, based on the $9/2^-[505]$ Nilsson configuration, is known to decay to the 77-keV state via the 287-keV transition [3]. In this study, a new μs isomer depopulated by a 46-keV transition has been found above the $K^\pi = 9/2^-$ state. The 46-keV transition was previously observed in coincidence with the 273-keV transition. However, this transition has not been placed in the level scheme [3]. As shown in Fig. 4(a), the present data confirm the coincidence relation between the 46- and 273-keV transitions. In addition, the 46-keV transition has been found in coincidence with the 77-, 124-, 149-, 201-, and 287-keV transitions as shown in Fig. 4(b), suggesting that the 46-keV transition feeds the the 364-keV state from the newly observed isomer with the excitation energy being 411 keV. The coincidence pattern of the 46-keV transition implies an unobserved 14-keV transition that connects the 350- and 364-keV states. The total intensity ratio (including the internal conversion correction) of the 287-keV transition to the 14-keV transition is estimated to be 3.8(26)%, assuming that the 14-keV (287-keV) transition is of pure $M1$ ($E2$) character. Information on the γ-ray transitions in ^{187}W is summarized in Table I.

To deduce the multipolarity of the 46-keV transition, the intensity balance of the γ-ray transitions above and below the 350-keV level was examined. Assuming pure $M1$ character for both the 149- and 273-keV transitions, we extracted the total conversion coefficient for the 46-keV transition as $\alpha_{\text{tot}} = 0.8(1)$. Comparing it with the calculated values [17] of $\alpha_{\text{tot}} = 0.6$ ($E1$), 8 ($M1$), and 128 ($E2$) indicates an $E1$ assignment for the 46-keV transition. This result supports an $I^\pi = 9/2^+$ or $11/2^+$ assignment for the 411-keV state. However, the former assignment is excluded as follows. If the 411-keV state has $I^\pi = 9/2^+$, the 61-keV $E1$ transition feeding the $I^\pi = 7/2^-$ state at 350 keV would be observed. In the present data, no such transition has been detected. The $I^\pi = 11/2^+$ assignment is therefore preferred for the 411-keV state. From the

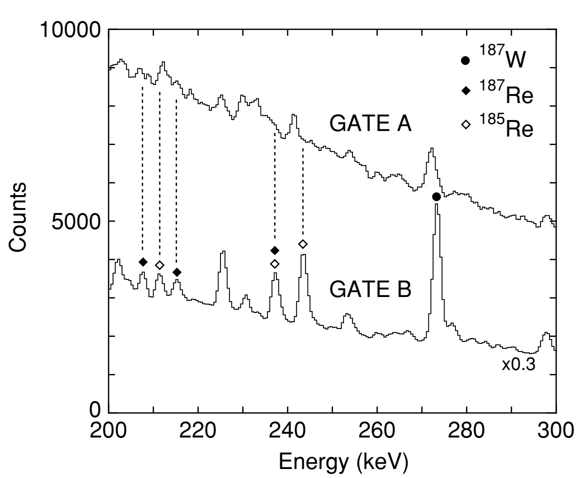

FIG. 2. γ-ray energy spectra in coincidence with PLFs in different energy ranges indicated in Fig. 1. The known γ rays from the isomers in ^{187}W (filled circle), ^{187}Re (filled diamonds), and ^{185}Re (open diamonds) are marked with symbols.

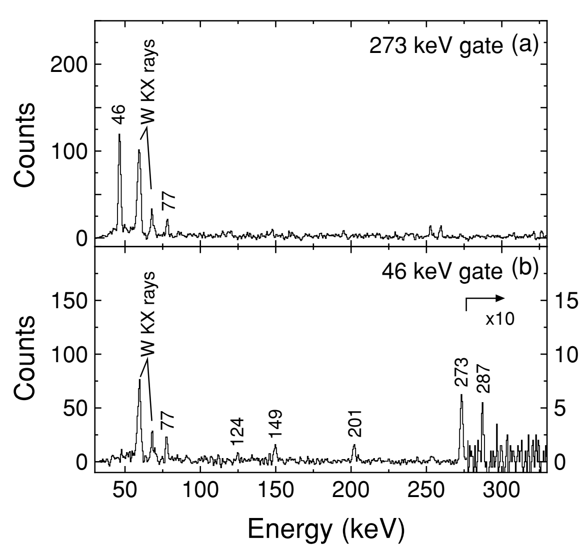

FIG. 4. Delayed γ-ray coincidence spectra gated on (a) the 273-keV and (b) the 46-keV transitions. Note that the vertical scale in panel (b) is changed at $E_\gamma = 275$ keV. The PLF-γ time (Δt) window is set to 150–1100 ns.

TABLE I. Energies, level assignments, and relative intensities of the γ-ray transitions in ^{187}W.

E_γ (keV)	E_i (keV)	J_i^π	$\rightarrow$	J_f^π	I_γ
14[a]	364.1	$9/2^-$	$\rightarrow$	$7/2^-$	—
45.8(3)	410.9	$11/2^+$	$\rightarrow$	$9/2^-$	1000
77.1(2)	77.1	$5/2^-$	$\rightarrow$	$3/2^-$	119(25)
124.1(2)	201.2	$7/2^-$	$\rightarrow$	$5/2^-$	46(30)
148.8(2)	349.9	$7/2^-$	$\rightarrow$	$7/2^-$	271(178)
201.2(2)	201.2	$7/2^-$	$\rightarrow$	$3/2^-$	140(27)
272.7(2)	349.9	$7/2^-$	$\rightarrow$	$5/2^-$	749(143)
287.0(3)	364.1	$9/2^-$	$\rightarrow$	$5/2^-$	45(30)

[a]The transition is not observed but deduced.

energy systematics of one-quasiparticle isomers in this mass region, the isomer at 411 keV can be considered to be based on the $11/2^+$[615] Nilsson configuration. Note that the $K^\pi = 11/2^+$ isomers are known at 309 keV in ^{183}W and 197 keV in ^{185}W [7]. The variation of the energy levels of the intrinsic states in the wolfram nuclei was explained by the Nilsson model calculation with introduction of hexadecapole deformation [5,18].

The decay slopes of the 46- and 273-keV γ rays shown in Fig. 5 correspond to half-lives of 1.59(24) and 1.53(15) μs, respectively, which were obtained by least-square fitting. By taking the weighted mean of these values, the half-life of the $K^\pi = 11/2^+$ isomer was determined to be 1.55(13) μs. Furthermore, the present data give an upper limit of 15 ns for the half-life of the $K^\pi = 9/2^-$ state at 364 keV.

Electromagnetic transitions involving the K change equal to or less than the transition multipolarity (i.e., $\Delta K \leqslant \lambda$) are allowed in the K selection rule, otherwise the transitions ($\Delta K > \lambda$) are forbidden. Both types of transitions can be discussed in terms of the hindrance factor $F = T^\gamma_{1/2}/T^W_{1/2}$ or the hindrance factor per degree of K forbiddenness $f_\nu = F^{1/\nu}$, where $T^\gamma_{1/2}$ is the partial γ-ray half-life, $T^W_{1/2}$ is the corresponding Weisskopf single-particle estimate, and ν is the order of K forbiddenness. The 364-keV state decays by the 287-keV, K-forbidden $E2$ transition with $\nu = 1$. The value of $f_\nu < 100$ for this transition is along the systematic behavior of the f_ν values, being consistent with $f_\nu = 10$–100, but too large to make a detailed discussion on the role of the K quantum number in this nucleus.

The $K^\pi = 11/2^+$ isomer decays by the 46-keV, K-allowed $E1$ transition, and its half-life of 1.56 μs is much shorter than those observed for the $K^\pi = 11/2^+$ isomers in

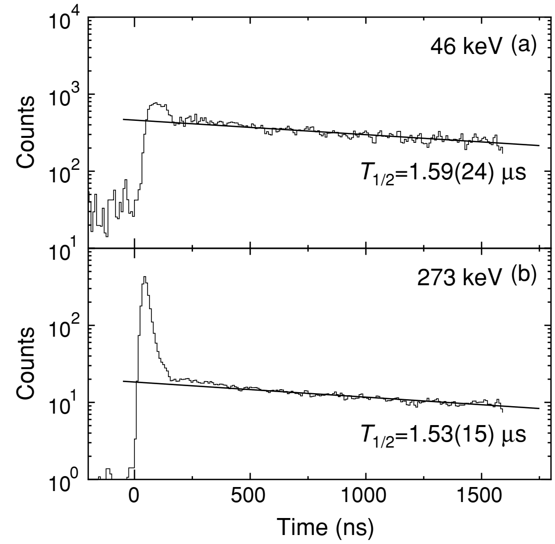

FIG. 5. TAC spectra obtained for the (a) 46-keV and (b) 273-keV γ rays in ^{187}W. The fast decay component seen in the decay curve for the 273-keV transition is attributed to the 5-ns isomer at 350 keV.

^{183}W ($T_{1/2} = 5.2$ s) and ^{185}W ($T_{1/2} = 100$ s). This is partly because the $K^\pi = 11/2^+$ isomer in ^{187}W decays by the K-allowed transition, whereas those in ^{183}W and ^{185}W decay by the K-forbidden transitions with higher multipoles ($M2$, $E3$). Assuming that the 46-keV transition has pure $E1$ character, we can extract the partial γ-ray half-life as 2.5 μs, corresponding to the hindrance factor of $F = 1.1 \times 10^6$. This is within the systematic value of $F \approx 10^3$–10^7 expected for K-allowed $E1$ transitions in this mass region [19].

In summary, excited states in neutron-rich ^{187}W have been populated via deep inelastic collisions between ^{82}Se and ^{186}W. From an analysis of the prompt-$\gamma\gamma$ and delayed-$\gamma\gamma$ coincidence matrices, a new isomer was identified at an excitation energy of 411 keV. The $11/2^+$[615] Nilsson configuration was assigned to this isomer. The measured half-life is 1.55(13) μs, and the observed $E1$ transition rate is consistent with the systematic value of K-allowed $E1$ transitions in this mass region.

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