Excited states in the highly neutron-deficient nucleus $^{162}\text{W}$ have been investigated via the $^{92}\text{Mo}(^{78}\text{Kr}, 2\alpha)^{162}\text{W}$ reaction. Prompt $\gamma$ rays were detected by the JUROGAM II high-purity germanium detector array and the recoiling fusion-evaporation products were separated by the recoil ion transport unit (RITU) gas-filled recoil separator and identified with the gamma recoil electron alpha tagging (GREAT) spectrometer at the focal plane of RITU. $\gamma$ rays from $^{162}\text{W}$ were identified uniquely using mother-daughter and mother-daughter-granddaughter $\alpha$-decay correlations. The observation of a rotational-like ground-state band is interpreted within the framework of total Routhian surface (TRS) calculations, which suggest an axially symmetric ground-state shape with a $\gamma$-soft minimum at $\beta_2 \approx 0.15$. Quasiparticle alignment effects are discussed based on cranked shell model calculations. New measurements of the $^{162}\text{W}$ ground-state $\alpha$-decay energy and half-life were also performed. The observed $\alpha$-decay energy agrees with previous measurements. The half-life of $^{162}\text{W}$ was determined to be $t_{1/2} = 990(30)$ ms. This value deviates significantly from the currently adopted value of $t_{1/2} = 1360(70)$ ms. In addition, the $\alpha$-decay energy and half-life of $^{166}\text{Os}$ were measured and found to agree with the adopted values.

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differential plunger for unbound nuclear states (DPUNS) device [7]. A 1.0-mg/cm² Mg degrader foil was applied to slow the recoils from \( v/c = 0.044 \) to \( v/c = 0.034 \) and was placed at nine different distances from 5 to 8000 \( \mu \)m downstream the target position during the irradiation. Prompt \( \gamma \) rays were detected by the JUROGAM II \( \gamma \)-detector array. Fifteen EUROGAM phase I [8] and GASP-type [9] germanium detectors were placed in two rings with five detectors at 157.6° and ten detectors at 133.6° relative to the beam direction. Twenty-four EUROBALL clover detectors [10] were placed in two rings with twelve at 104.5° and the other twelve at 75.5° relative to the beam direction. The total photo-peak efficiency was 6.0% at 1.3 MeV [11]. The separation of recoiling fusion-evaporation products from beam particles and fission products was performed by the gas-filled recoil ion transport unit (RITU) [12,13] separator. The reaction products were subsequently implanted at the focal plane of RITU into two double-sided silicon strip detectors (DSSSDs) of the gamma recoil electron alpha tagging (GREAT) [14] decay spectrometer. This composite detector installation additionally consisted of a multiwire proportional counter (MWPC), an array of Si PIN diode detectors, a planar germanium detector, and three clover-type germanium detectors. The recoiling fusion residues were discriminated from scattered beam components by means of the energy loss (\( \Delta E \)) in the MWPC and the time of flight between the MWPC and the DSSSDs. A triggerless total data readout (TDR) acquisition system [15] with 10-ns time-stamp precision was used for collecting data. This allowed accurate temporal correlations to be recorded between prompt \( \gamma \) rays detected at the target position, recoil implants at the RITU focal plane, and their subsequent radioactive decays. For practical reasons a maximum time window of 20 s was used for studies of correlations between implantation of fusion-evaporation residues and subsequent decays in the DSSSDs.

The events were reconstructed off line using the GRAIN software package [16]. In the off-line analysis, only events that could be associated with a recoil implantation signal in the DSSSDs were selected. Prompt \( \gamma-\gamma \) coincidences were selected from the \( \gamma \) rays detected in JUROGAM II at a preceding time corresponding to the flight time of fusion-evaporation residues through RITU to the DSSSDs. In addition, a narrow gate on the \( \gamma-\gamma \) time difference of 140 ns was applied. Then, the events were sorted into one- and two-dimensional \( \gamma \)-ray energy histograms with different conditions on the subsequent signals detected in the decay spectrometer. In the off-line analysis, the RADWARE software package [17] was used to construct the level scheme.

The \( \alpha \)-decay properties of \( ^{162}\text{W} \) were investigated using events where \( ^{162}\text{W} \) was produced as a primary reaction product as well as with events where \( ^{162}\text{W} \) was produced as a decay product of \( ^{166}\text{Os} \) (from the \( 2p2n \)-fusion-evaporation channel). Figure 1(a) shows the \( ^{162}\text{W} \)-\( \alpha \)-decay spectrum correlated with a recoil-mother (\( ^{166}\text{Os} \))–granddaughter (\( ^{158}\text{Hf} \)) chain in the same pixel of the DSSSD implantation detectors, and gives an indication of the purity of the event selection considering random correlations. The \( \alpha \)-decay spectrum for \( ^{162}\text{W} \) is produced without any time condition on its \( \alpha \) decay but requiring about three half-lives of search time as well as energy conditions on the \( ^{166}\text{Os} \) mother \( \alpha \) decay \( (t_{1/2} = 220(7) \text{ ms}, E_{\alpha} = 6000(6) \text{ keV}) \) and \( ^{158}\text{Hf} \) granddaughter \( \alpha \) decay \( (t_{1/2} = 2850(70) \text{ ms}, E_{\alpha} = 5269(4) \text{ keV}) \) as reported in Ref. [18].

In the spectrum, there is only evidence of the \( ^{162}\text{W} \alpha \) decay with the characteristic distribution from escaped events, i.e., \( \alpha \) particles which have left the DSSSDs without depositing their full energy. The half-life of \( ^{162}\text{W} \) was here determined to be \( t_{1/2} = 990(30) \text{ ms} \); see the inset of Fig. 1(a). This value deviates significantly from the currently adopted value of \( t_{1/2} = 1360(70) \text{ ms} \) [19]. The \( \alpha \)-decay energy for \( ^{162}\text{W} \), see Fig. 1(a), is consistent with the value of \( E_{\alpha} = 5541(5) \text{ keV} \) measured by Page et al. [18]. By analyzing the distribution of time differences between implanted recoils and subsequent \( ^{162}\text{W} \) decays (i.e., for events when \( ^{162}\text{W} \) is produced directly as a fusion product), a half-life value for \( ^{162}\text{W} \) consistent with the result shown in the inset of Fig. 1(a) was also obtained.
The same method was also used for measuring the half-life of $^{166}\text{Os}$, as shown in Fig. 1(b). The obtained value for $^{166}\text{Os}$ is $t_{1/2} = 210(6) \text{ ms}$, which is consistent with the value reported by Page et al. [18]. This possible influence from random correlations on the determination of the half-life values was studied by analyzing subsets of the data with different pixel recoil rates. The results are found to be free from any such bias. This was also checked by means of Monte-Carlo simulations. It should also be noted that there is no bias on the measured half-lives introduced from the overall time window of 20 s applied in the analysis of recoil implants and their subsequent decays in the DSSSDs. For both the $^{166}\text{Os}$ and $^{162}\text{W}$ half-life measurements the applied maximum correlation times for the associated events in the decay chains imply that at least ten half-lives are considered in each case.

A prompt $\gamma$-ray energy spectrum recorded by JUROGAM II at the target position in delayed coincidence with a recoil detected in the DSSSDs is shown in Fig. 2(a). It is dominated by much stronger fusion-evaporation channels than the 2$\alpha$-evaporation channel leading to $^{162}\text{W}$; mainly the $3\text{pn}$, $4\text{p}$, and $4\text{pn}$ channels leading to $^{166}\text{Re}$, $^{166}\text{W}$, and $^{165}\text{W}$, respectively. The selective power of the RDT technique is illustrated in Fig. 2(b), where a recoil-$\alpha$-$\alpha$ tagged prompt $\gamma$-ray spectrum is shown, obtained by selecting both the mother nucleus of $^{162}\text{W}$ $\alpha$ decays and $^{158}\text{Hf}$ daughter $\alpha$ decays with the search times between subsequent events in a given pixel of the DSSSDs set to 3 and 6 s, respectively. In this spectrum, all $\gamma$-ray lines which are indicated by their energy (in keV) are firmly assigned to originate from decays of excited states in $^{162}\text{W}$. Following implantation of $^{162}\text{W}$ fusion products in the DSSSDs, it was possible to follow the subsequent $\alpha$-decay chain down to its end point in $^{150}\text{Er}$. Both the $\alpha$-decay daughter ($^{158}\text{Hf}$) and granddaughter ($^{154}\text{Yb}$) are $\alpha$ emitters with significant $\alpha$-branching ratios of 45(3)% and 92(2)%, respectively [18]. Therefore, recoil-$\alpha$-$\alpha$-$\alpha$ correlations were also investigated. Figure 2(c) shows the recoil-mother-daughter-granddaughter correlated prompt $\gamma$-ray spectrum. This $\gamma$-ray spectrum confirms the assignment of $\gamma$ rays to $^{162}\text{W}$ from the recoil-$\alpha$-$\alpha$ correlated spectrum. Hence, despite the limited statistics, the clean $\alpha$-correlation chain and the unique identification of $\gamma$ rays with the RDT method enable a firm assignment of the identified $\gamma$ rays to $^{162}\text{W}$. This confirms the results reported by Dracoulis et al., for which the assignment of $\gamma$-ray transitions to a specific $Z$ value was based on coincidences with characteristic x rays [6].

The proposed level scheme deduced in this work is shown in Fig. 3. Based on the coincidence relationships and relative intensities, the $\gamma$ rays assigned to $^{162}\text{W}$ are arranged as a cascade of stretched $E2$ transitions. The most intense 449-keV peak is hence assigned as the $(2^+ \rightarrow 0^+)$ transition in $^{162}\text{W}$. This agrees with the earlier report, where a plot of a $\gamma$-ray energy spectrum in coincidence with the $(2^+ \rightarrow 0^+)$ 449 keV transition was shown [6].

Examples of recoil-$\alpha$ tagged $\gamma$-ray energy spectra for $^{162}\text{W}$ are shown in Fig. 4, which are obtained only from the clover detectors near 90° in order to avoid Doppler effects from the Plunger setup. Figure 4(a) presents the $\gamma$-ray spectrum coincident with the 449-keV $\gamma$-ray transition tagged by the $^{162}\text{W}$ $\alpha$-decay energy. In this spectrum, all the $\gamma$-ray transitions above the $(2^+)$ state in Fig. 3 are marked. The $\gamma$-ray peak

FIG. 2. (a) $\gamma$-ray spectrum of recoil-tagged singles. (b) $^{162}\text{W}$ mother-daughter correlated $\alpha$-decay-tagged $\gamma$-ray singles. The maximum correlation time between recoils and mother nucleus ($^{162}\text{W}$) $\alpha$ decays and subsequent daughter nucleus ($^{158}\text{Hf}$) $\alpha$ decays are 3 and 6 s, respectively. The unmarked peaks are the $\gamma$-ray transitions from the strong populated channels. (c) As in panel (b) with the additional requirement of granddaughter $^{154}\text{Yb}$ $\alpha$ decay correlated within 1.2 s in the same pixel of the DSSSDs.
around 627 keV is regarded as a doublet based on the peak width and its self-coincident nature. The spectrum gated on the 563-keV $\gamma$-ray transition with tagging on the $^{162}$W $\alpha$ decay is shown in Fig. 4(b). To highlight the weaker transitions in Fig. 3, a spectrum produced by adding all the gates below is shown in Fig. 4(c). In this figure, the 556- and 629-keV $\gamma$-ray transitions can be seen more clearly. The energies, relative intensities, suggested multipolarities, and tentative spin-parity assignments of initial and final states for the $\gamma$-ray transitions assigned to $^{162}$W are listed in Table I.

III. DISCUSSION

Figure 5 shows a systematic comparison between low-lying yrast excited-state level energies in neutron-deficient even-$N$ tungsten isotopes, ranging from $N = 94$ to the lightest $N = 84$ tungsten isotope ($^{158}$W) for which excited states are known. Note that the only excited state reported in $^{158}$W is an $\alpha$-decaying isomer at 1.888 MeV, assigned to the $\nu(f_{7/2}h_{9/2})8^+$ shell model configuration [20]. The variation of excited $8^+$ state energies in $^{162}$Os and neighboring nuclei has been discussed, e.g., in Ref. [25]. A gradual transition in the so-called collective character of the ground-state bands is observed, from a clear rotational-like pattern in $^{160}$W to a level sequence reminiscent of near-harmonic vibrational excitations in $^{164}$W. In the latter case a depression in the $8^+$ level energy might be associated with the so-called collective character of the ground-state bands.

Table II shows a systematic comparison between the lowest-lying yrast excited-state level energies in neutron-deficient even-$N$ tungsten isotopes, ranging from $N = 94$ to the lightest $N = 84$ tungsten isotope ($^{158}$W) for which excited states are known. Note that the only excited state reported in $^{158}$W is an $\alpha$-decaying isomer at 1.888 MeV, assigned to the $\nu(f_{7/2}h_{9/2})8^+$ shell model configuration [20]. The variation of excited $8^+$ state energies in $^{162}$Os and neighboring nuclei has been discussed, e.g., in Ref. [25]. A gradual transition in the so-called collective character of the ground-state bands is observed, from a clear rotational-like pattern in $^{160}$W to a level sequence reminiscent of near-harmonic vibrational excitations in $^{164}$W. In the latter case a depression in the $8^+$ level energy might be associated with the so-called collective character of the ground-state bands.

Pairing self-consistent Woods-Saxon-Strutinsky calculations using the total Routhian surface (TRS) approach [27,28] have been performed for $^{162}$W. The total Routhian surfaces starting from the ground-state (quasiparticle vacuum) configuration are shown in Fig. 6. The minimum points in the energy surfaces are indicated by red (gray) dots. At zero rotational frequency, the minimum point indicated at $Y = -0.15$ (on the noncollective axis) is equivalent to the minimum at $(\beta_2 = 0.15, \gamma = 0^\circ)$ on the prolate collective axis. A prolate ground-state shape is hence predicted with the quadrupole deformation parameter $\beta_2$ around 0.15. At a rotational frequency $\hbar \omega \approx 0.35$ MeV, the triaxial quadrupole deformation $\gamma$ starts to increase and the $\beta_2$ deformation decreases. The TRS minimum then collapses into a noncollective structure. This might be associated with the alignment of a pair of $\nu f_{7/2} / h_{9/2}$ quasiparticles.

TABLE I. $\gamma$-ray energies, relative intensities, tentative multipolarities, and spin-parity assignments for $^{162}$W. Intensities ($I_\gamma$) are adjusted for detector efficiencies and normalized to the strongest transition at $E_\gamma = 449$ keV. Statistical uncertainties are given in parentheses. Spin and parity assignments are tentative. Tentative assignments are given within parentheses.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Relative intensity</th>
<th>$I_\gamma \rightarrow I_\gamma$</th>
<th>Multipolarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>449.4(3)</td>
<td>100</td>
<td>$(2^+) \rightarrow (0^+)$</td>
<td>(E2)</td>
</tr>
<tr>
<td>563.1(3)</td>
<td>80(14)</td>
<td>$(4^+) \rightarrow (2^+)$</td>
<td>(E2)</td>
</tr>
<tr>
<td>556.2(6)</td>
<td>9(4)</td>
<td>$(10^+) \rightarrow (8^+)$</td>
<td>(E2)</td>
</tr>
<tr>
<td>619(1)</td>
<td>&lt;1</td>
<td>$(12^+) \rightarrow (10^+)$</td>
<td>(E2)</td>
</tr>
<tr>
<td>625.7(3)</td>
<td>54(9)</td>
<td>$(6^+) \rightarrow (4^+)$</td>
<td>(E2)</td>
</tr>
<tr>
<td>628.6(3)</td>
<td>42(7)</td>
<td>$(8^+) \rightarrow (6^+)$</td>
<td>(E2)</td>
</tr>
</tbody>
</table>

FIG. 4. Background-subtracted spectra of $\gamma$ rays tagged by the ground-state $\alpha$ decay of $^{162}$W and detected in prompt coincidence with the (a) 449-keV $\gamma$ ray, (b) 563-keV $\gamma$ ray, and (c) 449-, 563-, 626-, or 629-keV $\gamma$ rays.

FIG. 5. (Color online) Yrast level energies in the most neutron-deficient even-$N$ tungsten isotopes with $N = 84$–94 [20–24].
in the laboratory frame with respect to a reference rotor. The degree of quasiparticle alignment can be observed in the plot of aligned angular momentum, $i/\hbar$, versus rotational frequency, $\hbar\omega$, with respect to the same reference rotor. The experimental Routhians, $e'$, and alignments, $i$, are respectively expressed by

$$e'(\omega) = E(\omega) - \omega I_1(\omega) = E_{\text{ref}}(\omega)$$

and

$$i(\omega) = I_1(\omega) - I_{\text{ref}}(\omega).$$

Here, $I_1(\omega)$ is the projection of total angular momentum along the rotational axis $x$ and $E(I)$ is the energy at the intermediate value of the angular momentum $I$. The spin and energy of the reference configuration in the Harris description [29] are

$$I_{\text{ref}}(\omega) = J_0\omega + J_1\omega^3$$

and

$$E_{\text{ref}}(\omega) = \frac{1}{8J_0} - \frac{\omega^2}{2} J_0 - \frac{\omega^4}{4} J_1.$$

The extracted experimental Routhians and quasiparticle alignments versus rotational frequency are compared with the isotope $^{164}$W [22] and isotope $^{160}$Hf [26] in Fig. 7.

The ground-state band in $^{162}$W exhibits a sharp increase in aligned angular momentum of $\Delta i \approx 6\hbar$ at $\hbar\omega \approx 0.30$ MeV. This alignment is slightly delayed and is significantly reduced in amplitude with respect to the observed band crossing in $^{164}$W, which was assigned to be due to the first rotational alignment (AB) of a pair of $i_{13/2}$ neutrons [22]. However, at $N < 90$, the neutron Fermi level is significantly below the $i_{13/2}$ subshell and two-quasineutron alignments emanating from the mixed $f_{7/2}$ and $h_{9/2}$ subshells can compete with the pure $i_{13/2}$ two-quasineutron alignment as discussed, e.g., by Dracoulis et al. [6]; see Fig. 8 (upper panel). The amount of aligned angular momentum might indicate that the $S$-band in $^{164}$W is dominated by neutrons from the $f_{7/2}$ subshell. The isotope, $^{160}$Hf, exhibits a further delayed band crossing at $\hbar\omega \approx 0.32$ MeV, with an intermediate value for the aligned angular momentum ($\Delta i \approx 8\hbar$), which seems to be followed by yet another band crossing at $\hbar\omega \approx 0.35$ MeV. A paired quasiproton band crossing originating from the $h_{11/2}$ subshell is predicted by our cranked shell model calculations [30,31], see Fig. 8 (lower panel), at similar rotational frequencies as that due to the $v(f_{7/2}/h_{9/2})^2$ alignment. Hence, it is possible that the alignments observed for $^{160}$Hf are due to successive $v(f_{7/2}/h_{9/2})^2/\pi(h_{11/2})^2$ band crossings and that the difference compared with $^{162}$W is due to a difference in shape and position of the proton Fermi level. However, note that Murzel et al. [26] assigned the first band crossing in $^{160}$Hf to a $v(i_{13/2})^2$ AB quasiparticle alignment and discussed the reduced aligned angular momentum compared with the CSM predictions in terms of $\gamma$ softness of the nuclear potential.

The nuclear structure effect on the $\alpha$ decay is carried by the so-called $\alpha$-formation probability on the nuclear surface, which can be extracted from the experimental $\alpha$-partial half-life and decay value, $Q$, as in Refs. [33–35]. As discussed in the above references, in most cases the experimental $\alpha$-formation probabilities show a rather smooth behavior when going from a nucleus to its neighboring nuclei, which is related to the fact that the $\alpha$ clustering is dominated by the slowly varying nuclear pairing correlations. As a result, the abrupt change in the systematics of $\alpha$-formation probability would indicate a transition in the underlying nuclear structure. In Fig. 9, we plotted the experimental $\alpha$ formation probabilities thus...
FIG. 8. Cranked Routhians using the universal Woods-Saxon potential for quasineutrons (upper panel) and quasiprotons (the lower panel) in $^{162}$W with the deformation parameters $\beta_2 = 0.146$, $\beta_2 = 0.010$, and $\gamma = 0^\circ$ taken from TRS predictions. Different lines represent different parities and signatures ($\pi, \alpha$): solid denotes (+, +1/2), dotted denotes (+, −1/2), dot-dashed denotes (−, +1/2), and dashed denotes (−, −1/2). Quasiparticle alignments due to a pair of $h_{11/2}$ protons are predicted at $\hbar\omega \approx 0.36$ MeV while $f_{7/2}/h_{9/2}$ and $i_{13/2}$ neutrons are predicted to align at $\hbar\omega \approx 0.36$ and $\hbar\omega \approx 0.41$ MeV, respectively. The shell model labelings for quasiparticles in $^{162}$W are marked as below: A, $vi_{13/2}$ with positive signature; B, $vi_{13/2}$ with negative signature; E, $vf_{7/2}/h_{9/2}$ with negative signature; F, $vf_{7/2}/h_{9/2}$ with positive signature; c, $\pi h_{11/2}$ with negative signature; and f, $\pi h_{11/2}$ with positive signature.

FIG. 9. (Color online) $\alpha$-formation probabilities $|RF(R)|^2$ calculated from experimental $\alpha$-decay partial half-lives as a function of neutron number, $N$, for the $\alpha$ decays of even-even Hf, W, Os, and Pt isotopes. The experimental data represented by solid symbols are from NNDC [32]. Our new data for $^{162}$W is shown as the open symbol.