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Isomeric states in ^{165}W and ^{169}W

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Properties of isomeric states and the deexcitation paths to the ground state have been observed in ^{165}W and ^{169}W nuclei in experiments employing fusion-evaporation reactions at the Accelerator Laboratory of the University of Jyväskylä, Finland. The $(13/2^+)$ isomeric state in ^{165}W was measured to have a half-life of 7.4(2) μs and an excitation energy of 301.4(3) keV, while in ^{169}W, the $J^\pi = (9/2^+)$ isomeric state at 127.2(3) keV has $t_{1/2} = 7.4(5)$ μs. The observed hindrance factors are 6.9(2) for the $M2$ deexciting transition in ^{165}W and $2.29(15) \times 10^6$ for the $E1$ deexciting transition in ^{169}W, of which the former is a typical value in this region, while the latter is an order of magnitude larger than most other similar cases. The excited- and ground-state spin assignments are discussed.

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I. INTRODUCTION

Nuclei in the region between the $N = 82$ closed shell and the neutron midshell span an evolution from near-spherical to well-deformed prolate nuclear shapes. These structural changes can occur rapidly with the change of only a few neutrons. They are reflected in the smooth, characteristic variation of bandhead excitation energies built on the underlying single-particle states, whose relative ordering shifts with deformation in the Nilsson potential. Establishing the excitation energies of the bandheads is therefore an essential prerequisite to systematically probing competition between single-particle and collective degrees of freedom across this transitional region.

The value of these systematics is well established. The comprehensive reviews of Bunker and Reich [1] and Jain *et al.* [2] survey the bandhead energies of one-quasiparticle states across the deformed rare-earth region and their interpretation within the Nilsson model. Many of these bandheads are isomeric and their half-lives provide additional sensitivity to the underlying configuration. Furthermore, the coupling mode of the odd particle to the core is dependent on the configuration and evolves with particle number and deformation, directly determining the spin-parity of the bandhead and influencing the character and degree of hindrance of the isomeric decay.

These considerations are particularly relevant for the unique-parity $i_{13/2}$ intruder orbital. For example, the isomeric $\nu i_{13/2}$ bandheads in the neighboring nuclei ^{163}W, ^{167}Os, and ^{171}Pt were fixed relative to their respective ground states by Scholey *et al.* [3], who established the decay paths and isomer half-lives using recoil-isomer and recoil-decay tagging methods and determined the ground-state spin-parities of all three nuclei for the first time. The hindrance factor values for the $\nu i_{13/2} \rightarrow \nu h_{9/2}$ transitions were found to be constant at approximately 5.3 across the chain, reflecting the single-quasiparticle character of these states. Subsequent recoil distance Doppler-shift measurements of the $E2$ transition strengths within the $\nu i_{13/2}$ yrast bands in ^{167}Os [4] and ^{165}W [5] have revealed anomalously low $B_{4/2}$ ratios, placing these nuclei in a growing class of transitional W-Os-Pt nuclei

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whose electromagnetic properties are not well-reproduced by standard collective models, reinforcing the complexity of the interplay between single-particle and collective degrees of freedom in this mass region.

In the present work, we report on studies of decay paths from the $\nu i_{13/2}$ isomeric states in ^{165}W and ^{169}W. Previously, four bands have been discovered in ^{165}W by Simpson *et al.* [6], though no transitions reaching the ground state were observed. An α-decay study by Hild *et al.* [7] revealed additional excited states in connection with the ground state, but their relation to the previously observed structures remained elusive. Similarly, in ^{169}W, three "floating" bands have been observed by Recht *et al.* [8]. A study of β decay of ^{169}Re revealed several transitions in ^{169}W [9], though a decay scheme could not be constructed at the time. The advanced detector setup and the use of the recoil-decay tagging method [10,11] allowed us to link between the previously measured prompt γ radiations and the delayed γ-rays following the isomeric states in ^{165}W and ^{169}W.

II. EXPERIMENTAL DETAILS

The nuclei of interest, ^{165}W and ^{169}W, were studied in two separate experiments at the Accelerator Laboratory of the University of Jyväskylä (JYFL), Finland. The nuclei were produced via the ^{92}Mo(^{78}Kr, $4p1n$)^{165}W and ^{92}Mo(^{84}Kr, $1\alpha 2p1n$) ^{169}W fusion-evaporation reactions. The ^{78}Kr ions were impinged on a 0.55-mg/cm^2 ^{92}Mo target at an energy of 380 MeV, while the ^{84}Kr beam had an energy of 402 MeV and the ^{92}Mo target was 0.6 mg/cm^2 thick. The average beam currents and irradiation times were 4.6 pnA and 8 h for the ^{78}Kr beam and 4.7 pnA and 16 h for the ^{84}Kr beam, respectively. Both targets were isotopically enriched to a 97% purity. In both experiments, the recoiling reaction products ("recoils") passed through the vacuum mode separator MARA [12], which separated the recoils from the primary beam and distributed them according to their mass-to-charge (A/q) value at the focal plane. Carbon charge-reset foils of 400 and 48 μg/cm^2 thicknesses were situated at the entrance of MARA for the studies of ^{165}W and ^{169}W, respectively. The JUROGAM 3 Ge detector array [13] was used to detect prompt γ-rays around the target. The array comprises 15 tapered and 24 clover Compton-suppressed Ge detectors. However, in the ^{165}W experiment, only the 15 tapered detectors were present. In the ^{165}W experiment, the charge-particle veto detector JYUTube [14] was installed, though it was not used in the following analysis.

At the focal plane, the recoils passed through a multiwire proportional counter (MWPC) and were stopped in a double-sided silicon strip detector (DSSD). The DSSDs used in the experiments were a BB20 type and had thicknesses of 150 and 300 μm in the ^{165}W and ^{169}W experiments, respectively. In both experiments three broad-energy Ge (BEGe) detectors were arranged around the focal-plane vacuum chamber, with an additional clover Ge detector in the ^{165}W experiment. In the ^{169}W experiment, there was a tunnel of 500-μm-thick Si detectors upstream of the DSSD and a position-sensitive plastic scintillator detector Tuike [15] downstream of the DSSD, although neither of these were used in the analysis. In the latter case, the γ-ray detection efficiency was smaller because the focal plane Ge detectors were situated further away from the DSSD due to the vacuum chamber used being larger than the one used in the ^{165}W experiment. In the ^{165}W experiment, two 1-mm-thick Si detectors were attached to the back of the DSSD side-by-side to detect high-energy light-charged particles that were not stopped in the DSSD. A general description of the focal plane setup at JYFL can be found in Ref. [16]. Independently triggering data-acquisition channels with a 100-MHz sample rate were used to digitize and time stamp all detector events.

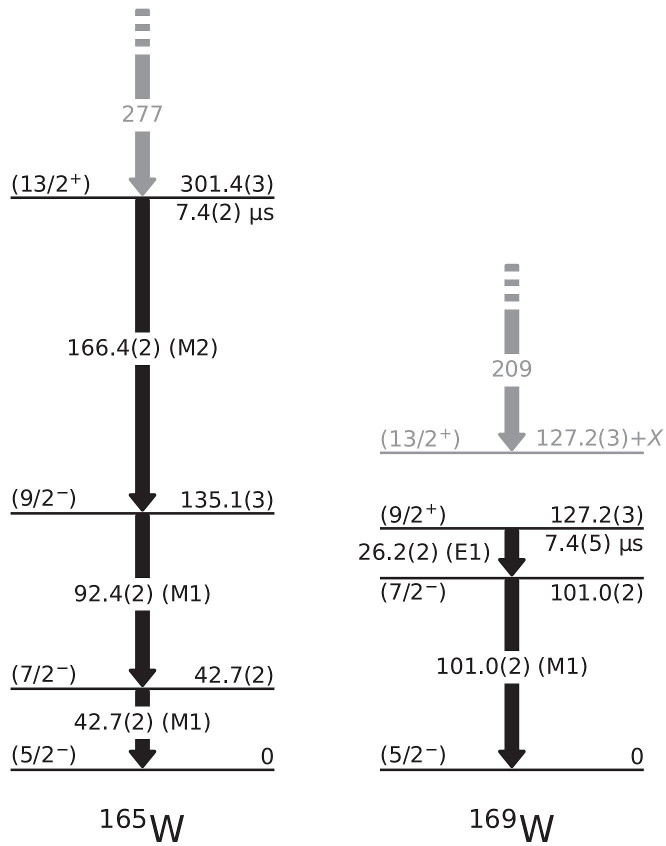

FIG. 1. Partial level schemes of ^{165}W and ^{169}W.

The original aim of both experiments laid in another nucleus, albeit in the same part of the nuclear chart. What is referred to as the "^{165}W experiment" here was also the internal proton calibration for another experiment. The ^{169}W experiment was part of a science outreach program and the goal was to probe ^{172}Pt. The setups were not, therefore, optimized with these tungsten isotopes in mind but were not so off as to exclude these nuclei entirely. This does, however, have consequences for the multiplicity assignment, as is further explained in the next section.

III. RESULTS

The partial level schemes for ^{165}W and ^{169}W constructed in this work are shown in Fig. 1. The states are inferred using the γ-rays observed in the present experiments for the two isotopes. The assigned spins and parities are based on the

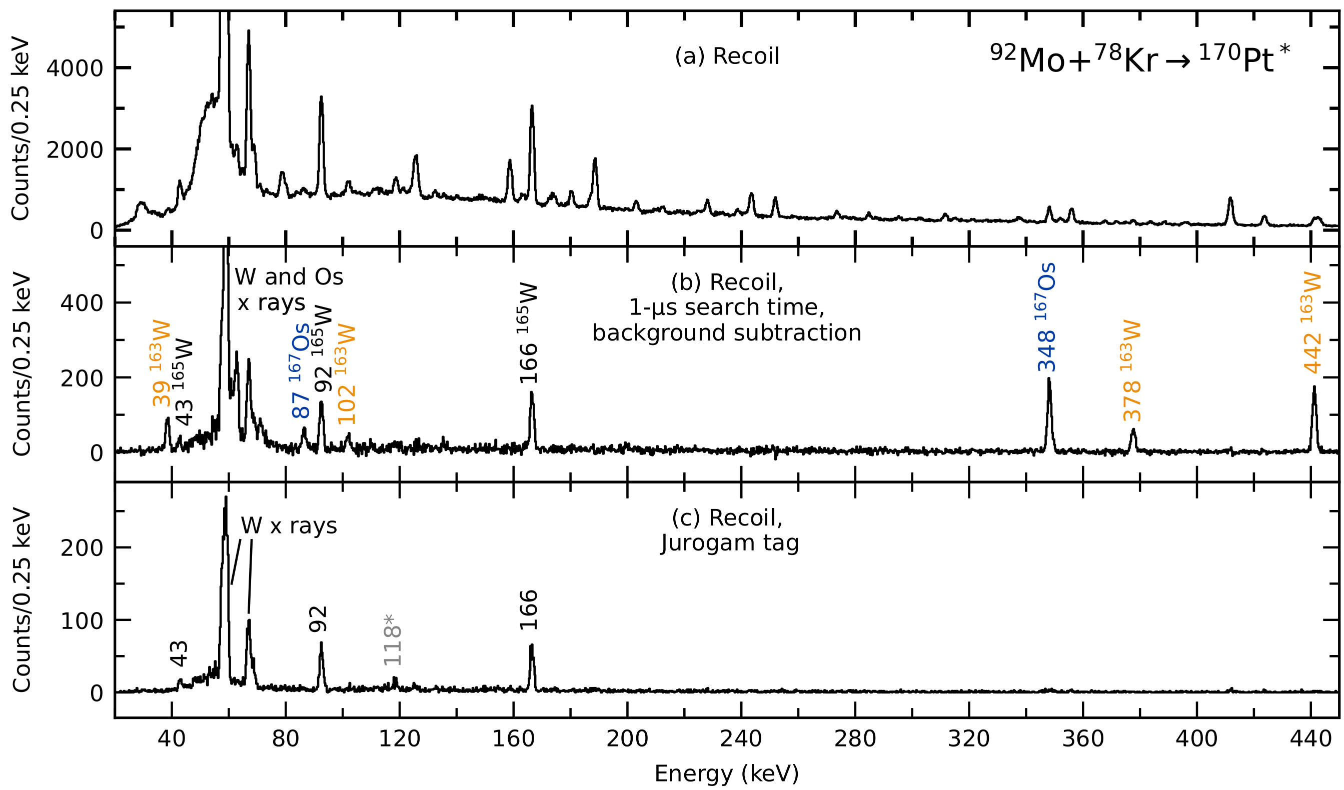

FIG. 2. Focal plane γ-ray energy spectra for the ^{78}Kr + ^{92}Mo reaction. Panel (a) shows the recoil-tagged spectrum. The spectrum in panel (b) is recoil tagged, the γ-rays have been observed within 1 µs after the recoil implantation and background has been subtracted using a time window of the same length, but before the recoil implantation. In the recoil-tagged spectrum of panel (c), the shown transitions are in delayed coincidence with prompt γ-rays from ^{165}W with energies of 277, 455, 572, and 648 keV. The origin of the peak marked with an asterisk is explained in text.

multipolarities determined in the following and the ground-state spins are justified using previous α-decay studies discussed in Sec. IV.

The delayed γ-ray energy spectrum measured at the focal plane for the ^{78}Kr + ^{92}Mo reaction is shown in Fig. 2(a). Several transitions can be observed, and they mainly originate from long-lived nuclei. This is demonstrated in Fig. 2(b), where a shorter searching-time window of 1 µs and a background subtraction have been applied. The background subtraction was carried out using γ-rays observed before the recoil implantation for an equally wide time window. In this case, the time window width was optimized to emphasize submicrosecond activities, whereas in other cases a 25-µs search-time window was used. By tagging on the remaining transitions and comparing the energies of both the delayed and prompt γ-rays, six transitions are easily identified as belonging to ^{163}W and ^{167}Os [3]. The remaining three transitions have energies of 42.7(2), 92.4(2), and 166.4(2) keV, and they can be identified as belonging to ^{165}W by the prompt γ-rays correlated to the same recoil, shown in Fig. 3(a). The energies of the prompt γ-rays match those of the yrast band identified by Simpson *et al.* [6] with a bandhead spin of $(13/2^+)$. Further proof that these transitions deexcite the isomeric state is shown in Fig. 2(c), where a sum of gates was set on prompt rotational band energies of 277, 455, 572, and 648 keV. The resulting delayed γ-ray spectrum clearly shows the three aforementioned γ-ray peaks. There is a small peak at 118 keV in this spectrum, but this is assumed to be the sum of two 59-keV tungsten K_α x-rays. Additionally, a 43-keV transition was also observed in Ref. [7] feeding the ground state of ^{165}W. The γ-γ coincidence analysis confirms that the 43-, 92-, and 166-keV transitions form a cascade. The γ-ray coincidence spectra for each transition are shown in Fig. 4. All three are also in coincidence with the tungsten x-rays, which also appear in Fig. 2(c), and this supports both the original and current element assignment. Furthermore, although not shown here, the mass-to-charge (A/q) distribution of the recoils observed in the MWPC matches that of $A = 165$. This was confirmed by a comparison to an A/q distribution belonging to ^{165}Os, which was identified by its α decay. The small additional peaks in Figs. 4(b) and 4(c) are interpreted as originating from the random background, since the energies match the peaks seen in Fig. 2(a) that disappear in Fig. 2(b).

For the ^{84}Kr + ^{92}Mo reaction, two transitions of 26.2(2) and 101.0(2) keV are observed at the focal plane [see Fig. 5(a)]. These can be shown to belong to ^{169}W as tagging on them reveals the known prompt ^{169}W transitions, as shown in Fig. 3(b). These prompt transitions belong to the yrast band and band 2 identified in Ref. [8]. The two peaks are more clearly seen in Fig. 5(b) by tagging on the prompt γ-rays with JUROGAM 3. In addition, the two most intense x-ray peaks belong to tungsten. Similarly to ^{165}W, the A/q distribution

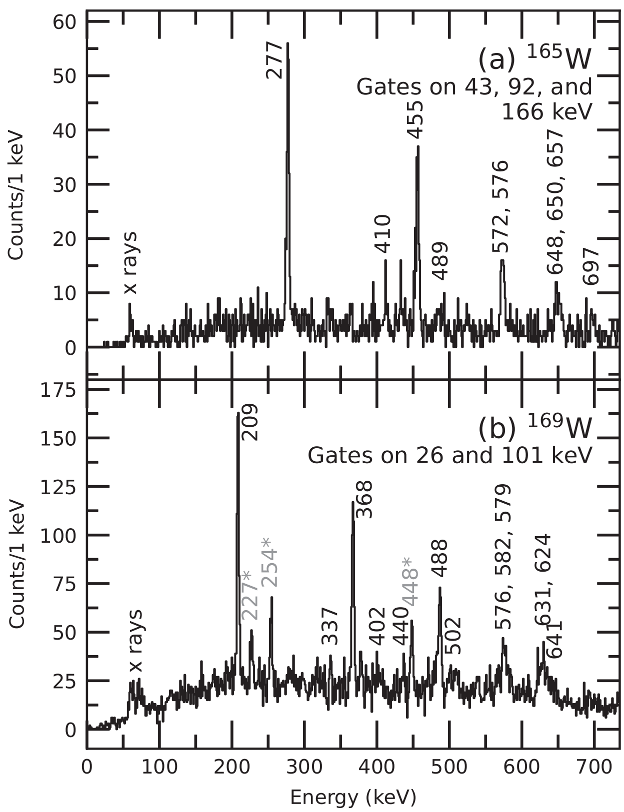

FIG. 3. Recoil-isomer tagged JUROGAM 3 prompt γ-ray energy spectra for the reactions (a) ^{78}Kr + ^{92}Mo and (b) ^{84}Kr + ^{92}Mo obtained by setting a sum of gates on delayed γ-ray transitions as indicated in the panels. The transitions written in gray and marked with asterisks belong to ^{171}Os or ^{172}Os.

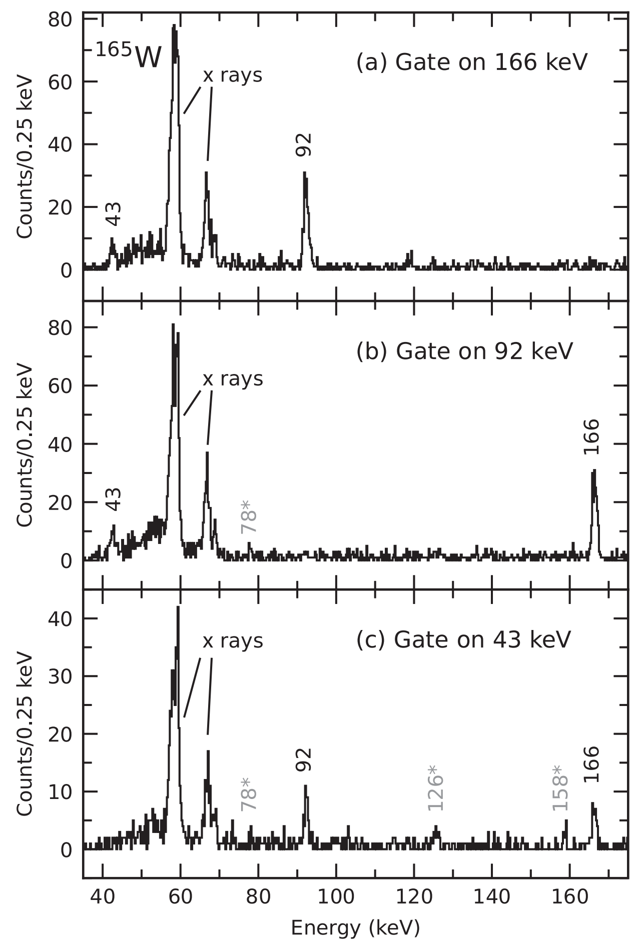

FIG. 4. γ-γ coincidences at the focal plane for ^{165}W. γ-rays in coincidence with the (a) 166-keV, (b) 92-keV, and (c) 43-keV transitions are shown. Peaks written in gray and marked with asterisks are from long-lived β activities.

was compared to that of ^{169}Os, identified by its α decay, and they were found to match. γ-rays with similar energies have been observed before in the β decay of ^{169}Re [9], where 101- and 27-keV γ-rays were identified as the most intense, but a reliable decay scheme could not be deduced.

Unfortunately, the statistics collected during the present experiments were insufficient for γ-γ coincidence analysis. However, it can be assumed that the two observed γ-ray transitions form a cascade. If they were parallel, one might expect the observation of a 75-keV transition, which is not present in Fig. 5(b). This could indicate that it is merely highly converted, but multipolarity considerations lead to conflicts with other observations. The two transitions being in a cascade, as well as their ordering, is also supported by other cases in this mass region, as is discussed later.

The majority of delayed γ-rays were observed in the BEGe detectors, which do not have as good an intrinsic time resolution in comparison to, for example, the clover Ge detector [17]. Therefore, for an optimal half-life fit, one has to take into account the effect of the finite time resolution, especially for the fastest isomers visible in the data. The fitting model used in this work was a convolution of the exponential decay, the Gaussian-shaped time resolution, and the constant background, resulting in four parameters: the lifetime, the number of initial decaying species, the detector time resolution, and the background counts per time unit. Additionally, precise information on the time 0 is essential for the model, so the energy-dependence of the time 0 of the BEGe detector relative to the recoil implantation was determined by maximizing the likelihood of the lifetime fits of observed isomeric transitions in ^{163}W, ^{167}Os, and ^{165}W. In the fit, the optimal parameter values were found using the method of maximum likelihood with Poisson statistics. The model with the fitted parameters was sampled to create a covariance matrix of the parameters. Half-lives of $\approx$210 and 740(30) ns were obtained for the isomeric states in ^{163}W and ^{167}Os, respectively. The latter agrees with the literature value of 700(10) ns from Ref. [3]. The larger deviation between the measured half-life and the literature value of 154(3) ns [3] for ^{163}W results from low statistics and poor time resolution of the BEGe detectors used in the current work combined with the short half-life. Lifetime fits were made separately for each delayed transition in ^{165}W and ^{169}W, and the extracted values indicate that there is only one isomer in each of these isotopes. Example fits for the 166-keV transition in ^{165}W and the 101-keV transition in

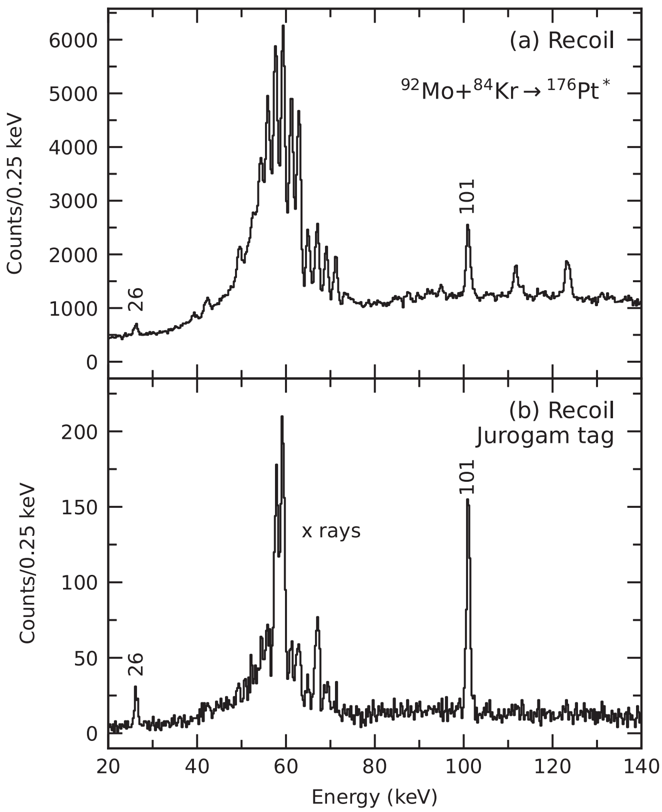

FIG. 5. Focal plane γ-ray energy spectra for the ^{84}Kr + ^{92}Mo reaction. Panel (a) shows the recoil-tagged γ-rays and panel (b) shows the recoil-tagged γ-rays in delayed coincidence with 209-, 368-, 488-, or 576-keV transitions of ^{169}W observed in JUROGAM 3. Due to the large overlap of peaks in the prompt γ-ray spectrum, x-rays belonging to elements other than tungsten are visible in panel (b).

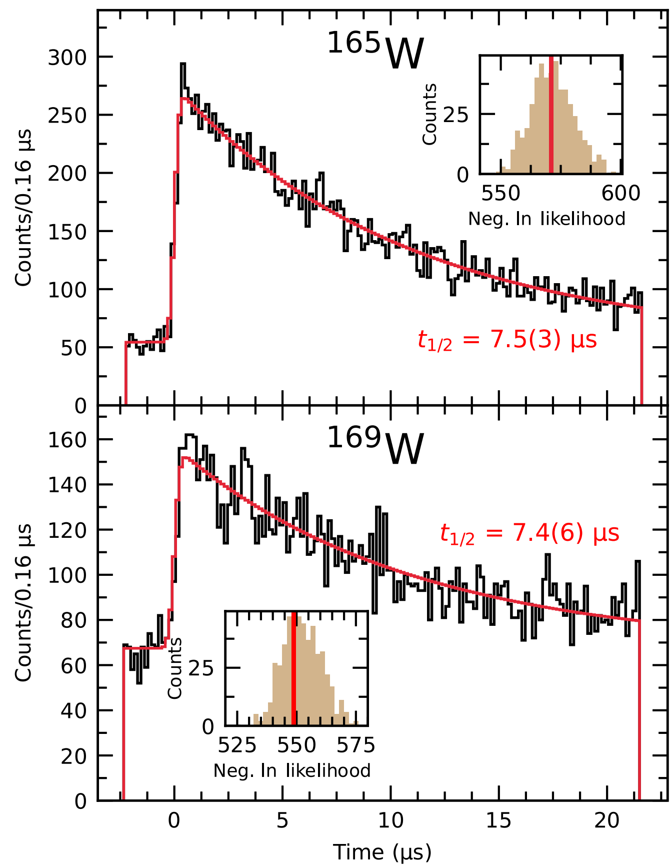

FIG. 6. Lifetime fits for the isomeric states in ^{165}W and ^{165}W. The shown data are for the 166- and 101-keV transitions, respectively. The insets show the negative logarithmic likelihood of the resampled data (brown distribution) and the fit (red line).

^{169}W are shown in Fig. 6. The final half-lives for the isomeric states in ^{165}W and ^{169}W are 7.4(2) and 7.4(5) μs, respectively, calculated as the weighted means of the delayed transitions. By coincidence, these isomers seem to have similar half-lives.

In general, the multipolarity of the transition of interest can be deduced by determining the K internal conversion coefficient, α_K, using the observed number of counts in the K x-ray and γ-ray peaks and known detection efficiencies. Unfortunately, the latter was not available in either experiment with sufficient accuracy. However, a maximum of the detection efficiency curve is estimated to appear in the energy range of 100–200 keV, a fact that can be exploited. The detection efficiency in the energy range of the x-rays (55–70 keV) is in this case smaller than or equal to that in the γ-ray energy range of interest (92–166 keV). Hence, calculating the ratio of the observed peak areas from Figs. 4(a), 4(b), and 5(b) gives a minimum value for the K conversion coefficient α_K, as the effect of the efficiency correction would be only to increase this value.

In the case of the 92- and 166-keV transitions in ^{165}W, the ratio of the counts in the x-ray and γ-ray peaks results in $\alpha_K \gtrsim 4$. By comparing to values given by the BrICC database [18], this excludes $E1$ and $E2$ multipolarity assignments for the 92-keV transition and $E1$, $M1$, $E2$, and $E3$ assignments for the 166-keV transition. Additionally, $E3$, $M3$, and higher multipolarities can be ruled out as they would yield half-lives longer than that measured for the isomeric state. Therefore, the most probable assignments for the 92- and 166-keV transitions are $M1$ and $M2$, respectively. This also sets the ordering of the two transitions, as the 92-keV $M1$ transition can be expected to be prompt. For the 43-keV transition, we adopt the $M1$ multipolarity assignment from Ref. [7] as well as that it populates the ground state.

Even though the above arguments point toward the 92-keV transition being a pure $M1$ transition, $M1/E2$ mixing cannot be ruled out. In this case, the mixing ratio can be estimated as there are only two transitions whose conversion produces x-rays, and the multipolarity of the other can be assumed to be fixed. Since the transitions are in a cascade, they have equal numbers of actual emissions. With these assumptions, and using the definition for the conversion coefficient, the following formula can be derived so that γ-ray detection efficiencies cancel out:

$$\frac{1+\alpha_{\rm tot}^{92}}{\alpha_K^{92}} = \frac{1+\alpha_{\rm tot}^{166}}{\alpha_K^{166}}\frac{N_{166}}{N_{92}}\frac{N_{{\rm x}(166),{\rm g}92}}{N_{{\rm x}(92),{\rm g}166}}. \quad (1)$$

The full derivation of this equation can be found in the Appendix. Here, $\alpha_{\rm tot}$ and $\alpha_{\rm K}$ are the total and K conversion coefficients for the transitions indicated in superscripts and the number of counts in the singles γ-ray spectrum for the 166- and 92-keV transitions are marked by N_{166} and N_{92}, respectively. $N_{x(166),g92}$ is the number of x-rays in the γ-γ spectrum with a gate on the 92-keV transition (i.e., x-rays from the conversion of the 166-keV transition), and $N_{x(92),g166}$ is the same quantity but obtained when gating on the 166-keV transition. Now, using the values given by the BrICC database [18] for a 166-keV $M2$ transition, Eq. (1) yields a value of 1.47(10). This corresponds to a mixing ratio of $\delta = 0.25^{+0.15}_{-0.25}$ if the conversion coefficients for a 92-keV $M1$ and $E2$ transition are adopted from the BrICC database.

Correspondingly in the case of the 101-keV transition in ^{169}W, the minimum value of the K internal conversion coefficient is found to be approximately 3, which excludes $E1$, $E2$, and $E3$ assignments. Additionally, $M2$ and higher multipolarities would mean half-lives longer than those observed. Therefore, we assign an $M1$ multipolarity to the 101-keV transition. In this case, it was not possible to determine the mixing ratio due to lack of detection efficiency information. The multipolarity of the 26-keV transition is most likely $E1$, because the conversion coefficient increases rapidly for higher multipolarities (Ref. [18] gives $\alpha_{tot} = 2.8$ for $E1$, 41 for $M1$, 2020 for $E2$, and so on), and in such a case, no γ-ray peak would have been observed.

IV. DISCUSSION

The ground-state spin and parity of ^{165}W have been set as $5/2^-$ by Hild *et al.* [7], who cite a β-decay study in a master's thesis that is unavailable to us. Another reliable way of determining the spins and parities of states is through chains of favored α decays. In the following, α-decay chains down to ^{165}W and ^{169}W starting from Hg isotopes with known ground-state spins and parities are presented. Hindrance factors for the transitions were calculated using the Rasmussen method [19] and information available in the references is presented in the following text. All values varied around unity, pointing toward favored α decays.

^{177}Hg, whose ground state has been assigned $J^\pi = 7/2^-$ in a laser spectroscopy measurement [20], has a favored ground-state–to–ground-state α-decay branch to ^{173}Pt [21,22]. ^{173}Pt undergoes a favored α decay to an excited state in ^{169}Os, followed by an $M1$ transition to the ground state, setting its spin and parity as $(5/2^-)$ [23]. This assignment by Peura [23] differs from the assignments in Refs. [21,24], where the summing of fast conversion-electron and α-particle signals was neglected. For the final step, Hild *et al.* [7] have measured a favored ground-state–to–ground-state α decay from ^{169}Os to ^{165}W, which supports the assignment of $J^\pi = (5/2^-)$, and thus the original ground-state J^π assignment is confirmed. Combined with the current observations, this assignment sets the spin-parity of the isomeric state as $(13/2^+)$, confirming the original assignment by Simpson *et al.* [6]. The 43-keV state was originally assigned a spin-parity of $3/2^-$ by Hild *et al.* [7]. However, the current observations of three transitions in a cascade, their multipolarity assignments, and the aforementioned ground-state spin and parity suggest that the 43-keV state has a spin-parity of $(7/2^-)$ instead.

The ground-state spin-parity of ^{169}W is most probably $5/2^-$ based on the systematics of the $N = 95$ isotones and the α-decay chain starting from ^{181}Hg. The ground state of ^{181}Hg has been measured as $J^\pi = 1/2^-$ by laser spectroscopy [20]. There is a favored α decay between the ground state of ^{181}Hg and an excited state in ^{177}Pt [25], from which a transition with an $E2$ character to the ground state has been observed [26], resulting in the latter having a ground-state spin-parity of $5/2^-$. There are then favored α decays between the ground states of ^{177}Pt, ^{173}Os, and ^{169}W [7,25,27,28], confirming $J^\pi = (5/2^-)$ for the ground state of ^{169}W. It is worth noting that the neighboring odd-mass tungsten isotopes ^{167}W [7] and ^{171}W [29] also have $5/2^-$ ground states.

With the $J^\pi = (5/2^-)$ assignment for the ground state of ^{169}W, the current observations of two transitions of $M1$ and $E1$ types indicate that the spin-parity of the isomeric state is $(9/2^+)$. The $(5/2^+)$ and $(7/2^+)$ assignments can be excluded because no transition directly to the $5/2^-$ ground state was observed. The $E1$ transition can be assigned to deexcite the isomeric state, as this is the case in many other 9/2+ isomers in this mass region (see, e.g., Refs. [30–34]).

A likely configuration for the ground states of ^{165}W and ^{169}W is $\nu 5/2[523]$ mixed with $\nu 5/2[512]$. This has been assigned as the ground-state configuration for many nuclei in this mass region, such as ^{165}Yb [33], ^{169}Hf [8], and ^{163}Hf [35]. The first-excited $(7/2^-)$ state in either nucleus is unlikely to be the $\nu 7/2[514]$ intrinsic Nilsson state, which is expected to lie higher in excitation energy. In the case of ^{169}W, the $(7/2^-)$ state likely belongs to a strongly coupled band based on the ground state, as is the case in the neighboring tungsten isotopes ^{167}W [7] and ^{171}W [36] as well as in the $N = 95$ isotones ^{171}Os [34] and ^{167}Hf [37,38]. The situation is more complicated for the $(7/2^-)$ state in ^{165}W, as in the neighboring ^{163}W [39] and ^{167}Os [40], the lowest $7/2^-$ states are based on a mixed $h_{9/2} \otimes f_{7/2}$ configuration. The $(9/2^-)$ state seen in ^{165}W could be based on the same mixed configuration as the $(7/2^-)$ state. A similar situation occurs in ^{171}Os [41], where a strong $M1$ branch is observed from the $(9/2^-)$ to the $(7/2^-)$ state, while the $E2$ branch to the $(5/2^-)$ ground state is weak.

The lowest-lying positive-parity Nilsson configuration above the ground state in ^{169}W is likely to be a 5/2[642] state. The yrast $i_{13/2}$ band can be interpreted as being built on this configuration. As demonstrated by the prompt-delayed γ-ray coincidences observed in this work, the prompt transitions of the yrast $i_{13/2}$ band observed by Recht *et al.* [8] feed the $(9/2^+)$ state, which is potentially the lowest member of the $i_{13/2}$ band. However, the lowest band member observed by Recht *et al.* has a spin-parity of $13/2^+$. An $E2$ transition between the yrast $13/2^+$ and $(9/2^+)$ states has not been observed in either work, possibly due to it being a highly converted and slightly delayed low-energy transition. An upper limit of roughly 100 keV for the potential $E2$ transition can be inferred from the current work using the experimental γ-ray efficiency for JUROGAM 3 [13] and conversion coefficients from Ref. [18]. A similar situation of an unobserved $E2$ transition to a $9/2^+$ state followed by a delayed $E1$ transition occurs in ^{173}Os [34]. $9/2^+$ isomers have been identified also in ^{157}Dy, ^{159}Er, ^{161}Er, and ^{165}Yb [31–33,42]. In these cases, the low-energy $E2$ transitions between the $13/2^+$ and $9/2^+$ states were observed.

The $(9/2^+)$ state in ^{169}W is depopulated by the $E1$ transition to the $(7/2^-)$ state, rather than an $E2$ transition to a $5/2^+$ state based on the 5/2[642] Nilsson configuration. This could indicate that the $5/2^+$ state lies at an excitation energy higher than that of the $(9/2^+)$ state. $9/2^+$ bandheads can also be found in ^{165}Yb [33], ^{159}Er [31], and ^{161}Er [32]. In the case of ^{165}W, the Nilsson configuration of the lowest positive-parity state is likely 3/2[651] [6].

Hindrance factors for the isomeric transitions can be calculated with $F_W = t^{\gamma}_{1/2}/t^{W}_{1/2}$, where $t^{\gamma}_{1/2}$ is the partial half-life for the γ-ray transition and $t^{W}_{1/2}$ is the corresponding Weisskopf estimate. For the calculation of F_W values for the transitions observed in this work, 100% branching ratios and $\delta = 0$ mixing ratios were assumed. The α_{tot} values were taken from the BrIcc database [18]. The hindrance factor for the $M2$ 166-keV transition in ^{165}W is 6.9(2), which is a typical value for single-particle transitions between $i_{13/2}$ and $h_{9/2}$ orbitals. For example, F_W values of 5.62(9), 5.9(3), 2.25(3), and 9.0(6) can be found for isomeric $M2$ transitions in ^{167}Os, ^{161}Hf, ^{171}Pt, and ^{173}Pt, respectively. These values were calculated using results reported in Refs. [3,23,43]. The F_W value for the $E1$ 26-keV transition in ^{169}W is calculated to be $2.29(15)\times10^6$. This is an order of magnitude larger than the typical values for $E1$ transitions, which have hindrances of the order of 10^5 [44]. For example, delayed $E1$ transitions in ^{157}Dy, ^{159}Er, ^{161}Er, and ^{165}Yb have hindrance values of $2.0(4) \times 10^5$, $1.37(14) \times 10^5$, $4.6(2) \times 10^4$, and $1.46(15) \times 10^5$, respectively, which were calculated from values given in Refs. [30,31,45,46]. Only an estimate of "several microseconds" [34] has been given for the half-life of the $9/2^+$ isomeric state in ^{173}Os, but using a lower limit of 2 µs yields a hindrance factor of 1.7×10^6, which is similar to that for ^{169}W measured in this work. The larger values may indicate that the composition of the isomeric states in ^{169}W and ^{173}Os differs from those in their neighboring nuclei, leading to more strongly hindered transitions.

V. SUMMARY

The lifetimes of $(13/2^+)$ and $(9/2^+)$ isomeric states in ^{165}W and ^{169}W, respectively, and their deexcitation paths have been studied using fusion-evaporation reactions. The isomeric state in ^{165}W was confirmed to be the $(13/2^+)$ bandhead of the yrast band, which was originally proposed in Ref. [6]. In the case of ^{169}W, we suggest that the observed $(9/2^+)$ isomeric state is a member of the $i_{13/2}$ band and that there is an unobserved $E2$ transition connecting it to the $(13/2^+)$ state deduced in the study by Recht *et al.* [8].

In this work, we have demonstrated that when delayed and prompt spectroscopy are combined, decay paths of floating bandheads to the ground states can be mapped. There remains a few alike cases in the surrounding mass region that are worth re-examining similarly as has been done in this study.

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DATA AVAILABILITY

The experimental data for this article, and the corresponding metadata, are stored in the Finnish National FAIRdata repository and are available from Refs. [47,48].

APPENDIX: DERIVATION FOR EQ. (1)

The K internal conversion coefficient for the 166-keV transition $\alpha_K^{166\,\mathrm{keV}}$, knowing the detection efficiencies, can be calculated using

$$\alpha_K^{166} = \frac{N_{\mathrm{x}(166),\mathrm{g}92}}{\varepsilon_{\mathrm{x}}}\frac{\varepsilon_{166}}{N_{166,\mathrm{g}92}}, \tag{A1}$$

where $N_{\mathrm{x}(166),\mathrm{g}92}$ and $N_{166,\mathrm{g}92}$ are the number of counts in the x-ray and the 166-keV peaks, respectively, in the γ-ray energy spectrum gated on the 92-keV transition of Fig. 4(b). Their respective detection efficiencies are denoted with ε. In a similar manner, a similar formula can be written for α_K^{92} by exchanging the labels for the transitions and using the peaks in Fig. 4(a) instead. One can then write

$$\frac{\alpha_K^{166}}{\alpha_K^{92}} = \frac{N_{\mathrm{x}(166),\mathrm{g}92}}{N_{\mathrm{x}(92),\mathrm{g}166}}\frac{N_{92,\mathrm{g}166}}{N_{166,\mathrm{g}92}}\frac{\varepsilon_{166}}{\varepsilon_{92}}, \tag{A2}$$

where the x-ray detection efficiencies have canceled out. On the other hand, as the 92-keV and 166-keV transitions are in a cascade, one can then write the following for the gating 92-keV transition in the case of Fig. 4(b):

$$N_{92} = \frac{N_{166,\mathrm{g}92}\left(1+\alpha_{\mathrm{tot}}^{166}\right)}{\varepsilon_{166}}, \tag{A3}$$

where N_{92} is the peak area of the 92-keV transition in the γ-ray singles spectrum. Again, the same formula can also be written for the 166-keV transition by exchanging labels. One can then solve $N_{166,\mathrm{g}92}$ from Eq. (A3) and $N_{92,\mathrm{g}166}$ from its equivalent and insert them into Eq. (A2). The detection efficiencies cancel out and after rearranging, and one has

$$\frac{1+\alpha_{\mathrm{tot}}^{92}}{\alpha_K^{92}} = \frac{1+\alpha_{\mathrm{tot}}^{166}}{\alpha_K^{166}}\frac{N_{166}}{N_{92}}\frac{N_{\mathrm{x}(166),\mathrm{g}92}}{N_{\mathrm{x}(92),\mathrm{g}166}}. \tag{A4}$$

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