

Lifetime measurements in ^{165}W and the spin evolution of $E2$ transition strength

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(Received 8 July 2025; revised 26 October 2025; accepted 13 November 2025; published 5 February 2026)

Lifetimes of low-lying states in the yrast $\nu i_{13/2}$ band in ^{165}W have been measured using the recoil distance Doppler-shift (RDDS) method. The excited states of interest were populated in the $^{92}\text{Mo}(^{78}\text{Kr}, 4p1n)^{165}\text{W}$ fusion-evaporation reaction and their decays were investigated via γ rays detected in the Jurogam II detector array in coincidence with nuclei separated and detected using the RITU gas-filled separator. From the experimental lifetimes, corresponding reduced transition strengths, $B(E2)$ values, were deduced and an unusually low experimental value of the ratio $\frac{B(E2; 21/2^+ \rightarrow 17/2^+)}{B(E2; 17/2^+ \rightarrow 13/2^+)} = 0.59(7)$ was extracted, similar to what has been observed in neighboring nuclei in this mass region. The experimental results have been compared with Woods-Saxon-type mean field and interacting boson-approximation (IBM-1) calculations.

DOI: 10.1103/2dtq-q465

I. INTRODUCTION

Reduced electromagnetic quadrupole transition strengths of low-lying states, $B(E2)$ values, are an important nuclear-structure observable that is a direct indicator of a change in nuclear structure between nuclear levels, for example, concerning collective dynamics or deformation. They can be measured directly via Coulomb excitation or deduced from the measured excited-state lifetimes. Within an isotopic or isotonic chain of nuclei, $B(E2)$ values are typically at their minimum for nuclei at a shell closure (i.e., with a “magic” number of neutrons or protons), with an increasing trend towards the midshell where they reach a maximum [1]. In

addition, for collective excitations they normally increase with increasing spin in a specific band structure, leading to $B(E2; 4^+ \rightarrow 2^+)/B(E2; 2^+ \rightarrow 0^+) > 1$ in nuclei with even numbers of neutrons and protons. For nuclei with an odd number of neutrons or protons we use a generalized definition of this “ $B_{4/2}$ ratio” as $B_{4/2} \equiv B(E2; I = K + 4 \rightarrow I = K + 2)/B(E2; I = K + 2 \rightarrow I = K)$, where K is the angular momentum of the single-particle configuration on which the band structure is built. For an ideal collective-vibrational system this ratio is $B_{4/2}=2$, while for an ideal rotor, $B_{4/2}=1.43$, which is known as the Alaga rule. Deviations from the expectation of $B_{4/2} > 1$ for collective excitations may appear in nuclei close to magic numbers where the so-called seniority quantum number (which refers to the number of unpaired nucleons, i.e., nucleons which are not pair coupled to angular momentum $J = 0$ as defined by Racah [2]) is approximately conserved. Alternatively, nuclei exhibiting shape coexistence might conceivably also exhibit such a decrease in $E2$ transition strength with spin but such cases are, to our knowledge, not known to date. Despite this, a relatively large number of cases of “anomalous” ($B_{4/2} < 1$) ratios have been observed among the neutron-deficient tungsten, osmium, and platinum nuclei with neutron numbers around $N \leq 94$ [3–7], which cannot easily

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be explained by the above mentioned exceptions. For ^{166}W a very low value of $B_{4/2} = 0.33(5)$ has been observed [5]. On the other hand, in the neighboring odd-A $^{163,167}\text{W}$ isotopes, $B_{4/2}$ values close to those of a harmonic vibrator or rigid axial rotor have been found [8,9]. For the osmium isotopic chain, the odd-valence neutron seems not to significantly influence the $B_{4/2}$ ratio in the odd-mass nuclei [7], even though a limited odd-even staggering effect is observed [10].

In this work, lifetimes of the yrast $17/2^+$ and $21/2^+$ states in ^{165}W were measured for the first time and the corresponding $E2$ transition strengths were extracted. The obtained value of $B_{4/2} = 0.59(7)$ is significantly below the predictions of collective models and follows the trend observed in neighboring isotopes.

II. EXPERIMENTAL SETUP

Excited states in ^{165}W were populated via the $^{92}\text{Mo}(^{78}\text{Kr}, 4p1n)^{165}\text{W}$ fusion-evaporation reaction, using a 380 MeV ^{78}Kr beam provided by the K130 cyclotron at the Accelerator Laboratory of the University of Jyväskylä. The ion beam impinged on a 0.6-mg/cm² thick ^{92}Mo target mounted inside the DPUNS plunger [11] device for recoil distance Doppler-shift (RDDS) measurements of nuclear excited-state lifetimes. The initial velocity of the fusion products after leaving the target was calculated from the observed Doppler shift as $v = 0.042(5)c$, while a 1-mg/cm² thick Mg degrader foil slowed down the recoiling fusion products to 80% of their initial velocity. Nine different target-degrader distances were used in the measurement, ranging from 7.6(2) to 8000(24) μm . The fusion-evaporation reaction products passing through the degrader foil were separated from the beam particles using the RITU gas-filled separator [12], implanted and detected in double-sided silicon strip detectors (DSSD) of the GREAT detector system [13] at the focal plane of RITU. γ rays emitted in the reactions were detected in delayed coincidence with the fusion products using the Jurogam II detector array consisting of 15 escape-suppressed Phase-I GASP-type detectors [14] placed at backward angles with respect to the beam axis, with five of them at 157.6° (Ring 1) and ten at 133.6° (Ring2), and 24 escape-suppressed Euroball segmented clover Ge detectors [15]. The raw data were sorted using the GRAIN data-analysis package [16], and the resulting γ - γ energy coincidence matrices were analyzed using the RADWARE [17] and ROOT [18] software packages.

III. DATA ANALYSIS AND RESULTS

The lifetimes of the levels of interest were measured using the recoil distance Doppler-shift (RDDS) method [19], where the use of a degrader foil after the target provides two γ -ray energy peaks for each transition, where the one due to the γ rays being emitted before the degrader (the fully shifted peak) is Doppler shifted towards lower energies since the germanium detectors used in the analysis are situated at angles $\theta = 133.6^\circ$ with respect to the beam. Lifetimes of excited states were deduced via the differential-decay curve method (DDCM) [20], based on the decay curves obtained as intensity

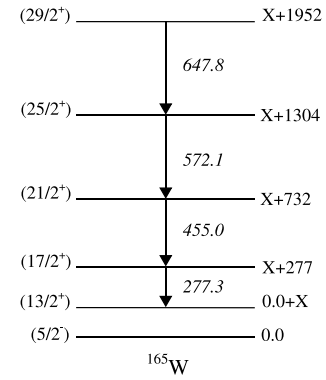


FIG. 1. Partial-level scheme of ^{165}W [22]. Excitation energy of the $(13/2^+)$ band head above the $(5/2^-)$ ground state is not known.

ratios of the degraded, I_d , and fully shifted, I_s , components of the transition depopulating each state of interest, as a function of the target-degrader distance. In this analysis, the ample statistics obtained for the reaction channel leading to ^{165}W made possible the use of prompt-correlated γ - γ coincidences by means of gating on the fully shifted component of the direct feeding transition. The partial level scheme of ^{165}W observed in this analysis is presented in Fig. 1. The lifetime of the state of interest was determined using the formula

$$\tau_i(x) = \frac{I_d(x)}{v \frac{dI_s(x)}{dx}}, \quad (1)$$

where I_d and I_s are the corresponding normalized intensities of the degraded and fully Doppler-shifted components of the investigated transition, respectively, v is the recoil velocity before the degrader, and the index i corresponds to a certain distance in the sensitive region of the target-degrader distances. Using this method the obtained lifetime is not influenced by side feeding or unobserved feeding transitions which are usually the main source of systematic uncertainties in measurements using single γ -ray spectra. The measured gated-energy spectra for the shifted and degraded components of the $17/2^+ \rightarrow 13/2^+$ and $21/2^+ \rightarrow 17/2^+$ transitions for a few of the target-degrader distances are presented in the left and right panel of Fig. 2, respectively. Some contaminant peaks from ^{166}W appear in the spectra gated on the fully shifted component of the $25/2^+ \rightarrow 21/2^+$ transition due to its energy overlap with the 567.1 keV transition in ^{166}W [21]. However, none of the contaminant peaks coincide with or influence the behavior of the peaks of interest.

In order to extract the lifetime of the $17/2^+$ state, γ -ray coincident energy spectra obtained by gating on the fully shifted component of the $21/2^+ \rightarrow 17/2^+$ transition were used. Only the data from Jurogam II detectors Ring 1 and Ring 2 placed at backward angles with respect to the beam axis were used in order to avoid the degraded component of the $21/2^+ \rightarrow 17/2^+$ transition shifted toward low energies while gating, since the γ peaks are not well resolved at low energies. Using only these data provides better selectivity while still keeping good statistics and gives a result compatible with that obtained from the data from all detectors. The flight curve of the fully shifted component of the

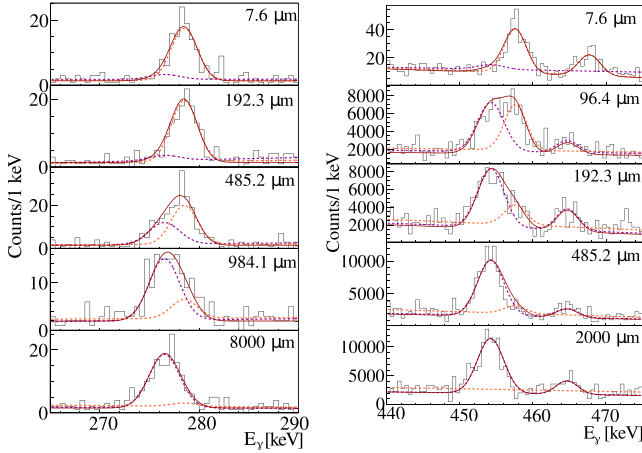


FIG. 2. Energy spectra of γ rays gated on the shifted component of the $21/2^+ \rightarrow 17/2^+$ (left) and $25/2^+ \rightarrow 21/2^+$ (right) transitions in the prompt γ - γ matrix. The fitted fully shifted (purple) and degraded (orange) components of $17/2^+ \rightarrow 13/2^+$ and $21/2^+ \rightarrow 17/2^+$ transitions are shown in the spectra.

observed $17/2^+ \rightarrow 13/2^+$ transition is presented in the top part of Fig. 3, while lifetimes for several distances where both components are observed are presented in the center panel of Fig. 3. The resulting lifetime, $\tau = 54(5)$ ps, was deduced for the $17/2^+$ state. In the same manner, the flight curve and lifetime of the $21/2^+$ state are presented in Fig. 3 (top and bottom panel, respectively), for which we used the γ -ray coincident energy spectra obtained by gating on the fully shifted component of the $25/2^+ \rightarrow 21/2^+$ transition, using the data from all the detectors. In this way, a lifetime of 8.3(6) ps was deduced for the $21/2^+$ state. The errors of

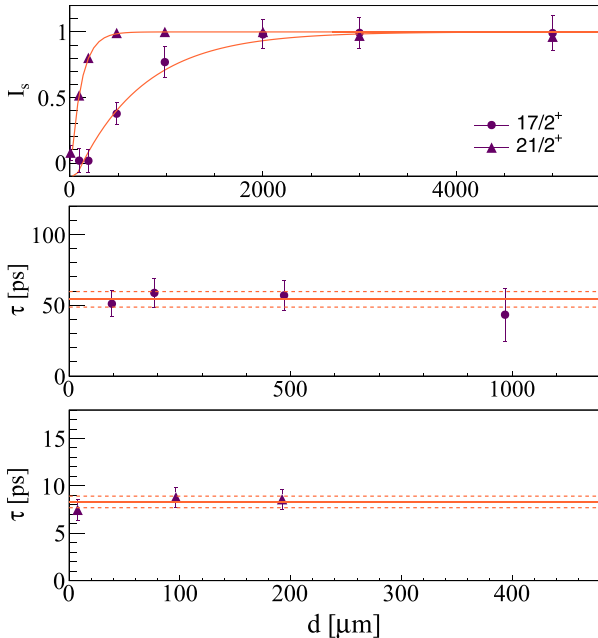


FIG. 3. Observed flight curves (top) and deduced lifetimes for the $17/2^+$ (center) and $21/2^+$ states (bottom) in ^{165}W .

TABLE I. Measured lifetimes for the $17/2^+$ and $21/2^+$ states in ^{165}W and their corresponding $B(E2; \downarrow)$ values. The quoted uncertainties include a systematic uncertainty from the determination of the recoil velocity.

Isotope	E_γ (keV)	$I_i \rightarrow I_f$	τ (ps)	$B(E2; \downarrow)$ (W.u.)
^{165}W	276.8(1)	$17/2^+ \rightarrow 13/2^+$	54(5)	155(16)
	454.3(1)	$21/2^+ \rightarrow 17/2^+$	8.3(6)	91(7)

the individual lifetimes at each distance are derived as a root of sum squares of statistical (including statistical uncertainties of the intensities of the degraded and shifted components) and systematic (target-degrader distance and recoil velocity) uncertainties, while the final result includes the weighted statistical uncertainties from the lifetime distribution over several target-degrader distances. The results are presented in Table I, together with the corresponding reduced E2 transition strengths, deduced using the following equation [23]:

$$B(E2; \downarrow) = \frac{BR}{1 + \alpha_c} \frac{817.66}{\tau E_\gamma^5} [\text{e}^2 \text{fm}^4], \quad (2)$$

where BR is the branching ratio and in this case $BR = 1$, α_c is the electron-conversion coefficient calculated using BrIcc [24], τ is the experimental lifetime in ps and E_γ is the γ -ray transition energy in MeV. An unusually low value of $B_{4/2}$ ratio of 0.59(7) is obtained.

IV. DISCUSSION

In Fig. 4, a comparison between E_{4+}/E_{2+} , $B(E2)$, and $B_{4/2}$ values for both even- A and odd- A , W, and Os isotopes are shown. The E_{4+}/E_{2+} ratios correspond to the ratios $(E(21/2^+) - E(13/2^+)) / (E(17/2^+) - E(13/2^+))$ in the odd- A isotopes, and they follow the same trend with increasing neutron number, N , until $N = 95$ where the observed ratios drop for odd- A isotopes towards the harmonic vibrational limit via a region characteristic of γ -soft rotors. On the other hand, for the even-even isotopes these energy ratios continue to increase towards the rigid-rotor (Alaga) limit beyond midshell. The observed bifurcation for the W isotopes at $N > 95$ is likely explained by the strong coupling of the odd $i_{13/2}$ valence neutron to the even core, similar to what has been observed for the osmium isotopes for $N < 98$ [7].

Experimentally observed $B(E2; 2^+ \rightarrow 0^+)$ and $B(E2; 17/2^+ \rightarrow 13/2^+)$ values for tungsten isotopes are shown in the middle panel of Fig. 4. After a sharp increase, the $B(E2)$ values can be seen to vary little for the $N \geq 90$ isotopes, despite the fact that the observed E_{4+}/E_{2+} and $(E(21/2^+) - E(13/2^+)) / (E(17/2^+) - E(13/2^+))$ ratios exhibit an evolution reminiscent of a structural change from a γ -soft to an axially symmetric rotational system in the same range of neutron numbers.

From the comparison between the observed $B_{4/2}$ values, presented in the bottom panel of Fig. 4, similar trends in the W and Os isotopes are found, with the $B_{4/2}$ values close to the Alaga rotational limit for $N \geq 94$ but ≤ 1 and rapidly decreasing with the removal of neutrons below $N = 94$. This stands in contrast with the evolution of the E_{4+}/E_{2+}

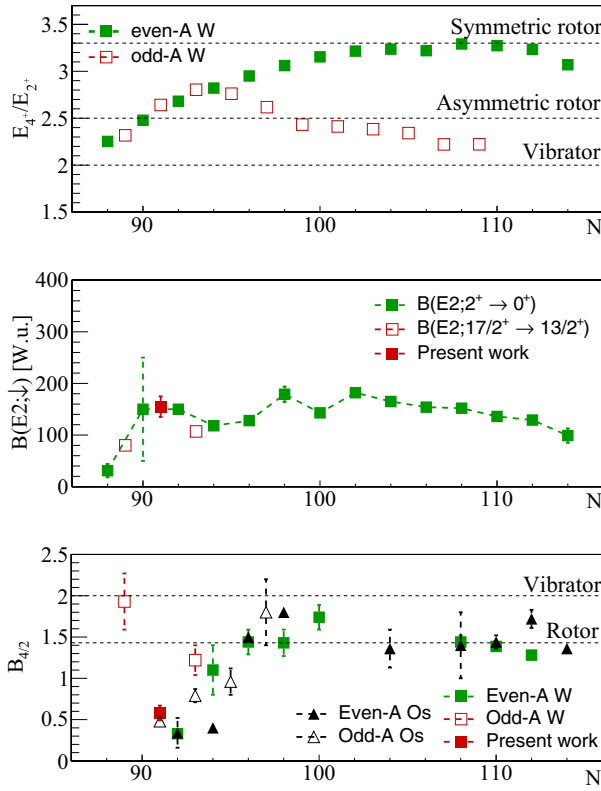


FIG. 4. Top: Comparison between energy ratios for first 4^+ and 2^+ levels in even-A W isotopes and the corresponding $\frac{(E(21/2^+) - E(13/2^+))}{(E(17/2^+) - E(13/2^+))}$ ratios in odd-A W isotopes. Center: Experimental $B(E2; 2^+ \rightarrow 0^+)$ and $B(E2; 17/2^+ \rightarrow 13/2^+)$ values in even-A and odd-A W isotopes. Bottom: $B_{4/2}$ ratios for W and Os isotopes with $89 < N < 114$. Results of the present work are indicated by filled red squares.

and $\frac{(E(21/2^+) - E(13/2^+))}{(E(17/2^+) - E(13/2^+))}$ energy ratios, which follow the same overall trend as a function of neutron number for $N \leq 96$. We note that both the W and Os isotopes appear to exhibit an odd-even staggering in the $B_{4/2}$ ratios, even though, given the experimental uncertainties, it is not conclusive. The obtained experimental results are compared with cranked Woods-Saxon-Bogoliubov-Strutinsky calculations, based on the total Routhian surface (TRS) approach [26]. The resulting potential-energy surfaces (PES) are presented in Fig. 5. The PES represent the total energy in the rotational reference frame as a function of the deformation parameters β_2 and γ , and are calculated for a given parity and signature quantum number at different rotational frequencies with fixed hexadecapole deformation parameter $\beta_4 = -0.0124$. The calculations were performed for the odd-A isotopes $^{163,165,167}\text{W}$, as well as for the even-A isotopes $^{164,166}\text{W}$. For the odd-A isotopes the configuration $(\pi, \alpha) = (+, +\frac{1}{2})$, corresponding to the yrast band built upon the $i_{13/2}$ valence neutron, was selected. The minima in the PES at $\hbar\omega = 0.00$ MeV and $\hbar\omega = 0.12$ MeV correspond approximately to the deformation parameters for the $17/2^+ \rightarrow 13/2^+$ and $21/2^+ \rightarrow 17/2^+$ transitions, respectively. The calculations predict PES

TABLE II. Comparison of experimental $B(E2)$ values and $B(E2)$ values from TRS calculations for the $^{163-167}\text{W}$ isotopes. For odd-A isotopes the $B(E2)$ values were calculated assuming $K = 3/2$, while for the even-A isotopes $K = 0$ was used. Rotational frequency $\hbar\omega = 0.00$ corresponds to the $17/2^+ \rightarrow 13/2^+$ ($2^+ \rightarrow 0^+$) transitions, while $\hbar\omega = 0.12$ corresponds to the $21/2^+ \rightarrow 17/2^+$ ($4^+ \rightarrow 2^+$) transitions in the odd-A (even-A) isotopes.

Isotope	$\hbar\omega$ (MeV)	β_2	γ	$B(E2)_{\text{exp}}$ (W.u)	$B(E2)_{\text{TRS}}$ (W.u)
^{163}W	0.00	0.16	0°	80(8) [8]	99
	0.12	0.16	8.2°	154(23) [8]	93
^{164}W	0.00	0.16	0°	150(100) [25]	59
	0.12	0.16	0°	—	84
^{165}W	0.00	0.17	1.3°	155(16)	107
	0.12	0.17	3.9°	91(7)	105
^{166}W	0.00	0.18	1.7°	150(9) [5]	70
	0.12	0.18	0.4°	50(7) [5]	101
^{167}W	0.00	0.19	0°	107(8) [9]	141
	0.12	0.19	0°	131(17) [9]	136

minima in the range $[0.16 \leq \beta_2 \leq 0.19, \gamma \leq 4^\circ]$ for all the states, suggesting only small deviations from a prolate shape. Hartree-Fock-Bogoliubov calculations based on the DIS Gogny effective nucleon-nucleon interaction [27] and covariant density-functional theory calculations [28] predict similar ground-state quadrupole deformations albeit somewhat varying with respect to the triaxiality parameter γ . The results of the PES calculations are presented in Table II, together with deduced $B(E2)$ values applying the collective Bohr Hamiltonian: namely, for nonaxial shapes, reduced transition probabilities can be expressed in terms of a triaxial deformation parameter γ as [29]

$$B(E2)_{\text{triax}} = B(E2)_{\text{axial}} \frac{1}{2} \left[1 + \frac{3 - 2 \sin^2 3\gamma}{\sqrt{9 - 8 \sin^2 3\gamma}} \right] \quad (3)$$

while [30]

$$B(E2)_{\text{axial}} = \frac{5}{16\pi} Q_0^2 \langle IK20 | I - 2K \rangle^2 e^2 \text{fm}^4 \quad (4)$$

where $\langle IK20 | I - 2K \rangle$ represent Clebsch-Gordan coefficients for a given transition and Q_0 is intrinsic the quadrupole moment calculated as

$$Q_0 = \frac{3}{\sqrt{5\pi}} (ZeR^2 \beta_2 (1 + 0.16\beta_2)), \quad (5)$$

where the nuclear radius, R , is defined as $R = 1.2 \times A^{1/3}$ fm. Theoretical collective-model $B(E2)$ values have been determined using the calculated (β_2, γ) values from the PES minima and are compared with the corresponding experimental ones in Table II, while Q_0 values have been determined from the experimental $B(E2; \downarrow)$ values assuming $K = 3/2$ and are also presented in Table II. The calculated values predict $B_{4/2} > 1$ for even-mass isotopes, while for odd-mass isotopes $^{163,165,167}\text{W}$, they give a value of $B_{4/2}$ slightly below 1. Recently, extended IBM-1 calculations including a

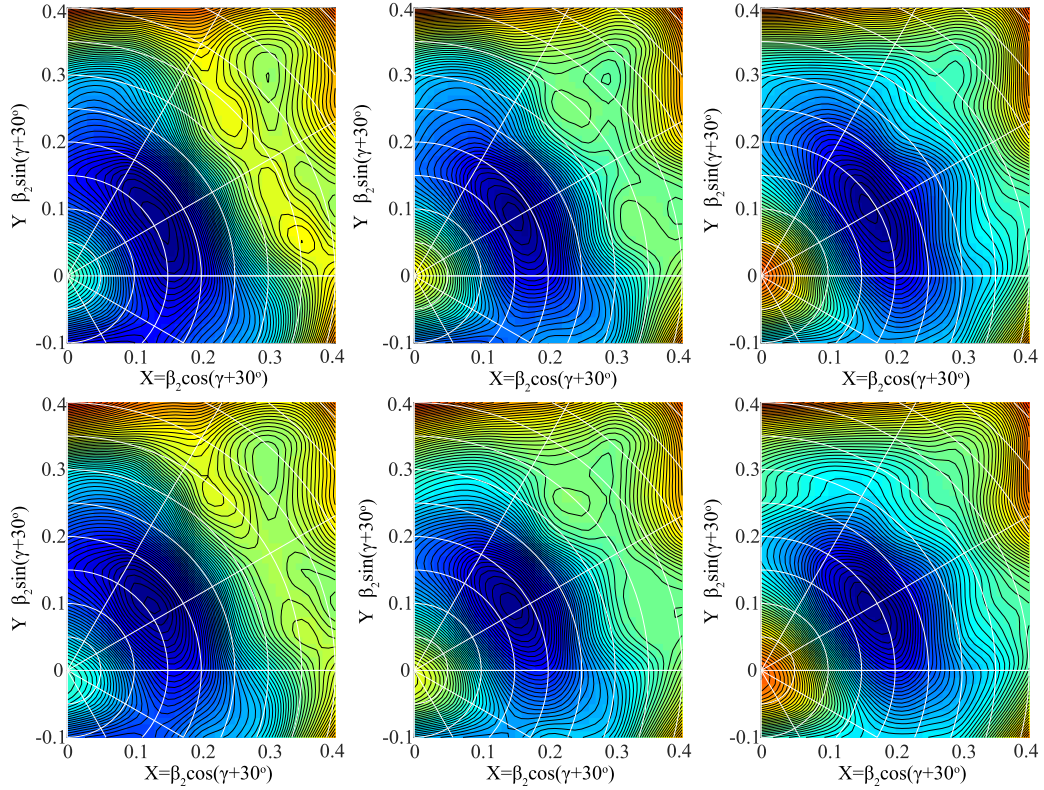


FIG. 5. TRS calculations, resulting potential-energy surfaces (PES) for $^{163,165,167}\text{W}$ isotopes are shown (left to right, respectively), corresponding to $\hbar\omega = 0.00$ MeV (top) and $\hbar\omega = 0.12$ MeV (bottom). Deformation parameters obtained for minimum PES are prescted in Table II, together with the ones obtained for even- A isotopes $^{164,166}\text{W}$.

SU(3) realization of a triaxial rotor have been reported [31,32]. The calculations predict $B(E2 : 4_1^+ \rightarrow 2_1^+)/B(E2 : 2_1^+ \rightarrow 0_{gs}^+) < 1.0$ and $E(4_1^+)/E(2_1^+) > 2.0$ in $^{168,170}\text{Os}$ as a result of a “realistic” finite- N effect. The predictions of $B_{4/2} < 1$ were limited to stable triaxial shapes or near-triaxial shapes within a relatively narrow range around 30° in the triaxiality parameter γ . More recently, the calculations have been extended to even-odd nuclei, in particular $^{169,171}\text{Os}$ [33]. More recently, similar calculations based on the proton-neutron interacting boson model (IBM-2) have successfully reproduced anomalous $B_{4/2} < 1$ values for ^{166}W , $^{168,180}\text{Os}$ and ^{172}Pt [34]. For ^{165}W the model predicts the energy ratio $\frac{E(21/2^+) - E(13/2^+)}{E(17/2^+) - E(13/2^+)} = 2.9$ and $\frac{B(E2; 21/2^+ \rightarrow 17/2^+)}{B(E2; 17/2^+ \rightarrow 13/2^+)} = 0.79$ [35]. The fact that the IBM-1 realization of a triaxial rotor reproduces the unusually low $B_{4/2} < 1$ values, while mean-field and collective-model calculations do not, is an inconsistency that points to underlying mechanisms beyond the rotational excitations of triaxial-deformed nuclei. A possible explanation is that other aspects of SU(3) symmetry included in the IBM-mapping of a triaxial rotor are responsible for the observed effect.

V. SUMMARY

Lifetimes of the yrast $17/2^+$ and $21/2^+$ states in ^{165}W were measured. Notably, a low $\frac{B(E2; 21/2^+ \rightarrow 17/2^+)}{B(E2; 17/2^+ \rightarrow 13/2^+)} = 0.59(7)$ ratio was observed, fitting into the observed evolution of $B_{4/2}$ ratios

for the W-Os-Pt isotopes with neutron numbers $88 \leq N \leq 98$. Such low $B_{4/2}$ values are normally associated with seniority symmetry and not expected significantly away from closed shells. A striking feature of the observed electromagnetic $E2$ transition strengths is also that the concurrent energy level systematics is consistent with that expected of systems exhibiting collective excitations. Self-consistent mean-field calculations of the Woods-Saxon-Strutinsky type or beyond mean-field calculations predict near-prolate shapes and roughly reproduce the absolute $B(E2)$ strengths but not the $B(E2)$ evolution as a function of angular momentum. On the other hand, a new type of IBM calculations including a triaxial rotor term seems to correctly reproduce $B_{4/2} < 1$, but with some limitations. This inconsistency deserves further investigation.

ACKNOWLEDGMENTS

This work was supported by the Swedish Research Council under Grant No. 2019-04808, the Carl Trygger foundation under Project No. CTS 22:2164, the European Union’s Horizon Europe Research and Innovation programme under Grant Agreement No. 101057511 (EURO-LABS), the Academy of Finland under the Finnish Centre of Excellence Programme (Nuclear and Accelerator Based Physics Programme at JYFL), by the Spanish MCIN/AEI/ 10.13039/501100011033 under Grant No. PID2021-126998OB-I00, and the European Union’s Horizon 2020 research and innovation programme

under the Marie Skłodowska-Curie Grant Agreement No. 847635, by the UKRI STFC through Grants No. ST/T001739/1, No. ST/P005101/1, No. ST/P004598/1, No. ST/V001027/1 and No. ST/Y000242/1. The authors acknowledge the support of the GAMMAPOOL for the Jurogam3 detectors. A.H. would like to thank the Slovak Research and Development Agency under Contact No. APVV-20-0532, and Slovak grant agency VEGA

(Contract No. 2/0175/24). T.M. would like to acknowledge partial support of the Ministry of Science, Technological Development and Innovation, Republic of Serbia (Grant No. 451-03-136/2025-03/200017).

DATA AVAILABILITY

The data that support the findings of this article are openly available [36], embargo periods may apply.

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