$B(E2)$ anomalies in the yrast band of ^{170}Os

A. Goasduff,[1,2,*] J. Ljungvall,[1] T. R. Rodríguez,[3] F. L. Bello Garrote,[4] A. Etile,[1] G. Georgiev,[1] F. Giacoppo,[5,6] L. Grente,[7] M. Klintefjord,[4] A. Kuşoğlu,[1,8,9] I. Matea,[10] S. Roccia,[1] M.-D. Salsac,[7] and C. Sotty[1,11]

[1]*CSNSM, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, 91405 Orsay, France*
[2]*Dipartimento di Fisica and INFN, Sezione di Padova, I-35131 Padova, Italy*
[3]*Departamento de Física Teórica and Centro de Investigación Avanzada en Física Fundamental-CIAFF, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
[4]*Department of Physics, University of Oslo, N-0316 Oslo, Norway*
[5]*Helmholtz Institute Mainz, 55099 Mainz, Germany*
[6]*GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
[7]*Irfu, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
[8]*Department of Physics, Faculty of Science, Istanbul University, Vezneciler/Fatih, 34134 Istanbul, Turkey*
[9]*ELI-NP, Horia Hulubei National Institute of Physics and Nuclear Engineering, 077125 Magurele, Romania*
[10]*Institut de Physique Nucléaire, CNRS-IN2P3, Université Paris-Sud, Université Paris-Saclay, 91406 Orsay Cedex, France*
[11]*Horia Hulubei National Institute of Physics and Nuclear Engineering-IFIN HH, 077125 Bucharest, Romania*

(Received 11 March 2019; revised manuscript received 30 July 2019; published 5 September 2019)

Background: The neutron-deficient osmium isotopic chain provides a great laboratory for the study of shape evolution, with the transition from the soft triaxial rotor in ^{168}Os to the well-deformed prolate rotor in ^{180}Os, while shape coexistence appears around $N = 96$ in ^{172}Os. Therefore, the study of the Os isotopic chain should provide a better understanding of shape changes in nuclei and a detailed scrutiny of nuclear structure calculations. In this paper, the lifetimes of the low-lying yrast states of ^{170}Os have been measured for the first time to investigate the shape evolution with neutron number.

Purpose: Lifetimes of excited states in the ground-state band of ^{170}Os are measured to investigate the shape evolution with neutron number in osmium isotopes and compare with state-of-the-art calculations.

Methods: The states of interest were populated via the fusion-evaporation reaction ^{142}Nd(^{32}S, $4n$) at a bombarding energy of 170 MeV at the ALTO facility from IPN (Orsay, France). Lifetimes of the 2_1^+ and 4_1^+ states in ^{170}Os were measured with the recoil-distance Doppler-shift method using the Orsay universal plunger system.

Results: Lifetimes of the two first excited states in ^{170}Os were measured for the first time. A very small $B(E2; 4_1^+ \to 2_1^+)/B(E2; 2_1^+ \to 0_1^+) = 0.38(11)$ was found, which is very uncharacteristic for collective nuclei. These results were compared to state-of-the-art beyond-mean-field calculations.

Conclusions: Although theoretical results give satisfactory results for the energy of the first few excited states in ^{170}Os and the $B(E2; 2_1^+ \to 0_1^+)$ they fail to reproduce the very small $B(E2; 4_1^+ \to 2_1^+)$, which remains a puzzle.

DOI: 10.1103/PhysRevC.100.034302

I. INTRODUCTION

The mechanisms of shape transitions remain a challenging topic in nuclear structure calculations, but are becoming experimentally more accessible. While the transition between shapes is generally gradual, the systems of interest are those that exhibit abrupt changes in observables with the addition or subtraction of a few nucleons. The osmium isotope chain provides such a test case, as it goes from a soft triaxial rotor in ^{168}Os to a mid-shell well-deformed prolate rotor in ^{180}Os, with the appearance of shape coexistence close to $N = 96$ in ^{172}Os. The osmium isotopic chain is the longest continuous chain of even-even isotopes with available spectroscopic data on the low-lying yrast states covering a mass range from $A = 162$ to $A = 198$. The evolution of the energies of the yrast 2^+ and 4^+ for those isotopes is reported in the upper panel of Fig. 1 together with the structural benchmark $E_{4_1^+}/E_{2_1^+}$ ($R_{4/2}$) in the lower panel. A transition from vibratorlike structures for the most neutron-rich nuclei to deformed prolate rotors close to the mid-neutron shell passing by γ-unstable or triaxial shapes is suggested by the data [1–4]. Moving close to the $N = 82$ shell closure at $A = 158$, the collectivity decreases and neutron-deficient osmium isotopes pass through shape coexistence at $A = 172$ [5] to a single-particle-like excitation in ^{162}Os [6].

Osmium isotopes with $N \approx 96$ lie at the edge of the region of neutron-deficient nuclei close to the $Z = 82$ shell closure where a large number of nuclei with shape coexistence [7] are found, making it fertile ground for nuclear structure research.

*alain.goasduff@pd.infn.it

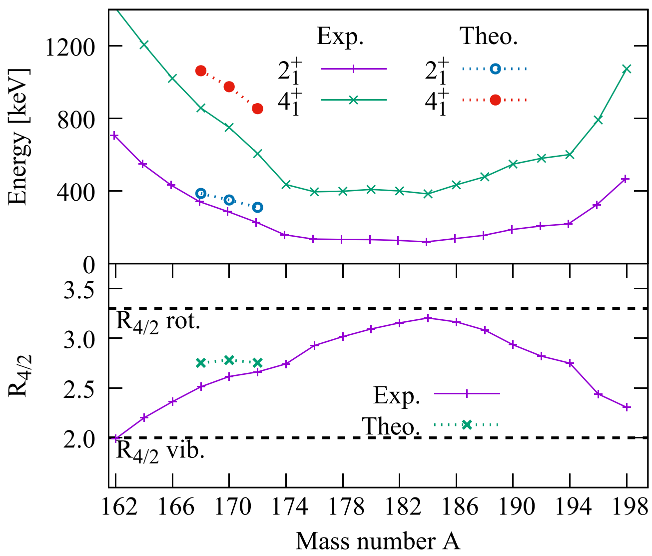

FIG. 1. The excitation energy systematic of the 2^+ and 4^+ yrast states in the osmium isotopes in the upper panel. The structural benchmark $R_{4/2} = E_{4_1^+}/E_{2_1^+}$ is presented in the lower panel together with the empirical limits for rotation and vibrational nuclei. The theoretical values for ^{168,170,172}Os are a part of this work.

A good example is ^{186}Pb with three 0^+ states close in energy [8]. Shape-coexistence phenomena have been evidenced in several nuclei in the lead region and recent lifetime measurements in Po [9], Pb [10–12], Hg [13–15], and Pt [16]. These discoveries have allowed a deeper understanding of the shape-coexistence origins. The model-independent measurements of the $B(E2)$ values in the yrast bands have given firm experimental evidence of several low-energy configurations highly mixed at low spins.

The question of shape coexistence in the neutron-deficient osmium isotopes has been addressed several times over the last few decades. The yrast sequence of ^{172}Os shows a sharp backbend near spin $14\hbar$ originated from the $i_{13/2}$ neutron alignment [17]. At a spin of $6\hbar$, an up-bend can be observed. The shape coexistence in ^{170,172}Os was discussed based on a three-band mixing model [18] reproducing level energies and moments of inertia. The work suggested that shape coexistence is as well present in ^{170}Os although the deformed structure responsible for the anomaly seen in the moments of inertia in ^{172}Os is shifted upwards in ^{170}Os, making its influence on the kinematic moments of inertia significantly smaller. To explain this variation in the moments of inertia around ^{172}Os several approaches were employed based on either particle alignment or phenomenological shape coexistence [17]. Although no firm conclusions could be drawn, shape coexistence is presented as a plausible explanation. The question of shape coexistence in ^{172}Os [19] was also addressed by means of lifetime measurements using the recoil-distance Doppler-shift (RDDS) method giving access to the transition quadrupole moment Q_t. A strong variation in the Q_t with increasing spin in the ground-state band was observed. This behavior could be explained by the model of three bands with strong mixing. Studying the spectroscopy of ^{168}Os [20] and using a similar theoretical approach of the three-band mixing model, a conclusion similar to that for ^{170}Os is reached concerning the presence of shape coexistence as the shaping force of the low-spin spectroscopy.

More recent studies concerning neutron-deficient Os isotopes such as ^{162}Os [21], including a lifetime measurement of the $17/2^+$ state in ^{167}Os [22] and of yrast and non-yrast states in ^{168}Os [23], give evidence for a shape transition from prolate deformation via γ-soft nuclei to spherical shapes close to the $N = 82$ shell gap. It is worth pointing out that for ^{168}Os Grahn *et al.* [23] measured a reduced transition probability for the yrast 4^+ resulting in $B_{4/2} = B(E2; 4_1^+ \rightarrow 2_1^+)/(B(E2; 2_1^+ \rightarrow 0_1^+) = 0.34(18)$. A $B_{4/2} < 1$ is very rare throughout the nuclear chart, with only a handful of examples away from closed shell nuclei, e.g., ^{48,50}Cr [24], ^{72,74}Zn [25], ^{114}Te [26], ^{114}Xe [27], ^{166}W [28], ^{168}Os [23], and ^{172}Pt [29]. These observations have not been reproduced so far by any type of state-of-the-art nuclear structure calculations, neither large-scale shell models nor beyond-mean-field models.

Beyond-mean-field calculations using the Gogny D1S force, allowing for triaxial shapes, have been used to investigate the shape coexistence phenomenon. For lighter nuclei such as Kr [30] and Se [31], it has been shown that triaxial shapes have to be included in the A ∼ 70 region for a correct reproduction of the observable. The importance of the triaxial degree of freedom has also been demonstrated in neutron-rich osmium [1].

The work presented here was initiated to elucidate the question of shape coexistence and shape evolution in neutron-deficient osmium isotopes. In this paper the result of an experiment where the lifetimes of yrast states in ^{170}Os have been measured via the RDDS method are presented. The results are compared to the state-of-the-art beyond-mean-field calculations.

II. EXPERIMENT AND RESULTS

The experiment was performed at the ALTO facility (IPN Orsay, France) using the Tandem accelerator. Excited states in ^{170}Os were populated in the reaction ^{142}Nd(^{32}S, $4n$)^{170}Os at a beam energy of 170 MeV. The isotopically enriched ^{142}Nd target had a thickness of 1 mg/cm^2. The Nd was evaporated onto a 2 mg/cm^2 thick Ta fronting facing the beam. The energy loss of the beam inside the Ta backing was taken into account in the determination of the bombarding energy. A 5 mg/cm^2 Au thick foil was used as a stopper foil for the fusion-evaporation fragments. Target and stopper were mounted on the Orsay universal plunger system (OUPS) plunger [32]. The γ rays were detected by the ORGAM germanium detector array composed of 10 Compton-suppressed high-purity germanium (HPGe) detectors distributed over two rings at backward angles (133.5° and 157.6°) and two additional detectors at forward angle (43°). The recoil velocity of the ^{170}Os nuclei was deduced from the Doppler shift of γ rays emitted in flight to be $\beta = v/c = 1.62 \pm 0.02\%$.

Data were collected for eight target-stopper separations between 18 and 740 μm. The normalization of the data for the different distances was obtained using the 278-keV line of ^{197}Au, resulting from the Coulomb excitation of the

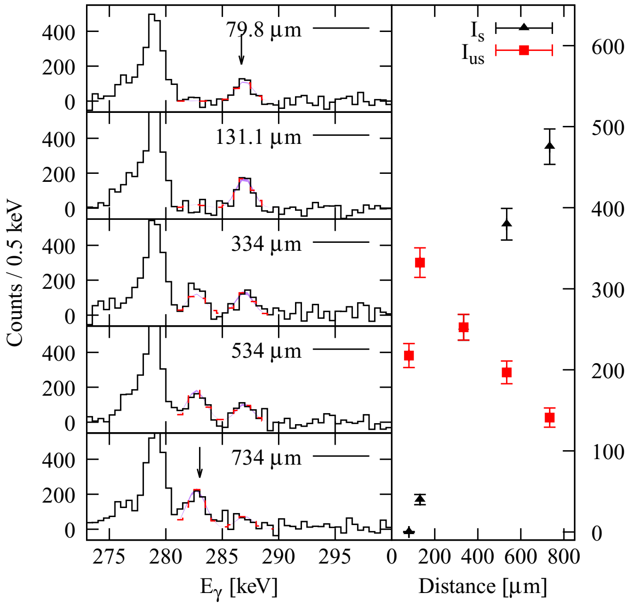

FIG. 2. Left: Background subtracted γ-ray spectra obtained by gating on the in-flight transition of the $4_1^+ \rightarrow 2_1^+$ for the detectors at 157.6°. The γ-ray spectra show the stopped and in-flight components of the $2_1^+ \rightarrow 0_1^+$. Only the distances in the sensitive range are presented. The stopped component is indicated by an arrow in the uppermost panel, and the in-flight component with an arrow in the lowest panel. The large peak at 279 keV is the Coulomb excitation of the gold stopper. Spectra are background subtracted. The fit used to extract the integral of the two components is displayed for each distance with the red dashed line. The purple curves correspond to the variations performed by the MINOS package to find the two-sided error on τ. Right: Normalized number of counts for the distances in the sensitive range used to extract the lifetime of the 2^+ state.

stopper foil. The normalization is thus directly proportional to the integrated beam current on the target. The γ-γ coincidences were reconstructed and used to avoid the side-feeding effect on the lifetime determinations. Lifetimes of the two first excited states were obtained using γ-γ coincidence and the differential decay-curve method (DDCM) [33,34] gating on the in-flight component of the feeding transition. The γ-γ coincidences were sorted ringwise and the background subtracted projection was then summed and used to extract the lifetimes of interest. The background subtracted spectra obtained by gating on the in-flight component of the 4_1^+ and 6_1^+ are presented in Figs. 2 and 3 for the detectors at 157.6° and in Figs. 4 and 5 for the ones at 133.5°, respectively. Because the spectra were contaminated with peaks from other nuclei and there was not sufficient statistics to work with triple coincidences, two independent methods were used to extract the lifetimes of interest: the traditional method, in which the intensities of the peaks were extracted from the in-flight gated spectrum using analytic functions, and a Monte Carlo–based approach. For the latter, GEANT4 Monte Carlo simulations taking into account all the relevant aspects of the experimental setup such as the position and resolution of individual detectors, target and degrader thickness, reaction kinematics, etc., were used to determine the line shapes of

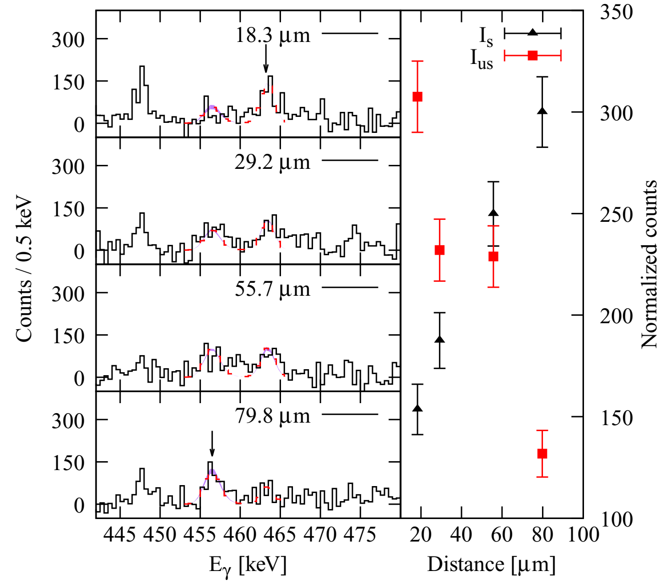

FIG. 3. Same as Fig. 2 for the $4_1^+ \rightarrow 2_1^+$ transition at 157.6° obtained by gating on the $6_1^+ \rightarrow 4_1^+$ in-flight transition.

the peaks. These line shapes were later used to extract the intensities of the stopped (I_{us}) and in-flight (I_s) intensities in the spectra as a function of the lifetime (τ) via the relation

$$I_{us} = \frac{dI_s}{dt}\tau. \tag{1}$$

I_{us} (red square) and Is (black triangle), after renormalization to the Coulomb excitation of the Au stopper, are given in the right-hand panels of Figs. 2 and 3 for the 2^+ and 4^+ states, respectively, and for the detectors placed at 157.6°. The same analysis was performed independently for the detectors at

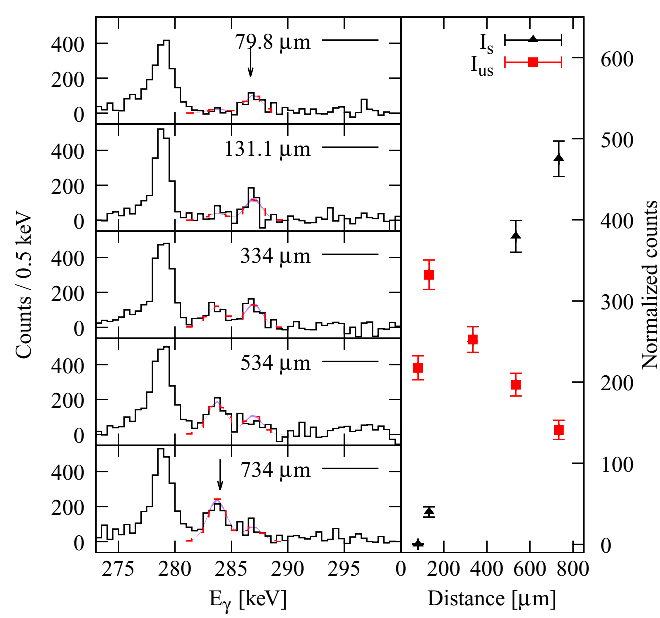

FIG. 4. Same as Fig. 2 for the $2_1^+ \rightarrow 0_1^+$ transition gated on the in-flight transition of the $4_1^+ \rightarrow 2_1^+$ for the detectors at 133.5°.

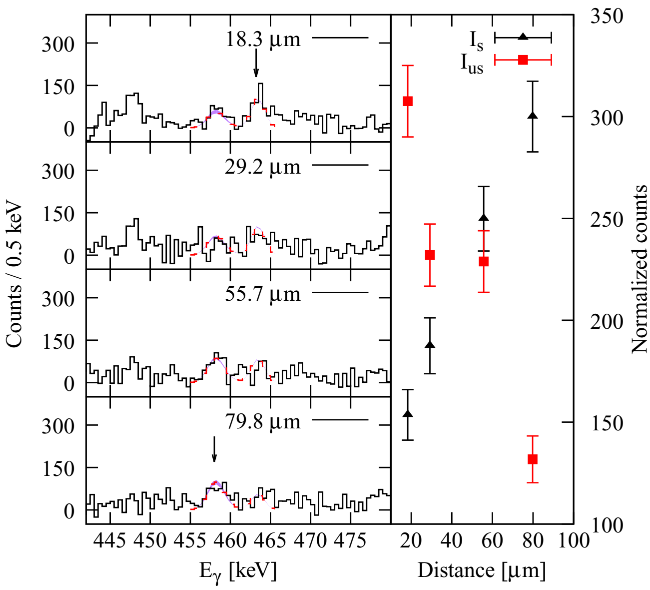

FIG. 5. Same as Fig. 3 for the $4_1^+ \rightarrow 2_1^+$ transition at 133.5° obtained by gating on the $6_1^+ \rightarrow 4_1^+$ in-flight transition.

133.5° and the results are presented in Figs. 4 and 5. Lifetimes were extracted using background subtracted spectra gated on the in-flight component of the feeding transition. Using such a gated approach allows one to get rid of the problem with long lived unseen feeding. Moreover, the second approach presents the advantage of taking into account the non-Gaussian shape of the peaks due to the angular aperture of the detectors, the velocity distribution, and slowing down of the recoiling nuclei in the target or stopper. For these reasons the more robust fit given by the second approach gives a more reliable determination of the lifetimes. The lines shapes were fitted to the experimental spectra using the MINUIT2 package [35] and the asymmetric errors were extracted using the MINOS function included in MINUIT2, leaving as free parameters only the number of counts in the two components. MINOS extracts the error on either side by varying the lifetime such that $\Delta\chi^2 = 1$ while minimizing the χ^2 on all other free parameters. In Figs. 2 and 3 the γ-ray spectra obtained by projecting the γ-γ matrices on the in-flight component of the feeding transition ($4_1^+ \rightarrow 2_1^+$ and $6_1^+ \rightarrow 4_1^+$, respectively) are presented (solid black line) for the distance in the sensitive range for the lifetime measurement. The corresponding fits are shown (dashed red line) for γ-ray spectra with detectors at the most backward angle, representing about half of the total statistic. Purple bands corresponding to the variations done by MINOS to find the two-sided errors are also shown. It should be noted that the two methods yielded compatible results using the same background subtracted spectra. While the results using the second methods are reported in Table I, the ones employing the first methods correspond to 80^{+11}_{-13} ps for the 2_1^+ and 20^{+8}_{-5} ps for the 4_1^+.

Reduced electromagnetic transition probabilities were obtained from the measured lifetime (τ) using the formula

$$\tau = 8.13 \times 10^{13} E_\gamma^{-5} [B(E2)\downarrow]^{-1} (1+\alpha)^{-1}, \qquad (2)$$

TABLE I. Spin and parities of the yrast states in ^{170}Os together with their excitation energies, lifetimes, and reduced electromagnetic transition probabilities (experimental and theoretical). The reported theoretical values are the ones obtained in this work using the symmetry-conserving configuration mixing method.

				$B(E2)\downarrow$ (e^2b^2)	
J^π	E (keV)	τ (ps)	$I_i^\pi \rightarrow I_f^\pi$	Expt.	Theor.
2_1^+	287	70^{+6}_{-6}	$2_1^+ \rightarrow 0_1^+$	$0.54^{+0.05}_{-0.05}$	0.53
4_1^+	750	18^{+6}_{-4}	$4_1^+ \rightarrow 2_1^+$	$0.21^{+0.07}_{-0.04}$	0.81

where E_γ is in units of keV, $B(E2)\downarrow$ in e^2b^2, τ in picoseconds, and α the total internal conversion coefficient evaluated using Ref. [36]. The results are summarized in Table I.

As this is a very unusual result the validity of the measured lifetime of the 4_1^+ state can be questioned. The data were analyzed in an independent manner by several of the authors using more than one way of estimating the peak intensities. Results scatter slightly but within errors and the anomaly of a $B_{4/2} < 1$ remains valid.

III. DISCUSSION

The measured B(E2; $2_1^+ \rightarrow 0_1^+$) of 0.54(0.05) e^2b^2 (97(8) W.u.) is in agreement with extrapolation from less neutron-deficient osmium isotopes. It is also in good agreement with earlier theoretical estimates [37]. The variable-moment-of-inertia (VMI) model [38] with the fitted parameters [18] gives an estimate of the $B(E2; 2_1^+ \rightarrow 0_1^+)$ of ^{170}Os, which is ~40% lower than the experimental value. A similar underestimate is obtained for ^{172}Os; however, the VMI model reproduces correctly the evolution of the $B(E2; 2_1^+ \rightarrow 0_1^+)$ going from ^{172}Os to ^{170}Os. Looking at the 2_1^+ state the ^{170}Os behaves as a transitional nucleus with the normal decrease in collectivity moving away from the neutron mid-shell.

The $B(E2; 4_1^+ \rightarrow 2_1^+)$ of 0.21(0.05) e^2b^2 is, in contrast to the "normal" $B(E2; 2_1^+ \rightarrow 0_1^+)$, surprisingly small, resulting in a $B_{4/2}$ ratio of 0.38(11). Similar results were obtained in ^{166}W [28], ^{168}Os [23], and ^{172}Pt [29]. Based on those measurements, Cederwall *et al.* [29] proposed a transition at $N = 94$ from a collective regime into a senioritylike scheme as a possible explanation for the $B_{4/2} < 1$, despite the presence of a large number of valence nucleons. The position of such a phase transition at $N = 94$ is supported by the present data. However, as ^{170}Os is rather collective the suggested explanation, i.e., a transition into a senioritylike scheme, is very surprising. Band-mixing calculations for ^{170}Os [18] cannot explain this phenomenon, as the ground-state band should be pure at such low spins. Moreover, it is worth noticing that the 2_1^+ states of these four nuclei follow the expected correlations between the $E(4_1^+)/E(2_1^+)$ or the product of the number of valence protons and neutrons and the $B(E2; 2_1^+ \rightarrow 0_1^+)$ [39].

To try to understand the small $B_{4/2}$ ratio, symmetry-conserving configuration mixing (SCCM) calculations were performed using the generator coordinate method framework with Hartree-Fock-Bogoliubov states found with variation after particle number projection (PN-VAP) [40,41]. In general

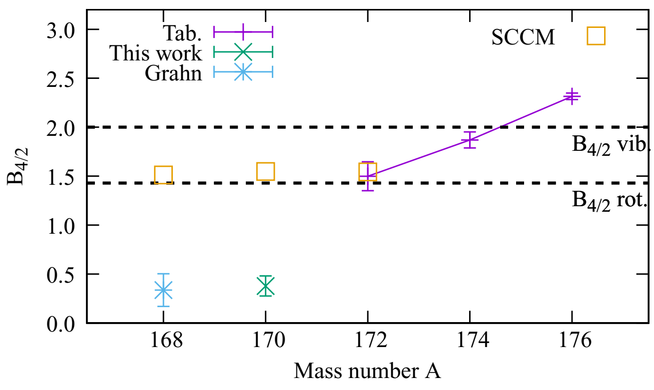

FIG. 6. The ratio between $B(E2;4_1^+ \rightarrow 2_1^+)$ and the $B(E2;2_1^+ \rightarrow 0_1^+)$ ($B_{4/2}$) for the neutron-deficient osmium isotopes. The tabulated values for ^{172,174}Os values were taken from National Nuclear Data Center and from Refs. [43,44] for ^{176}Os. The value reported for ^{168}Os is the one from the work of Grahn *et al.* [23]. The experimental value for ^{170}Os as well as the theoretical values for ^{168,170,172}Os are part of this work.

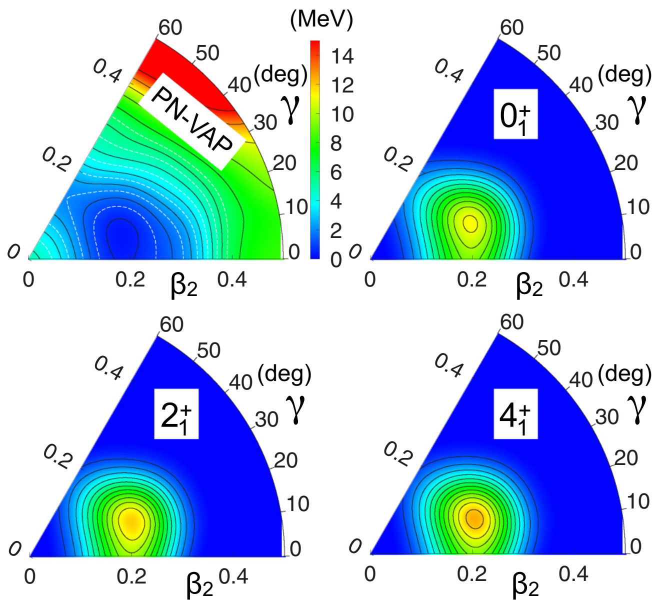

FIG. 7. The PN-VAP potential energy surface for ^{170}Os (top left) and collective wave functions for the ground state (top right) as well as the yrast 2^+ (bottom left) and 4^+ (bottom right) states. All calculated wave functions display a very similar structure.

the yrast states are given as close to prolate with $\beta \approx 20^\circ$ and $\gamma \leqslant 20^\circ$. For ^{172}Os, the yrast band is, however, triaxial with $\gamma \approx 30^\circ$. The energies for the lowest yrast and non-yrast states for ^{168,170,172}Os are presented in Fig. 1. The agreement between experimental and theoretical excitation energies is satisfactory (see Ref. [42] and references therein). In Fig. 6 experimentally known $B_{4/2}$ are shown together with the results of the calculations. The experimental $B_{4/2}$ are presented in Fig. 6 for $^{169-176}$Os and compared for $^{168-172}$Os to the present theoretical calculations. The $B_{4/2}$ for ^{172}Os is well reproduced by the model; however, the ones of ^{168,170}Os are overestimated by a factor of ∼4. As shown in Table I, the $B(E2;2_1^+ \rightarrow 0_1^+)$ of ^{170}Os is very well reproduced, as well as those of ^{168,172}Os. Thus the observed discrepancy on the $B_{4/2}$ for ^{168,170}Os is solely originated by the $B(E2;4_1^+ \rightarrow 2_1^+)$. Indeed a similar factor of ∼4 is found between the experimental and theoretical $B(E2;4_1^+ \rightarrow 2_1^+)$. While the experimental $B_{4/2}$ ratio is small, the resulting theoretical ratios are ∼1.5, close to that of a deformed rotor. The experimental $B_{4/2}$ ratio for ^{172}Os is 1.5(2), compatible with the present theoretical approach. The present results show that the structural change is more sudden than previously observed. Indeed the large drop in $B_{4/2}$ is already evidenced in ^{170}Os.

A possible explanation for the observed $B_{4/2}$ ratio is that the yrast 4^+ state does not belong to the same band as the 2_1^+ state. The origin for this mismatch could be the presence of a shape-coexistent rotational band whose 4^+ member would be below the 4^+ level of the ground-state band. The SCCM method calculations performed in this work show no evidence for such a sideband. In Fig. 7 the potential energy surface (PES) obtained using the PN-VAP method, and the collective wave functions for the 0_1^+, 2_1^+, and 4_1^+ states are plotted in the (β_2, γ) plane. The PES exhibits only one minimum at a slightly triaxial deformation $(\beta_2, \gamma) \sim (0.2, 15^\circ)$ and the collective wave functions have all the same structure, revealing that they belong to the same rotational band. The second 4^+ in the calculations (not shown) corresponds to a state in a γ band. Another possibility is that the experimental yrast 4^+ has a single-particle nature that could be produced, e.g., by the alignment of a pair at low spin as it was found in ^{44}S [42]. In order to search for such a state, calculations were expanded by performing PN-VAP calculations including cranking and by extending the range of triaxial quadrupole deformations to $-60^\circ < \gamma < 120^\circ$ as done in Ref. [42]. The full configuration mixing was not performed due to the large computational burden. Nevertheless, a 4^+ state with the sought-after characteristics to reproduce the low $B(E2;4_1^+ \rightarrow 2_1^+)$ value would manifest itself as a minimum for the projected $J \geqslant 4$ PES's not present in the $J = 0, 2$ PES's computed at non-zero intrinsic rotation (cranking) frequency, $\omega \neq 0$. Such a feature has not been found in the calculations and the origin of the observed transition probability remains unexplained within the employed formalism and/or variational space.

IV. CONCLUSION

The lifetimes of the first excited 2^+ and 4^+ states in ^{170}Os were measured for the first time using the RDDS method at the ALTO facility with the ORGAM γ-ray array coupled to the OUPS plunger. A surprisingly small $B(E2;4_1^+ \rightarrow 2_1^+)$ value was found. To understand this value, the results were compared to the state-of-the-art beyond-mean-field calculations. The model accurately reproduced the energies of the lowest-lying yrast states and the 2^+ reduced transition probabilities in ^{168,170,172}Os. Although the model described correctly the properties of the yrast 4^+ state of ^{172}Os, the sudden structural change observed when removing two neutrons is not present in the calculation. The question of the origin of the small $B_{4/2}$ in ^{168,170}Os remains open and merits experimental efforts in order to validate these surprising results and expand the known lifetimes to higher spin yrast and yrare states.

ACKNOWLEDGMENTS

The authors would like to thank the ALTO technical team for the good quality beam that was provided during the experiment. Dr. K. O. Zell and Dr. A. Blazhev from IKP Köln are thanked for the excellent quality Nd targets. We also thank the UK/France (STFC/IN2P3) Loan Pool and GAMMAPOOL European Gamma-Ray Spectroscopy Pool for the loan of the detectors for ORGAM. This work was supported in part by the 2214-TUBITAK (Scientific and Technological Research Council of Turkey) Programme, the Scientific Research Projects Coordination Unit of Istanbul University under Project No. 46811, and the European Community FP7 Capacities-Integrated Infrastructure Initiative-Contract ENSAR No. 262010. This work has been partly funded (A.G.) by the P2IO LabEx (ANR-10-LABX-0038) in the framework Investissements d'Avenir (ANR-11-IDEX-0003-01) managed by the French Agence Nationale de la Recherche (ANR). T.R.R. acknowledges support from Spanish Grants No. FIS-2014-53434-P MINECO and Programa Ramon y Cajal 2012 No. 11420, and computing time at GSI-Darmstadt.

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