

Lifetimes of the 2_1^+ and 4_1^+ states of the neutron-rich nuclide ^{200}Pt

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The lifetimes of the 2_1^+ and 4_1^+ states of ^{200}Pt were measured by applying the recoil-distance Doppler-shift method. Excited states were populated in the $^{198}\text{Pt}(^{18}\text{O}, ^{16}\text{O})^{200}\text{Pt}$ two-neutron transfer reaction at the 9-MV tandem accelerator at the IFIN-HH in Măgurele, Romania. The resulting $B(E2)$ values of the $2_1^+ \rightarrow 0_1^+$ and $4_1^+ \rightarrow 2_1^+$ transitions as well as the $B_{4/2}$ ratio of 2.10(31) indicate an evolution of the nuclear structure toward sphericity when approaching the neutron shell closure at $N = 126$. The $B(E2; 2_1^+ \rightarrow 0_1^+)$ values of Pt and Hg are compared to values of Te, Xe, and Ba where similar structural effects are exhibited.

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I. INTRODUCTION

The region of the nuclear chart below ^{208}Pb , i.e., neutron-rich isotopes from Hf to Pt, has been discussed in the context of a transition from prolate to oblate shapes [1–6]. Such a transition would cross through the limit of soft triaxiality (γ softness). While ^{190}W has recently been discussed as an isotope closest to the prolate-oblate transition [7], in particular ^{196}Pt has long been a textbook example of a γ -soft structure [8,9], in close proximity to the O(6) dynamical symmetry limit of the interacting boson model (IBM) [10]. However, moving to heavier isotopes, the proximity of the $N = 126$ neutron shell closure takes effect. The size of the available valence space, and hence the degree of collectivity, drops quickly toward the shell closure, and sphericity is expected to establish near $N = 126$.

A well-known measure for the degree of collectivity is the $E2$ transition strength of even-even nuclei. Since the reduced transition probability $B(E2)\downarrow \equiv B(E2; 2_1^+ \rightarrow 0_1^+)$ exhausts most of the $E2$ transition strength, it is an indicator of the evolution of structure over a series of isotopes or, more

generally, in a given region of the nuclear chart. To investigate the evolution toward the $N = 126$ shell closure, a study of ^{200}Pt is required, for which no $B(E2)\downarrow$ value is known to date. Moreover, the Pt isotopes are only four valence protons below the $Z = 82$ proton-shell closure, just below the Hg isotopes, which, when approaching the $N = 126$ shell, evolve toward sphericity with some degree of oblate deformation [2]. Hence, the $B(E2)\downarrow$ values of Pt isotopes with respect to those of Hg isotopes are of high interest as both should approach the spherical limit toward $N = 126$. In comparison to the Hg isotopes, the $B(E2)\downarrow$ values of the Pt isotopes only depend on the difference of two additional valence-proton holes, and may serve as a benchmark test of this neutron-shell closure. Furthermore, the $B_{4/2}$ ratio allows for comparison with theoretical values to evaluate spherical versus deformed structures toward $N = 126$.

In this paper, we report on the first measurement of the $B(E2; 2_1^+ \rightarrow 0_1^+)$ and $B(E2; 4_1^+ \rightarrow 2_1^+)$ values of ^{200}Pt via a direct measurement of the lifetimes of its first-excited 2^+ and 4^+ states.

II. EXPERIMENT

The $^{198}\text{Pt}(^{18}\text{O}, ^{16}\text{O})^{200}\text{Pt}$ two-neutron transfer reaction was used to populate low-lying excited states of ^{200}Pt . The ^{18}O beam of 75 MeV was delivered by the 9-MV tandem accelerator at the IFIN-HH in Bucharest-Măgurele and impinged on a $600\text{ }\mu\text{g}/\text{cm}^2$ thick self-supporting ^{198}Pt target foil. A gold foil was mounted parallel with respect to the target foil in

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order to stop the recoiling nuclei. Both foils were installed in the ROSPHERE plunger device [11], which is used to vary and stabilize the distance between target and stopper. Data were taken at six different target-to-stopper distances, i.e., 12, 40, 60, 80, 110, and 150 μm . An additional plunger offset of $-3.6(2)$ μm was taken into account that was determined using the capacitance method [12,13].

The γ radiation emitted from the decay of excited states was detected by 25 high-purity germanium (HPGe) detectors of the ROSPHERE array [11] which were mounted in five rings. These rings were placed at angles of 37° , 70° , 90° , 110° , and 143° with respect to the beam axis. The backscattered beamlike particles, i.e., ^{16}O and ^{18}O , were detected using the SORCERER solar cells [14]. The data of the particle detectors allow the creation of particle-gated spectra which facilitate the separation of the occurring reaction channels and select the two-neutron transfer reaction. Whereas events from fusion evaporation can be suppressed, the two-neutron transfer reaction channel could not be separated from those resulting from Coulomb excitation due to the limited energy resolution of the solar cells.

To demonstrate the overall quality of the data, Fig. 1 shows summed spectra of all detector rings taken at a target-to-stopper distance of 12 μm . A random-background subtracted particle gate is set on the peak in the particle- γ time-difference spectrum that relates to backscattered O isotopes. The particle gate serves to significantly enhance the peak-to-background ratio for peaks from Coulomb-excitation and two-neutron transfer, and to suppress γ rays from fusion-evaporation processes. The γ -coincidence conditions as shown in Fig. 1(c) aid in the identification of γ rays from ^{200}Pt and, hence, serve to clarify the population of low-lying states, although at a modest level of statistics.

The mean velocity of the recoiling ^{200}Pt ions after the target has been determined from the energies of the shifted and unshifted components of the $2_1^+ \rightarrow 0_1^+$ transition and amounts to $v/c = 1.4(1)\%$.

III. ANALYSIS

The γ -ray emission from the 2_1^+ state of ^{200}Pt was analyzed by applying the recoil-distance Doppler-shift (RDDS) method and its lifetime was determined using the differential decay curve method (DDCM). Both methods are explained in detail in Ref. [12].

In an RDDS experiment, the nucleus of interest is produced in a nuclear reaction which populates excited states. The produced nuclei recoil out of the target foil in the direction of a stopper foil. The γ decay of an excited state can occur either while the recoiling nuclei are in flight, which yields a Doppler-shifted peak in the energy spectra, or after they have come to rest in the stopper foil, resulting in a peak at the γ -transition energy. The flight time between the target and the stopper foils is of the order of 10 ps and varies with the chosen target-to-stopper distance, serving as the timescale for the intended lifetime measurement and defining its sensitive range.

The decay curve $R(t)$ is a time-dependent function of the intensities of the shifted $I_s(t)$ and unshifted $I_u(t)$ components

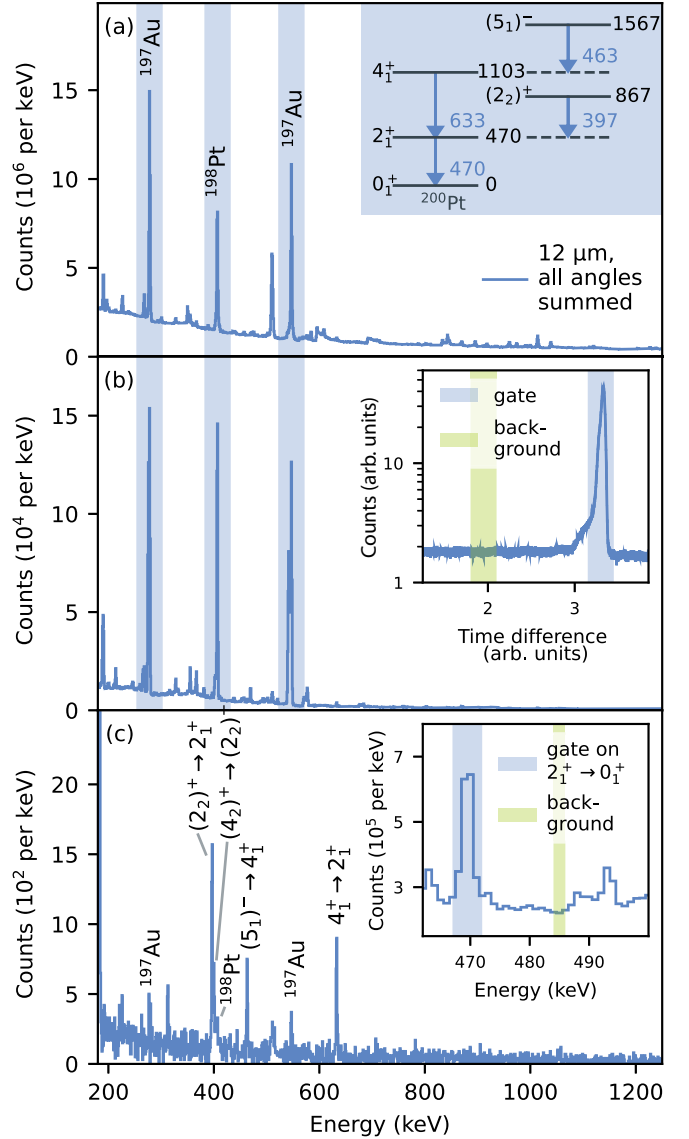


FIG. 1. γ -ray energy spectra at 12 μm with all angles summed up (a) without a coincidence condition, (b) with a background-corrected coincidence condition set in the particle- γ time-difference spectrum shown in the inset, and (c) with both the particle gate from before and an additional background-corrected coincidence condition set on the energy of the $2_1^+ \rightarrow 0_1^+$ transition shown in the inset. All observed transitions of ^{200}Pt are shown in the level scheme in panel (a).

of a γ -ray transition of interest,

$$R(t) = I_u(t)/(I_u(t) + I_s(t)), \quad (1)$$

where t is the time of flight of the recoiling ions, which is given by their velocity v and the set distance between the target and stopper foils. The lifetime of the γ -decaying excited state affects the time evolution of the shifted and unshifted intensities $I_{u,s}$. Data are normalized to the total number of counts in the prominent peak of the $5/2_1^+ \rightarrow 3/2_1^+$ transition of ^{197}Au at 279 keV in order to compensate for beam fluctuations and varying measurement times.

The lifetime of the 2_1^+ state can be obtained directly from the decay curve if the state is exclusively populated in the nuclear reaction and no feeding from higher-lying states is present. However, the 4_1^+ and $(2_2)^+$ states of ^{200}Pt , which also decay into the 2_1^+ state, were populated in the two-neutron transfer reaction as well. In Fig. 1(c), the feeding transitions $4_1^+ \rightarrow 2_1^+$ and $(2_2)^+ \rightarrow 2_1^+$ are marked. These transitions become clearly visible after setting a coincidence condition on the $2_1^+ \rightarrow 0_1^+$ transition. The statistics of the particle- γ gated data are not sufficient for a lifetime analysis using γ - γ coincidences. Therefore, the analysis had to be performed using particle-gated γ -ray singles spectra only.

The extraction of the shifted and unshifted intensities of the $2_1^+ \rightarrow 0_1^+$ transition of ^{200}Pt was hampered by the occurrence of other γ -ray transitions in the respective energy region. Figure 2 shows the fits of the shifted and unshifted components of the $2_1^+ \rightarrow 0_1^+$ transition as well as contaminating peaks originating from transitions of ^{197}Au , ^{198}Pt , and ^{200}Pt . The former two are present due to Coulomb excitation of the target and stopper foils. For the observed $(5_1)^- \rightarrow 4_1^+$ transition of ^{200}Pt at 463 keV, no shifted component was observed even at large distances; hence, its lifetime is larger than the sensitivity of the experiment. Note that the lifetime of the corresponding state of ^{196}Pt is known to be $\tau(5_1^-, ^{196}\text{Pt}) = 1.1(2)$ ns. Therefore, only an unshifted 463-keV transition needs to be considered for the fit of the present data. The intensity of the $(3)_1^+ \rightarrow 2_2^+$ transition of ^{198}Pt at 473 keV was found to be sufficiently small at all distances and angles to neglect its potential shifted component in the analysis. The intensities of the shifted and unshifted components of the $7/2_2^+ \rightarrow 5/2_1^+$ transition of ^{197}Au at 458 keV were disentangled from the higher-lying transitions in the energy region of interest via consistent fits of the data at all angles and distances. Through this iterative procedure, shifted and unshifted intensities of the $2_1^+ \rightarrow 0_1^+$ transition of ^{200}Pt were extracted.

The correction for the above-mentioned slow feeding from the 4_1^+ and $(2_2)^+$ states observed in the particle- γ gated spectra was done by subtraction [15]. The intensities of the unshifted components of the feeding transitions were subtracted from the intensities of the unshifted part of the $2_1^+ \rightarrow 0_1^+$ transition of ^{200}Pt .

The DDCM analysis for the 2_1^+ state of ^{200}Pt was performed after application of the above-mentioned steps to separate the respective contributions of γ -ray transitions and after feeding correction. Its lifetime τ_i is determined for each distance i following

$$\tau_i = \frac{I_u}{\frac{d}{dt}I_s} = \frac{I_u}{v \frac{d}{dx}I_s}. \quad (2)$$

The evolution of the intensities of both the shifted and unshifted components with the distance is shown in Fig. 2. Due to the differential approach of the DDCM only relative distances are required. The mean lifetime τ is determined via a χ^2 fit of the distance-wise determined lifetime values implemented in the program NAPATAU [16], separately for each ring of ROSPHERE. Exemplary fits that were used in the determination of the final value of τ are shown in Fig. 3. Since

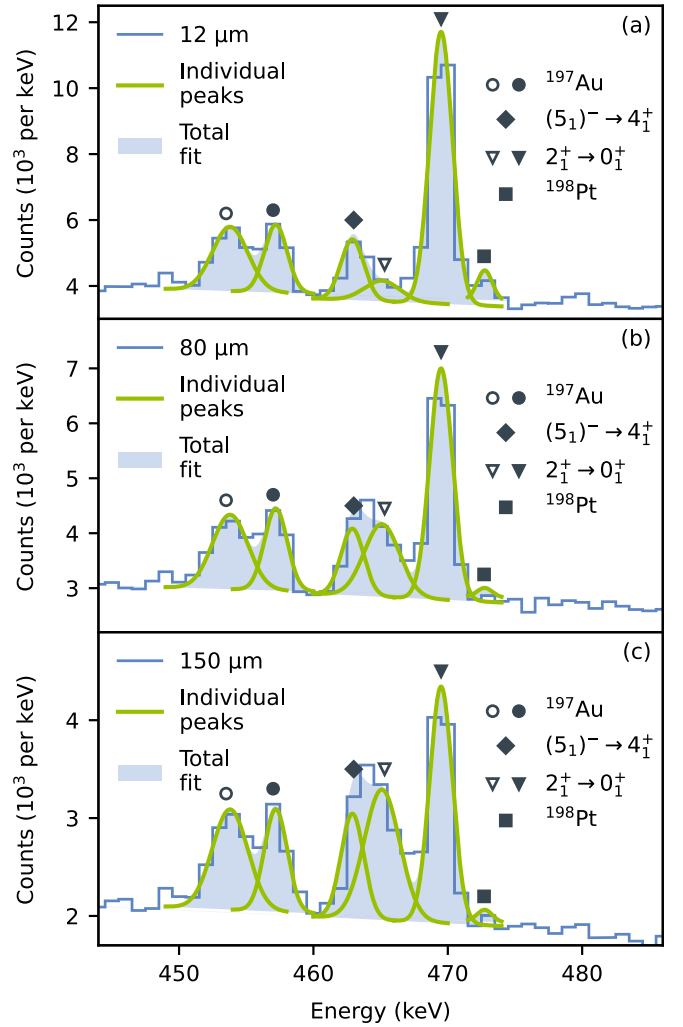


FIG. 2. Particle-gated γ -ray singles spectra at 143° at (a) 12 μm , (b) 80 μm , and (c) 150 μm . The origin of the shifted (open symbols) and unshifted (solid symbols) components are indicated. The fits of the shifted and unshifted components of the $2_1^+ \rightarrow 0_1^+$ transition of ^{200}Pt and the relevant contaminants are shown. The evolution of the intensity ratio of the shifted and unshifted components with flight distance is visible; the intensity of the shifted component increases with the distance while the intensity of the unshifted component decreases.

the shifted and unshifted components of the transition are related through Eq. (2) via the lifetime as a free parameter, both observables are fitted simultaneously by a quadratic spline function in NAPATAU. The weighted average of all distance values included in the fit is then determined for each detector ring.

The lifetime values obtained from each detector ring angle are included in Fig. 4. In particular, when averaging the data from each corresponding pair of rings relative to 90° , 37° and 143° (blue), and 70° and 110° (green), it is apparent that the lifetime values for the respective inner and outer angles do not agree, as indicated by the respective weighted averages for both angle pairs, and vary by almost 10 ps, with a total average of 26(2) ps.

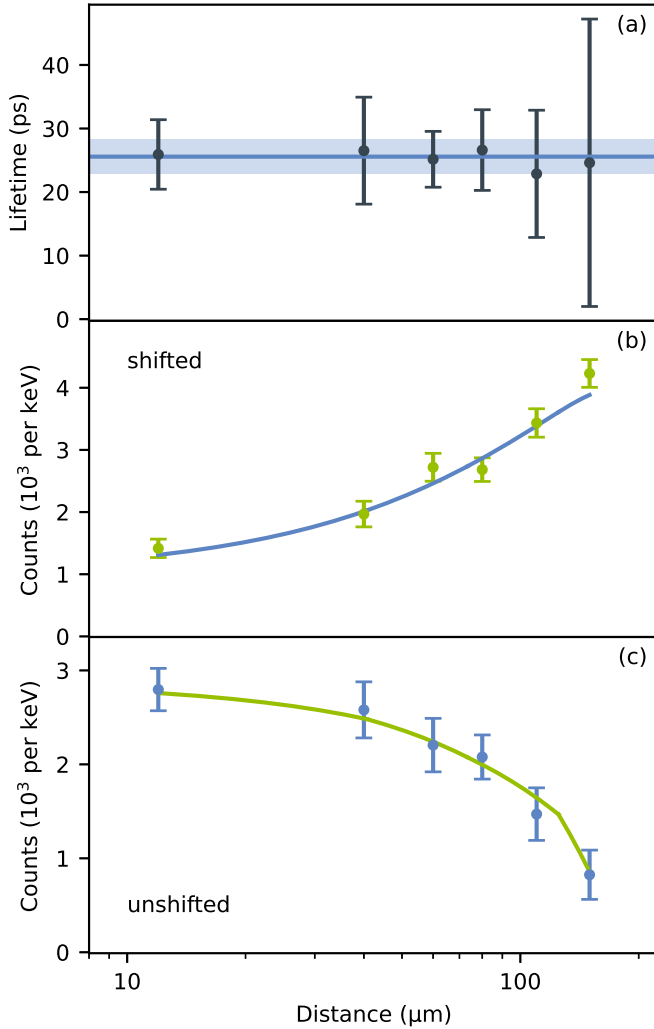


FIG. 3. Exemplary fits obtained in the DDCM analysis for the 143° detector ring. (a) The resulting lifetime values for each distance setting and their weighted mean value and its uncertainty indicated by a horizontal line and the shaded area, respectively. [(b), (c)] Normalized intensity of the shifted and unshifted components with the resulting second degree spline function and derivative of the spline function, respectively.

A potential source of this disagreement can be time-dependent angular distributions, which can be attributed to the de-orientation effect. This effect has frequently been used for the measurement of g factors using recoil-into-vacuum techniques [17, 18]. After the nuclear reaction, which produces ^{200}Pt in its excited states, the spins of the ^{200}Pt nuclei are aligned to some extent. The alignment leads to a distinct angular distribution of the decay γ rays [19]. Owing to the hyperfine interaction of the oriented nuclear spin and the random electronic spin of the remaining electrons of the recoiling ions, leading to a precession of the nuclear spins about the (randomly oriented) total spin, the initial angular distribution is attenuated with time. Despite little available statistics, the analysis of the total angular distributions of the $2_1^+ \rightarrow 0_1^+$ transition shows a time dependence. Figure 5 shows the time and, thus, distance dependence of the angular distribution for two

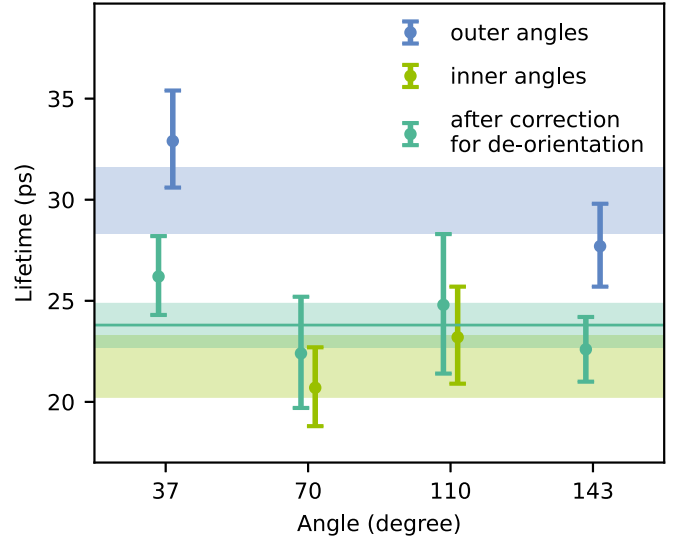


FIG. 4. Lifetime values before and after correcting the de-orientation effect. The data points representing the outer detector angles of 37° and 143° (blue) as well as the inner angles of 70° and 110° (green) agree with their respective mean values, represented by the shaded areas, but not overall. The lifetime values after the de-orientation correction of each detector angle along with their mean value are shown in cyan.

exemplary distance settings. The angular distributions were obtained by fitting the sum intensities with the normalized angular distribution function

$$\frac{W(\vartheta)}{A_0} = 1 + \sum_{i=2,4} \frac{A_i}{A_0} P_i(\cos \vartheta), \quad (3)$$

with the Legendre polynomials P_i , normalization parameter A_0 , and fit parameters A_i .

An effective way to correct the lifetime measurement for the de-orientation effect is to apply correction factors to the intensities [18], which renormalize the angular distributions

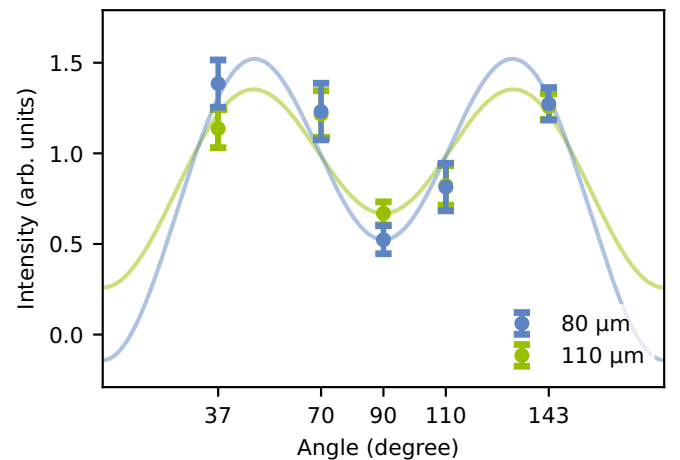


FIG. 5. Angular distributions of the $2_1^+ \rightarrow 0_1^+$ transition at distance settings of 80 μm (blue) and 110 μm (green), each normalized and fitted by the angular distribution function according to Eq. (3).

TABLE I. Resulting lifetimes and reduced transition strengths for the $4_1^+ \rightarrow 2_1^+$ and $2_1^+ \rightarrow 0_1^+$ transitions of ^{200}Pt determined in this work.

Transition $J_i^{\pi_i} \rightarrow J_f^{\pi_f}$	Lifetime (ps)	$B(E2; J_i^{\pi_i} \rightarrow J_f^{\pi_f})$	
		($e^2 \text{ fm}^4$)	(W.u.)
$2_1^+ \rightarrow 0_1^+$	23.8(11)	1450^{+80}_{-70}	$20.9^{+1.1}_{-1.0}$
$4_1^+ \rightarrow 2_1^+$	2.6(3)	3040^{+410}_{-320}	44^{+6}_{-5}

at each distance setting to an isotropic distribution. Since the nuclei which de-excite in the stopper are exposed for a longer time to the hyperfine interaction, de-orientation affects the unshifted component by more than an order of magnitude stronger than the shifted one. Therefore, the correction factors are only applied to the intensities of the unshifted component of the $2_1^+ \rightarrow 0_1^+$ transition of ^{200}Pt . The resulting lifetimes for all rings and their weighted average are included in cyan in Fig. 4. After the de-orientation correction the data of all rings match within their uncertainty, and the weighted average of $\tau(2_1^+, ^{200}\text{Pt}) = 23.8(11)$ ps is adopted as the final result. Using a transition energy of 470.1(2) keV and a conversion coefficient of $\alpha = 0.0288(4)$ [20], the corresponding E2 transition strength results in

$$B(E2; 2_1^+ \rightarrow 0_1^+) = 1450^{+80}_{-70} e^2 \text{ fm}^4 = 20.9^{+1.1}_{-1.0} \text{ W.u.}$$

As the statistics for the $4_1^+ \rightarrow 2_1^+$ transition is limited, the lifetime of the 4_1^+ state is determined as described in Ref. [21]. The ratio of the unshifted and shifted components fitted in the summed spectra of all distance settings, R_{sum} , is used to calculate the lifetime of the 4_1^+ state using

$$R_{\text{sum}} = \frac{I_u}{I_u + I_s} = \sum_i n_i R(x_i) \quad (4)$$

with the intensities of the shifted and unshifted components of the sum spectrum, I_s and I_u , the normalization factors n_i for each distance i , and the decay curve R , which can be expressed as the solution of the Bateman equations [22]. Feeding of the $(5_1)^- \rightarrow 4_1^+$ transition is taken into account as previously described. Further feeding transitions are not visible in the spectra but are considered as 10 % unobserved feeding as a systematic uncertainty. This procedure results in a lifetime of $\tau(4_1^+, ^{200}\text{Pt}) = 2.6(3)$ ps. Using a transition energy of 633.0(2) keV and a conversion coefficient of $\alpha = 0.01426(20)$ [20], the corresponding quadrupole transition strength amounts to

$$B(E2; 4_1^+ \rightarrow 2_1^+) = 3040^{+410}_{-320} e^2 \text{ fm}^4 = 44^{+6}_{-5} \text{ W.u.}$$

The lifetimes measured in this work and their resulting $B(E2)$ values are summarized in Table I.

IV. DISCUSSION

As the Pt isotopic chain approaches the $N=126$ major shell closure, a transition from quadrupole-deformed, γ -soft structures, as present in, e.g., ^{196}Pt , to spherical shapes is expected. A well-known indicator for nuclear structure is given

by the energy ratio

$$R_{4/2} = \frac{E(4_1^+)}{E(2_1^+)} \quad (5)$$

with benchmark values of $R_{4/2} = 3.33$ for well-deformed rotors, $R_{4/2} \approx 2.5$ for the γ -soft limit, and $R_{4/2} = 2$ in the spherical vibrational limit. For ^{200}Pt one obtains $R_{4/2}(^{200}\text{Pt}) = 2.34$, which is located right between these benchmark values and, hence, on a transition between deformed γ -soft to spherical shapes. For the low-lying levels of a near-spherical, vibrational nucleus, one expects a near-degenerate triplet of 4_1^+ , 2_2^+ , and 0_2^+ states. A tentative (0_2^+) state at 1118 keV, very close to the 4_1^+ -state energy of 1103 keV, has been observed in only one experiment [23]. The $(2_2)^+$ state at an energy of 868 keV, known from literature, however, is a bit lower than the other two potential members of the triplet. Therefore, level energies are not quite conclusive on the low-lying structure of ^{200}Pt .

A more direct probe of the wave functions of the respective states is offered through the now obtained $B(E2)$ values. The ratio

$$B_{4/2} = \frac{B(E2; 4_1^+ \rightarrow 2_1^+)}{B(E2; 2_1^+ \rightarrow 0_1^+)} \quad (6)$$

takes typical values of $B_{4/2} = 1.43$ in the axially symmetric and γ -soft deformed limits, and $B_{4/2} = 2$ in the spherical limit. From the values given in Table I one obtains $B_{4/2} = 2.10(31)$, which is in very good agreement with the spherical limit.

To further elucidate the evolution of collective structures in the Pt isotopic chain, we compare its $B(E2)\downarrow$ values to those of neighboring isotopic chains in Fig. 6(a). All displayed isotopic chains show $B(E2)\downarrow$ values dropping toward $N = 126$, while there is a flattening of $B(E2)\downarrow$ values around $N = 114, 116$, in particular for the Pt isotopes. Tentatively, such a trend is also observed in the Hg and W isotopic chains, shown in Fig. 6, and had been discussed in view of the prolate-oblate shape transition and subsequent approach to the $N = 126$ shell closure [7]. Beyond $N = 116$, $B(E2)\downarrow$ values drop near linearly with an increasing neutron number.

A similar trend is known from other regions of the nuclear chart. The isotopes near the $Z = 50$ proton shell, i.e., Te, Xe, and Ba isotopes, toward $N = 82$ can be viewed as a valence mirror region [48] to the Os, Pt, and Hg isotopes, replacing proton particles with proton holes. The linear trend of the $B(E2)\downarrow$ values, shown in Fig. 6(b), which is pronounced in the Te, Xe, and Ba isotopes, can be attributed to the spherical-vibrational character of these nuclei. In the vibrational limit, as given by the U(5) limit of the IBM, the $B(E2)\downarrow$ value is given by the simple relation

$$B(E2; 2_1^+ \rightarrow 0_1^+) = e_B^2 N_B \quad (7)$$

with the effective boson number N_B and the effective charge e_B , which can be determined from the slope of the data. The results of linear fits to the $B(E2)\downarrow$ values along the Te, Xe, Ba, Hg, and Pt isotopic chains in Table II show similar values for isotopes with the same amount of valence protons and holes. The Te, Xe, and Ba isotopic chains were fitted for $N = 70\text{--}82$

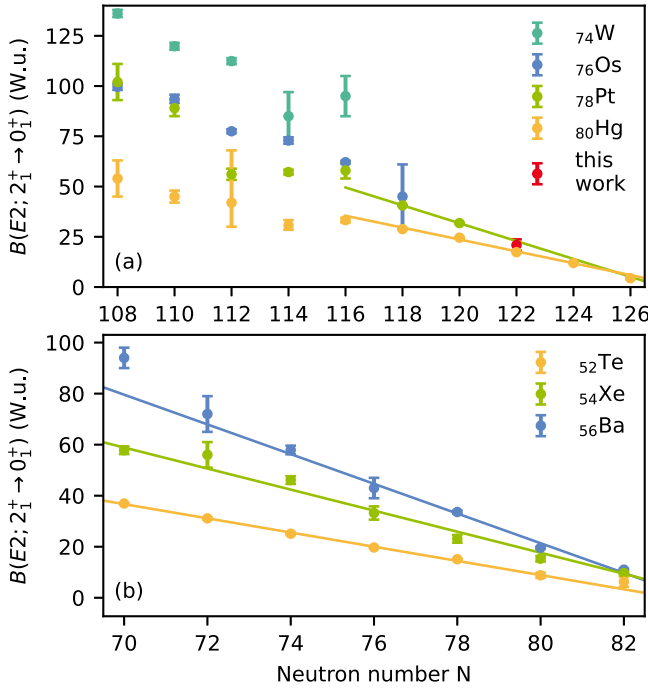


FIG. 6. Reduced transition strengths $B(E2)\downarrow$ for the (a) W, Os, Pt, and Hg isotopic chains and (b) Te, Xe, and Ba isotopic chains along with linear fits for the trend of the $B(E2)\downarrow$ value for Te, Xe, Ba, Pt, and Hg. The proximity of the two respective regions of the nuclear chart to the shell closures at $Z = 50$ and $N = 82$ as well as $Z = 82$ and $N = 126$ allows the investigation of mirror effects. The linear fits can be used to determine the effective charges within the U(5) limit of the IBM using Eq. (7). The data are taken from Refs. [7,20,24–47].

and the Pt and Hg isotopic chains for $N = 116$ – 126 . A difference between both nuclear regions, however, is that $B(E2)\downarrow$ values converge toward the neutron-shell closure at $N = 82$ in the lighter isotopes, whereas in the heavier region $B(E2)\downarrow$ values are already very close to each other at $N = 122$, four neutrons below the next neutron-shell closure. This behavior may be attributed to the specific underlying shell structure of the isotopes toward ^{208}Pb . The top orbitals of the proton shell, which are filled toward $Z = 82$, are the $\pi 2s_{1/2}$ and the $\pi 2d_{3/2}$ orbitals, which can be inferred from the lowest-lying states of heavier odd-proton isotopes. The low spin of these orbitals leads to a suppression of collectivity; in particular, the

TABLE II. Effective charges determined using a linear fit to the trends of the $B(E2)\downarrow$ value shown in Fig. 6. Note the similarity of the results for nuclei with the same number of valence protons (or holes).

Isotope	$e_B (\sqrt{\text{W.u.}})$	No. of valence protons (holes)
^{52}Te	1.67(1)	2
^{54}Xe	2.03(1)	4
^{56}Ba	2.41(4)	6
^{80}Hg	1.72(1)	2
^{78}Pt	2.11(2)	4

$s_{1/2}$ orbital cannot significantly contribute to collectivity in the 2^+ or 4^+ wave functions. In the neutron sector, the dominant orbitals below $N = 126$ are the $\nu 3p_{1/2}$ and the $\nu 2f_{5/2}$ orbitals. Again, a $p_{1/2}$ orbital hinders collectivity toward the major shell closure. Therefore, the effective valence space for the formation of the low-lying 2^+ and 4^+ states does not simply scale with the number of valence nucleons, but is suppressed by about one pair of active valence proton and neutron holes, each. Consequently, the occurrence of $j = 1/2$ orbitals could be responsible for the rather small difference in collectivity between Hg and Pt isotopes with two and four valence-proton holes, respectively, and four valence-neutron holes, each.

V. CONCLUSION

The lifetimes of the 2_1^+ and 4_1^+ states of ^{200}Pt were measured for the first time. The recoil-distance Doppler-shift (RDDS) method was applied. ^{200}Pt was produced in a two-neutron transfer reaction at the tandem accelerator at IFIN-HH. The $B(E2)$ values for the $2_1^+ \rightarrow 0_1^+$ and $4_1^+ \rightarrow 2_1^+$ transitions were determined, enabling the determination of the $B_{4/2}$ ratio. The obtained $B_{4/2}$ ratio is in good agreement with the theoretical limit of a vibrational nucleus indicating the structural evolution toward sphericity as the Pt isotopic chain approaches the neutron-shell closure at $N = 126$. Shell-model calculations are desirable to elucidate the role of low-spin orbitals.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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