

Revised $B(E2; 2_1^+ \rightarrow 0_1^+)$ value in the semi-magic nucleus ^{210}Pb

C. M. Nickel^{1,*}, V. Werner^{1,2}, G. Rainovski³, P. R. John¹, M. Beckers⁴, D. Bittner⁴, A. Blazhev⁴, A. Esmaylzadeh⁴,
C. Fransen⁴, J. Garbe⁴, L. Gerhard⁴, K. Geusen⁴, K. Gladnishki³, A. Goldkuhle⁴, K. E. Ide¹, J. Jolie⁴,
V. Karayonchev^{4,5}, R. Kern¹, E. Kleis⁴, L. Klöckner⁴, D. Kocheva³, M. Ley⁴, H. Mayr¹, N. Pietralla¹,
F. von Spee⁴, M. Steffan⁴, T. Stetz¹ and J. Wiederhold¹

¹*Institute for Nuclear Physics, Department of Physics, Technische Universität Darmstadt, Schlossgartenstraße 9, D-64289 Darmstadt, Germany*

²*Helmholtz Forschungsakademie Hessen für FAIR (HFHF), Campus Darmstadt, Schlossgartenstraße 2, D-64289 Darmstadt, Germany*

³*Faculty of Physics, University of Sofia St. Kliment Ohridski, 5 James Bourchier blvd., BG-1164 Sofia, Bulgaria*

⁴*Institute for Nuclear Physics, Universität zu Köln, Zùlpicher Straße 77, D-50937 Cologne, Germany*

⁵*Tri University Meson Facility TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3*



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The lifetime of the 2_1^+ state of ^{210}Pb was measured in the $^{208}\text{Pb}(^{18}\text{O}, ^{16}\text{O})^{210}\text{Pb}$ two-neutron transfer reaction by γ -ray spectroscopy employing the recoil-distance Doppler-shift method. The extracted absolute $B(E2)\downarrow$ value of $119_{-8}^{+9} e^2 \text{ fm}^4$ is consistent with previously reported measurements, but with significantly improved precision. The available experimental data for the $2_1^+ - 4_1^+ - 6_1^+ - 8_1^+$ multiplet are compared with shell-model calculations based on the well-established Kuo-Herling interaction. The new $B(E2)\downarrow$ value agrees well with the shell-model prediction, providing evidence that the properties of the 2_1^+ and 8_1^+ states of ^{210}Pb can be consistently described together within the nuclear shell-model framework.

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I. INTRODUCTION

The nuclear shell model provides a foundational framework for nuclear structure physics, notably explaining the emergence of magic numbers. The magic numbers arise from significant energy gaps between nucleonic orbitals determined by the shape of the nuclear potential and the spin-orbit coupling [1,2]. In conjunction with pairing correlations, the shell model is instrumental in interpreting the low-energy spectra of semi-magic nuclei. In these systems, low-energy excitations with total angular momentum $J > 0$, involving two or more valence nucleons occupying a single high- j orbital, typically originate from the angular momentum recoupling of unpaired nucleons. Such configurations form multiplets of states characterized by the number of unpaired nucleons, the quantum number ν known as seniority [3,4]. The generalized seniority scheme [4] is, in fact, an effective truncation of full shell-model calculations.

Shell-model calculations describe the experimental properties of excited nuclear states particularly well for nuclei near shell closures, where the valence spaces are computationally tractable using standard shell-model techniques. Modern

approaches, such as Monte Carlo methods [5,6], even allow access to nuclei approaching midshell regions, which involve a large number of valence nucleons. Nevertheless, nuclei with only a few valence nucleons, particularly those with two identical nucleons, are of special importance. These nuclei serve as benchmarks for validating microscopic nuclear interactions and for constraining key effective parameters such as nucleon effective charges and g factors. Semi-magic nuclei with just two valence particles are also central to the seniority scheme. These nuclei serve as reference points, providing the properties of the fundamental j^2 configurations, such as the energies of states with $\nu = 2$, as well as the absolute $E2$ transition strengths for seniority-changing transitions ($\Delta\nu = 2$, $2_1^+ \rightarrow 0_1^+$) and seniority-conserving transitions ($\Delta\nu = 0$) within the $\nu = 2$ multiplet [4].

The nucleus ^{212}Po provides a representative example of how the properties of semi-magic nuclei with two valence particles can influence the structure of open-shell nuclei. ^{212}Po contains two valence protons and two valence neutrons relative to the doubly magic ^{208}Pb core. It has been demonstrated [7] that the experimentally determined absolute transition strength for the $2_1^+ \rightarrow 0_1^+$ transition of ^{212}Po is smaller by a factor of 1.5 to 2.5 compared to values predicted by shell-model calculations. This discrepancy has been linked to the properties of the simpler two-valence particle-systems ^{210}Pb and ^{210}Po . In both nuclei, the energies of the yrast 2^+ , 4^+ , 6^+ , and 8^+ states exhibit seniority-like behavior, characterized by decreasing energy spacings between adjacent levels as the spin increases. While these energy patterns are well reproduced by both single- j and full

*Contact author: cnickel@ikp.tu-darmstadt.de

shell-model calculations, none of the shell-model approaches employed have consistently described the corresponding $B(E2)_{\downarrow} \equiv B(E2; 2_1^+ \rightarrow 0_1^+)$ values [7]. In the case of ^{210}Po , this problem is well known [8] and has raised concerns regarding the accuracy of the adopted $B(E2; 2_1^+ \rightarrow 0_1^+)$ value of $42(9) e^2\text{fm}^4$ [9]. As a result, a remeasurement of the lifetime of the 2_1^+ state of ^{210}Po was carried out [10]. The newly determined value of $B(E2)_{\text{exp}} = 136(21) e^2\text{fm}^4$ [10] has mitigated the disagreement between shell-model predictions of $B(E2)_{\text{SM}} = 135 e^2\text{fm}^4$ and experimental data for the $2_1^+ \rightarrow 0_1^+$ transition of ^{210}Po , although significant discrepancies still remain for the other yrast transitions [7,11,12].

It is noteworthy that the $B(E2; 2_1^+ \rightarrow 0_1^+)$ value of ^{210}Pb was determined using the same experimental technique as that employed to extract the earlier $B(E2)_{\downarrow}$ value of ^{210}Po [9] which was proven incorrect, namely, cross-section measurements from triton scattering experiments [13]. Even though the experimental $B(E2)_{\downarrow}$ value of ^{210}Pb of $105(30) e^2\text{fm}^4$ [13] and shell-model predictions of $109 e^2\text{fm}^4$ agree, a precise experimental value measured using a model-independent technique is necessary. The recently proposed theoretical framework for describing the structure of odd-even semi-magic and open-shell nuclei within a single- j approximation with state-dependent effective charges [14,15] requires accurate $B(E2)_{\downarrow}$ values in the neighboring nuclei with j^2 configurations. The experimental uncertainty associated with the $B(E2; 2_1^+ \rightarrow 0_1^+)$ value of ^{210}Pb exceeds 30%, which prevents the applicability of this approach for nuclei above ^{208}Pb . This limitation, together with the need to verify the adopted $B(E2; 2_1^+ \rightarrow 0_1^+)$ value of ^{210}Pb , has motivated the present measurement of the lifetime of the 2_1^+ state. The recoil-distance Doppler-shift (RDDS) method [16,17] was applied following a two-neutron transfer reaction to enable an accurate, model-independent determination of the $E2$ transition strength with higher precision than available in the literature.

II. EXPERIMENT

Low-lying excited states of ^{210}Pb were populated using the $^{208}\text{Pb}(^{18}\text{O}, ^{16}\text{O})^{210}\text{Pb}$ two-neutron transfer reaction. The ^{18}O beam was accelerated up to 85 MeV by the 10 MV FN-Tandem accelerator at the University of Cologne. The beam impinged on a target consisting of 0.8 mg/cm^2 ^{208}Pb of 99.14 % enrichment, which was evaporated on a 0.4 mg/cm^2 Mg foil. Another 1.7 mg/cm^2 Mg foil was placed parallel to the ^{208}Pb target and used to stop the recoiling nuclei. The target and stopper were mounted inside the Cologne plunger device [17].

The plunger device is used to vary and keep the distance between target and stopper and, thus, γ -ray energy spectra were taken at 11 target-to-stopper distances, i.e., 13 μm , 22 μm , 37 μm , 47 μm , 82 μm , 142 μm , 212 μm , 282 μm , 382 μm , 512 μm , and 912 μm . The distances are determined with respect to the point of electrical contact of the target and stopper foils using the capacitance method with a distance offset of 12(1) μm [17,18]. The γ rays emitted from the de-exciting nuclei were detected by 11 high-purity germanium (HPGe) detectors which were mounted in two rings. The five

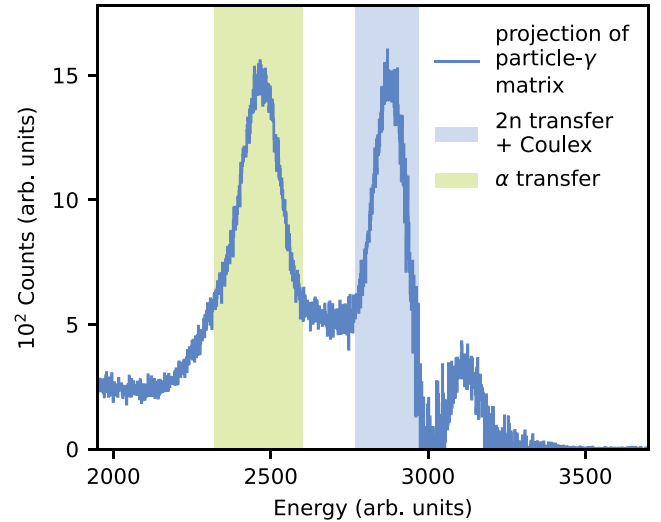


FIG. 1. Projection of a particle- γ matrix showing the relevant region for selecting the reaction products of interest. The green region indicates the peak originating from back-scattered ^{14}C nuclei associated with the α transfer whereas the blue region includes events from back-scattered O, e.g., ^{16}O and ^{18}O referring to two-neutron transfer and Coulomb excitation, respectively.

forward angle detectors were mounted at 45° and the six backward angle detectors at 142° with respect to the beam axis for the sensitive detection of Doppler shifts.

Due to the reaction kinematics the beam-like particles, in particular, ^{16}O , ^{18}O , and ^{14}C , are back-scattered and detected by six solar cells placed at backward angles. The placement of the solar cells facilitates the creation of particle-gated spectra in order to separate the different occurring nuclear reactions selecting the two-neutron transfer and suppressing sub-barrier fusion-evaporation reactions, which are more focused in forward directions. Figure 1 shows an exemplary particle spectrum. The two most prominent peaks include events from α transfer (green) or Coulomb excitation and two-neutron transfer (blue). The α transfer is associated with the detection of ^{14}C nuclei and produces ^{212}Po which was analyzed in [19]. Coulomb excitation and two-neutron transfer are related to ^{18}O and ^{16}O , respectively, and cannot be separated with the solar cells.

The γ -ray singles spectrum at the backward angle of 142° obtained by particle-gating on the two-neutron transfer reaction and summing up all distances is shown in Fig. 2. The transitions of ^{210}Pb which are relevant for the analysis are indicated as well as further occurring lines of transitions of other nuclei.

The velocity of the recoiling ^{210}Pb nuclei is determined by exploiting the Doppler-shifted energy of the $3_1^- \rightarrow 2_1^+$ transition. The more intense transitions were not chosen for the velocity determination, as the peaks of the $2_1^+ \rightarrow 0_1^+$ transition are affected by contaminants and the $4_1^+ \rightarrow 2_1^+$ transition barely develops a Doppler-shifted component due to the comparably large lifetime of the 4_1^+ state. The velocity of the ^{210}Pb nuclei amounts to $v/c = 1.2(1)\%$.

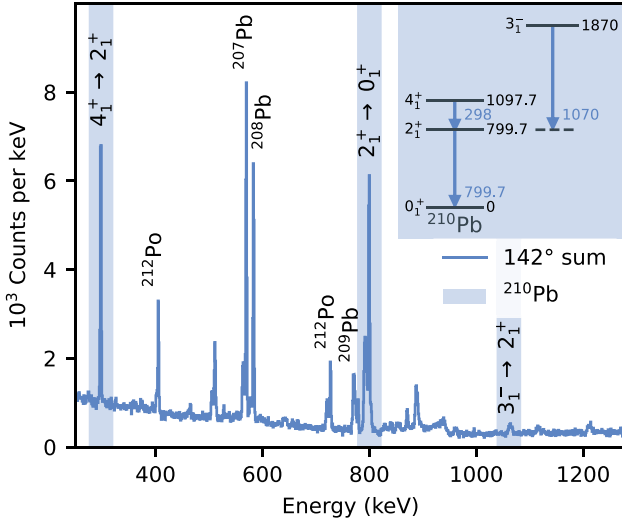


FIG. 2. Particle-gated γ -ray singles spectrum at 142° with all distances summed up. The occurring transitions of ^{210}Pb relevant for the analysis are indicated (blue) as well as lines originating from inelastic scattering off ^{207}Pb and ^{208}Pb . The limited energy resolution of the solar cells hampers a clear separation between α , one- and two-neutron transfer, hence also transitions of ^{209}Pb and ^{212}Po appear in the spectrum. The inset shows a part of the level scheme of ^{210}Pb with the observed transitions.

III. ANALYSIS

The 2_1^+ state of ^{210}Pb was analyzed 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. [17]. In an RDDS experiment the nucleus of interest is produced in a nuclear reaction and excited states are populated. The nuclei recoil out of the target foil in the direction of a stopper material. The decay of the excited states can take place when the nuclei are still in flight yielding a Doppler-shifted peak in the energy spectra whereas a de-excitation in the stopper results in a peak at the energy difference of the corresponding levels of the transition.

The lifetime of the 2_1^+ state of ^{210}Pb can directly be obtained from the distance-dependent ratios of the intensities of the shifted and unshifted components if the state is only directly populated in the nuclear reaction and no feeding from higher-lying states is present. However, the $4_1^+ \rightarrow 2_1^+$ transition of ^{210}Pb is visible in the spectra, such that a correction for feeding is required and was performed. The statistics are not sufficient to create particle-gated γ - γ matrices. With a lifetime of $0.9(2)$ ns [20] the 4_1^+ state of ^{210}Pb is comparably long-lived, so that the $4_1^+ \rightarrow 2_1^+$ transition does not develop a significant shifted component, even at the largest distance setting. Hence, the $4_1^+ \rightarrow 2_1^+$ transition takes place while the ^{210}Pb nuclei are already stopped, such that the corresponding feeding of the 2_1^+ state only contributes to the unshifted component of the $2_1^+ \rightarrow 0_1^+$ transition. Therefore, to correct for feeding the intensity of the $4_1^+ \rightarrow 2_1^+$ transition was explicitly subtracted from the intensity of the unshifted component of the $2_1^+ \rightarrow 0_1^+$ transition.

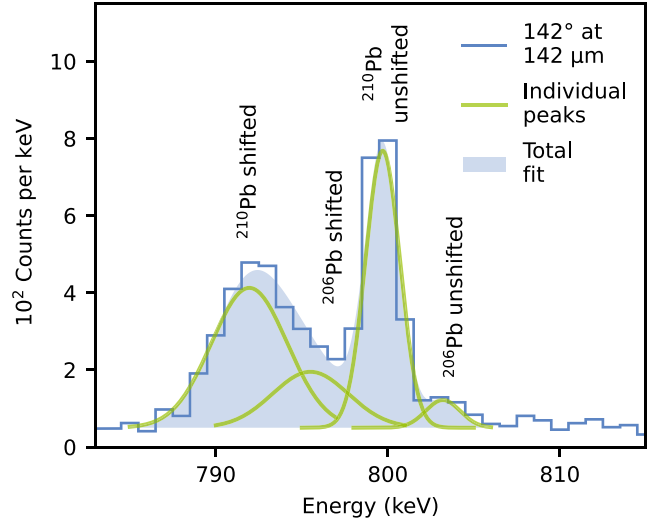


FIG. 3. Particle-gated γ -ray singles spectrum at 142° at $142\ \mu\text{m}$. The shifted and unshifted components of the $2_1^+ \rightarrow 0_1^+$ transitions of ^{206}Pb and ^{210}Pb are indicated as well as their corresponding fits (green).

Due to the competing fusion-evaporation channel yielding transitions at similar energies as the $2_1^+ \rightarrow 0_1^+$ transition of ^{210}Pb , using only γ -gated spectra for the analysis is not feasible. The only other observed feeder is the $3_1^- \rightarrow 2_1^+$ transition which is visible only in the sum spectra and its lifetime is short in comparison to the one of the 2_1^+ state. Hence and as the two-neutron transfer reaction favors the population of lower-lying states, further unobserved side feeding is considered to be negligible.

Further, the $2_1^+ \rightarrow 0_1^+$ transition of ^{210}Pb is affected by contaminants that need to be corrected before the lifetime of the 2_1^+ state can be determined. The γ -ray energy spectrum in Fig. 3 shows the shifted and unshifted components of the $2_1^+ \rightarrow 0_1^+$ transition of ^{210}Pb measured at the backward angle of 142° with a contaminant identified as the $2_1^+ \rightarrow 0_1^+$ transition of ^{206}Pb . Despite the high enrichment of the target material, small impurities and their Coulomb excitation explain the occurrence of the transition of ^{206}Pb in the spectra. The lifetime of the 2_1^+ state of ^{206}Pb is known to be $11.8(1)$ ps [21]. It is in the same order of magnitude as the lifetime of the 2_1^+ state of ^{210}Pb . Therefore, the $2_1^+ \rightarrow 0_1^+$ transition of ^{206}Pb also develops a shifted component. The shifted component of ^{206}Pb overlaps with both components of the $2_1^+ \rightarrow 0_1^+$ transition of ^{210}Pb . In order to correctly account for the ^{206}Pb contamination, an effective lifetime of the 2_1^+ state of ^{206}Pb was estimated from the decay behavior of its unshifted component at a detector angle of 142° . Using this effective lifetime, the peak area of the shifted component of the $2_1^+ \rightarrow 0_1^+$ transition of ^{206}Pb is calculated for the different plunger distances. The ^{206}Pb peak areas are fixed during fitting as shown in Fig. 3.

The γ -ray singles spectra created without applying a particle gate reveal another contaminant. The spectra are shown in Fig. 4(a) at an intermediate distance of $142\ \mu\text{m}$. At 788 keV the unshifted component of the contaminant is visible. The

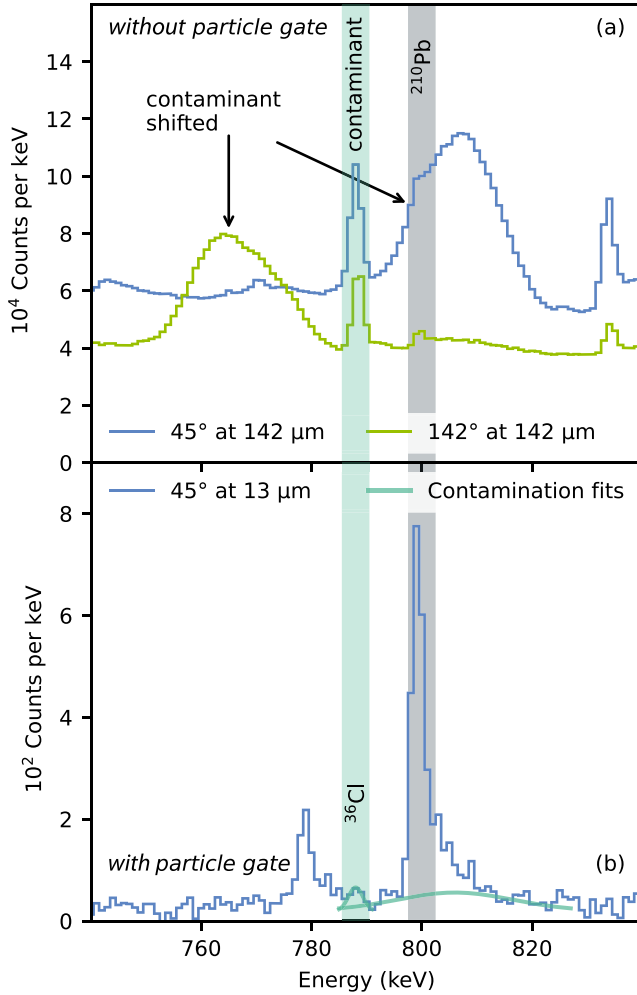


FIG. 4. (a) γ -ray singles spectrum at 45° (blue) and 142° (green) at $142\ \mu\text{m}$ without a particle gate. The unshifted components of the $2_1^+ \rightarrow 0_1^+$ transition of ^{210}Pb (grey) as well as the $3_1^+ \rightarrow 2_1^+$ transition of the ^{36}Cl contaminant (cyan) are indicated. (b) Particle-gated γ -ray singles spectrum at 45° at $13\ \mu\text{m}$. The fits of the shifted and unshifted components of the ^{36}Cl contaminant (cyan) are indicated. The energies, peak widths and areas of the contaminant were determined with the ungated spectra and kept fixed for the correction.

comparison of the two detector ring angles indicates the development of a shifted component of the contaminant. The corresponding γ -ray transition was identified as the $3_1^+ \rightarrow 2_1^+$ transition of ^{36}Cl which is produced in the fusion-evaporation channel following the reaction of the ^{18}O beam with Mg. At the forward angle of 45° the shifted component overlaps with both components of the $2_1^+ \rightarrow 0_1^+$ transition of ^{210}Pb .

A small fraction of the ^{36}Cl contaminant of about one per mille is left by the particle gate and the random background subtraction and its magnitude is indicated in the gated spectrum shown in Fig. 4(b). At $788\ \text{keV}$ a peak associated with the unshifted component of the $3_1^+ \rightarrow 2_1^+$ transition of ^{36}Cl is visible. As the intensity ratio of the shifted and unshifted components of the contaminant does not change with the distance in the ungated spectra, meaning that most of the reaction producing ^{36}Cl occurs in the stopper, it is used to estimate the

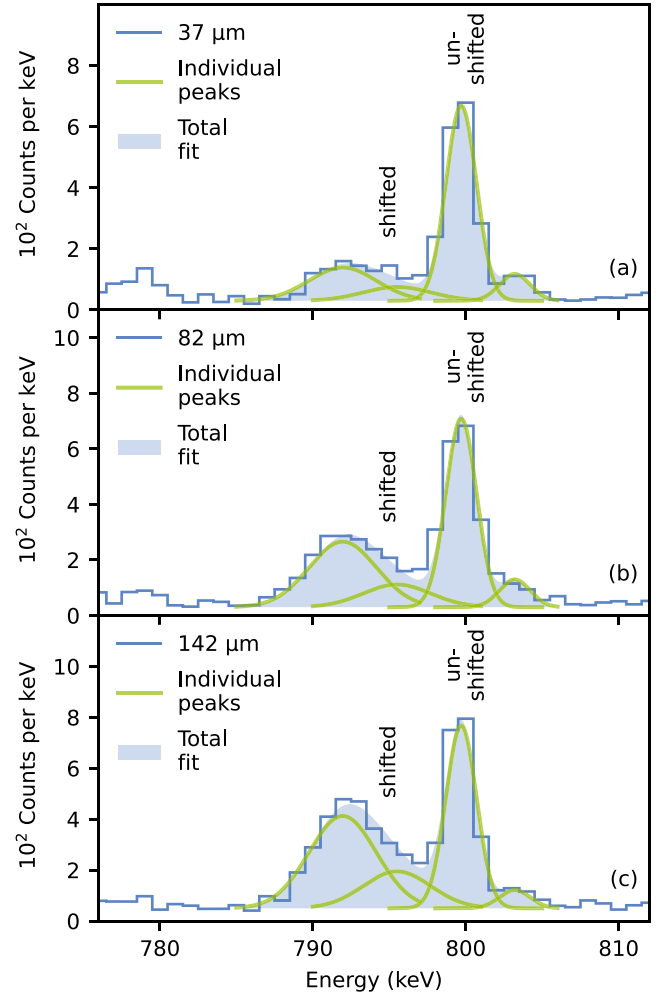


FIG. 5. Particle-gated γ -ray singles spectra at 142° at (a) $37\ \mu\text{m}$, (b) $82\ \mu\text{m}$, and (c) $142\ \mu\text{m}$. The fits of the $2_1^+ \rightarrow 0_1^+$ transition of both ^{210}Pb and the contaminant ^{206}Pb are depicted (green). The evolution of the intensity ratio of the shifted and unshifted components is visible. The intensity of the shifted component increases with the distance while the unshifted component decreases.

intensity of the shifted component in the gated spectra. The energy and width of the shifted component of the $3_1^+ \rightarrow 2_1^+$ transition of ^{36}Cl are determined with the ungated spectra as well in order to fix them in the gated spectra. The fits of the contaminant peaks are indicated in Fig. 4(b) and allow for the accurate determination of the peak areas of the shifted and unshifted components of the $2_1^+ \rightarrow 0_1^+$ transition of ^{210}Pb .

The DDCM analysis determines the lifetime τ at every distance following

$$\tau = \frac{I_u}{\frac{d}{dx} I_s} = \frac{I_u}{v \frac{d}{dx} I_s} \quad (1)$$

with the intensities of the shifted and unshifted components I_s and I_u and the velocity v . The evolution of the intensities of both components with the distance is depicted in Fig. 5 showing three exemplary distances. Due to the differential approach of the DDCM only relative distances are required which has the advantage of smaller uncertainties in

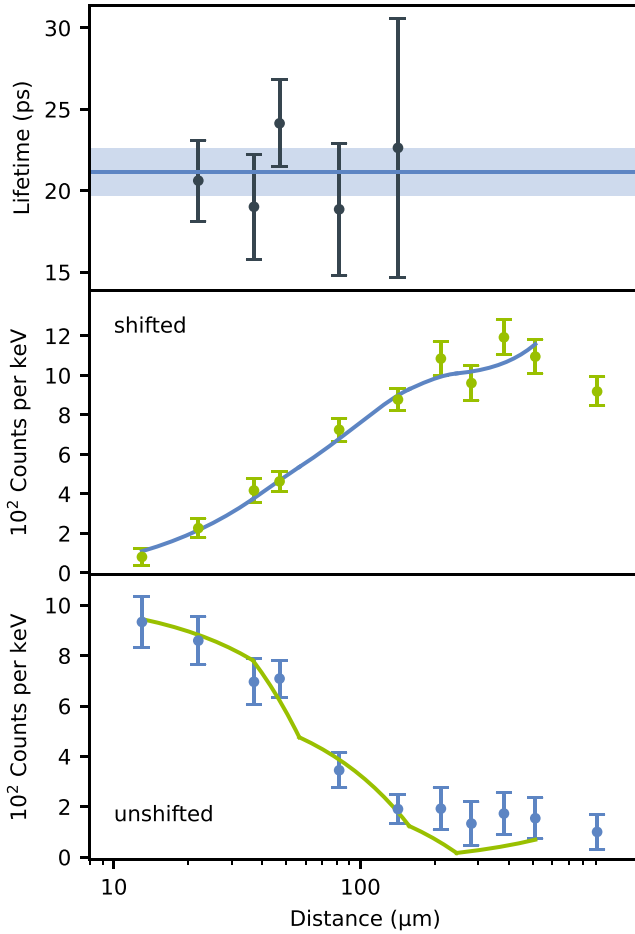


FIG. 6. Exemplary napatau fit obtained with the DDCM analysis at 142° . The top plot shows the values of the distance-wise determined lifetimes with their mean value and uncertainty. The centre and bottom plots illustrate the second degree spline functions of the intensities of the shifted and unshifted components. The distances for which the intensities remain constant are not sensitive for the lifetime measurement and are, thus, omitted from the mean value determination.

comparison to absolute distances. The initial distance dependence of the intensities is converted into a time dependence with the known velocity v of the ^{210}Pb nuclei. The mean lifetime of all distances is determined with a χ^2 fit implemented in the program napatau [22] and exemplary results are shown in Fig. 6.

The top part displays the distance-wise determined lifetime values with their mean value as the blue line and corresponding uncertainty as the blue band. The centre and bottom parts illustrate the second order spline fits of the shifted and unshifted components that describe the evolution of the intensities with the plunger distance. Due to the nonlinear velocity dependence of Eq. (1) the resulting lifetime uncertainties are asymmetric.

The DDCM analysis was performed for both detector ring angles separately yielding $20.0^{+2.0}_{-1.7}$ ps at the forward angle of 45° and $21.2^{+1.8}_{-1.7}$ ps at the backward angle of 142° . The weighted mean value results in a lifetime of $\tau = 20.7^{+1.4}_{-1.2}$ ps

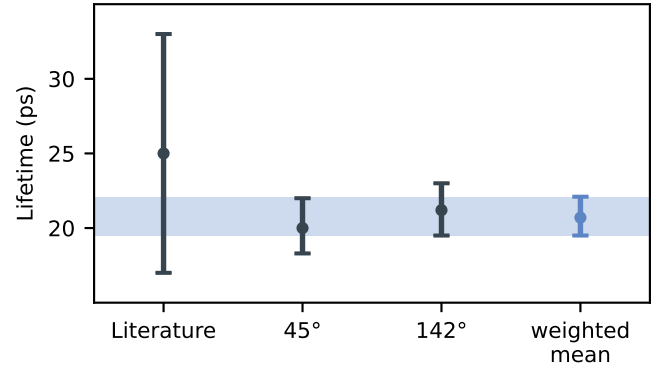


FIG. 7. Comparison between the values of the lifetime of the 2_1^+ state of ^{210}Pb from literature [13] and this work showing the individual results at detector angles of 45° and 142° and the weighted mean (blue).

which agrees with the literature value within its uncertainty. Figure 7 shows a comparison between the literature value for the lifetime of the 2_1^+ state and the results of this work and illustrates the improved precision. The corresponding quadrupole transition strength was calculated using a conversion coefficient of $\alpha = 0.010\,40(1)$ [23] and amounts to

$$B(E2; 2_1^+ \rightarrow 0_1^+) = 119^{+9}_{-8} e^2 \text{ fm}^4 = 1.61^{+0.12}_{-0.10} \text{ W.u.}$$

IV. DISCUSSION

The available experimental data on the properties of the yrast states of ^{210}Pb are summarized in Tables I and II. The newly determined $B(E2)\downarrow$ value for the $2_1^+ \rightarrow 0_1^+$ transition of $119^{+9}_{-8} e^2 \text{ fm}^4$ is in good agreement with the pre-

TABLE I. Comparison between the experimental and calculated (see text for details) properties of the yrast states of ^{210}Pb .

J_i^π	E_x (MeV)		J_f^π	$B(E2; J_i \rightarrow J_f) (e^2 \text{ fm}^4)$	
	Expt ^a	SM		Expt	SM ^b
2_1^+	0.7997(1)	0.837	0_1^+	119^{+9}_{-8} 105(30) ^d	126(15)
4_1^+	1.0977(10)	1.099	2_1^+	356(67) ^e	168(20)
6_1^+	1.195(4)	1.191	4_1^+	87(10) ^f 103(35) ^g 156(6) ^h	118(13)
8_1^+	1.278(5)	1.234	6_1^+	49(5) ⁱ	49(5)

^aThe experimental excitation energies are taken from Ref. [20].

^bCalculated with the experimentally determined $e_v = 0.88(5) e$, for details see the text.

^cFrom the present work.

^dFrom Ref. [13].

^eFrom the lifetime of the 4_1^+ state reported in Ref. [24].

^fFrom the lifetime of the 6_1^+ state of ^{210}Pb reported in Ref. [25].

^gFrom the lifetime of the 6_1^+ state of ^{210}Pb determined by gating on a direct feeding transition reported in Ref. [25].

^hFrom the lifetime of the 6_1^+ state of ^{210}Pb reported in Ref. [26].

ⁱFrom the lifetime of the 8_1^+ state of ^{210}Pb reported in Ref. [26] and confirmed in Ref. [25].

TABLE II. Comparison between the experimental and calculated (see text for details) magnetic (μ) and quadrupole (Q) moments of ^{210}Pb and ^{209}Pb isotopes. The experimental data are taken from Refs. [20,30].

	μ (μ_N)		Q (efm^2)	
	Expt	SM	Expt	SM
^{210}Pb				
6_1^+	-1.872(90)	-1.859	–	-10(1)
8_1^+	-2.496(64)	-2.501	–	-40(2)
^{209}Pb				
$9/2_1^+$	-1.4735(16)	-1.4735	-27(17)	-29(2)

viously reported value of $105(30) e^2\text{fm}^4$ (cf. Table I), but with significantly improved precision. This represents the main experimental result of the present study.

To assess how the new $B(E2; 2_1^+ \rightarrow 0_1^+)$ value fits within the widely accepted shell-model description of the yrast states of ^{210}Pb [7,25], we performed shell-model calculations using the code NuShellX [27] and the well-established Kuo-Herling interaction, as modified by Warburton and Brown (denoted KHPE in the NuShellX package) [28]. The neutron valence space encompassed the full $N = 126$ –184 major shell, including the $1g_{9/2}$, $0i_{11/2}$, $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, and $0j_{15/2}$ orbitals. The standard effective gyromagnetic factors $g_\pi^l = 1.107$, $g_\nu^l = -0.065$, $g_\pi^s = 3.234$, and $g_\nu^s = -2.083$ were adopted from Ref. [29], while the $g_{p,v}$ factor related to the tensor component of the $M1$ operator was fixed to -0.473 to reproduce the magnetic moment of the $9/2^+$ ground state of ^{209}Pb [30].

The radial part of the wave functions was calculated using a harmonic oscillator potential with $\hbar\omega = 6.863$ MeV. As suggested in Refs. [25,26], the neutron effective charge was fixed to reproduce the experimental $B(E2; 8_1^+ \rightarrow 6_1^+)$ value, resulting in $e_\nu = 0.88(5) e$. The main results from these shell-model calculations are presented under the columns labeled SM in Tables I and II.

The calculated level energies are in good agreement with the experimental values for the 2_1^+ , 4_1^+ , 6_1^+ , and 8_1^+ states with the largest discrepancy of 44 keV observed for the 8_1^+ state (cf. Table I). The wave functions of the yrast states of ^{210}Pb indicate that they are nearly pure seniority-2 states, with the $\nu(g_{9/2})^2$ configuration accounting for 94.5 % of the 2_1^+ state's structure and increasing to 98.9 % for the 8_1^+ state, as previously noted in Ref. [25]. The next most significant components are $\nu(g_{9/2})^1\nu(d_{5/2})^1$, $\nu(g_{9/2})^1\nu(d_{3/2})^1$, and $\nu(j_{15/2})^2$, each contributing less than 1 % to the total wave functions.

Both experiment and shell-model calculations yield nearly constant g factors for the 8_1^+ and 6_1^+ states. The shell-model calculations reproduce the experimental magnetic moments quantitatively (cf. Table II). This agreement provides strong indication that these levels are indeed built on identical configurations characterized by good seniority.

The newly measured $B(E2; 2_1^+ \rightarrow 0_1^+)$ value agrees with the shell-model prediction obtained using a neutron effec-

tive charge of $0.88(5) e$, which was fixed to reproduce the $B(E2)\downarrow$ value of the $8_1^+ \rightarrow 6_1^+$ transition (cf. Table I). This result stands in stark contrast to the case of ^{210}Po [7,10], and provides strong evidence that the properties of the 8_1^+ and 2_1^+ states of ^{210}Pb can be consistently described within the nuclear shell-model framework as being dominated by seniority $\nu = 2$.

The calculated $B(E2; 6_1^+ \rightarrow 4_1^+)$ value of $118(13) e^2\text{fm}^4$ differs markedly from the experimental value of $156(6) e^2\text{fm}^4$ reported in Ref. [26] and only slightly overestimates the experimental result of $87(10) e^2\text{fm}^4$ given in Ref. [25] which is calculated from the weighted average of two lifetime values for the 6_1^+ state that are determined with different gates. The discrepancy between shell-model calculations and experimental results may suggest that the individual lifetime result of the 6_1^+ state that was determined by gating on a direct feeding transition and reported as 113(22) ns in Ref. [25], corresponding to a $B(E2)\downarrow$ value of $103(35) e^2\text{fm}^4$, is more accurate than the adopted weighted average of 92(10) ns reported in Ref. [25].

The largest discrepancy between the calculated and experimental $B(E2)\downarrow$ values is observed for the $4_1^+ \rightarrow 2_1^+$ transition, amounting to a factor of more than two. The discrepancy may result from the limitations of the present shell-model calculations. The calculations employ a constant neutron effective charge e_ν , derived from the $B(E2)\downarrow$ value of the $8_1^+ \rightarrow 6_1^+$ transition which supposedly is the seniority-purest transition. While such an approach is adequate for a seniority analysis, it does not account for all $0\hbar\omega$ and other cross-shell excitations. Thus, the use of state-dependent effective charges may become necessary, as discussed in Ref. [31]. Given that the experimental $B(E2; 4_1^+ \rightarrow 2_1^+)$ value is based on an early lifetime measurement [24], this significant deviation highlights the need for a renewed experimental determination of the lifetime of the 4_1^+ state with higher precision and accuracy.

V. SUMMARY

The lifetime of the 2_1^+ state of ^{210}Pb was measured using the recoil-distance Doppler-shift method following a two-neutron transfer reaction. This measurement yielded a precise, model-independent value for the $E2$ transition strength of the $2_1^+ \rightarrow 0_1^+$ transition. The result is in good agreement with the previously reported value [13], but with significantly improved precision. It is consistent with the shell-model prediction, supporting a coherent description of both the 2_1^+ and 8_1^+ states. Overall, the shell-model calculations provide a satisfactory account of the 2_1^+ - 4_1^+ - 6_1^+ - 8_1^+ multiplet, as expected for states based on a nearly pure seniority-2 configuration. The enhanced precision of the new $B(E2; 2_1^+ \rightarrow 0_1^+)$ value strengthens its utility for modeling the structure of nuclei above Pb within a single- j framework employing state-dependent effective charges. Nonetheless, the remaining discrepancy between the calculated and reported $E2$ transition strengths of the $4_1^+ \rightarrow 2_1^+$ transition underscores

the need for an updated experimental determination of the lifetime of the 4_1^+ state.

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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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