Lifetime measurements of excited states in neutron-rich ^{44,46}Ar populated via a multinucleon transfer reaction

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Lifetimes of low-lying excited states of the neutron-rich ^{44,46}Ar nuclei, populated via multinucleon transfer reactions, are measured by means of the differential recoil distance Doppler shift method. The extracted electromagnetic transition probabilities are compared with previous intermediate-energy Coulomb-excitation measurements and with large-scale shell-model calculations. The increase in the deduced $B(E2; 2^+ \rightarrow 0^+)$ transition probability from ^{44}Ar to the closed-shell nucleus ^{46}Ar contradicts the earlier results of Coulomb-excitation experiments. Shell-model calculations using different effective interactions agree with the new measured values.

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I. INTRODUCTION

In recent years, studies of neutron-rich nuclei that lie at, or close to, magic numbers have demonstrated the fragility of the well-established shell closures. For example, there is now a wealth of theoretical and experimental work concerning the $N = 28$ shell gap below ^{48}Ca, which has indicated its continuous reduction with decreasing proton number and the appearance of deformed structures built on very low-lying excited 0^+ states eventually becoming the ground states [1–10]. From a radioactive beam transfer experiment, a 9% erosion of the $N = 28$ gap has been deduced after just two protons have been removed from doubly magic ^{48}Ca, in ^{46}Ar [9]. The 2^+ energy of ^{46}Ar [11,12] is considerably higher than that of ^{44}Ar [11] and ^{48}Ar [13] and suggests the persistence of the $N = 28$ energy gap in Ar nuclei. The same conclusion was drawn from measurements of the $B(E2; 0^+ \rightarrow 2^+)$ value in both ^{44}Ar and ^{46}Ar using intermediate-energy Coulomb-excitation experiments, which gave a larger value for the ^{44}Ar [7,12]. Shell-model calculations were able to reproduce the 2^+ excitation energy in both nuclei [7,11] but a large discrepancy was observed between the theoretical and the experimental $B(E2;\ 0^+ \rightarrow 2^+)$ in ^{46}Ar [2,7,14,15]: the theoretical value is almost 2.5 times higher that the experimental one. A sizable increase in the $B(E2;\ 0^+ \rightarrow 2^+)$ value from ^{44}Ar to ^{46}Ar is predicted by shell-model calculations [2,7], while the experimental data from Coulomb excitation show the opposite trend. Very recently, the $B(E2;\ 0^+ \rightarrow 2^+)$ value in ^{44}Ar has been remeasured in a low-energy Coulomb-excitation experiment [16]: the new value is in agreement with the previous intermediate-energy results and with the shell-model calculations available in the literature [2]. Relativistic and nonrelativistic mean-field calculations have been performed for exotic neutron-rich nuclei along the $N = 28$ shell closure that give different predictions for the quadrupole deformation

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β_2 of the ^{44,46}Ar nuclei [1,3]. The decreasing trend of the quadrupole deformation from $N = 26$ to $N = 28$ predicted in Ref. [1] agrees with the β_2 values deduced from the experimental $B(E2;\, 0^+ \to 2^+)$ value in Ref. [7]. The two relativistic mean-field approaches of Ref. [3] give an oblate deformation for ^{46}Ar but differ in the sign of the β_2 parameter for ^{44}Ar. This disagreement between different mean-field calculations can be explained by the behavior of the potential energy surfaces, as a function of deformation in these isotopes. They show either close-lying prolate and oblate minima, practically degenerate in energy, or a unique and very flat minimum centered around $\beta_2 = 0$.

The knowledge of $B(E2)$ transition probabilities is still scarce for neutron-rich nuclei. This is partially because they often depend on the availability of radioactive beams of the nuclei of interest to be accelerated for Coulomb-excitation experiments. Radioactive beams of Ar nuclei have been used to extract the $B(E2)$ values just discussed [7,12,16]. Using multinucleon transfer reactions [17], neutron-rich argon isotopes can be populated at moderately high spins. Recently, it has been shown that lifetime of states of the order of several picoseconds [18] can be measured using plunger techniques [19–21] following multinucleon transfer. Precise information about electromagnetic transition probabilities can hence be obtained and compared to the values from Coulomb-excitation experiments and to the calculations of different theoretical approaches. In this paper, we report on the measurement of lifetimes of excited states in ^{44,46}Ar using the differential recoil distance Doppler shift (RDDS) method developed for multinucleon transfer reactions in combination with the CLARA [22] and PRISMA [23] spectrometers. $B(E2)$ values extracted for $2^+ \to 0^+$ transitions in both nuclei, as well as for higher excited states in ^{44}Ar, are discussed and compared with large-scale shell-model calculations using the new SDPF-U interaction and with the other available theoretical predictions.

II. EXPERIMENT AND RESULTS

The ^{48}Ca + ^{208}Pb reaction has been used to populate neutron-rich nuclei in the vicinity of ^{48}Ca by means of multinucleon transfer processes. The ^{48}Ca beam, at a bombarding energy of 310 MeV, was delivered by the Laboratori Nazionali di Legnaro (LNL) tandem-ALPI accelerator complex. The beam intensity was limited to 1 pnA to avoid thermal stress of the plunger-target device. The procedure for simultaneously stretching the target and the degrader foils as well as the dedicated target holder was developed at the Institute of Nuclear Physics, University of Köln [19]. The target consisted of 1.0 mg/cm^2 enriched ^{208}Pb evaporated onto a 1.0 mg/cm^2 Ta support to accomplish the stretching of the target. A thick, 4 mg/cm^2 ^{nat}Mg foil used as an energy degrader of the recoiling ejectiles was positioned after the target. In this experiment, CLARA consisted of 23 Compton-suppressed-clover detectors. However, the 11 detectors placed around 90° with respect to the CLARA-PRISMA symmetry axis could not be used to measure lifetimes, as the Doppler shift of a γ ray emitted in flight is close to 0 for these detectors. Therefore, the number of useful detectors was 12 (8 at ∼130°, 3 at ∼154°, and 1 at ∼170°), with a total photopeak efficiency of the order of 1.2%. After passing through the Mg degrader, the projectile-like products were selected with the magnetic spectrometer PRISMA placed at the grazing angle $\theta_{\mathrm{LAB}} = 49°$. A schematic view of the experimental setup can be seen in Fig. 1 in Ref. [21]. An example of a mass spectrum obtained in this reaction is shown in Fig. 1 here, for the Ar isotopes. The mass resolution is ≈1/130 and is not deteriorated by the presence of the energy degrader foil.

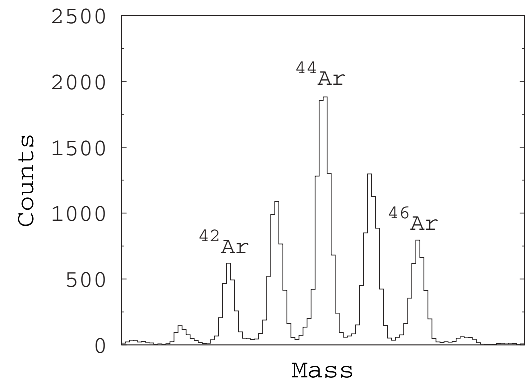

FIG. 1. Mass spectrum of argon isotopes produced in the ^{48}Ca + ^{208}Pb reaction at 310 MeV and for a target-to-degrader distance of 300 μm. They are detected in the PRISMA spectrometer after passing the energy degrader located behind the target.

In total, five target-to-degrader distances, 30, 100, 300, 1400, and 2200 μm, were employed during the experiment by using various metallic distance rings whose thickness was accurate to better than 1.0 μm. At the largest distance (2200 μm) however, the statistics for the Ar nuclei discussed in this work were insufficient to distinguish any peaks and therefore data are reported for distances up to 1400 μm. Because the angle between the target-degrader setup with respect to the PRISMA optic axis was 27° (see Fig. 1 in Ref. [21]), the effective distance traveled by the ions was ≈12% longer than the nominal one. For analysis of the lifetimes, the effective distances have been considered, while we refer to the nominal distances in the presentation of the data. Figure 2 shows Doppler-corrected γ-ray spectra in coincidence with ^{44}Ar for two target-to-degrader distances. Doppler correction was performed on an event-by-event basis using the velocity obtained by reconstruction of the recoil trajectories in PRISMA. The after-degrader velocity used for the Doppler correction is henceforth denoted β_{After}. In analogy with this, β_{Before} is also defined. Depending on whether the γ ray was emitted before or after the degrader foil, it exhibited a different Doppler shift. Therefore, if the lifetime of an excited level is in the appropriate time range, a single γ-ray transition de-exciting a level exhibits two peaks in the γ-ray spectrum. The higher energy peak, E_{After}, which presents an energy resolution of 0.6%, corresponds to γ rays emitted after the recoil was passed through the degrader foil, with an average relative velocity of $\langle\beta_{\mathrm{After}}\rangle \approx 8.0\%$. The lower energy peak, E_{Before}, corresponds to γ rays emitted before the degrader foil, with an average relative velocity of $\langle\beta_{\mathrm{Before}}\rangle \approx 10.0\%$.

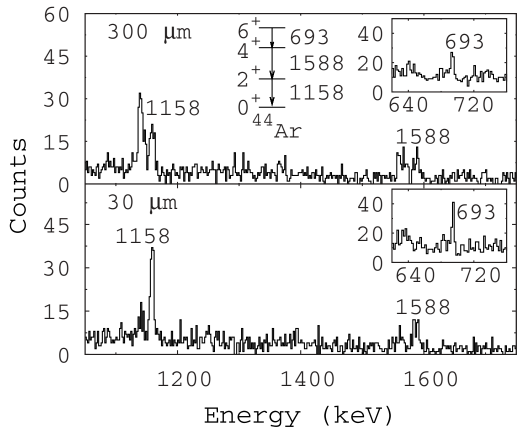

FIG. 2. Doppler-corrected γ-ray spectra for two target-to-degrader distances, showing the three transitions in coincidence with ^{44}Ar recoils. The higher energy and lower energy peaks correspond to the decays after and before the degrader, respectively.

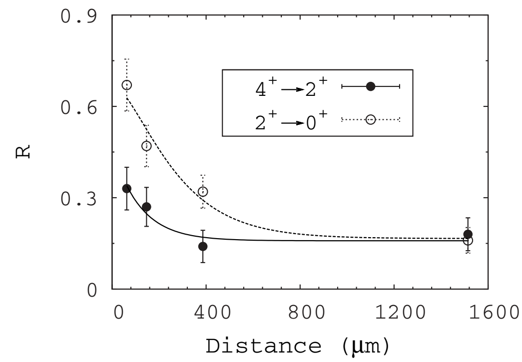

FIG. 3. Experimental ratio $R = I_{\mathrm{After}}/I_{2^+}$ plotted as a function of the effective target-to-degrader distance for the 1158-keV $2^+ \to 0^+$ and 1588-keV $4^+ \to 2^+$ transitions in ^{44}Ar. The least-squares fit through the points gives the lifetimes reported in Table I for the 2^+ and 4^+ states, assuming a lifetime longer than 40 ps for the 6^+ state.

Examples of these peaks are shown in Fig. 2. The relative intensities of the two peaks as a function of the target-to-degrader distance are used to determine the lifetime of the state from which the γ rays were emitted. In the following paragraphs we discuss the two nuclei studied in this work: ^{44}Ar and ^{46}Ar.

A. Lifetime of low-lying levels in ^{44}Ar

Several different level schemes of ^{44}Ar have been proposed as a result of a fragmentation reaction with radioactive beams [24], a multinucleon transfer experiment with a ^{48}Ca beam [11], and β-decay studies [25,26]. In Ref. [11], a sequence of three coincident γ rays (1158, 1588, and 693 keV) was observed; they were assigned to the decay of the 2^+, (4^+), and (6^+) states at 1158, 2746, and 3439 keV, respectively. A richer level scheme was proposed from β-decay studies, with two of the states coinciding within 2 keV with those assigned as 2^+ and (4^+) in the multinucleon transfer experiment. There is, however, a discrepancy between the two data sets. In the β-decay study, the state at 2748 keV de-excites to the 2^+ state through a 1588-keV transition in agreement with Ref. [11], but it also decays directly to the 0^+ ground state: this would be incompatible with a (4^+) assignment. However, it is well known [27] that multinucleon transfer and/or deep-inelastic reactions preferably populate yrast states. It is therefore likely that the 2748-keV state seen in β decay is a low-spin state lying very close in energy to the one at 2746 keV (de-excited by the 1588-keV transition) that is assumed to be the (4^+) level.

The previously measured $B(E2;\, 0^+ \to 2^+)$ value in ^{44}Ar was derived from an intermediate-energy Coulomb-excitation reaction [7,16]. In the present experiment the same population mechanism as in Ref. [11] was used. It was therefore expected that transitions de-exciting low-lying yrast levels up to (6^+) would be observed. Indeed the same three γ rays as reported in Ref. [11] are present in our spectra, as shown in Fig. 2. The 1158- and 1588-keV transitions, de-exciting the 2^+ and (4^+) levels, respectively, have, for the target-to-degrader distances used in this experiment, strong peaks in both the shifted and the unshifted components, indicating that the lifetimes are in the range of a few picoseconds. For the 693-keV $(6^+) \to (4^+)$ transition, the unshifted peak is dominant (see Fig. 2), even with the longest target-to-degrader distance, 1400 μm. This suggests a long (6^+) lifetime, outside the range of the plunger setup, and makes it difficult to distinguish the shifted component, if any, above the background. Taking into account the time range of the plunger setup and the low statistics of the peak, a lower limit of 40 ps for the lifetime of the (6^+) state was extracted. Because a considerable fraction of the (4^+) and 2^+ feeding proceeds through the (6^+) level, an unshifted component is also visible at all distances for the 1158- and 1588-keV transitions. For these two transitions, at all target-to-degrader distances, the ratio $R = I_{\mathrm{After}}/I_{2^+}$ was extracted, where I_{After} is the peak area of the transitions emitted after the degrader foil and the normalization factor I_{2^+} is the total intensity of the 2^+ state. Figure 3 shows such a ratio as a function of the effective target-to-degrader distance. For the 1588-keV transition the data have been fitted with a single exponential plus a constant function, to account for the longer feeding from above. The resulting lifetime for the (4^+) state is $\tau = 3.9^{+3.6}_{-2.9}$ ps, with an error larger than 90% owing to the low statistics. After correction for the contribution of the upper feeding, the unshifted part of the 1588-keV peak is still present at the 30-μm distance, which gives a lower limit for the (4^+) lifetime of 1.0 ps. In the fit of the $2^+ \to 0^+$ 1158-keV transition, we have included feeding from the (6^+) and (4^+) states with their respective lifetimes. A lifetime $\tau = 5.9(2.0)$ ps is extracted for the 2^+ state of ^{44}Ar. An equivalent analysis for ^{44}Ar has been done by minimizing the Bateman equation of the three excited levels, leading to the same results. A second 2^+ state at 2011 keV has been proposed from β-decay studies [25,26], which de-excites mostly through an 853-keV transition to the first 2^+ state at 1158 keV. The 853-keV transition, owing to the low statistics, is barely seen in the spectra taken at the different target-to-degrader distances. Nevertheless, when all the spectra are added together (see Fig. 4), only the shifted component of the transition is clearly seen, which implies a short lifetime for the second 2^+ state. In the recent Coulomb-excitation experiment in Ref. [16],

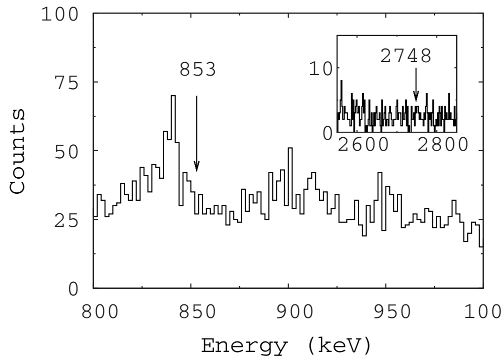

FIG. 4. The γ-ray spectrum in coincidence with ^{44}Ar for all target-to-degrader distances. The 853-keV $2_2^+ \to 2_1^+$ transition is clearly visible and presents only the shifted component at 841 keV, which implies a short lifetime for the state, in agreement with a recent measurement in Ref. [16]. The 2748-keV line is not present in the spectrum, confirming that the state seen in β decay [25,26] is different from the 4^+ state in our data set, decaying via the 1588-keV transition to the 2^+ state.

a strong $B(E2;\, 2_1^+ \to 2_2^+)$ value has been measured, which implies a lifetime of ≈1.5 ps for the 2_2^+ state. This value is compatible with our observation. The spectrum in the inset in Fig. 4 also excludes the presence of the 2748-keV transition and, consequently, the population in the present experiment on the 2748-keV state observed in β decay [25,26]. In fact, such a state decays through the 1588- and 2748-keV transitions with branching ratios of 60% and 40%, respectively. Given the intensity of the 1588-keV line (see, e.g., Fig. 2), the 2748-keV transition should be clearly visible in Fig. 4.

B. Lifetime of the 2^+ level in ^{46}Ar

Knowledge of excited states in ^{46}Ar comes mainly from experiments using a radioactive beam of ^{46}Ar produced after the fragmentation of a ^{48}Ca beam on Be targets [7,12,14,28]. Two level schemes are reported [14,28] that have in common the 2^+ state at ≈1.56 MeV and, probably, the 4^+ state at 3.9 MeV. In a β-decay study [26] a level scheme was proposed that agrees with the two results from fragmentation reactions only for the energy of the 2^+ state; the energy is measured more precisely at 1552.6 keV. The $B(E2)$ value has been measured in two intermediate-energy Coulomb-excitation experiments [7,12]. Excited states in ^{46}Ar nucleus have also been populated in a multinucleon transfer experiment with a stable beam [11] where only the 2^+ state was observed. Most recently, in the same kind of experiment, but using a different reaction (^{48}Ca + ^{238}U), new information has been obtained for ^{46}Ar [29]. The 2^+ level energy has been remeasured at 1552.3(3) keV, in agreement with Ref. [26], and two other transitions have been assigned to the nucleus. The proposed level scheme confirms the 4^+ state in Refs. [14] and [28] at 3862 keV and suggests a (5^+) state at 4835 keV.

In the present experiment, for target-to-degrader distances larger than 30 μm, only the peak corresponding to the shifted component of the 1552-keV $2^+ \to 0^+$ transition, at $E_\gamma \approx 1530$ keV, is observed. As an example, the γ spectrum taken at 300 μm is shown at the top in Fig. 5. This observation

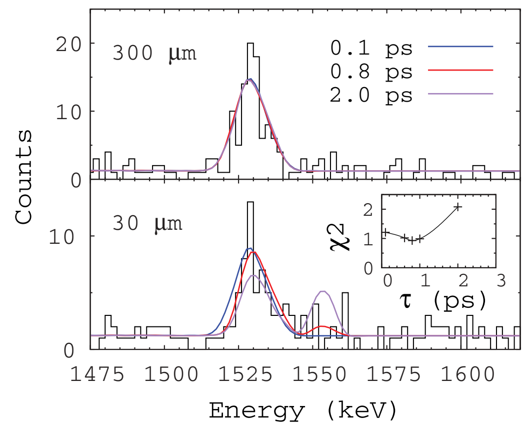

FIG. 5. (Color online) γ-ray spectra in coincidence with ^{46}Ar for target-to-degrader distances of 300 μm (top) and 30 μm (bottom). The region around the 1552-keV $2^+ \to 0^+$ transition is displayed. Monte Carlo simulations are shown, assuming three values for the lifetime of the 2^+ state, superimposed on the experimental spectra. Inset: A χ^2 analysis for the 30-μm spectrum, which gives a minimum for the lifetime of $0.8^{+0.3}_{-0.4}$ ps.

implies that the lifetime of the 2^+ state is short, less than a few picoseconds, as the flight time of the recoiling ions for a 100-μm target-to-degrader distance is around 3 ps. The spectrum taken with a target-to-degrader distance of 30 μm at the bottom in Fig. 5 shows that the shifted peak of the 1552-keV $2^+ \to 0^+$ transition is not symmetric as it is for the longer distances (Fig. 5, top), but a tail is visible on the right-hand side of the peak. Furthermore, few counts are visible at the position of the unshifted peak. It is therefore likely that the lifetime of the 2^+ state is comparable with the flight time of the ions, covering the target-to-degrader effective distance (34 μm in vacuum) and the degrader itself (26-μm effective thickness). The resulting spectrum in the energy region 1520–1560 keV is then generated by γ rays emitted before the degrader foil (the shifted peak with the same centroid as for the larger distances), emitted within the degrader (the tail at higher energies), and emitted after the degrader (the few counts above background at the unshifted position). The centroid of the symmetric shifted peak and its width can be obtained from the sum spectrum for the longer distances where only this peak is present, while the centroid of the unshifted peak is at 1552.3 keV and its width is known. One can then easily separate the three contributions (before, within, and after the degrader foil) from the 30-μm spectrum in Fig. 5 and, after associating them with an error, extract the lifetime of the 2^+ state. The result is $\tau = 0.84 \pm 0.25$ ps.

To extract the lifetime of the 2^+ state in an independent way, a Monte Carlo simulation was performed. The simulation takes into account the geometry of the CLARA and PRISMA spectrometers, the thickness of the degrader foil, and the slowing-down process of the ions in the degrader. Different lifetime values from 0.1 to 2.0 ps for the 2^+ level have been assumed so as to reproduce the complex shape of the peak at a 30-μm distance. More details on the simulations used in this work are given in Ref. [21]. Figure 5 shows the results of the simulations, superimposed on the experimental spectrum for both the 30-μm and the 300-μm distances. A χ^2 analysis for the various simulations with respect to experimental data gives a lifetime $\tau = 0.8^{+0.3}_{-0.4}$ ps. The minimum for the reduced χ^2 (20 df and 1 constraint) is 0.93 and it lies at 0.8 ps. The χ^2 minimum has a significance higher than 50%, while the χ^2 value corresponding to a 2.0-ps lifetime has a significance of less than 1%. The lifetime error was chosen by assuming a level of significance that is no worse than 30%. It can be noted here that a lifetime value $\tau \approx 2$ ps is expected from the $B(E2;\, 0^+ \rightarrow 2^+)$ value obtained in the Coulomb-excitation measurement [30]. Such a lifetime for the 2^+ state would produce an unshifted peak with an intensity comparable to that of the shifted peak, and this, in view of our experimental data shown in Fig. 5, is unlikely. A maximum likelihood estimation, more suitable when dealing with a low statistics population, gives a similar result, with a maximum and a minimum corresponding to the 0.8- and 2.0-ps lifetimes, respectively. As expected, all the simulations with such short lifetime values reproduce the peak shape in the spectrum at a 300-μm distance.

Because only a single point corresponding to the shortest target-to-degrader distance of 30 μm has been used in the analysis, the accuracy of this distance is of foremost importance to extract the lifetime of the 2^+ state in ^{46}Ar. As stated before, the thickness of the 30-μm metallic distance ring was measured with an accuracy of better than 1.0 μm. Nevertheless, the presence of a zero offset in the plunger setup cannot be excluded in principle, and this could affect the lifetime measurement. To give an estimation of a possible zero offset, we have analyzed the lifetimes of neighboring nuclei where data were available for more than two target-to-degrader distances. In all cases, the extracted lifetimes, when forcing a null zero offset, differ by less than 6% from the value obtained by leaving the zero offset as a free parameter. Because of the large error associated with the 2^+ lifetime measurement in ^{46}Ar, this additional 6% uncertainty is negligible.

The 2310-keV $4^+ \rightarrow 2^+$ transition [29] is not observed in the single spectra taken at the various distances, owing to the low statistics. Upon summing all the spectra, the shifted component of the 2310-keV transition is visible and its intensity is estimated to be 10% that of the 1552-keV $2^+ \rightarrow 0^+$ transition. Assuming a $B(E2)$ value for the $4^+ \rightarrow 2^+$ transition similar to that for the $2^+ \rightarrow 0^+$ transition, a lifetime of $\approx$0.1 ps is deduced for the 4^+ state. Upon correcting for the feeding of the 4^+ level, the lifetime of the 2^+ state becomes 6% shorter, and when expressed as a significant value it gives the 0.8-ps lifetime reported in Table I.

TABLE I. Lifetimes of excited states and γ-ray transition strengths in ^{44}Ar and ^{46}Ar derived in the present experiment.

Isotope	E_γ (keV)	$J_i^\pi \rightarrow J_f^\pi$	τ (ps)	$B(E2)$ (e^2fm^4)
^{44}Ar	1158	$2^+ \rightarrow 0^+$	5.9(2.0)	67^{+44}_{-17}
	1588	$4^+ \rightarrow 2^+$	$3.9^{+3.6}_{-2.9}$	21^{+60}_{-10}
	693	$6^+ \rightarrow 4^+$	>40	<128
^{46}Ar	1552	$2^+ \rightarrow 0^+$	$0.8^{+0.3}_{-0.4}$	114^{+67}_{-32}

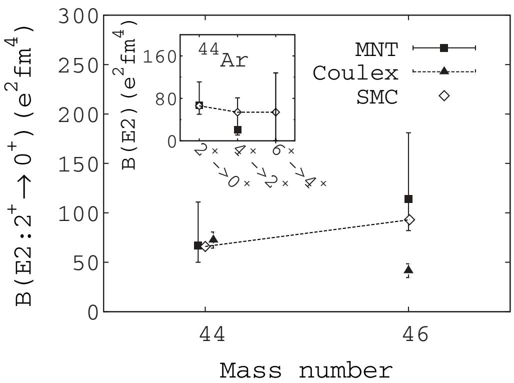

FIG. 6. $B(E2;\, 2^+ \rightarrow 0^+)$ values in ^{44,46}Ar derived in the present work (MNT) compared with values from Coulomb-excitation experiments with radioactive beams [7,12] and with shell-model calculations (SMC). Inset: Experimental $B(E2)$ values for the other transitions of ^{44}Ar, again compared with the shell-model calculations.

III. DISCUSSION

The transition probabilities in ^{44,46}Ar derived in the present work are shown in Fig. 6, where the $B(E2;\, 2^+ \rightarrow 0^+)$ values from the intermediate-energy Coulomb-excitation experiments are reported [7,12,16]. In the figure, there is a very good agreement between the present $B(E2)$ values for the $2^+ \rightarrow 0^+$ transition in ^{44}Ar and the previously measured values. In contrast, for the $2^+ \rightarrow 0^+$ transition of ^{46}Ar the present result is at least a factor of 2 larger than that from Coulomb excitation, even considering the large experimental uncertainty. To obtain a $B(E2)$ value consistent with that from the Coulomb-excitation experiment, the lifetime of the 2^+ level in ^{46}Ar should be $\tau \approx 2$ ps. In disagreement with the trend of the Coulomb-excitation data, the present work suggests an increase in the $B(E2; 2^+ \rightarrow 0^+)$ values from ^{44}Ar to ^{46}Ar, that is, from the $N = 26$ to the $N = 28$ shell closure. Indeed, this result was predicted from published shell-model calculations using different interactions in Refs. [2] and [7]. For ^{46}Ar more recent shell-model calculations [6,14,15] gave a theoretical $B(E2)$ value a factor of 2 larger than the experimental value from Coulomb excitation but in very good agreement with experimental results in the present work. The explanation for the large $B(E2;\, 2^+ \rightarrow 0^+)$ in ^{46}Ar is that, upon removal of protons from doubly magic ^{48}Ca, it becomes more convenient to promote neutrons across the $N = 28$ gap and to recover the cost in terms of single-particle energies by the gain in neutron-proton quadrupole correlation energy [6,15]. The strong quadrupole interaction between protons in the *sd* shell and neutrons in the *pf* shell brings an energy gain comparable to the $N = 28$ gap. The closed-shell configuration $(0f_{7/2})^8$ represents only $\approx$50% in the 0^+ state of ^{46}Ar [13,15]. The large number of particle-hole excitations points to an increased correlation, leading to the development of deformation. An oblate shape with $\beta_2 = 0.25$ is obtained for ^{46}Ar from the shell-model calculations in Refs. [6] and [13].

In the present work state-of-the-art shell-model calculations have been carried out using the SDPF-U interaction [31], which is an updated version of the *sdpf* interaction [32] and the code ANTOINE [33]. The valence space consists on the *sd* shell for protons and the *pf* shell for neutrons without any restrictions. For $B(E2)$ calculations the standard effective charges $e_\pi = 1.5e$ and $e_\nu = 0.5e$ have been used. The energies of the 2^+ state are in very good agreement with the calculations in both nuclei. The theoretical energies for the 4^+ and 6^+ states in ^{44}Ar and for the 4^+ state in ^{46}Ar are ≈300 keV lower than the values measured here. The theoretical results for the $B(E2)$ values are shown in Fig. 6. For the $2^+ \to 0^+$ transitions they are in good agreement with the values deduced in the present work, while they disagree with the Coulomb-excitation data of ^{46}Ar. Also, for the other transitions in ^{44}Ar the theoretical values are compatible with the present data, but the large uncertainties in the experimental data should be noted. The calculations with the SDPF-U interaction also predict the spectroscopic quadrupole moment for the 2^+ state in both nuclei: they are $-3.7e\text{fm}^2$ in ^{44}Ar and $+19.7e\text{fm}^2$ in ^{46}Ar. For the 2^+ state of ^{46}Ar a large (positive) spectroscopic quadrupole moment and an enhanced $E2$ transition ($92e^2\text{fm}^4$) are obtained. Assuming the Bohr-Mottelson expression for the intrinsic quadrupole moment, a $Q_0 = -69.0e\text{fm}^2$ is obtained for ^{46}Ar, which is compatible with the result deduced from the $B(E2)$ value. This corresponds to an oblate deformation with $\beta_2 = 0.25$, in agreement with the value obtained by previous calculations [13]. In ^{44}Ar, $B(E2)$ is reasonably large ($63e^2\text{fm}^4$), but the spectroscopic quadrupole moment is very small and negative ($-3.7e\text{fm}^2$) not far from the value $Q_s = -8(3)e\text{fm}^2$ recently measured in the low-energy Coulomb-excitation experiment [16]. Such a value gives a Q_0 very different from that obtained from the $B(E2)$ assuming an axial-symmetric rotor. Although a prolate shape is deduced from both the experimental and the theoretical Q_s, it is difficult to draw a conclusion about the deformation of ^{44}Ar, which is by all means smaller than in ^{46}Ar.

For the 2^+ state of ^{46}Ar the calculations suggest that the closed-shell configuration $(0f_{7/2})^8$ represents only ≈30% of the wave function. Nevertheless, for the 2^+ state in ^{44}Ar, the configuration with all six neutrons in the $f_{7/2}$ orbital, $(0f_{7/2})^6$, accounts for ≈60% of the wave function. The much higher probability of particle-hole excitations across the $N = 28$ gap in ^{46}Ar with respect to ^{44}Ar is therefore directly related to its larger $B(E2)$ value and to its larger deformation. The results obtained in the present work for ^{44,46}Ar nuclei with the SDPF-U interaction are consistent with the original calculations using the SDPF-NR interaction [2,15]. The SDPF-U interaction is a modified version of the SDPF-NR that also takes into account new experimental information coming from the most neutron-rich silicon isotopes [31]. With the new version a much better agreement with the experimental data is achieved for the neutron-rich silicon and magnesium isotopes, and also, the vanishing of the $N = 28$ neutron shell closure in ^{42}Si and ^{40}Mg is well accounted for.

Shell-model calculations using the SDPF-U interaction have recently been published for ^{44}Ar and ^{46}Ar [16,34]. In Ref. [34] the effective charges $e_\pi = 1.5e$ and $e_\nu = 0.5e$ were adopted, while in Ref. [16] $e_\pi = 1.35e$ and $e_\nu = 0.35e$, suggested in Ref. [31], were used. In the second case the data for S and Si isotopes were well reproduced. All these results are consistent with the calculations carried out in the present work, except for the $B(E2)$ values in Ref. [16], which are ≈30% smaller owing to the adopted effective charges. The $e_\pi = 1.5e$ and $e_\nu = 0.5e$ effective charges are therefore appropriate for reproduction of the experimental data on argon isotopes.

The nuclei ^{44}Ar and ^{46}Ar have also been studied theoretically via calculations based on relativistic and nonrelativistic mean-field approaches [1,3–5,16]. In the recent work by Zielinska *et al.* [16], an extensive discussion and comparison of those calculations are reported, together with the results from Coulomb-excitation experiments (see, in particular, their Table III and Fig. 3). These calculations are not in agreement with the present results, and only the angular momentum projected GCM approach (AMPGCM) reproduces the increasing trend of $B(E2)$ from ^{44}Ar to ^{46}Ar observed experimentally. The mean-field calculations are in better agreement with the experimental data while going farther away from the stability upon decreases in the proton number. In this case well-deformed structures are predicted, which are related to the breaking of the $N = 28$ shell closure and its collapse in Si and Mg nuclei.

IV. SUMMARY

Lifetimes in neutron-rich ^{44,46}Ar nuclei have been measured using the differential RDDS method. Nuclei, populated via multinucleon transfer reactions, have been identified by the PRISMA magnetic spectrometer, and their γ decay studied with the CLARA Ge array. In contradiction to data from intermediate-energy Coulomb-excitation reactions with radioactive beams, an increase in $B(E2; 2^+ \to 0^+)$ from ^{44}Ar to ^{46}Ar is observed. The larger value of $B(E2)$ at the $N = 28$ shell closure is well explained by the shell-model calculations, pointing to the importance of neutron-proton quadrupole correlations when protons are removed from doubly magic ^{48}Ca. With decreasing proton number at $N = 28$, correlations increase and eventually cause the vanishing of the $N = 28$ shell closure in ^{42}Si and ^{40}Mg.

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[1] T. R. Werner *et al.*, Phys. Lett. B **335**, 259 (1994); Nucl. Phys. A **597**, 327 (1996).

[2] J. Retamosa, E. Caurier, F. Nowacki, and A. Poves, Phys. Rev. C **55**, 1266 (1997).

[3] G. A. Lalazissis, D. Vretenar, P. Ring, M. Stoitsov, and L. Robledo, Phys. Rev. C **60**, 014310 (1999).

[4] S. Peru, J. L. Egido, and J. L. Robledo, Eur. Phys. J. A **9**, 35 (2000).

[5] R. Rodriguez-Guzman *et al.*, Phys. Rev. C **65**, 024304 (2002).
[6] E. Caurier, F. Nowacki, and A. Poves, Nucl. Phys. A **742**, 14 (2004).
[7] H. Scheit *et al.*, Phys. Rev. Lett. **77**, 3967 (1996).
[8] T. Glasmacher *et al.*, Phys. Lett. B **395**, 163 (1997).
[9] L. Gaudefroy *et al.*, Phys. Rev. Lett. **97**, 092501 (2006).
[10] B. Bastin *et al.*, Phys. Rev. Lett. **99**, 022503 (2007).
[11] B. Fornal *et al.*, Eur. Phys. J. A **7**, 147 (2000).
[12] A. Gade *et al.*, Phys. Rev. C **68**, 014302 (2003).
[13] S. Bhattacharyya *et al.*, Phys. Rev. Lett. **101**, 032501 (2008).
[14] L. A. Riley *et al.*, Phys. Rev. C **72**, 024311 (2005).
[15] E. Caurier, F. Nowacki, and A. Poves, Eur. Phys. J. A **15**, 145 (2002).
[16] M. Zielinska *et al.*, Phys. Rev. C **80**, 014317 (2009).
[17] L. Corradi, G. Pollarolo, and S. Szilner, J. Phys. G **36**, 113101 (2009).
[18] J. J. Valiente-Dobón *et al.*, Phys. Rev. Lett. **102**, 242502 (2009).
[19] A. Dewald *et al.*, Nucl. Instrum. Methods Phys. Res. A (to be published).
[20] A. Gadea *et al.*, Acta Phys. Pol. B **38**, 1311 (2007).
[21] D. Mengoni *et al.*, Eur. Phys. J. A **42**, 387 (2009)
[22] A. Gadea *et al.*, Eur. Phys. J. A **20**, 193 (2004).
[23] A. M. Stefanini *et al.*, Nucl. Phys. A **701**, 217c (2002).
[24] S. Wan *et al.*, Eur. Phys. J. A **6**, 167 (1999).
[25] J. A. Cameron and B. Singh, Nucl. Data Sheets **88**, 299 (1999).
[26] J. Mrazek *et al.*, Nucl. Phys. A **734**, E65 (2004).
[27] R. Broda, J. Phys. G **32**, R151 (2006).
[28] Zs. Dombradi *et al.*, Nucl. Phys. A **727**, 195 (2003).
[29] B. Fornal *et al.*, *Proceedings of the 9th International Spring Seminar on Nuclear Physics, Vico Equense, Italy, 20–24 May 2007* (World Scientific, Singapore, 2007), p. 283.
[30] S.-C. Wu, Nucl. Data Sheets **91**, 1 (2000).
[31] F. Nowacki and A. Poves, Phys. Rev. C **79**, 014310 (2009).
[32] S. Nummela *et al.*, Phys. Rev. C **63**, 044316 (2001).
[33] E. Caurier, *Shell-Model Code Antoine* (IreS, Strasbourg, 1989); E. Caurier and F. Nowacki, Acta Phys. Pol. B **30**, 705 (1999).
[34] S. J. Q. Robinson, Y. Y. Sharon, and L. Zamick, Phys. Rev. C **79**, 054322 (2009).