Lifetime measurement of the 167.1 keV state in ^{41}Ar

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The Advanced-Time-Delayed method was used to measure lifetimes of the states in ^{41}Ar populated in the β decay of ^{41}Cl. The nuclei ^{41}Cl were produced at ISOLDE by 1.4-GeV proton bombardment of a thick UC_x target and mass-separated as molecular ions, $XeCl^+$. Our measured half-life of the 167.1-keV state, $T_{1/2} = 315(15)$ ps, is significantly lower than the previously measured value of 410(30) ps. We have also determined $T_{1/2} = 260(80)$ ps and $T_{1/2} \leqslant 46$ ps for the 515.9- and 1867.7-keV states, respectively. These are the shortest lifetimes measured so far with the ultrafast timing method using the new $LaBr_3$(Ce) crystals for γ-ray detection.

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There is considerable interest in the doubly magic nuclei of ^{40}Ca and ^{48}Ca as well as in the nuclei below $Z = 20$ concerning the disappearance of old shell gaps and appearance of new ones. Our study focuses on ^{41}Ar, which has been studied [1] by the (n, γ) and $(d, p\gamma)$ reactions on ^{40}Ar as well as from the β^- decay of ^{41}Cl. The β decay of ^{41}Cl is not considered [1] to be well established. Only one investigation of this decay has been performed, having taken place more than 30 years ago [2], and incomplete results were reported in Ref. [3]. We have re-investigated the β decay of ^{41}Cl and measured lifetimes of selected states in ^{41}Ar.

The activity of ^{41}Cl was produced at the PSB ISOLDE facility at CERN by bombardment of a standard 45 g/cm^2 UC_x/graphite target with 1.4-GeV proton pulses from the PS Booster. The reaction products were stopped in the target matrix, then allowed to diffuse out of the 2100°C hot target and transit via a tantalum transfer line to the 1950°C hot ISOLDE-type FEBIAD ion source MK5 [4]. The latter is operated with a support gas of 95% Ar and 5% Xe at a rate of 1.8×10^{-6} mbar l/s. This explains the presence of xenon in the target and ion source unit. After ionization and acceleration to 60 keV, the molecular ions were mass-separated at mass 169 and sent to the experimental station to be deposited onto a thin aluminium stopper directly in front of a β detector. The beam was continuously deposited, creating a saturated source. It included short- and long-lived activities coming from

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a number of radioactive decays. The decay of ^{41}Cl constituted a few percent of the total activity.

The measuring station included five detectors positioned in a close geometry around the beam deposition point. The fast-timing β detector was a 3-mm-thick NE111A plastic scintillator placed directly behind the radioactive source. The γ-ray detectors included two fast-response scintillating crystals: a relatively large BaF_2 of Studsvik design and a small cylindrical 2.54 × 2.54 cm $LaBr_3$(Ce) and two Ge detectors with relative efficiencies of 100%. The $LaBr_3$(Ce) crystal with an effective Ce doping of about 5% was provided by Saint Gobain. The present experiment represents one of the first applications of the $LaBr_3$(Ce) crystals for ultrafast timing measurements.

The experimental setup and data collection were optimized for the application of the Advanced-Time-Delayed $\beta\gamma\gamma(t)$ method described in Refs. [5–7]; thus only a few details are given here. A three-parameter time-delayed $\beta\gamma(t)$ coincidence system was set between the β detector and each of the γ detectors and thus three parameters were required per coincident $\beta\gamma(t)$ event: the energies of the β particle and the γ ray and the time delay between the β- and γ-ray events. The triple-coincident $\beta\gamma\gamma$ events were identified when two $\beta\gamma(t)$ events were recorded at the same time. The data analysis involved coincident events collected in the β-Ge-Ge, β-Ge-BaF_2, or β-Ge-$LaBr_3$(Ce) combination of detectors. The first set allowed identification of γ rays observed in the spectra and construction or verification of the level schemes; moreover, it allowed for an identification of γ rays present in the coincident BaF_2 and $LaBr_3$ energy spectra characterized by much worse energy resolutions than the Ge spectra (see Fig. 2).

In the Advanced-Time-Delayed method [5–7] the time responses of the fast-timing γ detectors [BaF_2 and $LaBr_3$(Ce)] are carefully calibrated (to a picosecond precision) for various types of interactions of γ rays in the crystal (Compton and full-energy peak events), and it is also checked that the shape of time spectra for prompt radiation is close to symmetric semi-Gaussians over the range of γ-ray energies of interest. In particular, the time calibrations of the BaF_2 and $LaBr_3$(Ce) detectors were obtained on-line at ISOLDE using the decay of ^{138}Cs and off-line using a source of ^{140}Ba/^{140}La.

The activities observed at mass 169 included four radioactive chlorine isotopes, ^{38}Cl, ^{39}Cl, ^{40}Cl, and ^{41}Cl, which were firmly identified via $\gamma\gamma$ coincidences. Chlorine must have been bound into molecules to be found at mass 169. For the molecular partner, the simplest scenario is to consider just one chain of isotopes, which must be stable at specific mass numbers. These stable masses are 169 minus 38 to 41 and thus at mass numbers 131, 130, 129, and 128. There is only one chain of isotopes, namely xenon, that fulfills this requirement. Stable Xe isotopes have the following natural abundances: ^{124}Xe (0.10%), ^{126}Xe (0.09%), ^{128}Xe (1.91%),^{129}Xe (26.4%), ^{130}Xe (4.1%), ^{131}Xe (21.2%), ^{132}Xe (26.9%), ^{134}Xe (10.4%), and ^{136}Xe (8.9%). The first two are weakly present and, moreover, would have to be bound to very exotic and weakly produced ^{45}Cl and ^{43}Cl, and thus they are not expected to be observed. However, ^{35}Cl and ^{37}Cl are stable nuclei, and ^{33}Cl decays via β^+ in almost 99% to the ground state of ^{33}S; thus

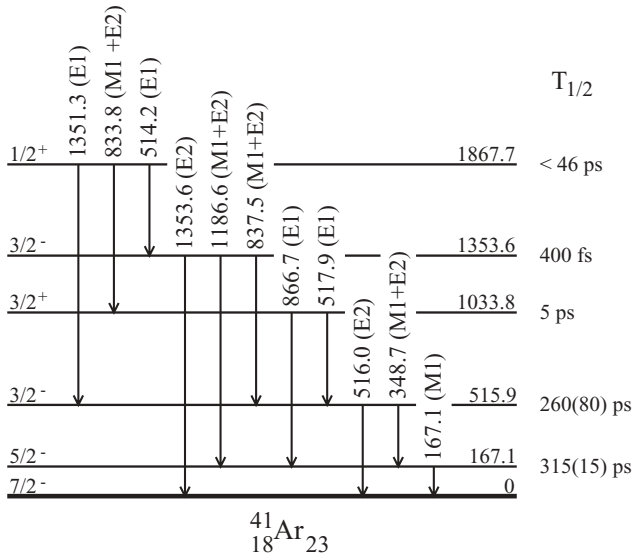

FIG. 1. The level scheme from the decay of ^{41}Cl into ^{41}Ar as determined in this work. The half-lives for the 1033.8- and 1353.6-keV levels are taken from Ref. [1].

none of them can be observed in β-gated $\gamma\gamma$ coincidences. This leaves only four eligible isotopes: ^{128}Xe, ^{129}Xe, ^{130}Xe, and ^{131}Xe, and indeed all four related radioactive products of chlorine, ^{38}Cl, ^{39}Cl, ^{40}Cl, and ^{41}Cl, have been unambiguously identified. We thus conclude that the beams of radioactive chlorine isotopes are observed in this experiment because of the very exotic $XeCl^+$ molecular ions.

The β-gated $\gamma\gamma$ coincidences in the β-Ge-Ge detectors served to verify the previously published [2] decay scheme of ^{41}Cl to ^{41}Ar. Our results, summarized in Fig. 1 and Table I, are consistent with those reported in Ref. [2]. An example of the $\gamma\gamma$ spectrum is shown in Fig. 2(a). Transition energies were determined from an internal calibration using γ-ray energies from different decays present

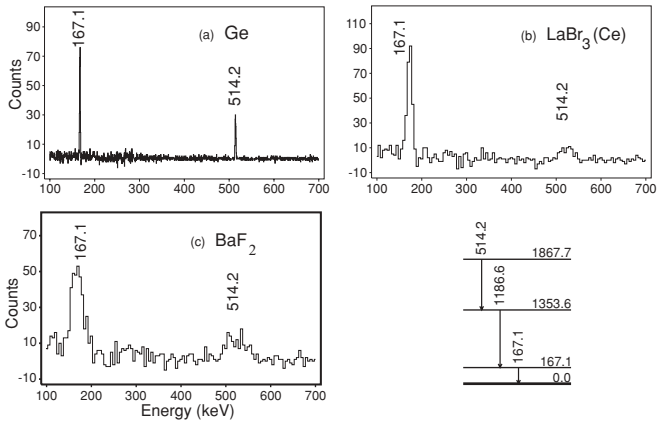

FIG. 2. Partial $\gamma\gamma$ coincidence energy spectra recorded in the (a) Ge, (b) $LaBr_3$(Ce), and (c) BaF_2 detectors, respectively, when the same gate was set on the 1186.6-keV γ peak in the coincident Ge detector. Note a superior energy resolution for $LaBr_3$(Ce) in comparison to the BaF_2 spectrum. The insert shows a simplified γ-decay scheme including only the 514.2-1186.6-167.1-keV γ cascade.

TABLE I. Level lifetimes and experimental and theoretical reduced transition probabilities in ^{41}Ar (see text for details).

Initial level (keV)	I_i	$T_{1/2}$ This work (ps)	$T_{1/2}$ Refs. [1,8] (ps)	E_γ (KeV)	I_γ Ref. [1]	I_f	$X\lambda$	$B_{\exp}(X\lambda)$ (W.u.)	Theory (Ref. [10])		
									E_{level} (keV)	$B^A_{\text{th}}(X\lambda)$ (W.u.)	$B^B_{\text{th}}(X\lambda)$ (W.u.)
167.1	$5/2^-$	315(15)	410(30)	167.1(1)	100	$7/2^-$	$M1$	$1.49(7) \times 10^{-2}$	178	1.25×10^{-2}	2.61×10^{-2}
515.9	$3/2^-$	260(80)	340(20)	348.7(2)	28(4)	$5/2^-$	$M1$	$4.4(15) \times 10^{-4}$	557	1.9×10^{-4}	16.6×10^{-4}
				516.0(3)[a]	100(4)	$7/2^-$	$E2$	5.5(17)		3.80	2.65
1033.8	$3/2^+$			517.9(3)[a]	79(9)	$3/2^-$	$E1$		868		
				866.7(2)	100(9)	$5/2^-$	$E1$				
1353.6	$3/2^-$		0.40(6)	837.5(3)	20(3)	$3/2^-$	$M1$	$1.5(3) \times 10^{-2}$	1156	3.76×10^{-3}	4.65×10^{-3}
				1186.6(1)	100(3)	$5/2^-$	$M1$	$2.7(4) \times 10^{-2}$		2.03×10^{-2}	1.47×10^{-2}
				1353.6(2)[a]	4(3)	$7/2^-$	$E2$	1.2(9)		1.82	1.54
1867.7	$1/2^+$	$\leqslant 46$		514.2(1)	100(11)	$3/2^-$	$E1$	$\geqslant 4.3 \times 10^{-5}$	2036		
				833.8(2)	54(11)	$3/2^+$	$M1$	$\geqslant 2.1 \times 10^{-4}$			
				1351.3(3)	60(11)	$3/2^-$	$E1$	$\geqslant 1.4 \times 10^{-6}$			

[a]Adopted from Ref. [1] or deduced as energy difference between levels.

in the source. We have clearly identified members of the multiplets at the energies of 514.2, 516.0, and 517.9 keV (partially mixed with a very strong 511-keV annihilation peak) and a doublet at 1351.3 and 1353.6 keV. Yet to get precise energies for three of them we have adopted the energy for the 516.0(3)-keV line from the NDS compilation [1], since that transition is well determined in the reactions using light particles, whereas in the cases of the 517.9(3) and 1353.6(2) keV, we have relied on the energy differences between the established levels. Our data provide a more precise energy determination for the 1867.7-keV level and the transitions de-exciting it. We have adopted transition intensities listed in Ref. [1], since our data were consistent with those values, yet our $\gamma\gamma$ spectra did not provide a means to obtain more precise results.

The Advanced-Time-Delayed method [5–7] was used to determine lifetimes of the 167.1-, 515.9-, and 1867.7-keV states. This method can be described approximately as a "stop watch" technique, where the β, $LaBr_3$(Ce), and BaF_2 detectors serve as sensors of the time events. The β event starts the stop watch and a γ event stops it. A high-precision time to amplitude converter (TAC) acts as this stop watch and is able to monitor time differences on the scale of picoseconds. For the lifetime determinations we have used $\beta\gamma\gamma$ coincidences from the β-Ge-BaF_2 and the β-Ge-$LaBr_3$(Ce) detectors. Lifetimes for the 1033.8- and 1353.6-keV levels were adopted from Ref. [1].

The lifetime limit for the 1867.7-keV state was obtained by a free shape fitting of the time-delayed spectrum shown in Fig. 3(a). It shows only a marginal asymmetry (slope), and thus a limit of $T_{1/2} \leqslant 46$ ps is deduced for the 1867.7-keV level. This spectrum represents a sum of three time-delayed spectra. All three were started by events in the β detector. The first two were stopped by the 514-keV full-energy events recorded in the BaF_2 detector. These events were in coincidence with the 167.1- and 1186.6-keV transitions, respectively, observed in the Ge spectrometer that precisely selected the decay path. To increase statistics we have added the time spectrum stopped by the 1186.6-keV transitions in the BaF_2 detector with the 167.1-keV γ rays selected in Ge. (Note the short lifetime of the 1353.6-keV level.)

The lifetime of the 515.9-keV level was measured by fitting the time spectrum started by β events and stopped by the 348.7-keV full-energy events in BaF_2 when the 167.1-keV transitions were selected in Ge. This spectrum, shown in Fig. 3(c), includes also a semi-prompt time component from Compton events at 349 keV caused by γ rays of higher energies that are coincident to the 167.1-keV transition. Thus a

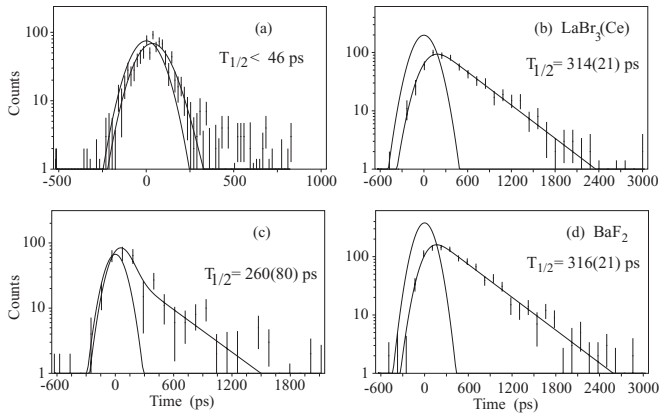

FIG. 3. Time-delayed spectra sorted from the $\beta\gamma\gamma(t)$ data. Transitions selecting the decay path were chosen in the Ge detector; the time-delayed spectra (a), (c), and (d) were measured between β events and γ rays recorded in the BaF_2 detector. No significant asymmetry is observed in spectrum (a); thus only an upper limit on the half-life is determined for the 1867.7-keV level. Spectrum (c) shows a mixture of a semiprompt (semi-Gaussian) spectrum and a slope that is due to the 515.9-keV level. Time-delayed $\beta\gamma\gamma(t)$ spectra (b) and (d) are gated by the de-exciting 167.1-keV transition in the $LaBr_3$(Ce) and BaF_2 detectors, respectively. Note the almost identical time spectra and slope determinations in (b) and (d). The slope is due to the lifetime of the 167.1-keV level in ^{41}Ar, with an average half-life of $T_{1/2} = 315(15)$ ps.

two-component fit was performed. The slope of $T_{1/2} = 260(80)$ ps is due to the lifetime of the 515.9-keV level.

Figures 3(b) and 3(d) show the time spectra, which served to determine the lifetime of the 167.1-keV state. The spectrum in Fig. 3(b) represents the sum of the β–514.2(Ge)–167.1($LaBr_3$) and β–1186.6(Ge)–167.1($LaBr_3$) spectra, and the spectrum in Fig. 3(d) represents a sum of equivalent time distributions obtained with the BaF_2 detector, namely the β–514.2(Ge)–167.1(BaF_2) and β–1186.6(Ge)–167.1(BaF_2) spectra. A strong asymmetry (slope) in the time spectra is due to the lifetime of the 167.1-keV state, for which we adopt the averaged value of $T_{1/2} = 315(15)$ ps.

The selection of full-energy events at 167.1 keV in the $LaBr_3$(Ce) and BaF_2 detectors is illustrated in Figs. 2(b) and 2(c), respectively. The present experiment allows intercomparison of the application of the $LaBr_3$(Ce) and BaF_2 crystals to the ultrafast time-delayed measurements. One observes similar time resolutions for both crystals and a superior energy resolution of $LaBr_3$(Ce).

The previous lifetime measurements for the 167.1- and 515.9-keV states were performed [8] over 40 years ago using the time-delayed method. Levels in ^{41}Ar were populated in the ^{40}Ar$(d, p\gamma)^{41}$Ar reaction whereas time-delayed proton-γ coincidences were measured with Si and NE102 plastic detectors, respectively, with an overall time resolution of about 1 ns FWHM. The modern timing detectors used in the present experiment had about five times better time resolution, giving much higher precision of the measurement. Our measured half-life for the 167.1-keV state is about 30% shorter than the previous value.

The experimental reduced transition probabilities in Weisskopf units for ^{41}Ar are given in column 9 of Table I. They were determined from our new level lifetimes (except for the 1353.6-keV level) and by using relative γ-ray intensities taken from Ref. [1]. Because of the lack of information on $E2/M1$ mixing ratios the experimental $B(M1)$ values were calculated as for pure $M1$ transitions. Possible $E2$ admixtures would diminish obtained $B(M1)$ values. However, the $E2$ component in the 167.1-keV transition must be negligible, since if this transition was pure $E2$ it would have $B(E2)$ value of the order of 1600 W.u., which is well above any reasonable limit for this nucleus. Similarly, for the 837.5- and 1186.6-keV γ rays the $B(E2)$ values would be of the order of 66 and 58 W.u., respectively, indicating that these transitions are predominantly of $M1$ type. Only in the case of the 348.7-keV transition would the $B(E2)$ value for pure $E2$ multipolarity be about 10 W.u., and thus a very significant $E2$ admixture cannot be ruled out.

The ^{41}Ar nucleus has an interesting shell model configuration with two proton holes in the $1d2s$ and three neutrons in the $1f2p$ major shells. Shell model calculations for this nucleus have been performed in Refs. [9–11]. All of them reproduce energies of the lowest negative-parity levels shown in Fig. 1 with fairly good accuracy. Table I (columns 10–12) provides a comparison of experimental level energies and reduced transition probabilities to the theoretical predictions of Ref. [10]. The theoretical $B(E2)$ values in columns 11 and 12 of Table I were calculated with effective charges $e_p, e_n = 1.29e, 0.49e$ and $1.35e, 0.35e$, respectively, whereas the $B(M1)$ values were calculated in (A) with the effective g factors and in (B) with the free-nucleon g factors, respectively; for details see Ref. [10]. Given the experimental uncertainties, the calculations correctly reproduce the $B(E2)$ and $B(M1)$ values, including a drop by two orders of magnitude in the $B(M1)$ value for the $3/2^-_1 \rightarrow 5/2^-_1$ transition. The calculated $B(M1)$ values using the effective g factors tend to systematically underestimate the experimental results.

To conclude, we have investigated the β decay of ^{41}Cl to ^{41}Ar using molecular ions of $XeCl^+$, confirmed the previously proposed decay scheme, and provided more precise determination of γ-ray energies. Our value for the lifetime of the 167.1-keV level is significantly lower than the previous result. The first application of a new crystal $LaBr_3$(Ce) has confirmed its superior energy resolution and comparable time resolution to the BaF_2 crystal.

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