High-precision half-life measurements of the $T = 1/2$ mirror β decays ^{17}F and ^{33}Cl

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Background: Measurements of the ft values for $T = 1/2$ mirror β^+ decays offer a method to test the conserved vector current hypothesis and to determine V_{ud}, the up-down matrix element of the Cabibbo-Kobayashi-Maskawa matrix. In most mirror decays used for these tests, uncertainties in the ft values are dominated by the uncertainties in the half-lives.

Purpose: Two precision half-life measurements were performed for the $T = 1/2$ β^+ emitters, ^{17}F and ^{33}Cl, in order to eliminate the half-life as the leading source of uncertainty in their ft values.

Method: Half-lives of ^{17}F and ^{33}Cl were determined using β counting of implanted radioactive ion beam samples on a moving tape transport system at the Système de Production d'Ions Radioactifs Accélérés en Ligne low-energy identification station at the Grand Accélérateur National d'Ions Lourds.

Results: The ^{17}F half-life result, 64.347 (35) s, precise to $\pm 0.05\%$, is a factor of 5 times more precise than the previous world average. The half-life of ^{33}Cl was determined to be 2.5038 (22) s. The current precision of $\pm 0.09\%$ is nearly 2 times more precise compared to the previous world average.

Conclusions: The precision achieved during the present measurements implies that the half-life no longer dominates the uncertainty of the ft values for both $T = 1/2$ mirror decays ^{17}F and ^{33}Cl.

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I. INTRODUCTION

High-precision measurements of $T = 1/2$ mirror β^+ decay ft values between isobaric analog states are used for testing the conserved vector current (CVC) hypothesis, to discriminate between theoretical models that describe isospin symmetry breaking, and for providing stringent tests of the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix for limiting possible extensions to the standard model description of electroweak interactions. Currently, high-precision measurements of 14 superallowed 0^+ to 0^+ nuclear Fermi β decays yield the most precise value for V_{ud} (the up-down matrix element of the CKM matrix) of 0.974 17(21) [1]. Due to the inherent difficulty associated with the determination of the neutron lifetime [2,3], the second most precise value of V_{ud} is presently obtained from isospin $T = 1/2$ mirror β transitions [4]. Recently, the first consistent test confirmed the CVC hypothesis using only $T = 1/2$ mirror β decays at the level of 10^{-3} precision, and it is the first such test involving nuclear decays other than superallowed [4]. Currently, five $T = 1/2$ decays are included in the CVC test and the evaluation of V_{ud} from nuclear mirrors: ^{19}Ne, ^{21}Na, ^{29}P, ^{35}Ar, and ^{37}K [4].

To perform these tests, ft values must be determined with sufficient precision. The ft value is a product of the statistical rate function f, which depends on Q-value measurements, and the partial half-life t, determined from experimental half-life and branching ratio measurements. The ft value is then modified by theoretical radiative as well as nuclear structure and isospin symmetry-breaking corrections to obtain the $\mathcal{F}t$ value (the corrected ft). For the case of $T = 1/2$ decays, $\mathcal{F}t$ values are in turn modified by ρ, the Gamow-Teller to Fermi mixing ratio, to calculate the nucleus-independent $\mathcal{F}t_0$ and V_{ud} for mirror β transitions [4,5]. The uncertainties in the $\mathcal{F}t$ values determined from $T = 1/2$ mirror β decays are, unlike the $\mathcal{F}t$ values derived from the superallowed Fermi transitions, dominated by experimental uncertainties. A survey of 19 cases of $T = 1/2$ mirror nuclei up to $A = 45$ has shown that, for the majority, the total uncertainties in the ft values are dominated by the uncertainties in the half-lives [5]. Presently, ^{19}Ne has the most precisely determined ft value for any of the $T = 1/2$ mirror decays because several recent measurements [6–8] have improved the half-life precision to $\pm 0.04\%$. A recent high-precision measurement of the ^{21}Na half-life [9] has reduced its uncertainty to $\pm 0.04\%$, making it one of the most precisely measured $T = 1/2$ mirror decay ft values. An order of magnitude improvement in the precision of the ^{37}K half-life was made recently, significantly improving the uncertainty in its ft value [10]. Given that the uncertainties in the half-lives are presently the main source of the limitation in extracting precise ft values for these nuclei, additional high-precision half-life measurements are necessary to reduce the uncertainty to less than 1 part in 1000 for nearly all of the $T = 1/2$ mirror transitions [5].

In the present work, the half-lives of two $T = 1/2$ mirror nuclei, ^{17}F and ^{33}Cl, are measured to reduce the total experimental uncertainty to a level such that the half-life

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uncertainty no longer dominates the uncertainty in the ft value. These measurements will motivate future high-precision measurements of the ^{17}F and ^{33}Cl Q values, measurements of the ^{33}Cl branching ratio, and measurements of angular-correlation coefficients to determine ρ that are required to perform tests of the CVC hypothesis and of the unitarity of the CKM matrix.

II. EXPERIMENT

Radioactive beams for the ^{17}F and ^{33}Cl measurements were produced at the SPIRAL (Système de Production d'Ions Radioactifs Accélérés en Ligne) facility at GANIL (Grand Accélérateur National d'Ions Lourds) located in Caen, France. Following fragmentation of a primary beam of $^{36}Ar^{18+}$ at 95 MeV/u on a graphite target, radioactive beams were ionized in a VADIS (versatile arc discharge ion source [11]) FEBIAD (forced electron beam ion arc discharge) ion source. After extraction from the ion source at 10 kV, ion beams were mass separated according to their charge-to-mass ratio (q/A) with a resolution of $m/\Delta m \approx 300$ and delivered to the SPIRAL low-energy identification station and tape transport system [12]. Beams of ^{17}F and ^{33}Cl were delivered as singly charged molecules ^{9}Be $^{17}F^{1+}$ ($A = 26$) and ^{9}Be $^{33}Cl^{1+}$ ($A = 42$) with average intensities of 1×10^6 and 1×10^5 ions/s, respectively. Mass-separated beams were implanted into an aluminized-Mylar tape in the implantation chamber of the tape station that was equipped with a hyperpure germanium (HPGe) detector at 0° with respect to the beam axis for beam purity and intensity measurements. After a defined implantation period, the samples were transported to the decay chamber for the half-life measurements that employed a 3-mm-thick, 40×40 mm^2 BC-404 fast plastic scintillator coupled to two photomultiplier tubes (Hamamatsu Model R2248) that were biased at -300 V inside the vacuum. The two signals from each photomultiplier tube were discriminated and, to reduce noise and potential after-pulsing effects, were combined in a logical AND and sent to a multichannel scaler module. The scaler module is free running and operates independently of the data acquisition trigger, and therefore it is not subject to the acquisition dead time. It has been previously tested up to 100 MHz without loss of events. However, for typical experiments the absolute count rate is preferably restricted to about 10 kHz at the beginning of the decay counting period by applying beam rate reductions as needed (the beam intensity can be controlled by a series of attenuators in the beam line). This scaler module has been used recently to perform high-precision measurements of the ^{19}Ne half-life to a precision of $\pm 0.03\%$ [6] and the ^{21}Na half-life to a precision of $\pm 0.04\%$ [9]. The latter experiment was performed using experimental conditions similar to those described below. Under these conditions, pile-up and dead-time losses are assumed to be negligible. The uncorrected (raw) experimental data are fit directly to obtain the half-life. Further information about the SPIRAL facility, the low-energy identification station and tape transport system, and associated electronics are described in detail in Ref. [12].

III. HALF-LIFE OF ^{17}F

Prior to this work, the world average half-life of ^{17}F was 64.61(17) s with a χ^2/ν of 8.2 [5]. This average was dominated by two measurements from nearly 40 years ago that were not in agreement at the level of more than 4 standard deviations [13,14]. The uncertainty in the ^{17}F ft value is thus dominated by the uncertainty in the half-life. Given the absence of uncertainty in the 100% branching ratio, a new high-precision measurement of the half-life will significantly improve the overall uncertainty in the ft value.

The ^{17}F beam was delivered at $A = 26$ as a molecular ^{9}Be $^{17}F^{1+}$ beam with an average intensity of 1×10^6 molecules/s. Prior to performing the half-life measurement, a search for possible isobaric contaminants was performed by implanting the $A = 26$ beam continuously for 15 min in the collection chamber and recording the decay of this collected sample for an additional 15 min. From the γ-ray energy spectrum obtained from the HPGe located at the implantation site, as well as the time dependence of the 511-keV γ-ray activity, isobaric contaminants of ^{26}Na ($T_{1/2} = 1.071\,28\,(25)$ s [15]) and ^{26m}Al ($T_{1/2} = 6.346\,54\,(76)$ s [16]), were observed with average intensities of 1×10^6 and 1×10^5 ions/s, respectively. Because both of these decays are significantly shorter lived than the decay of interest, and because their half-lives are extremely well known, their presence does not pose any significant difficulties for the ^{17}F half-life determination.

Although the γ-ray spectra collected by the HPGe detector at the implantation site did not show any evidence for any additional isobaric contaminants, our analysis was particularly concerned by the possibility that there could be trace amounts of ^{14}O because its half-life, $T_{1/2} = 70.619\,(11)$ s [17], is very similar to that of ^{17}F. Delivery of ^{14}O as a carbon-monoxide (CO) molecular beam at $A = 26$ has been previously observed at SPIRAL with intensities on the order of 10^3 molecules/s [12]. From the γ-ray spectra collected in the present experiment, we did not see the strong γ-ray transition at 2.3 MeV that follows ~99.4% of ^{14}O decays [1]. From the nonobservation of this γ ray, and with the measured HPGe detection efficiency at this energy, an upper limit of $<3.2 \times 10^3$ molecules/s at 95% confidence was established for the $^{12}C\,^{14}O^{+}$ beam intensity. The possible presence of ^{14}O and how this could affect the ^{17}F half-life determination are described below.

Following the yield measurements, data dedicated to the ^{17}F half-life determination were collected in cycles that consisted of a 10-s background collection period, followed by 2 s of beam implantation on tape, 3 s of tape movement from the implantation site to the measurement site in front of the scintillator, a 1300- to 1620-s decay counting period (greater than 20 ^{17}F half-lives and varied on a run-by-run basis), and 5 s of tape movement to remove any remaining residual activity away from the measurement site before the start of the next cycle. A total of 12 cycles were collected. The maximum initial counting rate in the scintillator was 5×10^3/s.

Because the decay counting period time settings varied from 1300 to 1620 s throughout the experiment, it was not possible to sum all of the cycles to obtain a single decay curve. Instead, the half-life of ^{17}F was determined by fitting the decay curve obtained from each cycle and taking their

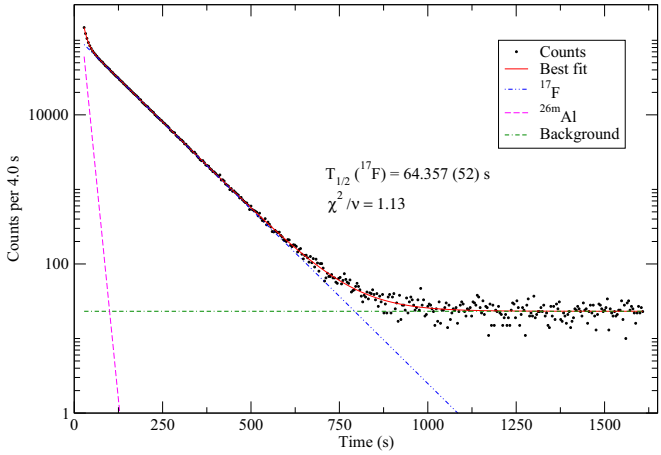

FIG. 1. (Color online) Typical decay curve of ^{17}F for one run (four cycles) with the fit result shown. The fast-decaying component from the decay of ^{26m}Al can be clearly seen.

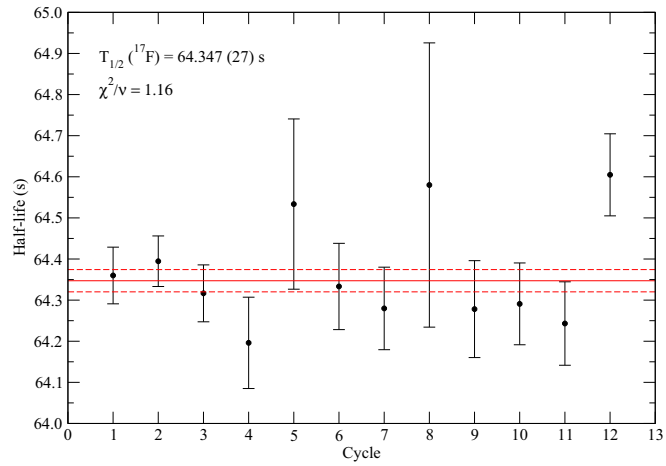

FIG. 2. (Color online) The half-life of ^{17}F determined from the cycle-by-cycle analysis.

weighted average. The fits were performed using the modified Levenberg-Marquardt χ^2 minimization method described in previous publications [15,18]. The start of the fit to the decay curve began at least 1 s after the tape motor was stopped to avoid any possible effects that may have arisen from the tape movement or the possibility that the tape was not at a complete stop in front of the scintillator at the end of its 3 s move.

Because the half-life of ^{26}Na is more than 60 times smaller (1.071 28 s) than the ^{17}F half-life, a significant portion decays during the 3 s of tape movement. To safely ignore the contribution of ^{26}Na, the fit to the decay curve was started sufficiently later, at least 16 s after the end of the sample implantation period. The decay component of ^{26m}Al was included in the fit to determine the half-life of ^{17}F due to its longer half-life of 6.346 54 s; therefore the fit function consisted of two exponentials (^{17}F and ^{26m}Al decays) plus a constant background with five total parameters: the intensity and half-life of ^{17}F, the intensity and half-life of ^{26m}Al, and a constant for the background. All parameters were free with the exception of the half-life of ^{26m}Al that was fixed at 6.346 54 s. The free constant background was constrained by the long decay period (1300 to 1620 s) chosen for the cycles. An example of a decay curve from the sum of four cycles and the resulting fit are presented in Fig. 1. The fast-decay component of ^{26m}Al can be clearly discerned at the start of the decay curve. The ^{17}F half-life deduced for each cycle is plotted in Fig. 2. The weighted average is 64.347(27) s with a reduced χ^2 of 1.16 for 11 degrees of freedom.

The present measurement of ^{17}F can be compared to one performed previously at the SPIRAL identification station as part of a commissioning run [12]. The half-life obtained during this measurement was 65.1(4) s, which agrees reasonably well with the present result but is more than 10 times less precise. The relatively low precision achieved during the commissioning experiment was primarily due to a ^{17}Ne contaminant in the beam at $A = 17$ produced from an electron cyclotron resonance ion source. The ^{17}Ne contaminant decays via a β-delayed α branch to ^{13}N that gives rise to a large β background with a half-life of 9.965 m. Because the present measurement was performed with a ^{9}Be^{17}F^{1+} molecular beam at $A = 26$, a significantly more precise value could be obtained because the $A = 26$ contaminants (^{26}Na and ^{26m}Al) are much shorter-lived than the ^{17}F decay of interest. The improved half-life of ^{17}F presented in this work therefore supersedes the previous result of Ref. [12].

Systematic uncertainties

Rate-dependent effects are potentially the most important source of systematic uncertainty and were searched for by removing successive leading channels (high-rate data) from the decay curve of each run. The data were refit using the same conditions described above to obtain a value of the ^{17}F half-life as a function of the initial counting rate. An example of the results of this analysis for one run (four cycles) is shown in Fig. 3. For comparison, this figure also shows the effect of ignoring the ^{26m}Al decay in the fit and demonstrates that after the removal of 15 channels (60 s or 9 ^{26m}Al half-lives) the contribution of ^{26m}Al could in principle be neglected. For comparison, the half-life of ^{17}F is 64.357(52) s when no channels are removed from the raw data and the ^{26m}Al component is included in the fit, and is 64.392(65) s after the removal of 15 channels and the contribution of ^{26m}Al is not included in the fit. As shown in Fig. 3, the removal of leading channels from the fit does not indicate any significant losses associated with the counting rate (such as dead time or pile up) or evidence of any additional contaminants.

The impact on the ^{17}F half-life from possible trace amounts of ^{14}O in the beam was investigated by adding an additional decay component to the fit function with a half-life fixed at 70.616 s [17] and with the beam intensity fixed at the upper limit of $<3.2 \times 10^3$ ions/s at 95% confidence as described above. Because the beam was turned on for only 2 s, this beam intensity corresponds to <15 counts/s in the plastic scintillator at the start of the decay cycle, which can be compared to 5×10^3 counts/s for ^{17}F decays. The average ^{17}F half-life derived from the 12 cycles when ^{14}O was included in the fit

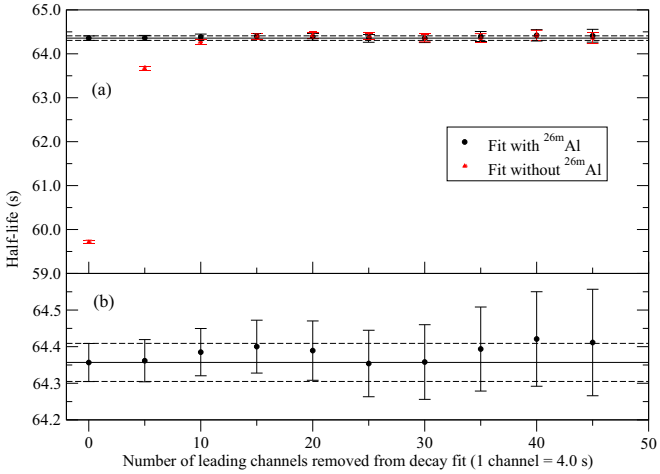

FIG. 3. (Color online) (a) Example of the effect of channel removal with and without including ^{26m}Al in the fit for one run (four cycles). The half-life and uncertainty when no channels are removed are shown as a guide to the eye. After the removal of 15 channels (60 s), the contribution of the ^{26m}Al half-life on the fit result is negligible. (b) Enlarged view of the effect of channel removal from the fit (with ^{26m}Al).

function was 64.366(27) s. The 0.019 s difference between this result and the value of 64.347(27) s when ^{14}O was not included in the fit is thus adopted as the maximum systematic uncertainty associated with the possibility that small amounts of ^{14}O may be present in the beam.

The effect of the uncertainty in the ^{26m}Al half-life on the ^{17}F half-life result was also investigated. The cycle-by-cycle decay curves were refit with the half-life of ^{26m}Al fixed at its minimum and maximum value (6.346 54(76) s [16]). The results show that the half-life uncertainty in ^{26m}Al contributes an uncertainty of ± 0.0002 s to the ^{17}F half-life and therefore can be considered negligible.

The methodology of the Particle Data Group was followed [19] to conservatively estimate an additional systematic uncertainty because there was no clear evidence of rate-dependent or other systematic effects based on the analysis described above. Following this method, the statistical uncertainty of the half-life of 0.027 s was multiplied by the square root of the largest χ^2/ν of 1.16 from the cycle-by-cycle analysis to obtain the total uncertainty of 0.029 s. Assuming that this uncertainty is independent of the statistical uncertainty, this yields an additional systematic uncertainty of ± 0.011 s.

A summary of all uncertainties associated with the ^{17}F measurement is presented in Table I. The final result for the

TABLE I. Uncertainties in the ^{17}F half-life measurement (see text for details).

Source	Uncertainty (s)
Statistical	0.027
Cycle analysis ($\chi^2/\nu = 1.16$)	0.011
Upper limit ^{14}O contaminant	0.019
Uncertainty in ^{26m}Al half-life	0.0002
Total (added in quadrature)	0.035

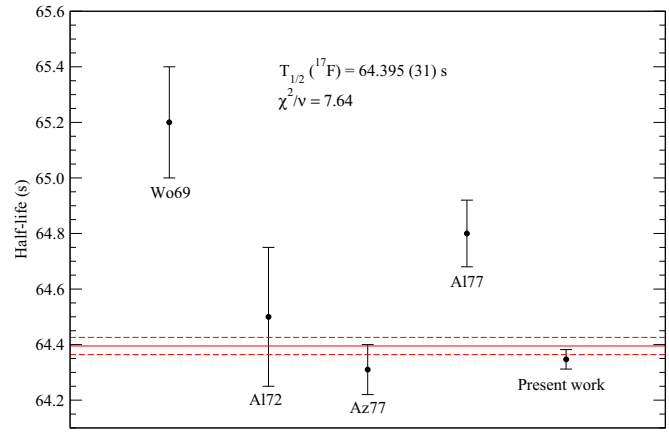

FIG. 4. (Color online) A summary of all ^{17}F half-life measurements performed to date. References to previous measurements are Wo69 [20], Al72 [21], Az77 [13], and Al77 [14]. The new world average is 64.395(31) s with a χ^2/ν of 7.64 for 4 degrees of freedom.

^{17}F half-life can be written as

$$T_{1/2} = 64.347(35)\ \text{s}, \tag{1}$$

representing a value that is a factor of 5 times more precise than the previous world average reported in Ref. [5]. The new world average including the result from the present work is $T_{1/2} = 64.395(31)$ s with a $\chi^2/\nu = 7.64$ for 4 degrees of freedom. Figure 4 shows the summary of all ^{17}F half-life measurements to date. Although the reduced χ^2 value is still rather large at 7.64 (reduced from 8.2 [5]), it is largely dominated by the results of Refs. [14,20]. The half-life from this work agrees with the results reported previously in Refs. [13,22] and differs by 4σ with that of Ref. [14]. Our present result may have solved the discrepancy between the two most precise measurements that previously dominated the world average [13,14] and that has persisted for nearly 40 years. As presented in the discussion below, our deduced half-life of ^{33}Cl is also in good agreement with the ^{33}Cl half-life value from Ref. [13].

IV. HALF-LIFE OF ^{33}Cl

The average half-life of ^{33}Cl is 2.5111(40) s with a reduced χ^2 value of 1.4 [5]. The uncertainty in the half-life ($\pm 0.16\%$) is the leading source of uncertainty in the determination of the ft value for this mirror nucleus.

As with ^{17}F described above, ^{33}Cl was also delivered to the decay station as a molecular beam of ^{9}Be^{33}Cl^{1+} at $A = 42$ with an average intensity of 1×10^5 molecules/s. Based on the γ-ray spectra collected from long implantation runs collected immediately before the half-life measurements, the long-lived ($T_{1/2} = 12.360$ h) contaminant ^{42}K^{1+} was observed with an average intensity of 6×10^3 ions/s. Because $A = 42$ isobars cannot have been produced from the fragmentation of the ^{36}Ar primary beam on the graphite production target, this contaminant is likely produced on the thin Ta entrance window of the ion source itself. There was no evidence for any additional contaminants.

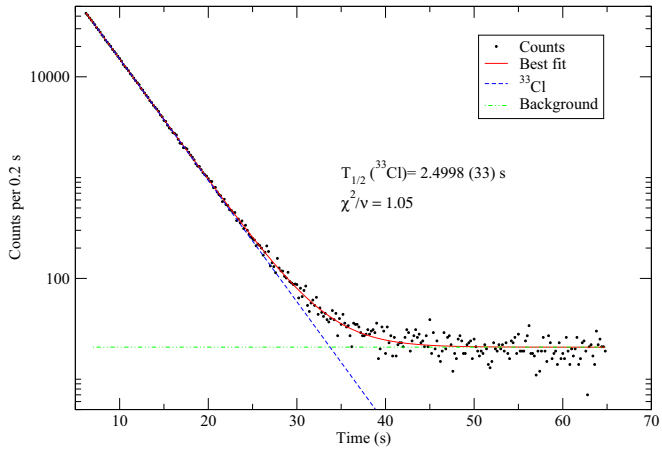

FIG. 5. (Color online) Typical decay curve of ^{33}Cl for one run (28 cycles) with the fit result shown.

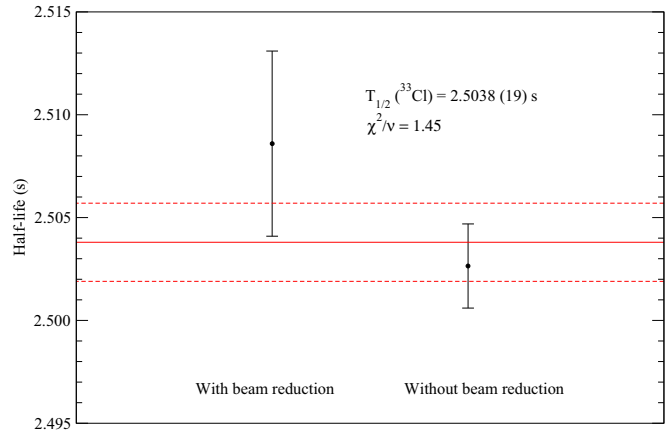

FIG. 6. (Color online) Half-life of ^{33}Cl with and without the factor of 10 beam reduction. Each data point corresponds to the average of two experimental runs.

Cycles for the ^{33}Cl measurement consisted of a 1-s-long background collection period, an implantation period that ranged between 2 and 8 s, 3 s of tape movement, a decay counting period of 40 to 60 s, and 5 s of tape movement. A total of four runs containing 144 cycles were collected during the experiment. The initial scintillator counting rate was varied between 2×10^4 and 2×10^5 Hz. A factor of 10 beam reduction was applied for the first half of the ^{33}Cl measurement to reduce the initial counting rate to approximately 10 kHz, the nominal operating rate for the decay station.

The ^{33}Cl half-life was obtained from the four runs collected during the experiment by fitting each decay curve with a three-parameter single-exponential decay curve fit. All three parameters (intensity and half-life of ^{33}Cl, background) in the fit function were free including the constant background that was well constrained given the sufficient length of the decay period of 40 to 60 s that was chosen (approximately 16 to 24 half-lives of ^{33}Cl). The half-life of ^{42}K was considered to be sufficiently long compared to that of ^{33}Cl so that on the time scale of our measurement it could be approximated as a constant and included as part of the free background parameter. An example of a typical decay curve and the resulting fit are shown in Fig 5. The weighted average ^{33}Cl half-life obtained from the four experimental runs is 2.5038(19) s with a χ^2/ν of 0.93 for 3 degrees of freedom. Grouping each of these runs according to whether or not the factor of 10 reduction in beam intensity was applied (two runs each) is shown in Fig. 6. The average ^{33}Cl half-life is identical to that of the run-by-run analysis with the reduced χ^2 value for this comparison being 1.45 for 1 degree of freedom.

Systematic uncertainties

Several tests were performed to identify possible rate-dependent systematic effects that could have biased the half-life result. First, an increasing number of leading channels was removed from the start of the fit for each of the four runs, and the decay curve was refit with the same function described above. An example of a leading-channel removal plot for one of the runs is shown in Fig. 7. It shows no obvious deviation from the half-life value before the removal of high-rate data at the start of the decay curve.

A cycle-by-cycle analysis was also carried out to determine the half-life for each of the 144 cycles. The decay curve from each cycle was fit using the three-parameter fit function employed in the analysis above. The 144 results from each cycle were averaged to obtain $T_{1/2} = 2.5032(19)$ s with a χ^2/ν of 1.01 (Fig. 8). The statistical precision is lowest for the first two runs for which the beam reduction (factor of 10) was applied, but no obvious systematic effects on any particular data subset can be discerned at this level of precision.

The effect of the counting rate was considered as an additional potential source of systematic uncertainty. The runs were grouped by beam reduction factor and the half-life was calculated for each data subset (Fig. 6). The half-life was determined to be 2.5086(45) s with the factor of 10 beam reduction (maximum scintillator rate of 10 kHz) and 2.5026(20) s without reduction in beam intensity (maximum scintillator rate of 100 kHz). The weighted average half-life

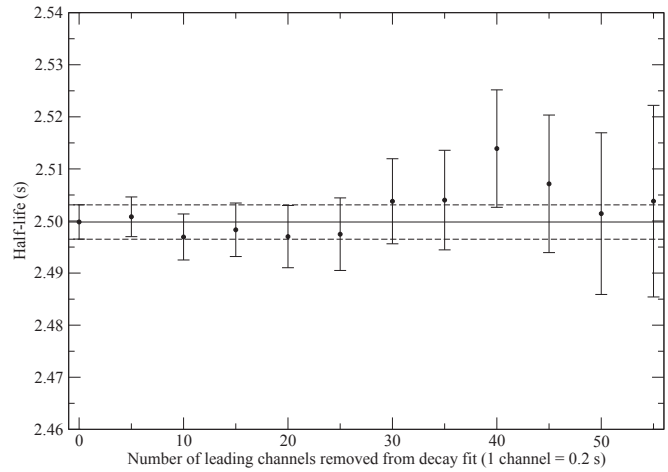

FIG. 7. Effect of the removal of an increasing number of leading channels on the ^{33}Cl half-life (one channel = 0.2 s) for one of the runs. The average ^{33}Cl half-life and statistical uncertainty are shown to guide the eye.

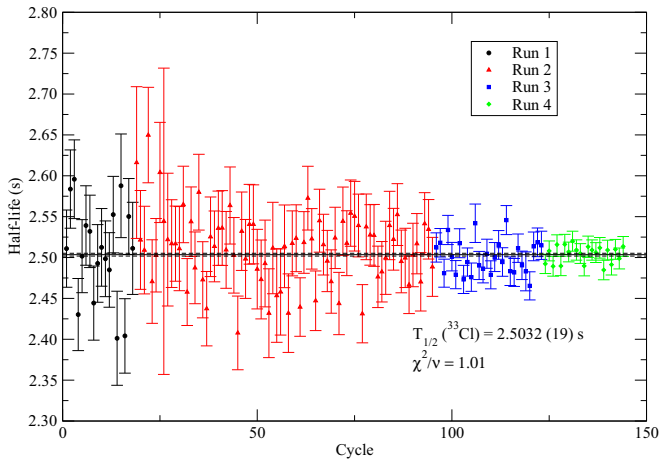

FIG. 8. (Color online) The half-life of ^{33}Cl determined from the cycle-by-cycle analysis. Runs 1 and 2 were collected with a factor of 10 beam reduction, and Runs 3 and 4 were collected without a beam reduction (see Fig. 6).

result from this analysis was 2.5038(19) s with a reduced χ^2 value of 1.45. There is no significant difference in the half-life with the initial scintillator counting rate at this level of precision. In fact, the half-life was expected to be higher if events were lost due to initial high rates requiring a dead time correction, and not slightly lower as was observed here.

As mentioned above, the contaminant ^{42}K was present in the beam with an average intensity of 6.5×10^3 ions/s, which represented less than 1.5% of the total background rate. Due to its very long half-life (12.360 h) compared to the half-life of ^{33}Cl, the decay component of ^{42}K was assumed in the above analysis to be a constant during the decay period and was included in the single constant background fit parameter. A simple Monte Carlo simulation was performed to test the validity of this assumption: decay curves of ^{33}Cl were simulated with a constant background plus the decay of ^{42}K at varying initial counting rates. Simulated decay curves were then fit with the same procedure used for the experimental decay curves (three-parameter single-exponential fit function). The simulation showed that even at initial ^{42}K beam intensities of 10^6 ions/s (3 orders of magnitude higher than the actual intensity), the ^{33}Cl half-life result was not influenced by the ^{42}K decay at the level of precision of the measurement (less than 0.1%). Based on the measured ^{42}K intensity, we determined that this assumption to include ^{42}K decay as part of the constant background would lead to a bias of no more than 10^{-6} s (Table II) on the ^{33}Cl half-life.

TABLE II. Uncertainties in the ^{33}Cl half-life measurement (see text for details).

Source	Uncertainty (s)
Statistical	0.0019
Initial count rate ($\chi^2/\nu = 1.45$)	0.0012
Background (^{42}K contaminant)	$<10^{-6}$
Total (added in quadrature)	0.0022

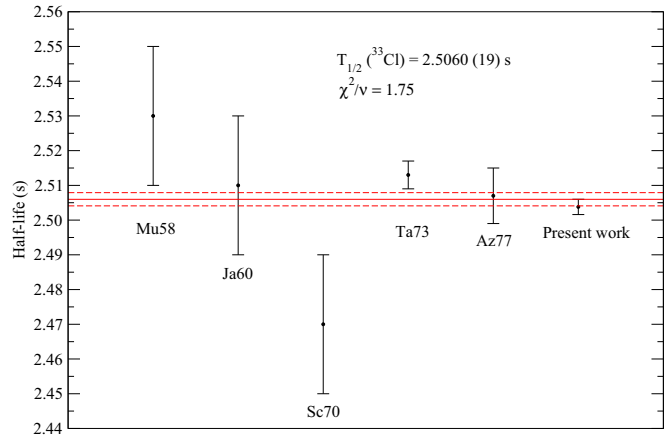

FIG. 9. (Color online) Summary of all ^{33}Cl half-life measurements performed to date. References to previous measurements are Mu58 [23], Ja60 [21], Ta73 [24], and Az77 [13]. The weighted average of all results is 2.5060(19) s with a χ^2/ν of 1.75 for 5 degrees of freedom.

The above analysis did not indicate the presence of any additional sources of rate-dependent systematic effects that could have had a significant impact on the value of the ^{33}Cl half-life deduced from these data. The methodology of the Particle Data Group [19] was again followed to provide a conservative estimate for any remaining sources of systematic uncertainty. The statistical uncertainty of the average half-life ±0.0019 s (Fig. 6) was multiplied by the square root of the largest χ^2/ν value of 1.45 (when the data were grouped by initial rate, before and after a factor of 10 beam reduction) to give a total uncertainty of ±0.0022 s (Table II). The final ^{33}Cl half-life obtained from this work is

$$T_{1/2} = 2.5038(22)\ \text{s}, \tag{2}$$

and represents a result that is about 2 times more precise than the previous average from Ref. [5]. A summary of all ^{33}Cl half-life results to date is shown in Fig. 9. The new world average is $T_{1/2} = 2.5060(19)$ s with a χ^2/ν of 1.75 for 5 degrees of freedom. Our present result for the ^{33}Cl half-life, as in the case of ^{17}F described above, is in excellent agreement with the half-life measurements of Ref. [13].

V. SUMMARY AND CONCLUSION

High-precision half-life measurements were performed for two $T = 1/2$ mirror nuclei, ^{17}F and ^{33}Cl, at the SPIRAL low-energy identification station and tape transport system. The precision in the half-life value of ^{17}F was improved by a factor of 5 to yield a result of 64.347(35) s, representing a precision of ±0.05%. The uncertainty in the half-life of ^{33}Cl was reduced by nearly a factor of 2 compared to the average of all previous measurements to yield a result of 2.5038(22) s, precise to ±0.09%. In both cases, the uncertainty in the half-life was the largest source of uncertainty in the calculation of the $\mathcal{F}t$ value to date, and the present measurement has reduced the half-life contribution to the $\mathcal{F}t$ error budget to less than 1 part in 1000. The present status of the uncertainties of the quantities that contribute to the $\mathcal{F}t$ values for ^{17}F and ^{33}Cl is

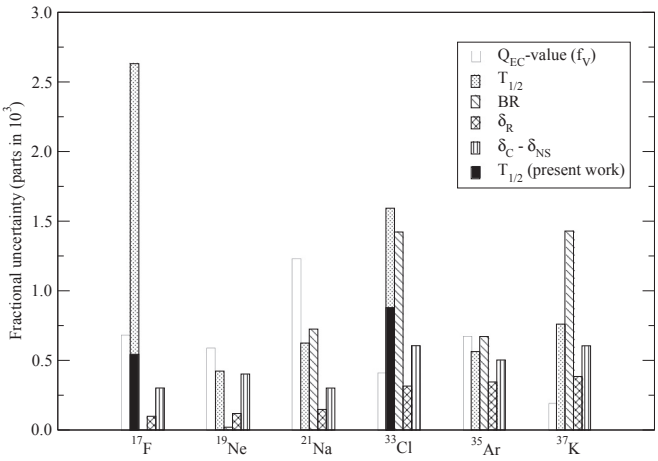

FIG. 10. Fractional uncertainties of the experimental and theoretical quantities required to calculate the $\mathcal{F}t$ value for $T = 1/2$ mirror decays. The improvement in $T_{1/2}$ precision of ^{17}F and ^{33}Cl shown from the present measurement means its uncertainty no longer dominates the uncertainty in $\mathcal{F}t$ for these nuclei. Other well-known mirror transitions, ^{19}Ne, ^{21}Na, ^{35}Ar, and ^{37}K, are shown for comparison. All values in the plot are adopted from Ref. [5], except for ^{19}Ne, ^{21}Na, and ^{37}K for which recent $T_{1/2}$ measurements have been performed [6–10] and their results are included in the plot.

shown in Fig. 10. The error budgets of the $\mathcal{F}t$ values for ^{19}Ne, ^{21}Na, ^{35}Ar, and ^{37}K, the other most precisely known $T = 1/2$ mirror decays, are shown for comparison.

Because the branching ratio of ^{17}F is 100%, the present factor of 5 improvement in the half-life precision means that it is now the second most precisely determined mirror decay in terms of the ft and $\mathcal{F}t$ values. To date, only one measurement of the β asymmetry parameter for ^{17}F has been performed [25]; however, the resulting uncertainty in ρ is too large for ^{17}F to be included in the calculation of $\mathcal{F}t_0$ and V_{ud} for mirror decays [4]. Because the half-life uncertainty no longer dominates the error budget of $\mathcal{F}t$ for ^{17}F and ^{33}Cl, there is a clear need for improved (and in the case of ^{33}Cl, never performed) measurements of angular-correlation coefficients so that these nuclei can be included in the $\mathcal{F}t_0$ determination for mirror transitions for testing the CVC hypothesis and obtaining a more precise value of V_{ud} from $T = 1/2$ nuclear mirror decays.

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