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Half-life of the superallowed β^+ emitter ^{18}Ne

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The half-life of ^{18}Ne has been determined by detecting 1042-keV γ rays in the daughter ^{18}F following the superallowed-Fermi β^+ decay of samples implanted at the center of the $8\pi\gamma$-ray spectrometer, a spherical array of 20 HPGe detectors. Radioactive ^{18}Ne beams were produced on-line, mass-separated, and ionized using an electron-cyclotron-resonance ionization source at the ISAC facility at TRIUMF in Vancouver, Canada. This is the first high-precision half-life measurement of a superallowed Fermi β decay to utilize both a large-scale HPGe spectrometer and the isotope separation on-line technique. The half-life of ^{18}Ne, 1.6656 ± 0.0019 s, deduced following a 1.4σ correction for detector pulse pile-up, is four times more precise than the previous world average. As part of an investigation into potential systematic effects, the half-life of the heavier isotope ^{23}Ne was determined to be 37.11 ± 0.06 s, a factor of 2 improvement over the previous precision.

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I. INTRODUCTION

Precision measurements of the *ft* values for superallowed-Fermi β decays between isobaric analog states provide stringent tests of weak interaction theory and have been the subject of much investigation for several decades (see [1] and references therein). These decays have confirmed the conserved vector current (CVC) hypothesis to better than three parts in 10^4, set limits on the existence of scalar and right-hand currents, and currently provide the most precise value for the up-down matrix element V_{ud} of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1,2]. This precise determination of V_{ud}, together with a recently updated value of V_{us} [3] provide the most demanding test of CKM unitarity, a fundamental tenet of the electroweak standard model. The present value of V_{ud} obtained from the superallowed data is $V_{ud} = 0.97377(11)(15)(19)$ [4], where the uncertainties result from (i) the experimental *ft* values combined with transition-dependent radiative corrections, (ii) a systematic discrepancy associated with two independent calculations of isospin-symmetry-breaking corrections, and (iii) the transition-independent radiative correction. The uncertainty in the latter correction has recently been significantly reduced [4], providing a reduction in the overall uncertainty of V_{ud} by more than a factor of 2. As the uncertainty of the transition-independent radiative correction remains a conservative estimate, a further reduction may be possible which would leave the isospin-symmetry-breaking corrections as the limiting factor in the overall precision of V_{ud}.

In the context of superallowed-Fermi β decay, the breaking of perfect isospin symmetry by charge-dependent forces in the nucleus is usually described by dividing the correction term δ_C into two components, $\delta_C = \delta_{C1} + \delta_{C2}$, where the first term reflects the different configuration mixing in the parent and daughter states, and the second accounts for the imperfect overlap of the radial wave functions arising from differences in the proton and neutron potentials and separation energies. The calculations of the δ_C corrections are obtained with either the model of Towner, Hardy, and Harvey [5,6] which use a shell-model diagonalization with a Woods-Saxon plus Coulomb potential or that of Ormand and Brown which employ a self-consistent Hartree-Fock calculation [7]. These calculations reveal a small, but systematic, difference in the predicted δ_C values used in the determination of V_{ud}, and the theoretical uncertainty associated with this difference outweighs the uncertainties in the experimental data and transition-dependent radiative corrections combined. Recent experimental effort has thus been focused on $T_z = 0$ superallowed emitters such as ^{62}Ga [8–11] and ^{74}Rb [12–14] in the $A \geqslant 62$ region where large δ_C corrections (>1%) are predicted, and on the $T_z = -1$ superallowed decays in the $18 \leqslant A \leqslant 42$ region, where the discrepancy between the δ_C calculations is either enhanced or, as in several cases including ^{18}Ne decay, the Woods-Saxon calculations are anomalously large while the Hartree-Fock calculations are not available.

The measurement of the *ft* values for the decays of $T_z = -1$ nuclei presents a considerable experimental challenge. These nuclei are further from stability than the well-known $T_z = 0$ cases, have unstable daughters, and exhibit multiple Gamow-Teller decay branches. In the decay of ^{18}Ne, the subject of the present work, the superallowed β branching

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ratio to the 0^+ excited state at 1042-keV in the daughter ^{18}F is only 7.69 ± 0.21% [15–17]. Despite the experimental challenges, high-precision measurements of the decays of $T_z = -1$ nuclei ^{22}Mg [18,19] and ^{34}Ar [20] have recently been achieved. In this work, we have determined the half-life of the $T_z = -1$ nucleus ^{18}Ne to a precision of 0.1% using a γ-ray counting technique [21] that records the number of 1042-keV γ-ray photopeaks following the superallowed β-decay branch to the first excited 0^+ state in ^{18}F.

II. EXPERIMENTAL SETUP

A method of measuring precise β-decay half-lives by detecting γ rays using the 8π spectrometer [22–24], an array of 20 Compton-suppressed HPGe detectors at TRIUMF's isotope separator and accelerator (ISAC) radioactive ion-beam facility [25], has been developed and investigated in detail using the β^- decay of ^{26}Na [21,24,26] as a test case. The present work is the first to apply this technique to a superallowed-Fermi β decay. Radioactive beams of ^{18}Ne were produced in collisions of 500-MeV protons from the TRIUMF cyclotron, with intensities of up to 30 μA, on a SiC target. Samples of ^{18}Ne were extracted using ISAC's electron-cyclotron-resonance (ECR) ion source [27] operating in its first experimental run. Following mass separation, a beam of $\sim 4 \times 10^{5}$ ^{18}Ne ions/s was delivered to the 8π spectrometer for approximately 90 h. The 30-keV beam was collected using a mylar-backed aluminum tape, of thickness 40 μm, moving through the mutual center of the 8π spectrometer and the Scintillating Electron-Positron Tagging Array (SCEPTAR), an array of 20 thin plastic (delrin) scintillators. The SCEPTAR array [22,23] is arranged in four pentagonal rings providing a one-to-one match with the HPGe detectors of the 8π spectrometer, and records the electrons and positrons that follow the β decay with approximately 80% efficiency. SCEPTAR, in conjunction with the 8π array, provides a powerful tool to perform β-γ coincidence spectroscopy [10,28] and its use as a β counter for high-precision half-life studies is being investigated. In this work, SCEPTAR was used solely for determining the levels of isobaric contaminants in the $A = 18$ beam of ^{18}F ($T_{1/2} = 109.77(5)$ min [29]), in addition to the ^{18}Ne daughter activity, and molecular H^{17}F ($T_{1/2} = 64.49(16)$ s [30]). Both ^{17}F and ^{18}F β^+ decay do not give rise to γ-ray radiation.

Samples of ^{18}Ne were implanted for 7 s ($\sim$ 4 half-lives) and the subsequent decay was measured for 40 s before the tape was moved and the cycle repeated. The γ-ray singles events were recorded and time-stamped using a precision 10 MHz oscillator during the entire implantation and decay cycle for 15 runs, each lasting several hours. A window was set for each run that rejected any cycle in which the total number of counts fell above or below the maximum and minimum values prescribed, thus eliminating from the analysis anomalous cycles such as those where the primary proton beam had tripped off. The 8π data-acquisition system [21,22] provides a pile-up indicator as well as software-selectable Compton-suppression and variable (measured event by event) or fixed nonextendible dead-times per event. Compton-suppression is not utilized in high-precision half-life determinations with the 8π due to the potential bias from rate-dependent false-vetos (see Ref. [21]). The nonextendible dead-times, as well as the shaping times of the amplifiers and the constant-fraction-discriminator (CFD) thresholds, were varied throughout the experiment in order to investigate possible systematic effects. Data were collected with combinations of three dead-time settings (variable, fixed 27 μs and fixed 40 μs), three HPGe spectroscopy amplifier shaping times (0.5 μs, 1.0 μs and 2.0 μs), and "low" and "high" CFD thresholds.

III. HALF-LIFE OF ^{18}Ne

A. Results

The half-life of ^{18}Ne was determined by selecting events in which the 1042-keV γ ray, which follows the superallowed decay of ^{18}Ne and connects the analog 0^+ state to the 1^+ ground state in the daughter ^{18}F, was detected. Sample γ-ray singles spectra obtained under different experimental conditions are shown in Fig. 1. The upper panel [Fig. 1(a)] was obtained with low CFD thresholds and amplifier shaping times set to 0.5 μs, while the lower panel [Fig. 1(b)] shows the corresponding spectrum with high CFD thresholds

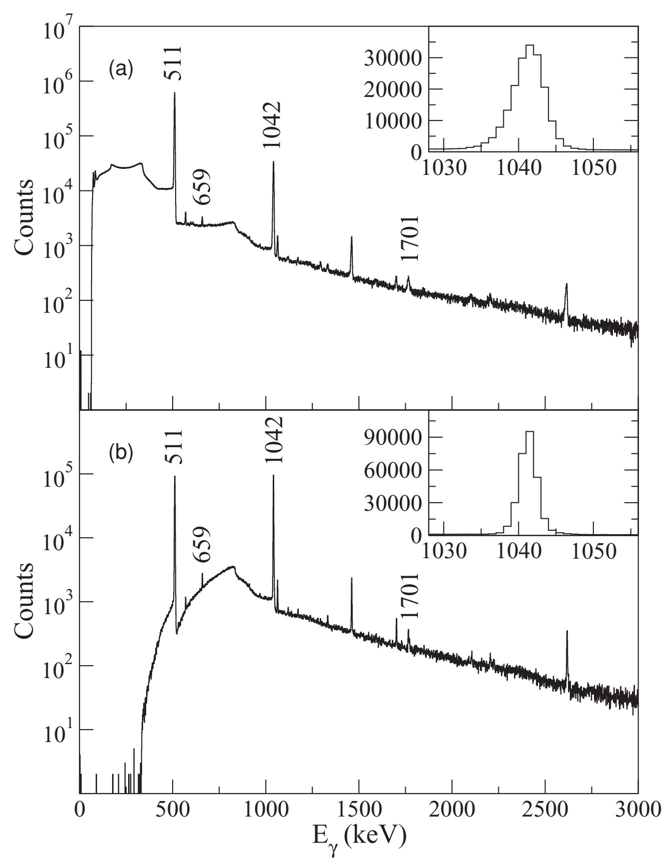

FIG. 1. Singles spectra of γ rays following the β decay of ^{18}Ne with (a) low CFD thresholds and 0.5 μs HPGe shaping times and (b) high CFD thresholds and 2 μs shaping times. Transitions between states in ^{18}F are labeled with their energy in keV. The insets show the region around the 1042-keV gating transition on a linear scale.

and 2.0 μs shaping times, illustrating the improvement in energy resolution.

Decay curves associated with the 1042-keV γ ray were dead-time corrected on a cycle-by-cycle basis using the procedure outlined in Refs. [21,31]. The nonextendible dead-time values of variable ($\sim$25 μs), fixed 27 μs, and fixed 40 μs were determined on an event-by-event basis by the individual event time-stamping information provided by a Stanford Research Systems high-precision 10 MHz $\pm$ 0.1 Hz oscillator. The dead-time values deduced by this method have been confirmed in previous studies via comparison with the source-plus-pulser technique [32]. In this experiment, the dead-time corrections were 10–40% at the start of the decay curves for the variable ($\sim$25 μs)-40 μs dead-time settings, respectively. Following the dead-time corrections the cycle-by-cycle decay-curve data were summed and fit using a maximum-likelihood χ^2-minimization technique that has been described in previous work [21,26,31]. A typical grow-in and decay curve from a single run, and the corresponding fit to the data is shown in Fig. 2 and includes corrections for dead-time and pulse pile-up effects using the method of Ref. [21]. The half-life obtained for each of the 15 experimental runs are plotted in Fig. 3 where the weighted average of these 15 values yield $T_{1/2} = 1.6656 \pm 0.0017$(stat.) s and a reduced χ^2 value of 0.55.

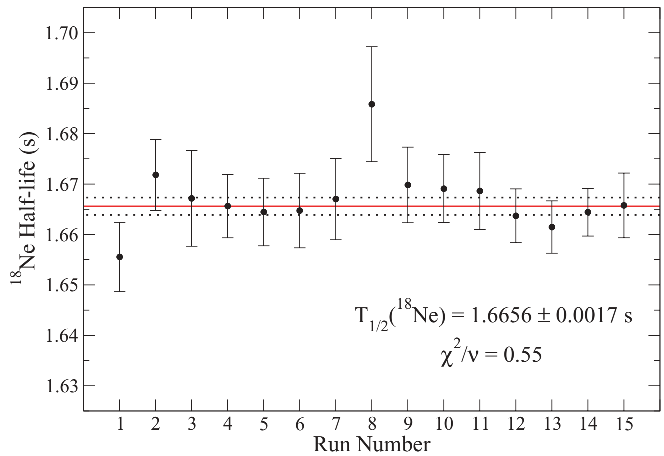

FIG. 3. (Color online) Half-life of ^{18}Ne versus individual run number. The weighted average of all 15 runs and its statistical error are displayed as horizontal solid and dotted lines, respectively.

B. Systematic uncertainties

Grouping each of the runs according to their common electronic setting (shown in Fig. 4) yields reduced χ^2 values of 1.30, 0.04, and 0.05 when combined according to the three shaping times, three dead-times, and two CFD threshold settings, respectively. Following the method of the Particle Data Group [3] we retain the largest χ^2 value of 1.30 as an estimate for any unidentified systematic effects and inflate our statistical error by the square root of this value. We therefore report a systematic uncertainty of $\pm$0.0009 s(syst.) so that when added in quadrature with the statistical uncertainty of $\pm$0.0017 s yields the total uncertainty of $\pm$0.0019 s.

The overall pile-up correction in this measurement amounted to a reduction in the deduced ^{18}Ne half-life by $\sim$1.4σ from a value $T_{1/2} = 1.6679 \pm 0.0016$(stat.) s that was obtained when the pile-up correction was not applied to the data. This correction is small compared with the pile-up corrections that have been successfully applied in our earlier studies with the 8π spectrometer, in which a 1.0% (equivalent to $\sim$30σ) pile-up correction in a $\pm$0.05% measurement for ^{26}Na was confirmed through a comparison with traditional β counting techniques [21]. From the ^{26}Na analysis, a systematic uncertainty in the application of the pile-up correction of 4% was assigned [21]. For ^{18}Ne this amounts to $\pm$0.05σ or $\pm$0.00009 s. The half-life of ^{18}Ne deduced in this work is therefore $T_{1/2} = 1.6656(17)(9)(1)$ s, where the uncertainties are statistical, an estimated systematic effect due to the electronic settings, and an estimated systematic effect resulting from the pile-up correction, respectively.

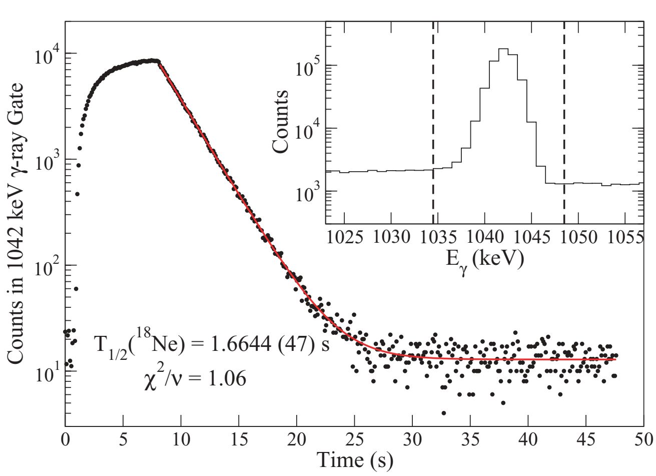

FIG. 2. (Color online) Typical grow-in and decay curve for ^{18}Ne (including corrections for dead-time and pile-up effects) following a γ-ray gate on the 1042-keV transition in the daughter ^{18}F.

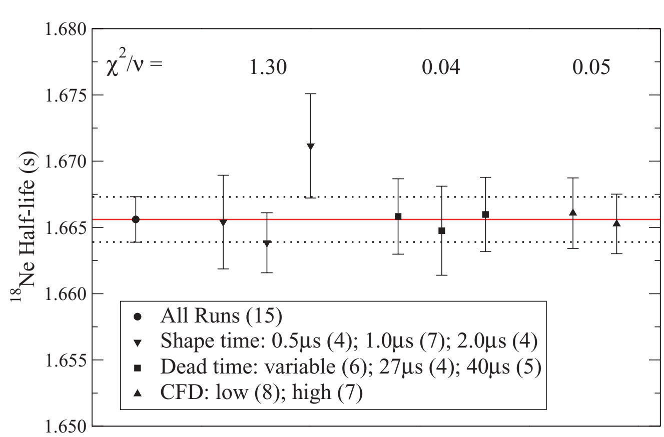

FIG. 4. (Color online) Half-life measurements of ^{18}Ne sorted by adjustable electronic setting. The reduced χ^2 values for each group are displayed at the the top and the number of runs that were combined into each particular group are indicated in the brackets.

1. Contaminants

While neither ^{18}F nor ^{17}F β decay give rise to γ radiation, bremsstrahlung from ^{18}F or ^{17}F β^+ particles, inner bremsstrahlung from the electron capture process, and in-flight annihilation processes may produce a small time-dependent background beneath the 1042-keV gating transition. Because the fractions of the total measured β activity from SCEPTAR at the start of the decay curve from ^{18}F and ^{17}F β decay were only 0.3% and 0.4%, respectively [33], it was expected that these processes would yield negligible contamination at 1042 keV in the γ-ray activity. In order to provide an estimate of these contaminant levels we consider only the bremsstrahlung from the β^+ particles, the dominant process at 1042 keV. Based on the Q_{EC} values of 1655 [29] and 2761 keV [30] for ^{18}F and ^{17}F respectively, only the latter could give rise to contamination at 1042 keV. The ratio of the expected bremsstrahlung yields of ^{17}F to ^{18}Ne ($Q_{EC} = 4446$ keV [29]) β particles in delrin at 1042 keV were calculated and led to a conservative upper limit of 10% that of the observed total ratio of 0.4% that was deduced from the β activity with SCEPTAR. Combined with a measurement of the observed bremsstrahlung yield of ^{18}Ne, obtained from taking a γ-ray gate directly above the 1042-keV photopeak, an upper limit for the ^{17}F bremsstrahlung intensity in the 1042-keV γ-ray gate was deduced for each run. For the data shown in Fig. 2 this upper limit is only $\leqslant 0.6$ counts per second at the start of the decay. The data for each run were refit using a function containing the exponential decays of ^{18}Ne and ^{17}F plus a constant background with the ^{17}F half-life fixed at $T_{1/2}(^{17}\mathrm{F}) = 64.49$ s, and the ^{17}F intensity fixed at the deduced upper limit for each run. The half-life of ^{18}Ne obtained via this procedure, $T_{1/2} = 1.6656 \pm 0.0017$(stat.) s, is identical to that above where no contamination from ^{17}F was considered. Bremsstrahlung contamination from ^{17}F β decay is therefore negligible. Inner bremsstrahlung and in-flight annihilation are expected to contribute at even lower levels than the 0.04% deduced from a calculation of the outer bremsstrahlung, however, we have also considered this possibility by performing an additional fit to the data that treated the ^{17}F intensity as a free parameter. From this analysis the ^{18}Ne half-life was unchanged and the ^{17}F intensities deduced were consistent with zero, but with large uncertainties, due to a large covariance between the ^{17}F intensity and the constant background rate. For ^{18}F, outer bremsstrahlung is not possible at 1042 keV thus any contamination could only come from annihilation in-flight or inner bremsstrahlung processes. The data were also fit using a free ^{18}F intensity (and included the grow-in from ^{18}Ne decay) which also had no effect on the half-life of ^{18}Ne presented here.

To test for unknown rate-dependent systematic effects, the data from the first three seconds (~2 half-lives or 75% of the data) after the beam was switched off were eliminated from the data set channel-by-channel and re-fit using the function described above that assumed a negligible contribution from ^{17}F. The results are plotted in Fig. 5 where no evidence for a change in the half-life, and hence the presence of rate-dependent systematic effects, were detected.

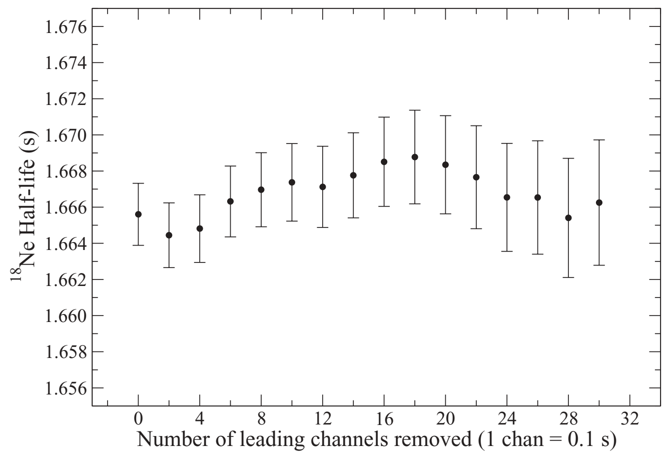

FIG. 5. Deduced half-life of ^{18}Ne versus the number of leading channels removed (one channel = 100 ms). These data are not randomly scattered about the mean because they are highly-correlated, with each data point containing all of the data to the right of it.

2. Diffusion and the half-life of ^{23}Ne

Another potential systematic effect in the study of half-lives of implanted noble-gas isotopes using the techniques described here is associated with their potential diffusion from the implantation site that would systematically bias the deduced half-life to a smaller value. It has been observed [34] that for noble-gas ions implanted into Al, approximately 10% of the implanted ions diffuse out with diffusion "half-lives" of <100 ms. Short-lived diffusion effects for a portion of the ^{18}Ne atoms in this experiment have already been shown to be less than the statistical error in our experiment from Fig. 5 where a systematic increase in the deduced ^{18}Ne half-life as channels are removed from the start of the decay curve was not observed. To test whether diffusion effects could be present on longer time scales (>1 s), the half-life of the longer-lived ^{23}Ne was determined using the same experimental

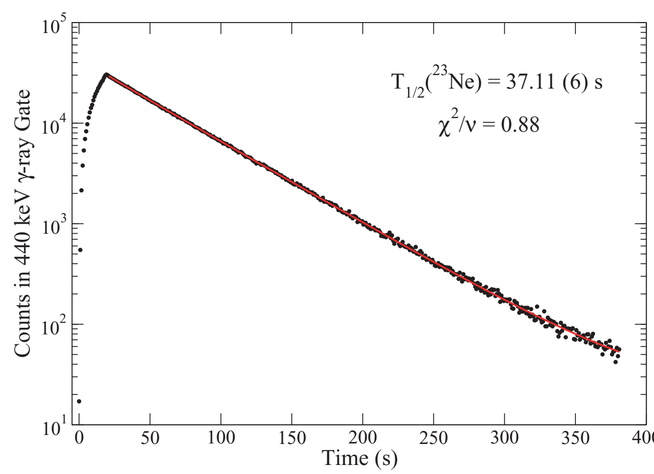

FIG. 6. (Color online) Grow-in and decay curve for ^{23}Ne obtained from a gate on the 440-keV transition in the daughter ^{23}Na including corrections for pile-up and dead-time effects.

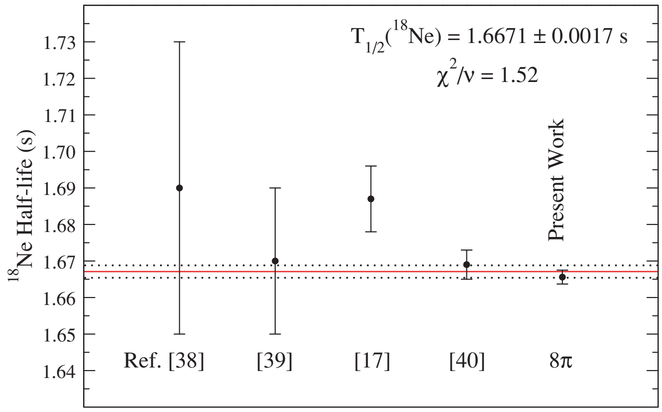

FIG. 7. (Color online) Comparison of previous ^{18}Ne half-life measurements with the current result. The new world average obtained from a weighted average of these five results, $T_{1/2} = 1.6671 \pm 0.0017$ s, is overlayed for comparison.

set-up employed in the ^{18}Ne measurement. The $A = 23$ beam was cycled with an 18.6 s implant and 400.0 s decay for 20 cycles. The resulting grow-in and decay curve obtained following a gate on the 440-keV γ ray in the ^{23}Na daughter, is presented in Fig. 6. These data were fit using a two-exponential function with one of the exponentials having a fixed half-life corresponding to that of ^{23}Mg, $T_{1/2}(^{23}\mathrm{Mg}) = 11.317(11)$ s [35,36], an isobaric contaminant in the beam. Following corrections for dead-time and pile-up effects, the half-life of ^{23}Ne was determined to be $T_{1/2} = 37.11 \pm 0.06$ s and was not affected when we varied the ^{23}Mg half-life between its $\pm 1\sigma$ limits. This result is a factor of 2 more precise than, and consistent with, a previous measurement of the ^{23}Ne half-life that obtained $T_{1/2} = 37.24 \pm 0.12$ s [37] by trapping the noble gas ions in a stainless steel counting cell and was therefore free of diffusion effects. When channels were systematically removed from the beginning of the data set (as described above for ^{18}Ne), no evidence for a change in half-life was observed and we conclude that diffusion at these time scales can be considered negligible for implanted ^{23}Ne, and therefore ^{18}Ne, ions.

C. Comparison to previous results

Treating the statistical, electronic systematic, and pile-up systematic uncertainties as independent, we combine these in quadrature to obtain the half-life of ^{18}Ne, $T_{1/2} = 1.6656 \pm 0.0019$ s. A comparison of the present work with the results of four previous measurements [17,38–40] is presented in Fig. 7. Our measurement agrees with three of the four previous half-life determinations and is four times more precise than the previously-accepted value $T_{1/2} = 1.672 \pm 0.008$ s [15,29] that was comprised of two measurements [17,40] that do not agree within experimental uncertainty. The new world average, obtained from averaging all measurements, is $T_{1/2} = 1.6671 \pm 0.0017$ s with a reduced χ^2 value of 1.52 and is overlayed with the five experimental measurements in Fig. 7.

IV. CONCLUSION

We have determined the half-life of the superallowed-Fermi β^+ emitter ^{18}Ne to be $T_{1/2} = 1.6656 \pm 0.0019$ s, representing an improvement in precision by a factor of 4 over the previously adopted world average. This result is the first high-precision superallowed half-life measurement determined via γ-ray counting with the 8π spectrometer at ISAC and includes a 1.4σ correction from a newly developed technique to correct for detector pulse pile-up effects.

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