Improved half-life determination and \(\beta\)-delayed \(\gamma\)-ray spectroscopy for \(^{18}\text{Ne}\) decay

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The half-life of the superallowed Fermi \(\beta^+\) emitter \(^{18}\text{Ne}\) has been determined to \(\pm 0.07\%\) precision by counting 1042 keV delayed \(\gamma\) rays that follow approximately 8% of all \(\beta\) decays. The deduced half-life, \(T_{1/2} = 1.6648 (11)\) s, includes a 0.7% correction that accounts for systematic losses associated with rate-dependent detector pulse pileup that was determined using a recently developed \(\gamma\)-ray photopeak-counting technique. This result is a factor of two times more precise than, and in excellent agreement with, a previous lower-statistics measurement that employed the same experimental setup. High-resolution \(\beta\)-delayed \(\gamma\)-ray spectroscopy results for the relative \(\gamma\)-ray intensities and \(\beta\)-decay branching ratios to excited states in the daughter \(^{18}\text{F}\) are also presented.

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I. INTRODUCTION

High-precision measurements of the \(fT\) values for superallowed Fermi \(\beta\) decays between \(0^+\) isobaric analog states provide fundamental tests of the standard model description of electroweak interactions. Following the application of small corrections for radiative effects and isospin-symmetry breaking, the resulting \(fT\) values set strict limits on the validity of the conserved-vector-current (CVC) hypothesis, constrain the possibility for the existence of physics beyond the standard model, and provide the most precise value for \(V_{ud}\), the up-down element of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. Due to the high precision achieved experimentally, particular attention has recently focused on the theoretical nuclear-structure-dependent corrections that account for isospin-symmetry breaking by Coulomb and charge-dependent nuclear forces. In general, these \(\delta_C\) corrections for the set of the 13 most precise \(T = 1\) superallowed emitters range in size from approximately 0.2% for \(^{10}\text{C}\) to 1.6% for \(^{74}\text{Rb}\). However, their evaluation depends very sensitively on both the theoretical model employed and the size of the shell-model spaces chosen in the nuclear structure calculations. These model dependencies can be significant with calculated values ranging by factors of four or more depending on the theoretical approach [2–7]. The impact of these model uncertainties on the evaluation of the world-average \(fT\) value and \(V_{ud}\) from the set of 13 most precisely measured superallowed decays was recently described in Ref. [8].

Experimental insight into the relative accuracy of these theoretical calculations can be obtained by studying specific decays where the corrections are expected to be large, where nuclear-structure and isospin effects may result in a relative enhancement for a particular case, or where theoretical predictions exhibit the greatest variation [9–15]. The set of \(T_C = -1\) superallowed decays are particularly attractive as the isospin-symmetry breaking corrections are, in general, larger than the \(T_C = 0\) cases due to the influence of the additional proton that serves to increase the radial-overlap mismatch between the proton and neutron wave functions in the parent and daughter nuclei, respectively. However, high-precision measurements of the \(fT\) values for these decays are significantly more challenging than for the \(T_C = 0\) cases. The parent nuclei are further from stability and production cross sections (beam intensities) are significantly reduced. The daughter nuclei (the \(T_C = 0\) emitters) are also unstable and will subsequently \(\beta\) decay, giving rise to unwanted but unavoidable time-dependent backgrounds. In addition, several low-lying \(T = 0\) states in the daughters can be strongly fed by Gamow-Teller transitions. If the isobaric-analog state is an excited state in the daughter, determination of the superallowed branching ratio requires a very precise knowledge of the absolute \(\gamma\)-ray detection efficiency. This provides a significant experimental challenge that is evidenced by the absence of high-precision \(fT\) values for the majority of the \(T_C = -1\) emitters. However, given the importance of these particular transitions for potentially discriminating between theoretical corrections of isospin-symmetry breaking, exhaustive detector calibrations using specialized sources and short-lived radioactive beams [16] as well as extensive simulation work have demonstrated that this challenge can, to a large extent, be overcome. A branching-ratio measurement performed for \(^{22}\text{Mg}\) achieved an overall precision of \(\pm 0.15\%\) [17] and additional cases such as \(^{18}\text{Ne}, \; ^{26}\text{Si}, \; ^{34}\text{Ar}, \; \text{and} \; ^{38}\text{Ca}\) will also be feasible in the near future using similar techniques [18].

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In the present work, we focus on the $T_{\beta}^- = -1$ superallowed decay of $^{18}\text{Ne}$ to its isobaric analog, a $0^+$ excited state located 1042 keV above the $1^+$ ground state in the daughter $^{18}\text{F}$. The decay-level scheme is shown in Fig. 1. This decay is of particular interest for investigating theoretical descriptions of isospin-symmetry breaking as model predictions exhibit some of the largest differences than for any of the other cases. Calculated $\delta_C$ corrections range from 0.27%, obtained using a self-consistent relativistic Hartree and Hartree-Fock approach based on the random-phase approximation [4], to 1.41% that was recently calculated using isospin and angular-momentum projected nuclear density functional theory (DFT) [6,7]. The present standard in this field is the set of shell-model calculations performed by Towner and Hardy whose radial corrections range from 0 27% [1]. The same set of calculations were repeated using Hartree-Fock wave functions with different Skyrme interactions and yielded 0.36% [1].

One reason for the large variation in the calculated $\delta_C$ corrections for this particular case arises from shape differences between the $^{18}\text{Ne}$ parent and the $^{18}\text{F}$ daughter. Several low-lying intruder states are known in $^{18}\text{F}$, including a deformed $0^+$ state at 1081 keV that is only 39 keV above the $0^+$ analog state of interest here. In addition, the second $0^+$ excited state at 4.75 MeV is located only 3.71 MeV above the $0^+_1$ state. Configuration mixing between the spherical two-particle $0^+$ state and the four-particle, two-hole $0^-$ intruder is enhanced by the relatively small energy difference between these states.

The precise degree of mixing between these configurations is difficult to obtain with the shell model and calculations relying on effective interactions [19] while shape differences between the spherical parent and deformed daughter nuclei are known to increase the size of the $\delta_C$ corrections obtained with the DFT approach [6,7].

The $f_I$ value for the superallowed decay of $^{18}\text{Ne}$, $f_I = 2919 (79)$ s [1], is not yet sufficiently precise to be included in the survey of the 13 highest-precision cases. The $f_I$ value characterizes any $\beta$-decay transition and is obtained experimentally from three quantities. The $Q$ value, which is required to calculate the phase-space integral $f_I$, has been established to $\pm 0.02\%$ precision through a $^{18}\text{Ne}$ mass measurement that employed a Penning-trap mass spectrometer [20] in addition to the several concordant measurements of the mass of the daughter $^{18}\text{F}$ and the 1042 keV excitation energy of the $0^+$ analog state [21,22]. The half-life of $^{18}\text{Ne}$, $T_{1/2} = 1.6656 (19)$ s, was previously determined by our group to $\pm 0.11\%$ precision [23] from an experiment that used the first online beams from a prototype electron-cyclotron-resonance (ECR) ion source developed at TRIUMF’s Isotope Separator and Accelerator (ISAC) facility. The absolute branching ratio to the $0^+$ analog state, $B = 7.70 (21)\%$, was last measured nearly 40 years ago [24] and is currently by far the limiting factor in extracting a precision $f_I$ value for this decay.

In anticipation of a high-precision branching-ratio measurement, the present study aims to improve upon the previously reported half-life measurement and reduce its overall uncertainty by a factor of two to a level that will be negligible when compared to the expected precision of $\sim 0.2\%$ that is likely to be achieved in a future measurement of the branching ratio. The half-life measurement follows our previous work [23,25] and relies on a technique that was developed to correct $\gamma$-ray gated decay activity curves for rate-dependent detector pulse pileup effects. Several long implantation activity curves were also measured over the course of the present experiment, which have permitted high-statistics measurements of the relative branching ratios and $\gamma$-ray yields for various excited states in $^{18}\text{F}$ populated in the $\beta$ decay. The present article begins with a description of the experimental setup, describes the high-resolution $\beta$-delayed $\gamma$-ray spectroscopy analysis, which was also valuable for assessing the beam purity, and concludes with the improved half-life measurement for $^{18}\text{Ne}$.

II. EXPERIMENT

The experiment was performed at the TRIUMF-ISAC radioactive ion-beam facility located in Vancouver, Canada. Radioactive beams of $^{18}\text{Ne}$ were produced from spallation reactions on a thick SiC target induced by a beam of 500 MeV protons, with an average intensity of 70 μA, delivered by TRIUMF’s main cyclotron. Reaction products released from the target were subsequently ionized in a forced electron beam-induced arc-discharge (FEBIAD) ion source coupled directly to the target [26]. Singly ionized, low-energy beams were extracted from the ion source at 60 keV, mass analyzed through a $\Delta m/m \approx 1/1000$ mass separator, and sent to the experimental hall. In the present experiment, the
beam intensity of $^{18}$Ne varied between $8 \times 10^5$ ions/s and $2 \times 10^6$ ions/s. This was between two to five times higher than our previous experiment [23] and is primarily due to the higher proton current used on target in the present study (only 30 $\mu$A were used previously). A long-lived beam contaminant of $^{18}$F ($T_{1/2} = 109.7$ min [27]) was also present in the mass-separated $A = 18$ beam with an average intensity of $2.5 \times 10^7$ ions/s. Analysis of the $\beta$-coincident and $\gamma$-ray singles spectra (Fig. 2) and the time-dependent $\gamma$-ray gated activity curves (Fig. 3) did not provide any evidence for the presence of additional contaminants in statistically significant quantities. A summary of the beam intensities and purities that were delivered in both experiments are compared in Table I.

Low-energy (60 keV) beams of $^{18}$Ne were implanted under vacuum into a movable mylar-backed aluminum tape at the mutual center of the Scintillating Electron-Positron Tagging Array (SCEPTAR) [28] and the $8\pi$ $\gamma$-ray spectrometer [29,30]. The $8\pi$ is a spherical array consisting of 20 coaxial high-purity germanium (HPGe) detectors and covers $\sim 13\%$ of the $4\pi$ solid angle. The absolute photopeak efficiency of the array is approximately 1.0% for 1.3 MeV photons. The back and sides of each HPGe crystal are surrounded by bismuth-germanate (BGO) scintillators that can be used for Compton suppression and their front faces are collimated with 2.54-cm-thick heavy metal (tungsten alloy) that prevents $\gamma$ rays from directly striking the BGO. The collimators are covered with 1-cm-thick plastic (Delrin) absorbers that are used to minimize the amount of bremsstrahlung radiation produced from energetic $\beta$ particles from reaching the detectors.

Preamplifier output signals from the HPGe detectors were split into two branches for energy and timing purposes, respectively. The energy signals were amplified using Ortec 572 spectroscopy amplifiers, and shaping times were varied between 0.5, 1.0, and 2.0 $\mu$s throughout both experiments. Analog output signals were then digitized using Ortec AD114 14-bit peak-sensing analog-to-digital convertors (ADCs). The inhibit output signals, generated from an internal pileup rejection circuit incorporated in the amplifiers, were used in the subsequent analysis for performing detector pulse pileup corrections. An adjustable front-panel potentiometer was used to manually set the threshold of the gated baseline restore as close as possible to the noise level. The second set of HPGe preamplifier outputs were sent to a timing-filter amplifier and were discriminated using Ortec 583b constant-fraction discriminators (CFDs). The fast outputs of the CFDs were used to generate both the trigger logic and the HPGe timing relative to the delayed master trigger using 32-channel LeCroy 3377 multi-hit time-to-digital convertors (TDCs) operated in
common-stop mode. Additional TDC modules were used for the 20 BGO timing signals for optional Compton suppression to be performed in software (not used in the present analysis since the rate-dependent probability of false vetoes are known to bias the resulting half-life determination [25]) and for the 20 pileup detection inhibit signals from the spectroscopy amplifiers for performing the pileup corrections. If one or more hits were recorded in the pileup TDC of a particular detector and if there was a corresponding time in the germanium TDC for that same detector, the event was considered to be piled up. Analysis of the time-dependent ratios of piled-up events to the total number of trigger events were then used to quantify and apply the pileup corrections to the \( \gamma \)-ray gated decay data according the method described in Ref. [25].

The 20 plastic (BC-404) scintillators of SCEPTAR each have a thickness of 1.6 mm and were arranged into four pentagonal rings so that one plastic was positioned directly in front of each of the 20 HPGe detectors. The detectors were mounted inside a spherical plastic (Delrin) implantation chamber that housed the moving tape and surrounded the beam implantation site. The entire ensemble was under vacuum during beam delivery. Each scintillator was positioned approximately 3 cm from the beam collection point. The solid angle coverage of the entire array was \( \sim 80\% \). The 20 scintillators were optically coupled to plastic (lucite) light guides that were used to transport the scintillation light to photomultiplier tubes located outside the array. Signals from the photomultiplier tubes were amplified with Phillips 776 fast amplifiers. One of the outputs of the fast amplifiers were delayed and digitized using 12-bit LeCroy 4300 fast-encoding readout amplifier (FERA) charge-to-digital convertors (QDCs). The second outputs were discriminated using Ortec 935 CFDs and were sent to LeCroy 3377 TDCs for timing. Additional signals from the CFDs were used to generate the trigger logic and were multiscaled using a 32-channel scalar in VME.

Event-by-event \( \beta \)- and \( \gamma \)-ray trigger data generated from the SCEPTAR and the 8 \( \pi \) data streams were individually time stamped to 100 ns precision using two LeCroy 2367 universal logic modules. The time standard for the data acquisition was a 10 MHz \( \pm 0.1 \) Hz dual-ovenized oscillator from Stanford Research Systems. The trigger was selected in software between singles events from one or both streams (with a rate-divided option), and/or hardware coincidences between the two. Using the event-by-event time-stamp information, \( \beta \)-\( \gamma \) coincidences were reconstructed in the offline analysis. Dead times of the data acquisition were also determined on an event-by-event basis using the time-stamp information. Their values could also be specified and fixed for a nonextendible duration for every trigger event. In both experiments, dead times were periodically varied on a run-by-run basis between a “variable” setting (measured event by event) and fixed and nonextendible durations of either 27 or 40 \( \mu s \), which were both chosen to be larger than the maximum time required by the data acquisition for processing any single event.

### A. Delayed \( \gamma \)-ray spectroscopy

Data were collected in cycles that consisted of a period \( t_b \) of background counting, a beam-on-tape collection period \( t_c \), and a beam-off (decay) measurement interval of duration \( t_d \). The tape was then moved a distance of 1.5 m to remove any residual and daughter activities from the collection and counting position to a shielded tape storage box outside the array. All cycling times and tape movements were controlled
by the data acquisition with a Jorway 221 timing and sequence module. Implantation and decay cycles with a total duration of $t_b + t_\alpha + t_d$ were optimized depending on the particular beam of interest, the half-life of its decay, and the half-lives of the contaminants and daughters (if present). The moving-tape collector system was necessary in the present study to remove the long-lived $^{18}$F activity that was delivered in the beam itself and was produced as the daughter of $^{18}$Ne decay. Several long cycles, each with a total duration of 171 s, were recorded to search for and quantify potential beam contaminants in addition to the known $^{18}$F daughter activity. All of these cycles had a time structure of $10^{-120-40-1}$ s corresponding to $t_b$, $t_\alpha$, $t_d$, and the tape movement, respectively. The trigger for the data acquisition, which was running continuously throughout each cycle, was generated from $\beta$-rays coincident events, or $\gamma$-ray singles events detected in the 8π spectrometer, or $\beta$ singles events detected in SCEPTAR with a scale-down factor of 100 applied. The maximum instantaneous rates that were observed in SCEPTAR and the 8π spectrometer were $6 \times 10^5$ Hz and $3 \times 10^4$ Hz, respectively.

Table II. Relative $\gamma$-ray intensities $I$ deduced in the present work and comparison to previous results.

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>$I_\gamma/I_{1042}$ (%)</th>
<th>Ref. [24] (%)</th>
<th>Ref. [32] (%)</th>
<th>Ref. [33] (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>620</td>
<td>&lt;0.003a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>659</td>
<td>1.733 (12)</td>
<td>2.1 (3)</td>
<td>1.69 (4)</td>
<td>1.72 (5)</td>
</tr>
<tr>
<td>1042</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1081</td>
<td>0.0288 (27)</td>
<td>0.0297 (22)</td>
<td>0.0289 (26)</td>
<td></td>
</tr>
<tr>
<td>1701</td>
<td>0.659 (7)</td>
<td>0.71 (17)</td>
<td>0.646 (21)</td>
<td>0.687 (13)</td>
</tr>
</tbody>
</table>

\footnotesize{aUpper limit with 90% confidence. See text for details.}

B. Beam composition and purity

In the first $^{18}$Ne experiment, contamination from $^{17}$F was observed in the $A = 18$ mass-separated beam with an average intensity of $2.1 \times 10^4$ ions/s. This isotope ($T_{1/2} = 64.5$ s [36]) was produced in the target and transported from the ECR ion source as a singly ionized HF molecule. While neither $^{17}$F nor $^{18}$F positron decays give rise to any characteristic $\gamma$ rays, their relative amounts can be determined from the time-dependent activity of the 511 keV $\gamma$ ray that follows positron annihilation. A typical activity curve for 511-keV-gated $\gamma$-ray singles events is shown in Fig. 3(a) for an individual run consisting of 24 cycles ($\sim$1 hour of data collection). These data were dead-time and pileup corrected according to the methods described below.

Fits to the grown-in and decay activity were used to deduce the individual contributions of each beam constituent to the total measured activity curve and to determine the overall $\gamma$-ray feeding into the 1042 keV level.

Table III. Relative $\beta$-decay branching ratios $B$ deduced in the present work and comparison to previous results.

<table>
<thead>
<tr>
<th>$E_{\beta}$ (keV)</th>
<th>$I^\beta$</th>
<th>$B/B_{1042}$ (%)</th>
<th>Ref. [24] (%)</th>
<th>Ref. [32] (%)</th>
<th>Ref. [33] (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1042</td>
<td>0+</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1081</td>
<td>0−</td>
<td>0.0278 (31)</td>
<td>0.0278 (33)</td>
<td>0.0270 (35)</td>
<td></td>
</tr>
<tr>
<td>1701</td>
<td>1+</td>
<td>2.436 (14)</td>
<td>2.87 (35)</td>
<td>2.376 (46)</td>
<td>2.449 (53)</td>
</tr>
</tbody>
</table>
both experiments are compared in Table I. Molecules or prevent their formation. Beam intensities from 
17F beam intensity fixed to 0) are overlayed for comparison in 
the same data. The only difference is the 
resulting half-life, T1/2 = 1.6656 (19) s, was 
enhanced by at least an order of magnitude 
relative to 18Ne (see Table I). The higher plasma temperature in the 
FEBIAD appears to be sufficient to dissociate HF 
molecules or prevent their formation. Beam intensities from 
both experiments are compared in Table I.

Although significant amounts of 18F were present in the 
and created from the decay of 18Ne, its long-life 
aged ensured that the unwanted β and 511 keV γ-ray activities 
produced from their decays were relatively small compared to the 
18Ne activity. Assuming beam implantation times of either 5 s or 120 s that are relevant to the present work, the 
individual contributions of each of these species to the total activity is shown in Table IV. With a beam-on time of only 5 s 
for example, 98.2% of the total activity is from 18Ne decay.

The sample purity of the activity can be greatly improved by selecting γ rays that uniquely follow the decay of the isotope(s) of interest. The activity spectrum for the 1042 keV γ-rays that follow ∼8% of all 18Ne decays is shown in Fig. 3(b). It should 
be emphasized that both spectra in Fig. 3 were obtained from 
the same data. The only difference is the γ-ray gate that has 
been applied. This degree of selectivity to achieve high-purity
decay activity curves is one of the main motivations for using delayed γ rays to determine β-decay half-lives with high 
precision and motivated the need for a technique, which 
has now been developed, to accurately correct for pileup 
losses associated with γ-ray detection [25]. Small and time-
dependent backgrounds underneath the 1042 keV photopeak 
could, in principle, arise due to Compton scattering from 
higher-energy γ-rays and inner-bremsstrahlung produced 
from electron-capture processes. For the only measured 
contaminant, 18F, all of these processes are energetically 
forbidden given that the electron-capture Q value is only 
1655 keV [21]. While these processes would be energetically 
allowed for the case of 17F, the activity from the decay of this 
isotope was already undetectable in the 511 keV γ-ray gated 
data obtained from long implantation times. Employing short 
beam-on times and gating on 1042 keV γ rays would imply that 
this possibility can be safely neglected. A fit to the 1042 keV 
γ-ray-gated activity spectrum of Fig. 3(b) that considered only 
18Ne decay and a constant background provides an excellent 
overall description of these data. The half-life deduced 
from this fit, T1/2 = 1.670 (9) s, is also in good agreement 
with the average 18Ne half-life T1/2 = 1.6670 (19) s [1]. We 
therefore conclude that the 1042 keV γ-ray-energy 
gate can be used to provide 18Ne decay-activity curves with 
negligible time-dependent contributions from the 
decays of the measured in-beam contaminants in the present experiment.

### III. Half-Life Measurement

In the first experiment, the half-life of 18Ne was deduced 
from a total of 4254 implantation-and-decay cycles with an 
average beam intensity of ∼4 × 10^5 ions/s. The overall precision 
obtained in the resulting half-life, T1/2 = 1.6656 (19) s, was 
entirely limited by the ± 0.0017 s statistical uncertainty [23]. 
A small systematic uncertainty of ±0.0009 s was added in 
quadrature that was estimated from the variation of the half-
lives obtained at each individual amplifier shaping-time setting 
and the estimated systematic uncertainty of 4% of the pileup 
correction that has been conservatively assigned to the correc-
tion method itself [25]. In the second experiment, an additional 
3192 decay cycles were obtained over 54 experimental runs 
using the higher-intensity 18Ne beam provided by the FEBIAD 
ion source. The statistical precision in the half-life for this 
new data set is ±0.0009 s, which is approximately a factor of 
two times more precise. Given that the experimental apparatus 
and the analysis methods are identical for the two data sets, the 
systematic uncertainties (if derived independently) cannot 
be trivially combined at the end. However, since the previous 
result was limited by statistics rather than systematic effects, 
the 15 runs from the original data set have been reanalyzed with 
the 54 runs of the present data set. A systematic uncertainty 
is then deduced from the combined data set. The improved 
half-life of 18Ne presented below therefore supersedes, and 
should not be averaged with the previously published value in Ref. [23].

Data were collected with cycle times of 5-t_0-40-1 s where 
the beam-on time was either t_0 = 2.5 s (16 runs), 5.0 s
(38 runs), or 7.0 s (15 runs). The decay time of $t_d = 40$ s, or approximately 24 half-lives of $^{18}$Ne, was chosen to be long enough to ensure that the $^{18}$Ne activity had sufficient time to decay to a negligible level so that the overall constant background (a free fit parameter) could be adequately constrained. A total of 7446 cycles were collected under several conditions that were varied throughout the two experiments on a run-by-run basis. As described above, amplifier shaping times were varied between 0.5 s, 1.0 s, and 2.0 s and the dead time of the data acquisition was chosen to be “variable” (measured event-by-event using the time stamp of the data acquisition), 27 μs fixed and nonextendible, or 40 μs fixed and nonextendible. Dead-time corrections varied between 10% and 50% at the start of the decay activity.

The half-life was determined by selecting events in which the 1042 keV photopeak was detected in any of the 20 HPGe detectors of the $8\pi$ spectrometer. After applying detector energy calibrations, the widths of the $\gamma$-ray-energy gates used in the analysis were common for every detector at a particular amplifier shaping time. Energy gates were chosen to include the entire photopeak plus one channel of background on either side. This corresponded to gate widths of 14, 18, and 26 keV for the 2.0 μs, 1.0 μs, and 0.5 μs shaping times, respectively. For each run, a minimum threshold was applied to the number of 1042 keV counts collected in each cycle in order to remove those cycles where the beam delivery was interrupted. The final cycle in every run was also rejected from the analysis as the acquisition was often stopped before it was completed. These selection criteria removed a total of 294 cycles, or approximately 4% of the 7446 total cycles collected over the course of the two separate experiments.

Decay data gated on the 1042 keV $\gamma$ ray were dead-time and pileup corrected on a event-by-event basis using the procedures described in Ref. [25]. In the high-rate data set, pileup corrections at the start of the decay activity ranged between approximately 2%, 4%, or 6% for the amplifier shaping times of 0.5 μs, 1.0 μs, or 2.0 μs, respectively. The pileup corrections of ≈6% at the start of the decay activity for the 2 μs shaping times are comparable to the largest corrections that were applied in Ref. [25] and are significantly larger than the corrections required in the previous $^{18}$Ne half-life measurement [23]. In Fig. 4, a comparison between sample time-dependent pileup probability distributions that were used to correct the $\gamma$-ray-gated decay data on a bin-by-bin basis, are shown for three separate runs collected at the three different shaping times. These distributions were obtained from the time-dependent ratio between all piled-up events to the total number of trigger events for each run. No $\gamma$-ray gate was applied to these data since, by definition, energy information is lost for true pileup events. Pileup probabilities decrease approximately exponentially with a half-life that is very nearly half that of $^{18}$Ne (≈0.8 s) because true pulse pileup requires at least two $\gamma$ rays. In all cases, a minimum appears around 8 s and arises from a low rate of saturating events (cosmic rays) that have a very high probability for individually triggering the pileup circuitry of the amplifiers. These events dominate the shape of the pileup probability distributions at late times where the probability for two or more $\gamma$-ray

FIG. 4. (Color online) Typical pileup probability curves and resulting best fits for single runs with amplifier shaping times of (a) 2.0 μs, (b) 1.0 μs, and (c) 0.5 μs. The dashed lines are the corrections applied to the $\gamma$-ray-gated data. See text for details.
pileup events in the background is extremely low. With longer shaping times, the probability for true pulse pileup of two or more events is larger and thus the minima are suppressed with increasing shaping time. In the half-life analysis, this cosmic-ray contribution must be subtracted from the total fit to obtain the time-dependent pileup corrections (dashed lines in Fig. 4) that should be applied to the $\gamma$-ray-gated decay data, as described in detail in Ref. [25].

Following the corrections for dead-time and pileup losses, the half-life of $^{18}$Ne was determined by fitting the sum of the individual cycles in each run using a maximum-likelihood $\chi^2$ minimization routine that has been described previously [37,38]. The fit function considered only the exponential decay of $^{18}$Ne because additional sources of time-dependent decay activity in the 1042 keV $\gamma$-ray-energy gate were considered to be negligible from the discussion above in Sec. II B. The fit function included free parameters for the initial activity of $^{18}$Ne, its half-life, and an overall constant background. A sample decay curve from 1042 keV $\gamma$-ray-gated events that consists of 75 cycles is shown in Fig. 5(a) with the corresponding best-fit and reduced $\chi^2$ value. The relevant portion of the $\gamma$-ray spectrum with the $\gamma$-ray-energy gate that was applied in the analysis is shown in Fig. 5(b). The bin-by-bin fit residuals are provided in Fig. 5(c). The statistical precision from an individual run was approximately $\pm 0.25\%$.

The half-lives of $^{18}$Ne deduced from each of the 69 experimental runs that were collected over the 2 experiments are presented in Fig. 6. Treating each run as independent measurements, the average half-life and its statistical uncertainty is $T_{1/2} = 1.6648(8)$ s, with a reduced $\chi^2$ value of 1.16. This result is a factor of two more precise than, and in excellent agreement with, the previous value $T_{1/2} = 1.6656(17)$ s obtained from only the first experiment (the first 15 runs in Fig. 6), as reported in Ref. [23].

FIG. 6. (Color online) Half-life of $^{18}$Ne determined for each of the 69 experimental runs. The average half-life and its statistical uncertainty $T_{1/2} = 1.6648(8)$ s are indicated by the solid and dashed lines, respectively.

FIG. 7. Half-life of $^{18}$Ne versus the number of leading channels removed (1 channel = 0.1 s). The deduced half-life is compared with and without the corrections applied for detector pulse pileup out to 5.0 s or three half-lives of $^{18}$Ne. The statistical uncertainty ($\pm 1\sigma$) of the pileup-corrected half-life when no channels have been removed is overlaid for comparison.

A. Systematic uncertainties

 Searches for possible sources of rate-dependent systematic effects that could bias the high-precision half-life determination included a leading-channel removal analysis where the half-life of $^{18}$Ne was deduced as data collected at the highest rates were incrementally removed. This analysis is presented in Fig. 7 for the entire data set when the pileup correction has been applied to the data (closed circles) and when it has been neglected (open circles). Each data point represents the half-life of $^{18}$Ne obtained from the weighted average of the entire 69 runs when data are removed from the start of the decay activity curve for each run in steps of 5 channels (0.5 s) up to a total of 50 channels (5.0 s) or three half-lives of $^{18}$Ne. When the pileup corrections are not included, there is a clear correlation between the deduced half-life and the counting rate that is absent once the pileup corrections have been applied to the data. After removing the first $\sim 3.5$ s (two half-lives of $^{18}$Ne), the corrected and uncorrected half-lives agree, indicating that counting rates are sufficiently low at this time that the pileup corrections are negligible. At the start of the decay activity, the $^{18}$Ne half-life was deduced to be $T_{1/2} = 1.6648(8)$ s from the data with the pileup correction applied and $T_{1/2} = 1.6765(8)$ s from the uncorrected data. In terms of the half-life, the total correction for detector pulse pileup is therefore $\sim 0.7\%$, or nearly 15 statistical standard deviations. The longer half-life obtained in the uncorrected analysis is consistent with the fact that 1042 keV $\gamma$-ray photopeak events are more likely to be piled up and thus lost from the analysis at high counting rate.

In radioactive-beam experiments with noble-gas ions, time-dependent diffusion of a particular fraction of the implanted sample from the collector material can be a significant concern [39–41]. The above channel-removal analysis indicates that any rapid release of significant quantities of the implanted...
18Ne ions is negligible compared with the level of statistical precision obtained in the experiment. The possibility of diffusion on longer time scales was studied in the previous work by comparing the deduced half-life of the longer-lived 23Ne isotope ($T_{1/2} = 37$ s) to a previous measurement performed by trapping 23Ne atoms in the gas phase [42]. The excellent agreement between these two results demonstrated that diffusion on longer time scales can similarly be neglected in the analysis of 18Ne ions with our experimental apparatus. In addition, a high-precision 19Ne half-life measurement was performed using the same experimental setup and the result, $T_{1/2} = 17.262 (7)$ s [43], has been confirmed at the level of $\pm 0.04\%$ by an independent measurement recently performed at GANIL [44]. Given these considerations, we conclude that any diffusion of implanted 18Ne ions in the present experiment is negligible in comparison to the $\pm 0.05\%$ statistical precision of our measurement.

During the course of the experiment, several modifications to the electronics settings were made on a run-by-run basis to ascertain whether or not additional sources of systematic uncertainty could arise from the electronics modules themselves or by the correction and analysis procedures that were applied to the data. Amplifier shaping times were adjusted between 0.5 $\mu$s, 1.0 $\mu$s, and 2.0 $\mu$s and, as described above, this modifies the probability for pileup and hence the magnitude of the resulting pileup corrections (see Fig. 4). Acquisition dead times were also adjusted on a run-by-run basis. The average 18Ne half-lives obtained for each particular group of runs collected under each of these electronics settings were calculated and the results are shown in Fig. 8. As every run can only have a single shaping time or dead time, the average half-life of each group is equivalent to $T_{1/2} = 1.6648 (8)$ s, the weighted average of the entire data set. A third group is also shown in Fig. 8 that calculates the average 18Ne half-life from the previous experiment $T_{1/2} = 1.6656 (17)$ s and compares it to the result, $T_{1/2} = 1.6646 (9)$ s, obtained from the new data added in the second experiment.

To estimate a systematic uncertainty from these comparisons, reduced $\chi^2$ values were calculated on a run-by-run basis in Fig. 6, and for each group of adjustable electronic settings as indicated in Fig. 8. The largest reduced $\chi^2$ value was 1.68 and was obtained from the 18Ne half-lives grouped according to the dead-time setting. Following the method of the Particle Data Group [45], the square root of this value is used to increase the statistical uncertainty in order to account for any remaining and unidentified systematic effects. Assuming that the total uncertainty of $\pm 0.0010$ s obtained from this procedure can be expressed as the quadrature sum of the statistical and systematic uncertainties, the value of $\pm 0.0007$ s is obtained for the systematic uncertainty, which is nearly equivalent to the $\pm 0.0008$ s statistical precision. An additional source of systematic uncertainty arising from the application of the pileup correction procedures described here has been conservatively estimated to be 4% of the total correction itself as described in Ref. [25]. From the 0.0117 s difference between the half-lives obtained with and without the pileup corrections applied, this additional systematic uncertainty is $\pm 0.0005$ s.

The half-life of 18Ne deduced in the present work can be written as $T_{1/2} = 1.6648 (8) (7) (5) s$, where the first uncertainty is statistical, the second is systematic and was estimated from the variation of the deduced half-lives grouped by the dead-time setting of the data-acquisition system, and the third is a systematic uncertainty associated with the pileup-correction methodology. Combining these uncertainties in quadrature gives the final result, $T_{1/2} = 1.6648 (11) s$, for the half-life of 18Ne. This is approximately a factor of two times more precise than the value previously reported from the first experiment [23]. Our new value replaces the previous one because the data from this first experiment have been included in the present evaluation. The half-life of 18Ne is also in agreement with $T_{1/2} = 1.669 (4)$ s [48], the most precise measurement prior to our own, although it is nearly four times less precise. A summary of all previous 18Ne
half-life measurements is presented in Fig. 9. According to the procedures adopted in Ref. [1] for combining these results, the world-average $^{18}\text{Ne}$ half-life is $T_{1/2} = 1.6654 (11) \text{ s}$. The evaluation of the uncertainty on the average includes a scale factor of 1.05 (see Ref. [1]) obtained from the square root of the reduced $\chi^2$ value of 1.11 for these data. With an overall precision of $\pm0.07\%$, which is dominated by the half-life measurement presented in this work, the half-life of $^{18}\text{Ne}$ has now been determined to be at least $\sim3$ times more precise than is likely feasible for a high-precision branching-ratio measurement of this superallowed Fermi transition. The $^{18}\text{Ne}$ half-life is therefore not expected to be a limiting factor in establishing a high-precision $f/t$ value for the superallowed decay of $^{18}\text{Ne}$ in the foreseeable future.

IV. SUMMARY AND CONCLUSION

High-resolution $\beta$-delayed $\gamma$-ray spectroscopy has been performed following the decay of $^{18}\text{Ne}$ ions implanted at the center of the 87r $\gamma$-ray spectrometer at TRIUMF’s ISAC facility. The half-life of $^{18}\text{Ne}$ has been determined to be $T_{1/2} = 1.6648 (11) \text{ s}$ following the application of a 0.7% correction that was required to account for systematic and rate-dependent losses associated with detector pulse pileup. This result is approximately a factor of two times more precise than, and in excellent agreement with, our previous measurement that was performed with a prototype ECR ion source. Improved precision on the relative $\beta$-decay branching ratios and delayed-$\gamma$-ray intensities were also obtained and are in very good agreement with previous measurements. These results will provide important input towards future experiments that aim to improve the precision of the $^{18}\text{Ne}$ $f/t$ value to the level of $\pm0.2\%$ that has now been achieved in two other $T_z = -1$ cases. The case of $^{18}\text{Ne}$ is particularly attractive because it potentially provides a means to discriminate between several theoretical models of isospin-symmetry breaking and can be used to investigate the role of nuclear deformation in the calculation of these corrections.

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