High-Precision Half-Life Measurement for the Superallowed β^+ Emitter $^{26}\mathrm{Al}^m$

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A high-precision half-life measurement for the superallowed β^+ emitter $^{26}\mathrm{Al}^m$ was performed at the TRIUMF-ISAC radioactive ion beam facility yielding $T_{1/2} = 6346.54 \pm 0.46_{\mathrm{stat}} \pm 0.60_{\mathrm{syst}}$ ms, consistent with, but 2.5 times more precise than, the previous world average. The $^{26}\mathrm{Al}^m$ half-life and ft value, 3037.53(61) s, are now the most precisely determined for any superallowed β decay. Combined with recent theoretical corrections for isospin-symmetry-breaking and radiative effects, the corrected $\mathcal{F}t$ value for $^{26}\mathrm{Al}^m$, 3073.0(12) s, sets a new benchmark for the high-precision superallowed Fermi β-decay studies used to test the conserved vector current hypothesis and determine the V_{ud} element of the Cabibbo-Kobayashi-Maskawa quark mixing matrix.

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High-precision ft values for superallowed Fermi β decay transitions between spin $J^\pi = 0^+$ and isospin $T = 1$ states have proven to be an invaluable probe of the standard model [1]. The validity of the conserved vector current (CVC) hypothesis [2], which states that the vector coupling constant G_V is not renormalized in the presence of strong interactions, has been established by the superallowed data at the level of 1.3×10^{-4} [3]. Combined with the Fermi coupling constant for purely leptonic decays G_F, G_V from the superallowed data also currently provides the most precise determination of $V_{\mathrm{ud}} = G_V/G_F = 0.974\,25(22)$ [1], by far the most precisely determined element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix relating the quark weak eigenstates to their mass eigenstates. To achieve this precision, the 13 superallowed ft values measured to better than $\pm 0.3\%$ must be corrected to obtain transition-independent $\mathcal{F}t$ values [1]:

$$\mathcal{F}t \equiv ft(1 + \delta_R')(1 + \delta_{\mathrm{NS}} - \delta_C) = \frac{K}{2G_V^2(1 + \Delta_R^V)}, \quad (1)$$

where K is a constant, Δ_R^V is the nucleus-independent component of the radiative correction, δ_R' and δ_{NS} are, respectively, the nuclear-structure-independent and dependent components of the radiative correction for each transition, and δ_C accounts for the breaking of isospin symmetry by Coulomb and charge-dependent nuclear forces [4].

Applied to the world superallowed data evaluated in Ref. [3], these corrections yield $V_{\mathrm{ud}} = 0.974\,25(8)_{ft,\delta_R'}(10)_{\delta_{\mathrm{NS}}-\delta_C}(18)_{\Delta_R^V}$ [1], where the uncertainty from the nuclear-structure-dependent corrections includes a contribution due to a systematic difference between two independent models for calculating the isospin-symmetry-breaking (ISB) corrections. The transition-independent-radiative correction $\Delta_R^V = 2.361 \pm 0.038\%$ [1] currently dominates the uncertainty in V_{ud}. While the central value of Δ_R^V has changed little in the last 20 years [5,6], a recent reevaluation of hadronic corrections [6] has led to a reduction of its uncertainty by a factor of 2. The calculations of the nuclear-structure-dependent ISB corrections, on the other hand, have undergone significant revisions in the last decade [4,7], leading to shifts as large as 50% of their own values in some cases, and to a general *increase* in their individual quoted uncertainties. A further reduction in the uncertainty assigned to Δ_R^V could potentially be achieved via lattice QCD calculations [8], ultimately leading to a value of V_{ud} limited by the nuclear-structure-dependent correction terms. The ISB corrections in superallowed Fermi β decays have thus become the focus of intense study in recent years from a variety of theoretical approaches [3,4,9–12], as well as semiempirical analysis [13]. Continued development, and refinement, of independent first principles approaches to ISB corrections, and the testing of these models against experimental data, thus remain crucial to the test of the CVC hypothesis and the extraction of V_{ud} from the superallowed β-decay data. Direct constraints on one component of these calculations have been set by measuring the β-decay branching ratios to nonanalog 0^+ states [14,15]. An alternative is to improve the precision in the experimental ft values for particular cases where the theoretical corrections are predicted to be the smallest. This approach yields high-precision $\mathcal{F}t$ values which serve to highlight discrepancies between the different ISB models.

Of the 13 superallowed emitters with ft values known to better than $\pm 0.3\%$, $^{26}\mathrm{Al}^m$ has the smallest nuclear-structure dependent corrections [4]. The uncertainty assigned to these corrections is also the smallest for any of the superallowed emitters. These factors make $^{26}\mathrm{Al}^m$ an ideal case to pursue a reduction of the uncertainty in the experimental ft value. Prior to the work presented here, the uncertainty in the $^{26}\mathrm{Al}^m$ ft value was dominated by the uncertainty in its half-life. In this Letter, we report a measurement of the $^{26}\mathrm{Al}^m$ half-life with a precision of 0.012%, the most precise superallowed β-decay half-life measurement to date [3].

The experiment was performed at TRIUMF's Isotope Separator and Accelerator (ISAC) facility. A 40 μA beam of 500 MeV protons impinged on a 14.35 $\mathrm{g/cm^2}$ SiC target, inducing spallation reactions whose products diffused from the target. The TRIUMF Resonant Ionization Laser Ion Source [16] was used to selectively ionize aluminum isotopes, enhancing the abundance of $^{26}\mathrm{Al}^m$ relative to the dominant isobaric contaminant $^{26}\mathrm{Na}$ following mass separation of the reaction products. A 30 keV beam was delivered to a tape-transport and 4π continuous-flow gas-proportional counter system at a rate of approximately 10^6 $^{26}\mathrm{Al}^m/\mathrm{s}$, 10^7 $^{26}\mathrm{Na/s}$, and 10^9 $^{26}\mathrm{Al}^g/\mathrm{s}$. The beam was implanted under vacuum into the 25-mm-wide aluminized mylar tape for 6–14 s, then allowed to "cool" for 26–34 s, reducing the activity of the $^{26}\mathrm{Na}$ contaminant ($T_{1/2} = 1.071\,28(25)$ s [17]) to a negligible level. The sample was then moved to the center of the 4π gas counter [18], which was operated within its plateau region between 2700 and 2900 V. The signal from the preamplifier was sent through a discriminator and then split into two data streams. Fixed, nonextendable dead times, chosen to be much longer than the total series dead time of the system, were applied to each stream using two LeCroy 222N nonretriggerable gate-and-delay generators. The dead-time-affected pulses were then registered using two independent multichannel scaler (MCS) modules into 250 bins. Dwell times of 500, 600, and 700 ms per bin were used in this experiment, with a Stanford Research Systems 1 MHz ± 2 Hz precision laboratory clock providing the time standard. The discriminator level, dwell time, and detector voltage were altered run-by-run to investigate potential systematic effects, and the outputs of the two gate-and-delay generators providing the fixed dead times were interchanged regularly between the inputs of the two MCS modules. These dead times were measured to be $\tau_1 = 4.0162(25)$ μs and $\tau_2 = 2.9949(24)$ μs via the source plus pulser technique [19], and were found to be stable within their quoted uncertainties as a function of time.

A total of 2059 implantation-cool-transport-count cycles were collected over 51 runs with different experimental conditions. A lower limit, unique to each run, was set during the analysis on the number of counts in each cycle to remove those during which the proton beam had tripped off. A total of 50 such cycles were removed, with one additional cycle removed due to a visible noise burst in the gas counter. These cycles represented 0.7% of the counts in the entire data set. The remaining 2008 cycles were dead-time corrected [17,18] and summed for each run.

The dead-time-corrected decay data were fit using a minimization routine [17] that employs a direct application of maximum likelihood to the Poisson probability distribution [20]. The fitting routine included a component for the $^{26}\mathrm{Al}^m$ activity, the $^{26}\mathrm{Na}$ activity, and a constant background. With a half-life of $7.17(24) \times 10^5$ yr [21] and a measured yield of $10^9/\mathrm{s}$, the contaminant $^{26}\mathrm{Al}^g$ constituted approximately 0.001% of the observed background rate. The extreme scenario of attributing the entire background to decays of $^{26}\mathrm{Al}^g$ was investigated by allowing the background parameter to decay with the very long half-life of $^{26}\mathrm{Al}^g$. This was found to yield an identical half-life for $^{26}\mathrm{Al}^m$ and the background was treated as a constant in the final analysis. The yield of $^{26}\mathrm{Na}$ from the production target was also measured prior to the experiment to be $8.7 \times 10^6/\mathrm{s}$ which corresponded to a maximum $^{26}\mathrm{Na}$ activity at the beginning of the counting period of $0.43/\mathrm{s}$. Fixing the initial activity of $^{26}\mathrm{Na}$ to this maximum value for all cycles was found to have no effect on the deduced $^{26}\mathrm{Al}^m$ half-life compared to fixing the $^{26}\mathrm{Na}$ activity to zero. As a consistency check, the activity of $^{26}\mathrm{Na}$ was also included as a free parameter in the fit with a fixed half-life of $1.071\,28(25)$ s [17]. The initial activity of $^{26}\mathrm{Na}$ derived from the fit was found to be consistent with zero and was fixed to zero in the final analysis. A dependence of the deduced $^{26}\mathrm{Al}^m$ half-life on the rate in the gas counter was investigated by removing leading channels from the fit up to two half-lives, and no statistically significant rate dependence was observed.

Figure 1 shows the data, fit, and residuals for a typical run. The weighted average of the fit results for all 51 runs, shown in Fig. 2, yields a value for the $^{26}\mathrm{Al}^m$ half-life of $6346.49(46)_{\mathrm{stat}}$ ms and a $\chi^2/\nu = 1.020$, indicative of statistical consistency among the 51 runs. To further explore possible systematic effects, the deduced half-lives were grouped according to the various experimental settings as shown in Fig. 3. The two independent MCS units and two fixed dead times, each of which represent all of the data recorded under different conditions, yield consistent results. Breaking the data into the three different dwell times and five different implant-cool times also lead to statistically consistent groupings. Grouping the data into the four discriminator settings and five voltage settings, however, yields χ^2/ν values of 2.67 and 2.36, respectively. For 3 and 4 degrees of freedom χ^2/ν values this large or larger have probabilities of $\approx 5\%$. To be conservative, we adopt the Particle Data Group's procedure of inflating the statistical uncertainty of our half-life measurement by $\sqrt{\chi^2/\nu} = 1.63$ for the largest χ^2/ν of these groupings to account for a

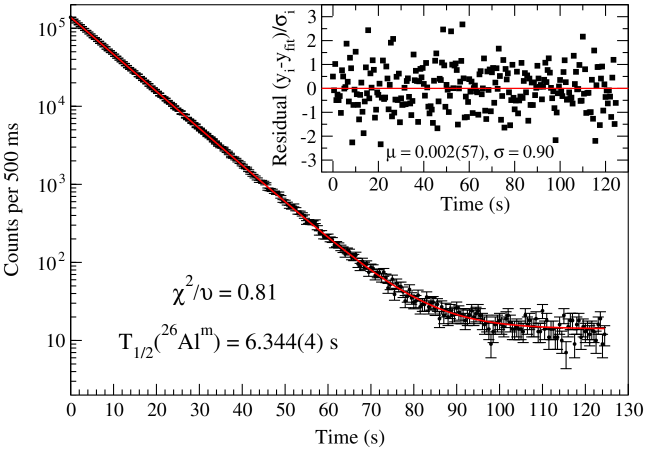

FIG. 1 (color online). Typical dead-time-corrected decay curve for a single run, with fit overlayed. The residuals from the fit are shown in the inset.

possible systematic effect, equivalent to ±0.59 ms, associated with the experimental parameters.

The contribution to the error budget from the uncertainty in the measured dead times, determined by fitting the data with the dead times fixed at their $\pm 1\sigma$ limits, was ±0.045 ms, which we add in quadrature with the above ±0.59 ms systematic uncertainty. Finally, an independent analysis was carried out in parallel with that reported above using independent analysis procedures and fitting routines. Extensive Monte Carlo simulations were performed encompassing, and exceeding, the range of the experimental conditions and verified the accuracy of the fitting routines at the level of one-fifth of the statistical precision of this data set. The half-life deduced from this independent analysis, $T_{1/2} = 6346.59(48)_{\mathrm{stat}}$ ms, was in excellent agreement with the value quoted above. The small, 0.10 ms difference was found to be entirely attributable to the aforementioned cycle-removal criteria, unique to each analysis, and not to differences associated with the fitting routines. The half-lives determined from these two independent analyses were averaged and a systematic uncertainty of ±0.05 ms, half their difference, assigned to the difference in cycle selection yielding a final result of $6346.54(46)_{\mathrm{stat}}(60)_{\mathrm{syst}}$ ms. This value is in excellent agreement with the current world average of 6345.0(19) ms [3], but is 2.5 times more precise, yielding a new world average for the $^{26}\mathrm{Al}^m$ half-life of 6346.32(70) ms, now the most precisely determined of any superallowed emitter.

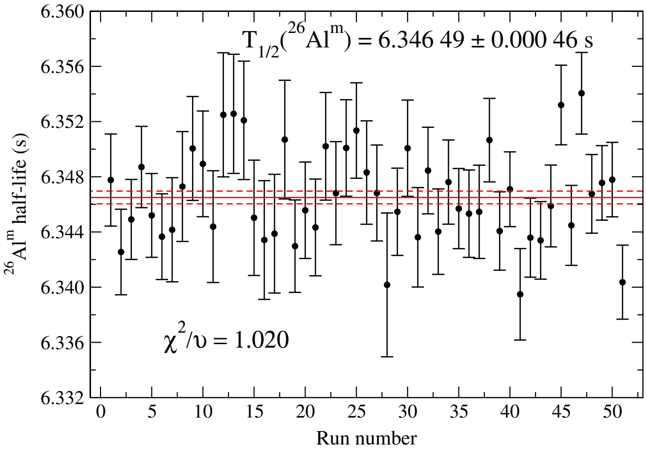

FIG. 2 (color online). Run-by-run $^{26}\mathrm{Al}^m$ half-life measurements. The weighted average of all 51 runs, $T_{1/2} = 6.346\,49(46)$ s, is displayed as a solid line with $\pm 1\sigma_{\mathrm{stat}}$ limits shown as dotted lines.

Combined with world-averaged Q-value measurements, the new world-average half-life for $^{26}\mathrm{Al}^m$ yields an ft value of 3037.53(61) s. As shown in Fig. 4(a), this is the most precisely determined ft value for any superallowed decay. Using the radiative and recent Woods-Saxon ISB corrections of Towner and Hardy [4] yields a corrected $\mathcal{F}t$ value for $^{26}\mathrm{Al}^m$ of 3073.0(12) s which, as shown in Fig. 4(b), is also the most precisely determined for any superallowed emitter. The precision of the $^{26}\mathrm{Al}^m$ $\mathcal{F}t$ value now rivals that of all of the other 12 high-precision cases combined ($\overline{\mathcal{F}t} = 3072.0(10)$ s), setting a new benchmark for the superallowed decays. The high-precision $\mathcal{F}t$ value for $^{26}\mathrm{Al}^m$ is also in excellent agreement with the other 12 precision cases. The $\mathcal{F}t$ values obtained using the Woods-Saxon ISB corrections of Towner and Hardy thus continue to form an impressively consistent set, lending strong support to the CVC hypothesis.

To test for model dependence, a new set of the radial-overlap components δ_{C2} of the ISB corrections has been calculated by Towner and Hardy [3] using a Skyrme-Hartree-Fock mean field in place of the Woods-Saxon potential used to derive the radial wave functions. The $\mathcal{F}t$ values obtained using these new Hartree-Fock ISB corrections are presented in Fig. 4(c). While the average of the other 12 precision cases ($\overline{\mathcal{F}t} = 3072.3(10)$ s) is in excellent agreement with the value of $\overline{\mathcal{F}t} = 3072.0(10)$ s obtained using the Woods-Saxon corrections, the Hartree-Fock-derived $\mathcal{F}t$ value for $^{26}\mathrm{Al}^m$, 3069.0(19) s, is fully 3.3 s below the average of the other 12 precision cases obtained with the Hartree-Fock corrections and 4.0 s lower than the $^{26}\mathrm{Al}^m$ $\mathcal{F}t$ value obtained using the Woods-Saxon ISB corrections. This large difference in

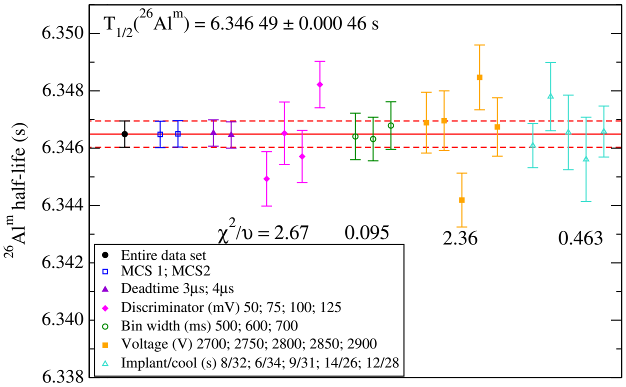

FIG. 3 (color online). Half-life measurements of $^{26}\mathrm{Al}^m$ grouped by experimental parameters. See text for details.

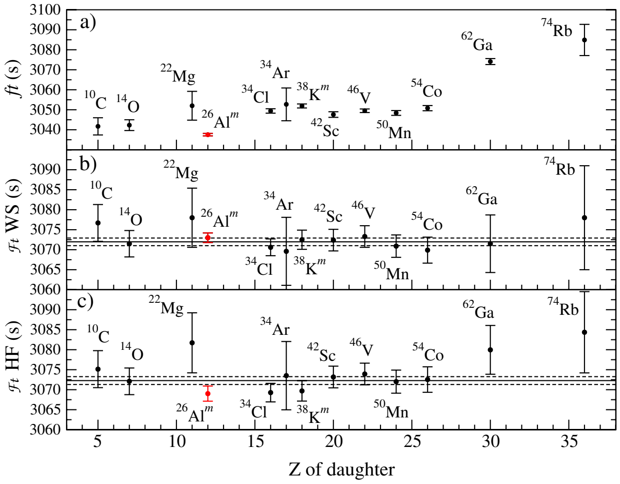

FIG. 4 (color online). The 13 precision superallowed (a) ft and (b),(c) $\mathcal{F}t$ values, using the (b) Woods-Saxon and (c) Hartree-Fock ISB corrections of Towner and Hardy [3,4]. The averages of the other 12 $\mathcal{F}t$ values, excluding ^{26}Al^m, yield (b) $\overline{\mathcal{F}t} = 3072.0(10)$ s and (c) $\overline{\mathcal{F}t} = 3072.3(10)$ s, and are displayed as solid lines with their $\pm 1\sigma_{\text{stat}}$ limits shown as dotted lines. The ^{26}Al^m $\mathcal{F}t$ values, (b) 3073.0(12) s and (c) 3069.0 (19) s, combined with the other 12 precision cases yield (b) $\overline{\mathcal{F}t} = 3072.38(75)$ s and (c) $\overline{\mathcal{F}t} = 3071.59(87)$ s, respectively.

the corrected $\mathcal{F}t$ values for ^{26}Al^m is associated entirely with the $\delta_{C2} = 0.410(50)\%$ obtained in the most recent Hartree-Fock calculations, a value significantly larger than the 0.280(15)% [4] obtained in the most recent Woods-Saxon calculations, as well as older Woods-Saxon, 0.230 (10)% [7], and Hartree-Fock, 0.29(9)% [22], calculations.

In their most recent review of the world superallowed β-decay data [3], Towner and Hardy average the $\overline{\mathcal{F}t}$ values obtained using their Woods-Saxon and Hartree-Fock ISB corrections when extracting G_V, and hence V_{ud}, with half the difference assigned as a model-dependent systematic uncertainty. As the high-precision ^{26}Al^m $\mathcal{F}t$ value carries the largest weight in each of the two $\overline{\mathcal{F}t}$ averages, and there is a particularly large discrepancy between the two ISB calculations for ^{26}Al^m, the improved precision in the experimental ft value for ^{26}Al^m reported here *increases* the discrepancy between the Woods-Saxon and Hartree-Fock derived average $\overline{\mathcal{F}t}$ values. Following the prescription of Ref. [3], the systematic uncertainty assigned to the world-average superallowed $\overline{\mathcal{F}t}$ value due to the model dependence of the ISB corrections increases from 0.55 s [3] to 0.79 s, a value that now exceeds the uncertainty in the weighted average, 3072.38(75) s, resulting from all of the experimental uncertainties, the theoretical uncertainties in the nucleus-dependent radiative corrections δ_R, and the *assigned* theoretical uncertainties in the Woods-Saxon ISB corrections combined. A resolution of the discrepancy between the two most recent calculations for the ^{26}Al^m radial-overlap correction is thus critical if the ±0.02% precision of the experimental ft value for this decay is to be fully exploited.

In summary, a high-precision half-life measurement for ^{26}Al^m has been performed yielding

$$T_{1/2} = 6346.54 \pm 0.46_{\text{stat}} \pm 0.60_{\text{syst}}\ \text{ms}\quad \text{(this work)}, \tag{2}$$

$$T_{1/2} = 6346.32 \pm 0.70\ \text{ms}\quad \text{(new world average)}. \tag{3}$$

The ft value for this β decay, $ft = 3037.53(61)$ s, is established to ±0.02%, the most precisely determined among the superallowed emitters. This experimental precision, combined with the nuclear-structure-dependent corrections for ^{26}Al^m, yields an $\mathcal{F}t$ value, 3073.0(12) s, with a precision that rivals that of all of the other 12 precisely determined cases combined. To take advantage of this precision, however, a discrepancy between the most recent Woods-Saxon and Hartree-Fock radial-overlap corrections for ^{26}Al^m must be understood and resolved.

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