High-Precision Half-Life Measurements for the Superallowed β^+ Emitter ^{10}C: Implications for Weak Scalar Currents

M. R. Dunlop,[1,*] C. E. Svensson,[1] G. C. Ball,[2] G. F. Grinyer,[3] J. R. Leslie,[4] C. Andreoiu,[5] R. A. E. Austin,[6] T. Ballast,[2] P. C. Bender,[2] V. Bildstein,[1] A. Diaz Varela,[1] R. Dunlop,[1] A. B. Garnsworthy,[2] P. E. Garrett,[1] G. Hackman,[2] B. Hadinia,[1] D. S. Jamieson,[1] A. T. Laffoley,[1] A. D. MacLean,[1] D. M. Miller,[2] W. J. Mills,[2] J. Park,[2] A. J. Radich,[1] M. M. Rajabali,[2] E. T. Rand,[1] C. Unsworth,[2] A. Valencik,[6] Z. M. Wang,[2] and E. F. Zganjar[7]

[1]*Department of Physics, University of Guelph, Guelph, Ontario N1G 2W1, Canada*
[2]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[3]*GANIL, CEA/DRF-CNRS/IN2P3, Bvd Henri Becquerel, 14076 Caen, France*
[4]*Department of Physics, Queen's University, Kingston, Ontario K7L 3N6, Canada*
[5]*Department of Chemistry, Simon Fraser University, Burnaby, British Colombia V5A 1S6, Canada*
[6]*Department of Astronomy and Physics, Saint Mary's University, Halifax, Nova Scotia, B3H 3C3, Canada*
[7]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana, 70803, USA*

(Received 10 February 2016; published 28 April 2016)

Precision measurements of superallowed Fermi β-decay transitions, particularly for the lightest superallowed emitters ^{10}C and ^{14}O, set stringent limits on possible scalar current contributions to the weak interaction. In the present work, a discrepancy between recent measurements of the ^{10}C half-life is addressed through two high-precision half-life measurements, via γ-ray photopeak and β counting, that yield consistent results for the ^{10}C half-life of $T_{1/2} = 19.2969 \pm 0.0074$ s and $T_{1/2} = 19.3009 \pm 0.0017$ s, respectively. The latter is the most precise superallowed β-decay half-life measurement reported to date and the first to achieve a relative precision below 10^{-4}. A fit to the world superallowed β-decay data including the ^{10}C half-life measurements reported here yields $b_F = -0.0018 \pm 0.0021$ (68% C.L.) for the Fierz interference term and $C_S/C_V = +0.0009 \pm 0.0011$ for the ratio of the weak scalar to vector couplings assuming left-handed neutrinos.

DOI: 10.1103/PhysRevLett.116.172501

The standard model (SM) description of weak interactions involves an equal mixture of vector (V) and axial vector (A) currents that maximizes parity violation, commonly referred to as the "$V-A$" theory. Additional couplings naturally arise in theories beyond the SM and must be measured, or constrained, by experiments. Searches for such "exotic" couplings are performed in both high-precision low-energy nuclear and neutron β-decay experiments, and at energy frontier particle colliders, often with complementary sensitivities to different components of the non-SM interactions [1].

Precision low-energy measurements of superallowed Fermi β decays [2] between nuclear isobaric analogue states with spin-parity $J^\pi = 0^+$ and isospin $T = 1$ currently provide the most stringent limit on the Fierz interference term b_F, which, under the assumption of a time-reversal invariant coupling to left-handed neutrinos ($C_S = C'_S$), is related to the ratio of weak scalar to vector couplings as $b_F = -2C_S/C_V$ [3]. The presence of a scalar interaction would remove the constancy of the "corrected" ft values, denoted $\mathcal{F}t$ [2], for the superallowed decays of different nuclei enforced by the conserved vector current hypothesis [4] through the introduction of an additional term to the integrand of the β-decay phase-space integral f. This additional term has the form $(1 + b_F\gamma/W)$, where W is the total positron energy in electron rest mass units and $\gamma = \sqrt{1-(\alpha Z)^2}$, with Z the atomic number of the daughter nucleus and α the fine structure constant [5]. As the β-decay Q values, and hence the mean positron energies, for the superallowed emitters increase monotonically with Z, it is the lightest superallowed emitters, ^{10}C and ^{14}O, that have the largest values of $\langle W^{-1}\rangle$ and thus the greatest sensitivity to a possible weak scalar current contribution. The superallowed β decay of ^{14}O has been the subject of intense study in recent years, with new measurements of all three of the quantities required to determine the experimental ft value, namely, the half-life [6], Q_{EC} value [7], and branching ratio [8]. For ^{10}C, a precise determination of the superallowed Q_{EC} value through modern Penning trap mass measurements has been performed [9]. The precision of the challenging ^{10}C superallowed branching-ratio measurement is, however, dominated by two experiments from the 1990s [10,11], and there is also a significant disagreement between the two most recent, and precise, measurements of the ^{10}C half-life [12,13]. In the present work, we address the latter issue and discuss its impact on the scalar current limits set by the superallowed Fermi β-decay data.

As shown in Fig. 1, half-life measurements for ^{10}C have a somewhat checkered history. Although several of the earlier, and less precise, measurements are no longer included in modern evaluations [2], the unfortunate situation remains that the two most recent, and precise, measurements, $T_{1/2} = 19.310 \pm 0.004$ s [13] and $T_{1/2} = 19.282 \pm 0.011$ s [12], show very poor agreement, with a $\chi^2 = 5.7$. In the most recent survey of the world superallowed data, which retains only the four most precise measurements shown in Fig. 1, the inconsistency in the ^{10}C half-life measurements led to the adoption of a world average value of $T_{1/2}(^{10}\mathrm{C}) = 19.3052 \pm 0.0071$ s [2], with a significantly inflated uncertainty, as shown by the solid bar in Fig. 1. The "unsatisfactory" [12] situation is further illustrated by the ideograph for the four most precise ^{10}C half-life measurements shown in Fig. 1, which reveals two distinct peaks. Because of the low Q value for the ^{10}C superallowed decay, and hence its high sensitivity to a potential scalar current contribution, the half-life of ^{10}C has a significant impact on the determination of b_F from the superallowed data. While the recent survey of the world superallowed data [2] included 222 measurements of comparable precision, the difference in the ^{10}C half-life between the two peaks of the ideograph shown in Fig. 1 would, by itself, shift the central value of the Fierz interference term determined from the *entire* world superallowed data set by more than half of its quoted uncertainty. An accurate, and precise, determination of the ^{10}C half-life is thus critical to the limits on b_F set by the superallowed data. In this Letter, we address this issue through two new, and independent, measurements of the ^{10}C half-life via γ-ray photopeak and β counting, the latter representing the most precise superallowed β-decay half-life measurement reported to date and the first to achieve a relative precision better than 10^{-4}.

The two experiments were performed at TRIUMF's Isotope Separator and Accelerator (ISAC) facility [19].

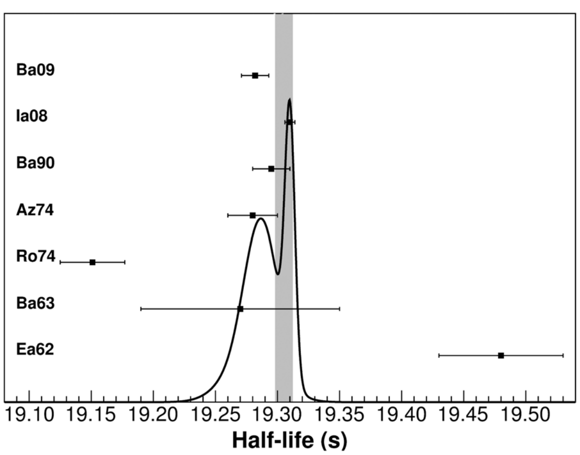

FIG. 1. Previous ^{10}C half-life measurements as reported in Ba09 [12], Ia08 [13], Ba90 [14], Az74 [15], Ro74 [16], Ba63 [17], and Ea62 [18]. The solid curve is an ideograph representing the sum of normal curves from the four most precise measurements [12–15], yielding the adopted world average [2] shown by the gray band.

A 14 μA beam of 480 MeV protons from TRIUMF's main cyclotron was incident on a composite NiO/Ni target with a thickness of 23.8 g/cm^2 Ni and 3.2 g/cm^2 O. The spallation products subsequently diffused from the target and were ionized with a forced electron beam induced arc discharge ion source [20]. A high-resolution mass separator was then used to select a singly ionized radioactive beam of either molecular $^{10}\mathrm{C}^{16}\mathrm{O}^+$ ($A = 26$) with an average yield of 1.5×10^5 s^{-1} or atomic $^{10}\mathrm{C}^+$ ($A = 10$) with an average yield of 2.5×10^4 s^{-1}, which were delivered to the experimental facilities at an energy of 20.4 keV.

The first experiment was performed with the 8π γ-ray spectrometer, an array of 20 high-purity germanium (HPGe) detectors [21,22]. The $A = 26$ molecular radioactive beam was delivered to the 8π spectrometer and implanted into the thick (9.4 μm) Al layer of an aluminized Mylar tape at the center of the spectrometer. Measurements were performed in cycles composed of 9 s of background counting, a "beam-on" period of 60 s during which a $^{10}\mathrm{C}^{16}\mathrm{O}$ sample was accumulated in the tape, followed by a decay period of approximately 500 s (≈25 ^{10}C half-lives) during which the decay activity was measured, with the radioactive beam deflected after the mass separator. Following the decay, the tape was moved from the center of the array into a box shielded by a lead wall in order to remove any potential long-lived contaminants. The cycle was then repeated. Approximately 10 such measurement cycles composed a "run," after which electronic settings, such as the HPGe spectroscopy amplifier shaping times or fixed system dead times, were modified and a new run was started.

In the 8π experiment, the ^{10}C half-life was measured by selecting the characteristic 718-keV γ ray that follows 100% of ^{10}C β decays by requiring the detection of this γ photopeak in the high-resolution HPGe detectors. Special care was taken to ensure that the effects of both system dead time and pileup in the HPGe detectors were taken into account as described in Ref. [23]. Following the inspection of each individual cycle, the pile-up and dead-time corrected data were summed for each run and the total activity within the 718-keV photopeak gate was fit to a function that included the integral over each time bin of an exponential ^{10}C decay, with free initial activity and half-life, as well as a constant background component, using a Poisson log-likelihood function in a Levenberg Marquardt χ^2 minimization method [24]. The run-by-run half-lives and the resulting fit to the summed global data set during the beam-off decay period are shown in Fig. 2, and yield $T_{1/2} = 19.2969 \pm 0.0052_{(\mathrm{stat})}$ s with a $\chi^2/\nu = 1.19$.

Possible contributions within the 718-keV photopeak gate arising from contaminants in the $A = 26$ beam were carefully considered and upper limits set on each such contaminant were found to have negligible impact on the deduced ^{10}C half-life compared to the statistical uncertainty

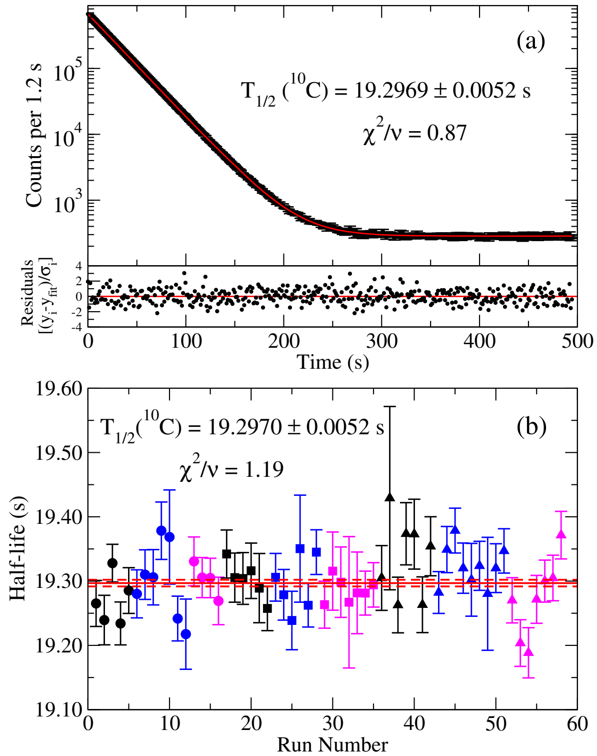

FIG. 2. (a) The summed pile-up and dead-time corrected data (black) and the best fit (red) from the γ-ray counting experiment. (b) The run-by-run ^{10}C half-life determinations. The blue, magenta, and black data points correspond to applied dead times of 40 μs, 27 μs, and variable, respectively, and the circles, squares, and triangles correspond to shaping times of 0.5, 1.0, and 2.0 μs, respectively.

quoted above. These included (i) ^{26}Na ($T_{1/2} = 1.07128 \pm 0.00025$ s [24]), for which the absence of the 1809-keV γ ray from ^{26}Na decay in the data from the initial beam-on period set very stringent limits on its contribution to the spectrum, (ii) ^{26m}Al ($T_{1/2} = 6346.02 \pm 0.54$ ms [2,25]), which does not emit γ radiation but could make a contribution to the γ-ray spectrum at 718 keV due to bremsstrahlung from the stopping of the ^{26m}Al decay positrons, alone or in coincidence with the positron annihilation radiation, for which a dedicated β counting measurement with the mass separator retuned for the ^{26m}Al mass showed no evidence, and (iii) ^{13}N ($T_{1/2} = 9.9670 \pm 0.0037$ min [26]), which also does not emit γ radiation but was observed in the β counting experiment as an $A = 26$ molecular beam contaminant (likely as $^{13}N_2$ or $H^{12}C^{13}N$, either of which would not be separated from $^{10}C^{16}O$ by the mass separator), but for which a GEANT4 simulation of the bremsstrahlung production and annihilation radiation indicated an expected contribution of less than two counts within the 718-keV γ ray gate in the entire experiment.

To further investigate potential rate-dependent effects, a channel chop analysis was performed in which the data from leading channels were removed and the remaining data refit. The procedure was repeated until the data from approximately 3 half-lives were removed. No statistically significant change in the ^{10}C half-life was observed.

Finally, sources of systematic uncertainties were considered by searching for any statistically significant changes in the ^{10}C half-life under the different experimental running conditions. Grouping the data according to the different experimental conditions indicated in Fig. 2(b) resulted in a $\chi^2/\nu = 1.01$ for the different amplifier shaping times and a $\chi^2/\nu = 2.01$ for the different system dead times. Although a $\chi^2/\nu \geq 2$ is expected 13% of the time for 2 degrees of freedom, we follow the conservative convention of the Particle Data Group [27] and scale the statistical uncertainty by the largest $\sqrt{\chi^2/\nu} = \sqrt{2.01}$. The final ^{10}C half-life values from the γ-ray photopeak counting experiment is thus

$$T_{1/2}(^{10}\mathrm{C})_\gamma = 19.2969 \pm 0.0074 \text{ s}. \tag{1}$$

The second experiment was performed using both $^{10}C^{16}O$ molecular and ^{10}C atomic radioactive beams delivered to a second experimental station which houses a 4π continuous-flow gas proportional counter that detects β particles with near 100% efficiency [28]. The beam was implanted under vacuum into the thick (17.2 μm) Al layer of an aluminized Mylar tape [28]. Following implantation, the sample was first allowed to "cool" for 6–44 s in order to limit the maximum rate in the gas counter to $\lesssim$14 kHz ($\lesssim$10 kHz for the majority of the running time). The tape was subsequently moved to position the sample at the center of the 4π gas counter where the activity was measured for approximately 500 s. As a systematic check, two different gas counters with different voltage plateau regions of 2700–2800 and 2400–2600 V were used at different stages of the experiment. During the decay period, the amplified and discriminated pulses from the gas counter were fanned to two LeCroy 222N gate-and-delay generators, enforcing two different fixed and nonextendible dead times, measured to be 3.0039 ± 0.0079 and 4.0127 ± 0.0080 μs, respectively, by the source-plus-pulser technique [29]. The dead-time-affected data from the two gate-and-delay generators were simultaneously multiscaled in two multichannel scalars, with channel dwell times that were varied between 1.0 and 1.4 s. The tape was then moved into a tape disposal box in order to remove any long-lived contaminants, and the cycle was repeated.

A single contaminant, identified as ^{13}N, was measured in the $A = 26$ molecular beam and was included as a component in the fitting procedure with free initial activity and fixed half-life [26]. A sample decay curve as well as the run-by-run half-lives are shown in Fig. 3. A total of 83 different runs were taken in which experimental conditions were varied before the start of each new run, including the discriminator threshold, the detector bias voltage, the dwell

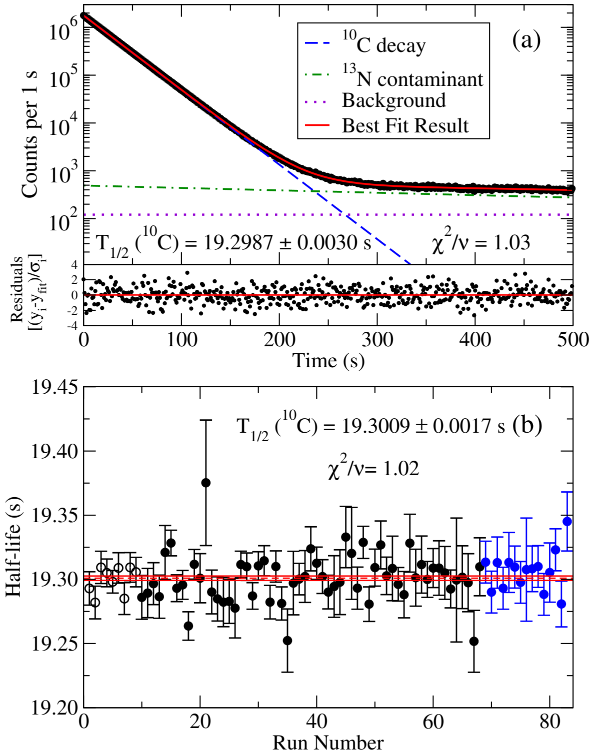

FIG. 3. (a) The decay curve and fit from the subset of the β counting data with a dwell time of 1.0 s and a radioactive beam of $^{10}C^{16}O$. The run-by-run half-life determinations are shown in (b) where the open (solid) circle data points represent runs taken with a ^{10}C ($^{10}C^{16}O$) beam and the black (blue) data points represent the data taken with gas counter 1 (2).

time, the initial ^{10}C activity, the atomic ^{10}C or molecular $^{10}C^{16}O$ radioactive beam, and the two separate gas counters. The systematic groupings for each of these parameters are shown in Fig. 4. Since there is no grouping with $\chi^2/\nu > 1$, the statistical uncertainty is inflated by $\sqrt{\chi^2/\nu} = \sqrt{1.02}$ obtained from the 83 run-by-run half-lives, resulting in no change in the quoted uncertainty.

Additionally, the ^{13}N half-life and the measured dead times were varied within their $\pm 1\sigma$ limits to determine their effect on the deduced half-life. Although no change in the ^{10}C half-life is obtained when the ^{13}N half-life is varied, varying the dead times did add an additional uncertainty of 0.0004 s. This is included as a systematic uncertainty; however, when added in quadrature with the statistical uncertainty, no change is obtained. Including all of the aforementioned systematic uncertainties, the deduced ^{10}C half-life is

$$T_{1/2}(^{10}\mathrm{C})_\beta = 19.3009 \pm 0.0017 \text{ s}. \qquad (2)$$

This represents the single most precise superallowed half-life measurement reported to date.

An updated ideograph of the ^{10}C half-life measurements including the β and γ-ray counting measurements reported here is shown in Fig. 5 and represents a significant improvement in the confidence that should be placed in this important half-life compared to the prior situation depicted in Fig. 1. The six most precise half-life measurements shown in Fig. 5 give $\chi^2/\nu = 1.90$ and, following the procedures of Ref. [5] for scaling of the uncertainty, result in a new world-average half-life for ^{10}C of $T_{1/2} = 19.3015 \pm 0.0025$ s. Including this updated ^{10}C half-life, as well as recent improvements in the ^{14}O superallowed Q_{EC} value [7] and branching ratio [8], the reciprocal of the corrected $\mathcal{F}t$ values for the 14 precisely determined superallowed decays [2] are plotted versus $\gamma\langle W^{-1}\rangle$ in Fig. 6. The

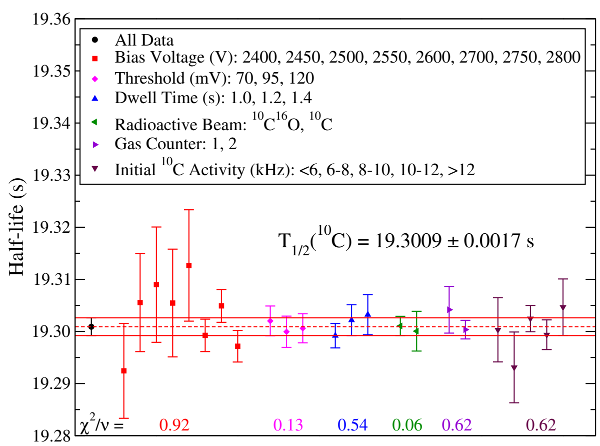

FIG. 4. Grouping of the data according to the different experimental parameters used in the β counting experiment as described in the text. No statistically significant systematic effects were observed.

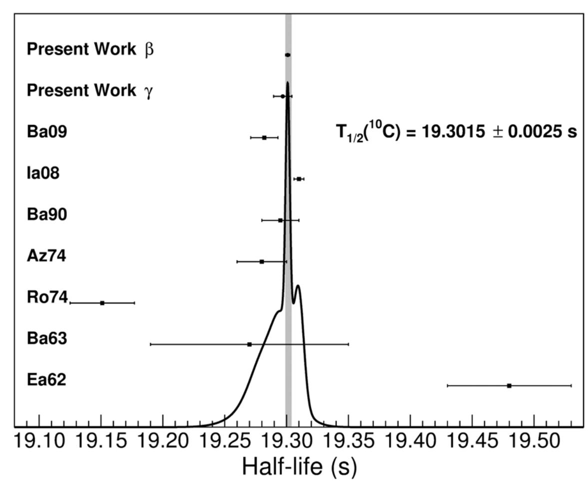

FIG. 5. Individual ^{10}C half-life measurements [12–18], including the two measurements reported in this work. The black curve is the sum of normal curves from the six most precise measurements, with the shaded band representing the new ^{10}C world average half-life of 19.3015 ± 0.0025 s calculated from these six measurements.

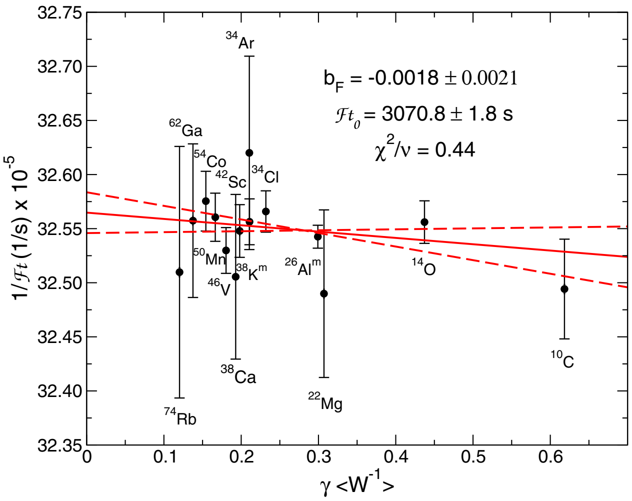

FIG. 6. Plot of $(\mathcal{F}t)^{-1}$ as a function of $\gamma\langle W^{-1}\rangle$ for the 14 most precisely measured $0^+ \to 0^+$ superallowed emitters. The slope yields an updated value of $b_F = -0.0018 \pm 0.0021$ for the Fierz interference term.

slope of this plot yields $b_F = -0.0018 \pm 0.0021$, including a small systematic uncertainty contribution from the transition-dependent radiative corrections [2], and remains fully consistent with the absence of weak scalar currents, yielding $C_S/C_V = +0.0009 \pm 0.0011$ under the assumption of left-handed neutrinos. The reduction in the uncertainty on b_F from the value of ± 0.0026 that has been reported in all surveys of the superallowed data for the past decade [2,5] results primarily from the recent reduction in the ^{14}O superallowed $\mathcal{F}t$-value uncertainty [7,8], while the high-precision ^{10}C half-life measurements reported here resolve the possibility of a significant ($\sim 0.5\sigma$) shift in the central value of b_F raised by the inconsistencies in the previous ^{10}C half-life measurements shown in Fig. 1. Further improvements in b_F from the superallowed β-decay data will require a higher-precision branching-ratio measurement for ^{10}C [10,11] and/or improvements in the nuclear-structure-dependent theoretical corrections [2,30], which now dominate the uncertainties in the $\mathcal{F}t$ values for all of the other 9 superallowed decays with experimental ft values determined to better than $\pm 0.15\%$.

This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Canada Research Chairs Program. TRIUMF receives federal funding via a contribution agreement through the National Research Council of Canada. This research received funding from the CNRS(France)/TRIUMF (Canada) PICS program (No. PICS 6207).

*boudream@uoguelph.ca

[1] O. Naviliat-Cuncic and M. Gonzaléz-Alonso, Ann. Phys. (Berlin) **525**, 600 (2013).
[2] J. C. Hardy and I. S. Towner, Phys. Rev. C **91**, 025501 (2015).
[3] J. D. Jackson, S. B. Treiman, and H. W. Wyld, Phys. Rev. **106**, 517 (1957).
[4] R. P. Feynman and M. Gell-Man, Phys. Rev. **109**, 193 (1958).
[5] J. C. Hardy and I. S. Towner, Phys. Rev. C **71**, 055501 (2005).
[6] A. T. Laffoley *et al.*, Phys. Rev. C **88**, 015501 (2013).
[7] A. A. Valverde *et al.*, Phys. Rev. Lett. **114**, 232502 (2015).
[8] P. A. Voytas, E. A. George, G. W. Severin, L. Zhan, and L. D. Knutson, Phys. Rev. C **92**, 065502 (2015).
[9] T. Eronen *et al.*, Phys. Rev. C **83**, 055501 (2011).
[10] G. Savard, A. Galindo-Uribarri, E. Hagberg, J. C. Hardy, V. T. Koslowsky, D. C. Radford, and I. S. Towner, Phys. Rev. Lett. **74**, 1521 (1995).
[11] B. K. Fujikawa *et al.*, Phys. Lett. B **449**, 6 (1999).
[12] P. H. Barker, K. K. H. Leung, and A. P. Byrne, Phys. Rev. C **79**, 024311 (2009).
[13] V. E. Iacob, J. C. Hardy, V. Golovko, J. Goodwin, N. Nica, H. I. Park, L. Trache, and R. E. Tribble, Phys. Rev. C **77**, 045501 (2008).
[14] P. H. Barker and G. D. Leonard, Phys. Rev. C **41**, 246 (1990).
[15] G. Azuelos, J. E. Crawford, and J. E. Kitching, Phys. Rev. C **9**, 1213 (1974).
[16] D. C. Robinson and P. H. Barker, Nucl. Phys. **A225**, 109 (1974).
[17] F. J. Bartis, Phys. Rev. **132**, 1763 (1963).
[18] L. G. Earwaker, J. G. Jenkin, and E. W. Titterton, Nature (London) **195**, 271 (1962).
[19] J. Dilling, R. Krücken, and G. Ball, Hyperfine Interact. **225**, 1 (2014).
[20] P. Bricault, F. Ames, T. Achtzehn, M. Dombsky, F. Labrecque, J. Lassen, J.-P. Lavoie, and N. Lecesne, Rev. Sci. Instrum. **79**, 02A908 (2008).
[21] C. E. Svensson *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **204**, 660 (2003).
[22] A. B. Garnsworthy and P. E. Garrett, Hyperfine Interact. **225**, 121 (2014).
[23] G. F. Grinyer *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **579**, 1005 (2007).
[24] G. F. Grinyer *et al.*, Phys. Rev. C **71**, 044309 (2005).
[25] P. Finlay *et al.*, Phys. Rev. Lett. **106**, 032501 (2011).
[26] M. M. Bé *et al.*, in *Table of Radionuclides* (Bureau International des Poids et Mesures (BIPM), Sèvres, Cedex, 2004), Vol. 1.
[27] K. A. Olive *et al.* (Particle Data Group), Chin. Phys. C **38**, 090001 (2014).
[28] A. T. Laffoley *et al.*, Phys. Rev. C **92**, 025502 (2015).
[29] A. P. Baerg, Metrologia **1**, 131 (1965).
[30] I. S. Towner and J. C. Hardy, Phys. Rev. C **77**, 025501 (2008).