Superallowed beta decay

J.C. Hardy, V.E. Iacob, H.I. Park, N. Nica, M. Bencomo, T. Eronen, V. Horvat, L. Chen, and I.S. Towner

Superallowed $0^+ \rightarrow 0^+$ beta decay between T=1 analogue states has been a subject of continuous and often intense study for five decades. The *ft* values of such transitions are nearly independent of nuclear-structure ambiguities and depend uniquely on the vector part of the weak interaction. Their measurement gives us access to clean tests of some of the fundamental precepts of weak-interaction theory, and, over the years, this strong motivation has led to very high precision being achieved both in the experiments and in the theory used to interpret them. We have had a major program at the Cyclotron Institute to study superallowed beta decay.

To obtain the *ft* value for any transition, three quantities must be measured: the half-life $t_{1/2}$ of the parent, the Q_{EC} value for the transition of interest, and the branching ratio *R* for that transition. Our most recent complete survey of world data on these superallowed decays, published in 2015 [1], provides a critical evaluation of all the experimental data and obtains final *ft* values from the averaged results. Radiative and isospin-symmetry-breaking corrections were then applied in order to derive a final set of "corrected ft values", denoted $\mathcal{F}t$, for 14 transitions known to ~0.1% precision. Fig. 1 shows the results from our 2018 update of the survey, which has now been increased to 15 transitions through inclusion of our new precise measurement of the superallowed transition from ^{26}Si [2]. Excellent consistency among the average $\mathcal{F}t$ values for all 15 transitions – an expected consequence of the conservation of vector current (CVC) – confirms the validity of the correction terms; and our recent measurements focusing on pairs of mirror superallowed transitions with *A* = 26, 34 and 38 further supports that validity [2-4].

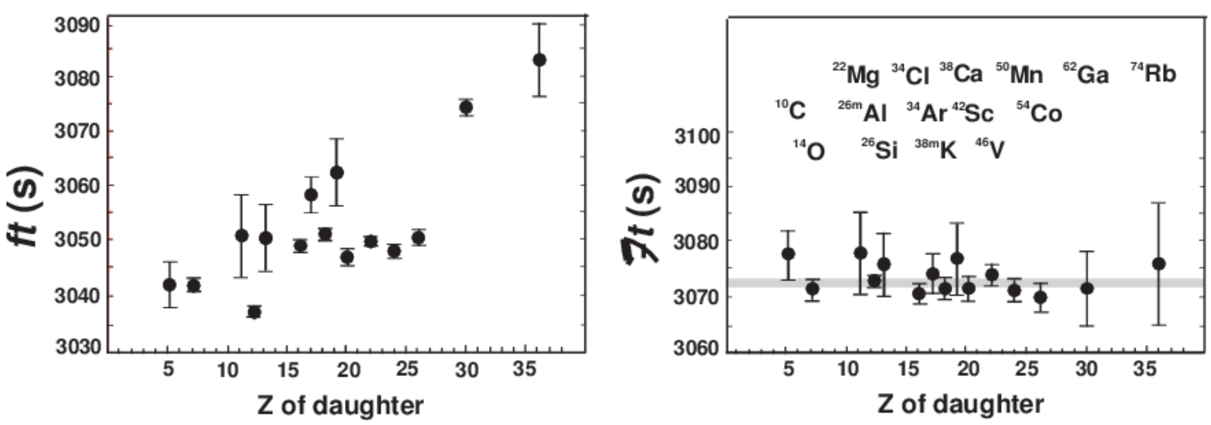

FIG. 1. Results from the 2015 survey [1] updated to 2018: The uncorrected *ft* values for the 15 best known superallowed decays appear on the left; the same results but incorporating the radiative and isospin-symmetry-breaking correction terms are on the right. The grey band in the right panel is the average $\mathcal{F}t$ value and its uncertainty.

The resultant average $\mathcal{F}t$ value, when combined with the muon lifetime, yields the up-down quark-mixing element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, V_{ud} = 0.97420(21), a result that is consistent with, but more precise than, values we have obtained in previous analyses of superallowed β decay. The unitarity test on the top row of the matrix becomes $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99939\ (47)$ if the Particle Data Group recommended value for V_{us} is used. Finally, from the $\mathcal{F}t$ -value data we also set a limit on the possible existence of a scalar interaction.

Although recent adjustments to the value of V_{us} have driven the top-row sum slightly more than a standard deviation below unity, it can still be viewed as a significant verification of the standard model, and the quoted uncertainty used to provide tight limits on any possible new physics beyond the standard model, such as right-hand currents, extra *Z* bosons or supersymmetric models. In short, superallowed $0^+ \rightarrow 0^+$ beta decay provides a high-profile application of nuclear-physics measurements to the study of fundamental symmetries, a subject of vital interest to both nuclear and particle physicists. Although much has already been achieved in this field by nuclear physicists, improvements are still possible. Reducing the uncertainty on the unitarity sum – and, with it, the scope for new physics – has been the primary goal of our research program.

Our approach follows from the observation [1] that the second largest contributor to the uncertainty in V_{ud} is the theoretical uncertainty in the nuclear-structure-dependent corrections, δ_{NS} and δ_C, used in the derivation of the $\mathcal{F}t$ values. Though these corrections are only of order 1%, their effect is very significant: The two panels of Fig. 1 show the result of applying the nuclear-structure-dependent corrections, δ_{NS} and δ_C (together with δ'_R, which is nearly independent of *Z*). Obviously they act very well to remove the considerable “scatter” in *ft* values apparent in the panel on the left, replacing it with the consistent set of corrected $\mathcal{F}t$ values appearing on the right. Since these corrections were determined [5] completely independently of the superallowed decay data, this consistency in $\mathcal{F}t$ values is already a powerful validation of the calculations, but obviously the remaining uncertainty still influences the final result for V_{ud}.

Even though the 2015 survey [1] included more than 222 individual measurements (and the 2018 update includes over a dozen more) relating now to 15 precisely known *ft* values, it is still possible for well selected experiments to make real improvements in the validation tests of the nuclear-structure-dependent correction terms. At TAMU we have been focusing on adding to the *ft*-value list new superallowed transitions, selected from amongst those with *large* calculated corrections. If the *ft* values measured for cases with large calculated corrections also turn into corrected $\mathcal{F}t$ values that are consistent with the others, then this must verify the calculations' reliability for the existing cases, which have smaller corrections. We study decays from $T_z = -1$ parent nuclei, which consistently have higher predicted structure-dependent correction terms than the well-known $T_z = 0$ cases.

Of particular importance are the four $T_z = -1$ parent nuclei – ^{26}Si, ^{34}Ar, ^{38}Ca and ^{42}Ti – whose decays are mirrors to well-known superallowed decays from $T_z = 0$ parents. Specifically, the mirror-decay pairs are $^{26}\text{Si} \rightarrow {}^{26m}\text{Al} \rightarrow {}^{26}\text{Mg}$, $^{34}\text{Ar} \rightarrow {}^{34}\text{Cl} \rightarrow {}^{34}\text{S}$, $^{38}\text{Ca} \rightarrow {}^{38m}\text{K} \rightarrow {}^{38}\text{Ar}$ and $^{42}\text{Ti} \rightarrow {}^{42}\text{Sc} \rightarrow {}^{42}\text{Ca}$. Their importance stems from our observation that the ratio of mirror *ft* values for such cases is very sensitive to the model used to calculate the small isospin-symmetry-breaking corrections δ_{NS} and δ_C. The details have been described in our report on the first measurement of a mirror pair, with *A* = 38 [3].

What made decay measurements on these $T_z = -1$ parent nuclei possible was that, after a long period of incremental upgrades to our experimental techniques, we succeeded in pushing our precision in branching ratio measurements close to ±0.1. This is crucial for the characterization of T_z = -1 parent decays, which – unlike T_Z = 0 decays – exhibit a number of strong Gamow-Teller branches that compete with the superallowed Fermi branch. A first demonstration of our success in this endeavor was our measurement of the superallowed branching ratio for the decay of ^{38}Ca ($t_{1/2}$ = 444 ms) to a precision of ±0.21%, where that precision was actually limited by counting statistics, not systematics [3,4]. Our next precise branching ratio [2] for a T_z = -1 parent nucleus was for ^{26}Si ($t_{1/2}$ = 2.245s), which achieved a precision of ±0.18%, also limited by statistics. To our knowledge, these are the most precise direct branching-ratio measurements ever made for short-lived beta emitters.

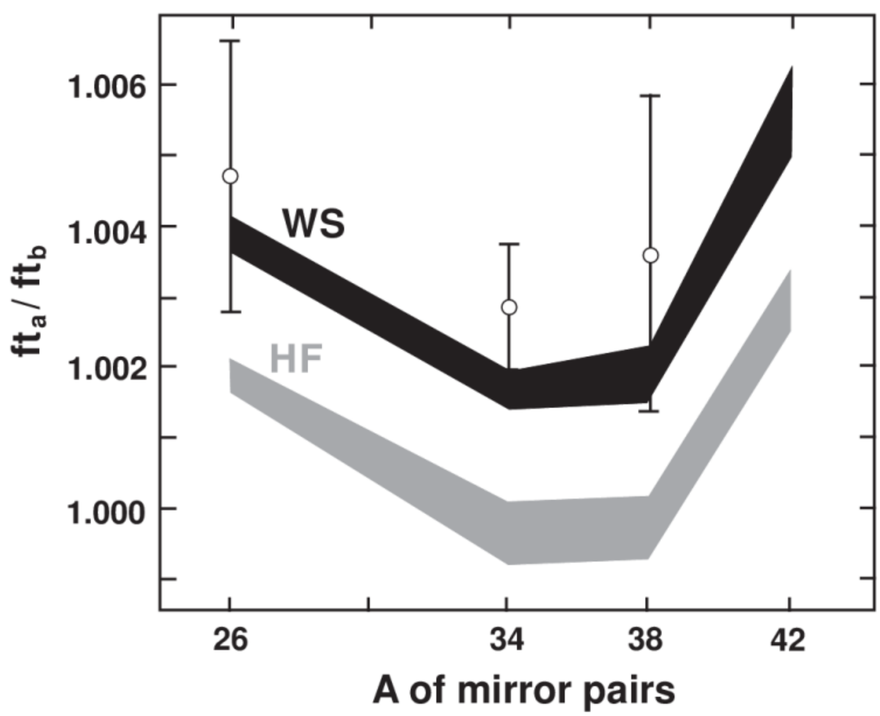

FIG. 2. Mirror-pair ft_a/ft_b values for A = 26, 34, 38 and 42. The black and grey bands connect calculated results that utilize Woods-Saxon (WS) and Hartree-Fock (HF) radial wave functions, respectively. The measured results for A = 26, 34 and 38 appear as open circles with error bars. The A = 34 result is preliminary.

The current status of the mirror-pair measurements is shown in Fig. 2, which also includes our preliminary result for ^{34}Ar. The measured ratios clearly distinguish between the Saxon-Woods-based radial-overlap corrections incorporated in δ_C, and the ones based on Hartree-Fock radial wave functions. All three favor the former over the latter.

We have already completed measurements of the half-life [6] and branching ratio for the superallowed decay of ^{34}Ar. However, the branching-ratio result depends critically on the gamma-branching of the 666-keV level populated by beta decay in the daughter, ^{34}Cl, which decays primarily with a 666-keV γ ray but also weakly with a 519-keV γ ray; the latter is masked in our γ-ray spectrum by the tail of the strong 511-keV annihilation peak. Before publishing our ^{34}Ar results, we have to establish the relative intensity of these two gamma rays. To do so, we have made a ^{33}S (p, γ) ^{34}Cl measurement at Notre Dame University [7]. The analysis is not complete but a preliminary result was used to arrive at the ratio result shown in Fig. 2.

Finally, for ^{42}Ti decay we have completed a successful measurement of its half-life, as well as a test measurement of its branching ratio. A final branching-ratio measurement will occur in 2019.

With a somewhat different focus, in late 2015 we began a new measurement of the branching ratio for the superallowed decay of ^{10}C. Currently the uncertainty on the branching ratio dominates the uncertainty in the ^{10}C $\mathcal{F}t$ value. However, more interesting than just the precision of the $\mathcal{F}t$ value itself is its relationship to the world average of $\mathcal{F}t$ values for transitions in heavier nuclei, since the ^{10}C transition is the most sensitive to the possible presence of a scalar current. Currently the $\mathcal{F}t$ value for ^{10}C is slightly higher than the world average $\mathcal{F}t$ value, with an error bar that just about touches the world average value's error bar. If a more precise $\mathcal{F}t$ value of ^{10}C were found to deviate with greater statistical significance, it would be a signal for the existence of a scalar current. This work is still in progress.

Note that J.C. Hardy, the Principal Investigator for this research program, officially retired at the end of August 2018. He is nevertheless committed to completing the experiments described in this report, but will undertake no new initiatives.

[1] J.C. Hardy and I.S. Towner, Phys. Rev. C **91**, 025501 (2015).
[2] M. Bencomo, J.C. Hardy, V.E. Iacob, H.I. Park, L. Chen, V. Horvat, B.T. Roeder, A. Saastamoinen, and I.S. Towner, submitted to Phys. Rev. C.
[3] H.I. Park, J.C. Hardy, V.E. Iacob, M. Bencomo, L. Chan, V. Horvat, N. Nica, B.T. Roeder, E. Simmons, R.E. Tribble, and I.S. Towner, Phys. Rev. Lett. **112**, 102502 (2014).
[4] H.I. Park, J.C. Hardy, V.E. Iacob, M. Bencomo, L. Chen, V. Horvat, N. Nica, B.T. Roeder, E. McCleskey, R.E. Tribble, and I.S. Towner, Phys. Rev. C **92**, 015502 (2015).
[5] I.S. Towner and J.C. Hardy, Phys. Rev. C **77**, 025501 (2008).
[6] V.E. Iacob *et al*., *Progress in Research,* Cyclotron Institute, Texas A&M University (2018-2019), p. I-5.
[7] H.I. Park *et al*., *Progress in Research*, Cyclotron Institute, Texas A&M University (2018-2019), p. I-8.