Superallowed beta decay

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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 in both the experiments and the theory used to interpret them. We have a major program at the Cyclotron Institute to study superallowed beta decay.

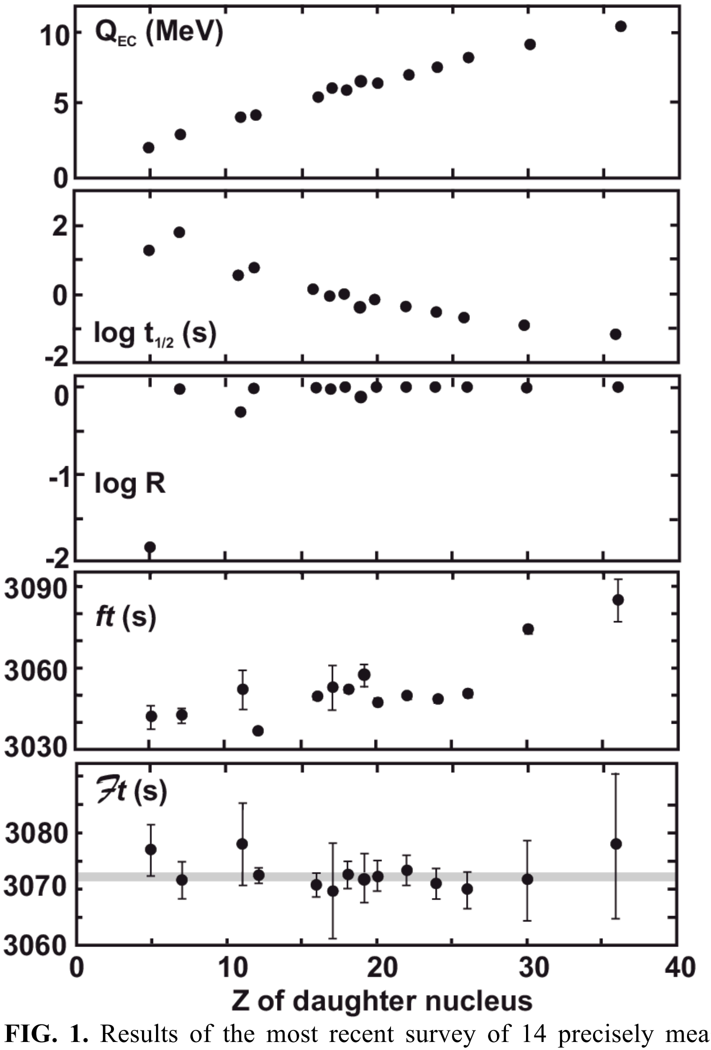

FIG. 1. Results of the most recent survey of 14 precisely measured superallowed $0^+ \rightarrow 0^+$ β transitions [1]. The parents of these trans-itions are ^{10}C, ^{14}O, ^{22}Mg, ^{26m}Al, ^{34}Cl, ^{34}Ar, ^{38m}K, ^{38}Ca, ^{42}Sc, ^{46}V, ^{50}Mn, ^{54}Co, ^{62}Ga and ^{74}Rb. The top three panels present the average Q_{EC}, log $t_{1/2}$ and log R values for each transition. The bottom two panels give the corresponding ft and $\mathcal{F}t$ values. The shaded horizontal line in the bottom panel is the average $\mathcal{F}t$ value for all transitions. Where no error bars are visible, they are smaller than the data point.

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 final *ft* values obtained from the averaged results, to which radiative and isospin-symmetry-breaking corrections have been applied in order to derive a final set of "corrected ft values", denoted $\mathcal{F}t$ for 14 transitions known to ~0.1% precision (see Fig. 1). Excellent consistency among the average $\mathcal{F}t$ values for all 14 transitions – an expected consequence of the conservation of vector current (CVC) – confirms the validity of the correction terms; and our recent measurement of ^{38}Ca decay [2, 3], which closely compares a pair of mirror superallowed transitions with $A = 38$, further supports that validity.

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, $V_{ud} = 0.97417(21)$, 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 $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99978\ (55)$ if the Particle Data Group recommended value for V_{us} is used. However, recent lattice QCD calculations, not included yet in the PDG evaluation, have introduced some inconsistency into kaon-decay measurements of V_{us} and V_{us}/V_{ud} . In ref. [1], we have examined the impact of these new results on the unitarity test and conclude that there is no evidence of any statistically significant violation of unitarity. Finally, from the $\mathcal{F}t$-value data we also set limits on the possible existence of scalar interactions.

This result is not only a significant verification of the standard model but the uncertainty quoted on the sum provides a tight limit 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 – remains 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 bottom 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 second panel from the bottom, replacing it with the consistent set of corrected $\mathcal{F}t$ values appearing in the bottom panel. Since these corrections were determined [4] completely independently of the superallowed decay data, this consistency in $\mathcal{F}t$ values is already a powerful validation of these calculated corrections, 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 relating to 14 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 are currently 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 are studying 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 [2]. Until very recently, none of the T_z = -1 parent decays was known precisely enough to provide a statistically significant constraint on the correction terms via the ratio of mirror *ft* values, but we are now well on our way to rectifying this situation.

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%, our ultimate goal. 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 demonstration of our success in this endeavor is our measurement of the superallowed branching ratio for the decay of ^{38}Ca ($t_{1/2}$ = 444 ms) to a precision of ±0.2%, where that precision was actually limited by counting statistics, not systematics [2, 3]. An important aspect of these decays is the possibility of weak beta decays to highly excited states in the daughter, which are too weak to be observed individually but in total could constitute sufficient strength to affect the branching ratio obtained for the superallowed branch. These have been investigated theoretically for ^{34}Ar and ^{38}Ca decay, and found to be negligibly small [3, 5].

To our knowledge, this is the most precise direct branching-ratio measurement ever made for a short-lived beta emitter. It also provides the first mirror pair of $0^+ \rightarrow 0^+$ superallowed emitters (^{38}Ca and $^{38}\text{K}^m$) that is precise enough to distinguish meaningfully between the Saxon-Woods-based radial-overlap correction, δ_{C2}, and the one based on Hartree-Fock radial wave functions. It favors the former over the latter, but we must await results from the other mirror pairs before we can be confident of the verdict. We are now well embarked on the measurement of the remaining three accessible pairs. We have already made a measurement of the branching ratio for the superallowed decay of ^{34}Ar, which is being prepared for publication; and we have also re-measured its half-life [6]. In addition, we have made a successful measurement of the ^{26}Si beta-decay branching ratios, which is under analysis as the thesis project of M. Bencomo [7]. Finally we have made an initial measurement of the half-life of ^{42}Ti [8], which is also now under analysis. Likely a follow-up measurement will be required for us to achieve the precision we seek.

Our 2015 survey incorporated 20 superallowed transitions [1], which we deemed to be all those that were likely to be accessible in the near future. By the time the survey was published our prediction had already been proven wrong by the publication from GSI of a new measurement of the half-lives and Gamow-Teller branching ratios for the β decays of ^{42}Ti, ^{46}Cr, ^{50}Fe and ^{54}Ni. Although the ^{42}Ti superallowed transition was included in our survey, the other three were not. Consequently we have published an addendum to our 2015 survey [9], in which we extended the same evaluation of world data to the three new superallowed parents [10], and we also included calculations of the correction terms [11] required to understand the results. These decays are not yet known precisely enough to contribute to the determination of V_{ud}, but all the required information is now available for the time when more precise measurements are available.

We are also endeavoring to improve our data acquisition techniques for half-life measurements by a variety of means, including the addition of a TDC-based approach, and a digital-pulse-analysis system. The TDC system has already proved very useful in disentangling a problem with our ^{42}Ti measurement [8], and the digital system is currently being upgraded to increase its gain so as to avoid rate-dependent threshold effects [8]. We continue to test both these new systems while continuing to rely on our tried-and-true analog system to provide our primary data. We also continue to refine our measurement techniques [12] and to explore potential improvements in the statistical handling of our data [13].

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