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.

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, just published [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], 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.

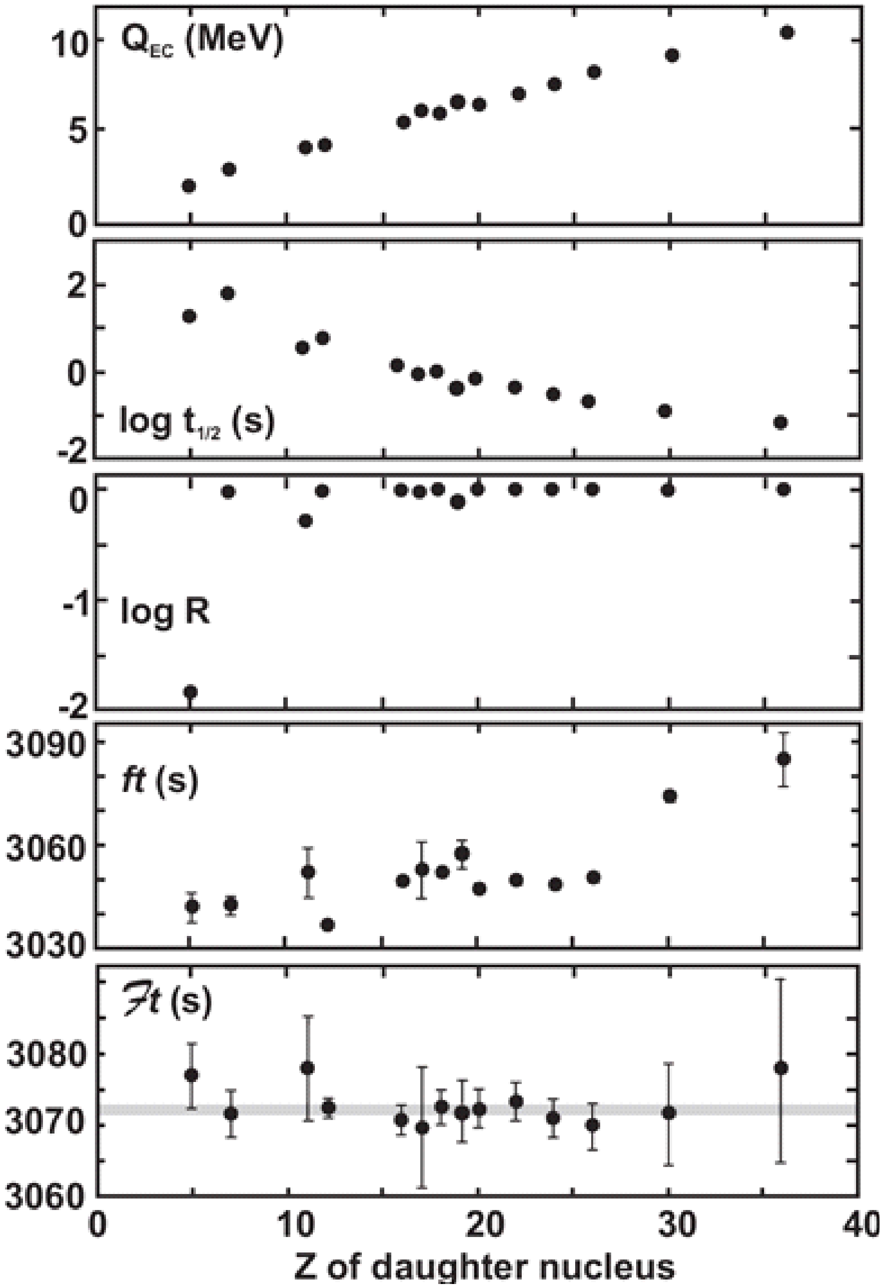

FIG. 1. Results from the most recent survey of 14 precisely measured superallowed $0^+ \rightarrow 0^+$ β transitions [1]. The parents of these transitions, from left to right, are ^{10}C, ^{14}O, ^{22}Mg, ^{26m}Al, ^{34}Cl, ^{34}Ar, ^{38m}K, ^{38}Ca, ^{42}Sc, ^{46}V, ^{50}Mn, ^{54}Co, ^{62}Ga and ^{74}Rb. The top three panels present the average of measured 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 represents the overall average $\mathcal{F}t$ value for all transitions. All error bars are shown: in the cases where none are visible, they are smaller than the data point.

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 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 [3] 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 $^{26}\mathrm{Si} \rightarrow {}^{26m}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}$, $^{34}\mathrm{Ar} \rightarrow {}^{34}\mathrm{Cl} \rightarrow {}^{34}\mathrm{S}$, $^{38}\mathrm{Ca} \rightarrow {}^{38m}\mathrm{K} \rightarrow {}^{38}\mathrm{Ar}$ and $^{42}\mathrm{Ti} \rightarrow {}^{42}\mathrm{Sc} \rightarrow {}^{42}\mathrm{Ca}$. 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 [2,4]. 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 [5].

To our knowledge, this is the most precise direct branching-ratio measurement ever made for short-lived beta emitter. It also provides the first mirror pair of $0^+ \rightarrow 0^+$ superallowed emitters (^{38}Ca and ^{38}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, the data from which are currently being analyzed [6]; and we have also re-measured its half-life [7]. In addition, we have also made a successful measurement of the ^{26}Si beta-decay branching ratios, which is under analysis as the thesis project of M. Bencomo [8]. Finally, successful test measurement of the half-life of ^{42}Ti [9] has led to a full-blown measurement now scheduled for June 2015.

We are also endeavoring to improve our data acquisition techniques for half-life measurements by a variety of means, including a digital-pulse-analysis system for the signals from our 4π proportional gas counter. We have been exploring a variety of algorithms for distinguishing real beta pulses from spurious ones [10,11] and have been testing our results on the data from an experiment to measure the half-life of another $T_z = -1$ superallowed emitter, ^{30}S, in which we have used three different methods for taking data from the proportional gas counter: our standard analog technique, a TDC-based approach, and the digital-pulse-analysis system. The results, which are still under study, will determine whether we can improve our half-life precision in future and, if so, by which path. It will also yield the first precise study of this previously neglected superallowed emitter.

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