

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 of the parent, the Q_{EC} value for the transition of interest, and the branching ratio for that transition. Our most recent complete survey of existing data on these superallowed decays, published in 2009 [1], provided a critical evaluation of all the experimental data and obtained final ft values from the averaged results, to which improved radiative and isospin-symmetry-breaking corrections [2] were applied in order to derive a final set of “corrected ft values”, denoted $\mathcal{F}t$ (see Fig. 1). One of the new features added at that time was that we calculated the radial-overlap correction, δ_{C2} , with Hartree-Fock radial wave functions as well as the Saxon-Woods wave functions we have used before. The differences in the results from these two methods are used as a measure of the systematic uncertainty to be applied to the theoretical corrections. These differences also offer the possibility that measured ft values with the highest precision could actually distinguish between the two methods and thereby reduce the systematic uncertainty.

With the updated world data and improved corrections the $\mathcal{F}t$ values were seen to be completely consistent with one another, thus demonstrating the constancy of G_V to 1.3 parts in 10^4 . Not only is this an important confirmation of the Conserved Vector Current (CVC) hypothesis but it sets the stage for using the average value of G_V to test a fundamental principle of the electroweak standard model: the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The up-down quark mixing element of that matrix, V_{ud} , is given by $V_{ud} = G_V / G_F$, where G_F is the weak interaction constant for the purely leptonic muon decay. The value of V_{ud} is a key component of the most demanding test available for the unitarity of the CKM matrix, the sum of squares of its top-row elements [1]. As elaborated in our 2010 review article on the evaluation of V_{ud} [3], superallowed nuclear beta decays provide by far the most precise and reliable value for V_{ud} and, in fact, that element is also the most precisely known one in the CKM matrix – by an order of magnitude! Its current value [1,3,4] is 0.97425(22), a result that yields the most up-to-date CKM unitarity sum of 1.0008(56) [4], in full agreement with the standard-model expectation, and carrying the smallest uncertainty yet obtained.

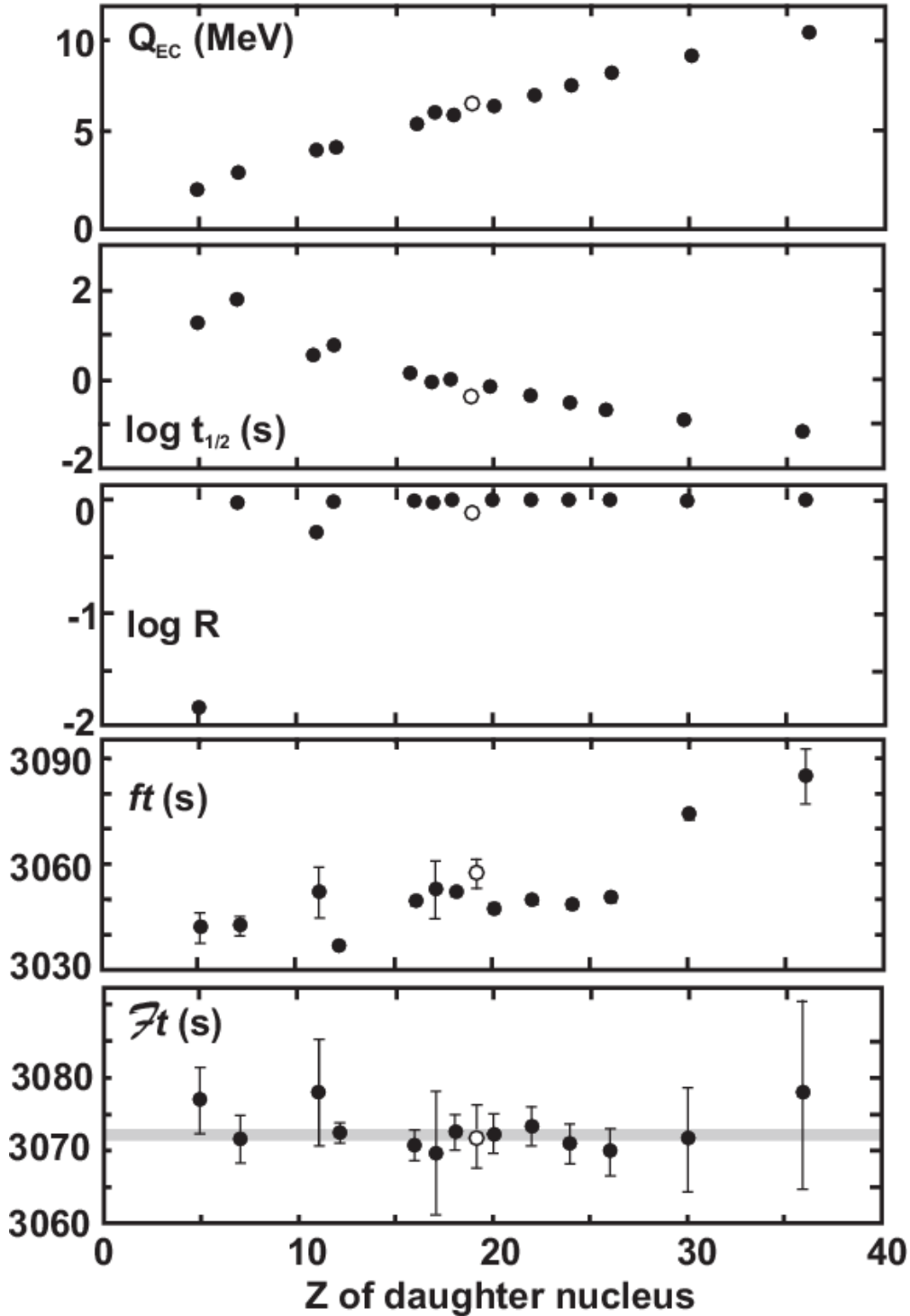


FIG. 1. Results from the most recent survey of 13 precisely measured superallowed $0^+ \rightarrow 0^+$ β transitions appear as solid black circles. The parents of these transitions, from left to right, are ^{10}C , ^{14}O , ^{22}Mg , $^{26}\text{Al}^m$, ^{34}Cl , ^{34}Ar , $^{38}\text{K}^m$, ^{42}Sc , ^{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 Ft values. The shaded horizontal line in the bottom panel represents the overall average Ft value for all transitions. All error bars are shown: in the cases where none are visible, they are smaller than the data point. Recent results for ^{38}Ca are shown as open circles.

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 [1,3,4] 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 $\mathcal{F}t$ 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 [2] 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 2009 survey [1] included more than 145 individual measurements relating to 13 precisely known $\mathcal{F}t$ 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 $\mathcal{F}t$ -value list new superallowed transitions, selected from amongst those with *large* calculated corrections. If the $\mathcal{F}t$ 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 $^{26}\text{Si} \rightarrow ^{26}\text{Al}^m \rightarrow ^{26}\text{Mg}$, $^{34}\text{Ar} \rightarrow ^{34}\text{Cl} \rightarrow ^{34}\text{S}$, $^{38}\text{Ca} \rightarrow ^{38}\text{K}^m \rightarrow ^{38}\text{Ar}$ and $^{42}\text{Ti} \rightarrow ^{42}\text{Sc} \rightarrow ^{42}\text{Ca}$. Their importance stems from our observation that the ratio of mirror $\mathcal{F}t$ 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 are described elsewhere in this Progress Report [5]. 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 $\mathcal{F}t$ 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 have succeeded in pushing our precision in branching ratio measurements close to $\pm 0.1\%$, 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 very recent determination of the superallowed branching ratio for the

decay of ^{38}Ca ($t_{1/2} = 444$ ms) to a precision of $\pm 0.2\%$, where that precision was actually limited by counting statistics, not systematics. This experiment, the results of which were published recently in Physical Review Letters [6], is described briefly elsewhere in this report [7].

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 $^{38}\text{K}^m$) 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 , the data from which are currently being analyzed [8]; we have had a successful test experiment on ^{42}Ti [9]; and we have a run to measure the branching ratio from ^{26}Si scheduled for August 2014

We are also endeavoring to improve our data acquisition techniques for half-life measurements by a variety of means, including a new TDC-based data-acquisition system, which allows us to determine half-lives by time-interval analysis [10], and a digital-pulse-analysis system for the signals from our 4p proportional gas counter. We have just completed 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, the new TDC-based approach, and the digital-pulse-analysis system. The results 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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