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 $\mathcal{F}t$. 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 recent 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] is 0.97425(22), a result that yields a CKM unitarity sum of 0.99990(60) [3], in full agreement with the standard-model expectation, and carrying the smallest uncertainty yet obtained.

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] 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: Fig. 1, which is taken from our 2009 survey [1], shows 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 left panel, replacing it with the consistent set of corrected $\mathcal{F}t$ values appearing in the right 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}.

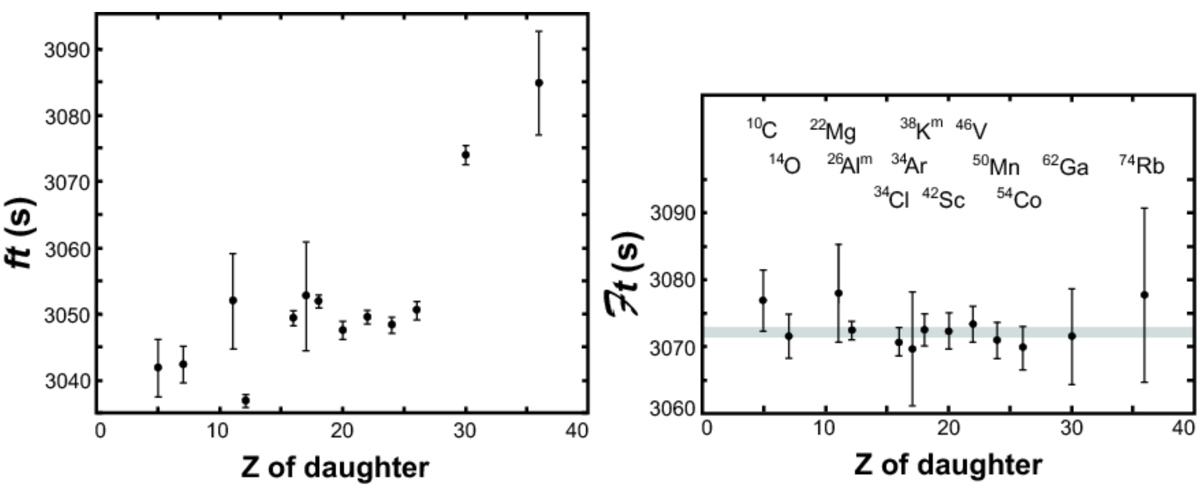

Figure 1. Results from the 2009 survey [1]. The uncorrected *ft* values for the thirteen best known superallowed decays (left) are compared with the same results after corrections have been applied (right). The grey band in the right-hand panel is the average F*t* value, including its uncertainty.

Even though the 2009 survey [1] included more than 145 individual measurements relating to 13 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. In that context, during this past year we have published our half-life measurement for the decay of ^{38}Ca [4], which means that we have now published new precise half-lives for five such T_z = -1 superallowed emitters: ^{10}C, ^{22}Mg, ^{26}Si, ^{34}Ar and ^{38}Ca. We are also hard at work on improving the precision of our branching-ratio measurement capability, which (unlike for the T_z = 0 cases) is crucial to the characterization of T_z = -1 parent decays. To this end, we have made considerable improvements to our electronics and data-acquisition system [5] using off-line sources to generate β-γ coincidences. On-line measurements have so far focused on ^{38}Ca as a test case [6]. At the same time, we have continued to explore from a theoretical perspective [7] what else can be learned from a more exact experimental characterization of the nuclear-structure-dependent correction terms.

There are also compelling reasons to confirm and improve the *ft* values for the T_z = 0 cases as well. After all, these are the transitions that principally determine the value of V_{ud}. Since ^{46}V was a key transition that led to important improvements in the structure-dependent corrections when its Q_{EC} value was found to have been incorrectly measured by reaction studies in the past, we published a re-measurement of its Q_{EC} value last year [8] and this year published its half-life [9]. This confirmed that no errors were lurking in either place.

Each superallowed *ft*-value determination depends critically on the precision of the corresponding Q_{EC}-value measurement, which enters to the fifth power in the determination of *f*. In recent years we have made many such measurements with the JYFLTRAP Penning-trap mass spectrometer at the University of Jyvaskyla cyclotron facility in Finland, where we collaborate with the team there. This facility is ideally suited to the measurement of Q_{EC}-values to sub-100-eV precision. By now we have measured the Q_{EC}-values for 10 superallowed emitters there: ^{10}C, ^{26}Al^{m}, ^{34}Cl, ^{34}Ar, ^{38}K^{m}, ^{38}Ca, ^{42}Sc, ^{46}V, ^{50}Mn and ^{54}Co. A review of this work and the steps we have taken to increase its precision has recently been published [10].

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 [11] and a digital-pulse-analysis system for the signals from our 4π proportional gas counter [12]. We are working to eliminate spurious pulses and to reduce our system dead time. Since we limit our count rate to avoid too large a dead-time correction, any reduction in the dead time itself will translate directly into improved statistical uncertainties on our measurements.

Finally, this year in collaboration with D. Melconian and his group we addressed the question of isospin symmetry breaking in the $1^+ \rightarrow 1^+$ superallowed decay of ^{32}Cl to ^{32}S [13]. This is a particularly interesting case since the daughter 1^+ (T = 1) analog state in ^{32}S is at high excitation energy and is surrounded by numerous T = 0 states. Thus the opportunities for isospin mixing are much greater than they are in the $0^+ \rightarrow 0^+$ decays we use to test CKM unitarity. Consequently, the ^{32}Cl superallowed decay branch provides an excellent test of the calculations we use to evaluate isospin symmetry breaking. The calculated δ_C for this case was an unprecedentedly large 4.6(5)%, which turned out to be in fine agreement with the value we measured: 5.3(9)%. In obtaining this result we recognized another complication resulting from the high level density within the β-decay window in ^{32}S, which required our taking special care to account for the Pandemonium effect in the decay analysis [14].

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