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. This year, our complete new survey of existing data on these superallowed decays was published [1]. It replaced our previous one [2], which was already out of date. Although the latter was published as recently as 2005, there had been an avalanche of new measurements – some from our group and some from a variety of other groups worldwide – that had been published in the intervening time.

As in all our surveys, the new one provides a critical evaluation of all the experimental data and obtains final *ft* values from the averaged results, to which improved radiative and isospin-symmetry-breaking corrections [3] have been applied in order to derive a final set of “corrected ft values”, denoted $\mathcal{F}t$. One of the new features added this 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 are 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} [4], 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 [1,4] is 0.97425(22), a result that yields a CKM unitarity sum of 0.99990(60) [4], 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.

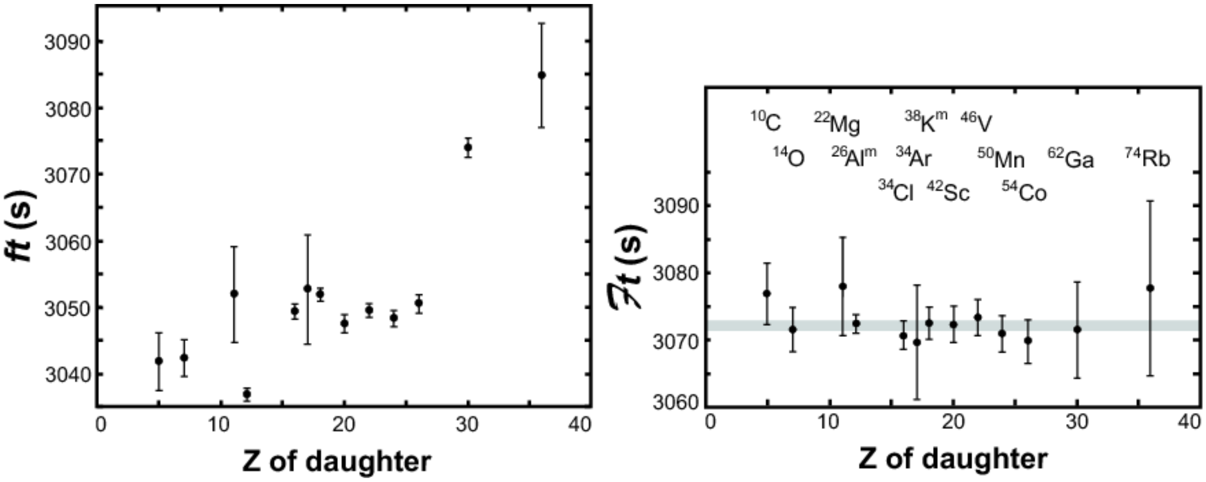

FIG. 1. Results from the 2009 survey [1]. The uncorrected *ft* values for the thirteen best known superallowed decays (left) are compared with the same results after corrections have been applied (right). The grey band in the right-hand panel is the average $\mathcal{F}t$ value, including its uncertainty.

Our approach follows from the observation [1,4] 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: 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 [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 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 continued to work on half-life measurements for the decays of ^{26}Si [5] and ^{38}Ca [6]. A manuscript describing the former has now been submitted to Physical Review C, while the latter is nearing completion and has been reported on at the Washington APS Meeting. At the same time, we have been exploring 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 have been re-measuring its half-life [8] to be sure that no errors are lurking there. In addition we have extended Penning-trap measurements of Q_{EC} values to ^{34}Cl and ^{38}K^{m} [9], which has significantly improved the precision on these two values and has effectively eliminated the possibility of there being systematic differences between reaction-based and Penning-trap-based Q_{EC} value measurements.

We also endeavor to improve our data acquisition techniques for half-life measurements by a variety of means, from x-ray analysis of possible contaminant activities [10] and a new TDC-based data-acquisition system [11] to digital pulse analysis 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. Improvements have also been made to the equipment we use to measure branching ratios [13].

[1] J.C. Hardy and I.S. Towner, Phys. Rev. C **79**, 055502 (2009).

[2] J.C. Hardy and I.S. Towner, Phys. Rev. C **71**, 055501 (2005).

[3] I.S. Towner and J.C. Hardy, Phys. Rev. C **77**, 025501 (2008).

[4] I.S. Towner and J.C. Hardy, *Progress in Research,* Cyclotron Institute, Texas A&M University (2009 -2010), p. III-17; I.S. Towner and J.C. Hardy, Rep. Prog. Phys. **73**, in press.

[5] V.E. Iacob, J.C. Hardy, A. Banu, L. Chen, V.V. Golovko, J. Goodwin, V. Horvat, N. Nica, H.I. Park, L. Trache and R.E. Tribble, *Progress in Research,* Cyclotron Institute, Texas A&M University (2009-2010), p. I-5; submitted to Phys. Rev. C .

[6] H.I. Park, J.C. Hardy, V.E. Iacob, L. Chen, J. Goodwin, V. Horvat, N. Nica, L. Trache and R.E. Tribble, *Progress in Research,* Cyclotron Institute, Texas A&M University (2009-2010), p. I-9

[7] I.S. Towner and J.C. Hardy, *Progress in Research*, Cyclotron Institute, Texas A&M University (2009-2010), p. III-18.

[8] H.I. Park, J.C. Hardy, V.E. Iacob, L. Chen, J. Goodwin, V. Horvat, N. Nica, E. Simmons, L. Trache and R.E. Tribble, *Progress in Research,* Cyclotron Institute, Texas A&M University (2009-2010), p. I-10.

[9] T. Eronen, V.-V Elomaa, J. Hakala, J.C. Hardy, A. Jokinen, I.D. Moore, M. Reponen, J. Rissanen, A. Saastamoinen, C. Weber and J. Aysto, Phys. Rev. Lett. **103**, 252501 (2009); J.C. Hardy, *Progress in Research,* Cyclotron Institute, Texas A&M University (2009-2010), p. I-11.

[10] V. Horvat and J.C. Hardy, *Progress in Research,* Cyclotron Institute, Texas A&M University (2009-2010), p. V-27.

[11] V. Horvat and J.C. Hardy, *Progress in Research,* Cyclotron Institute, Texas A&M University (2009-2010), p. V-24.

[12] L. Chen and J.C. Hardy, *Progress in Research,* Cyclotron Institute, Texas A&M University (2009-2010), p. V-22.

[13] L. Chen and J.C. Hardy, *Progress in Research,* Cyclotron Institute, Texas A&M University (2009-2010), p. V-29.