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. We produced a complete survey of existing data on these superallowed decays two years ago [1, 2]. There, all the experimental data for each transition were critically evaluated and final *ft* values obtained; then, small radiative and isospin-symmetry-breaking corrections [3] were applied and a final set of "corrected ft values", denoted $\mathcal{F}$t, were obtained.

In the two years since our review was published, a number of new experimental results have appeared, some from our group and some from a variety of other groups worldwide. Furthermore, the largest radiative correction – the "inner" one – was revisited and its uncertainty reduced by a factor of two [4]. Figure 1 shows the raw *ft* values and corrected $\mathcal{F}$t values for the most precisely known superallowed $0^+ \rightarrow 0^+$ transitions as they are now known in mid 2007. The constancy of the $\mathcal{F}$t values is evident, their average being 3073.9(8) s, with a normalized χ^2 of 0.9.

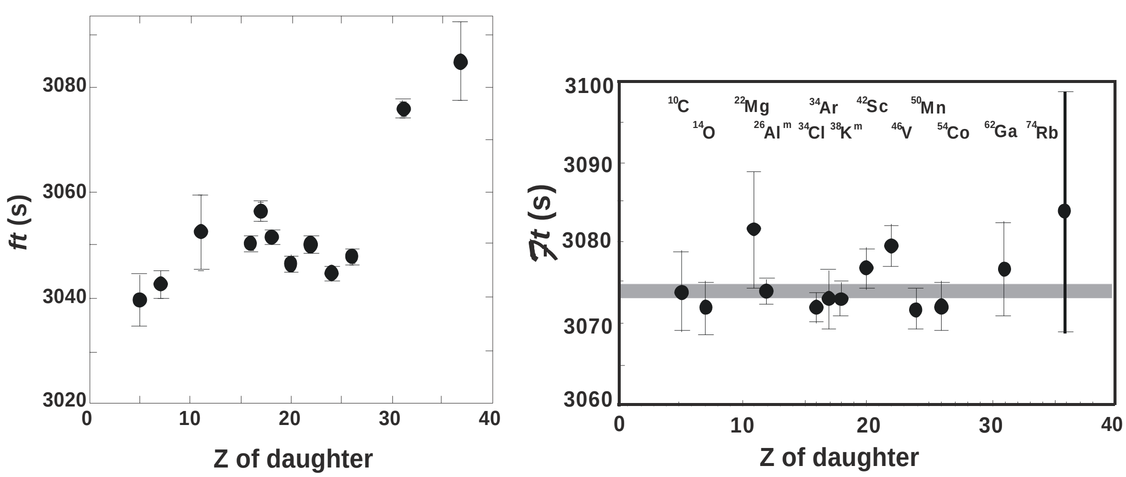

Figure 1. Results from the 2005 survey [1] updated with more recent published results. The uncorrected *ft* values for the thirteen best known superallowed decays (left) are compared with the same results after corrections have been applied (right). The grey band in the right-hand panel is the average $\mathcal{F}t$ value, including its uncertainty.

Since these corrected $\mathcal{F}t$ values are inversely proportional to the square of the vector coupling constant, G_V, the constancy of G_V is demonstrated 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 explained elsewhere in this Progress Report [5], superallowed nuclear beta decays provide by far the most precise and reliable value for V_{ud} and, in fact, that element now is also the most precisely known one in the CKM matrix – by an order of magnitude! Its current value is 0.97378(27)

For several decades, the top-row unitarity sum has differed from unity by several standard deviations but, over the past several years, new results from kaon decay have demonstrated that the value of another element of the top row, V_{us}, was not correct. There is still some dispute over the exact theoretical correction terms to use in determining V_{us}, but the consensus at the moment favors a value for V_{us}, which, when combined with the nuclear value for V_{ud}, yields a unitarity sum of 0.9992(11). This confirmation of CKM unitarity 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.

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.

The principal difference between the left and right panels of Fig 1, is the inclusion of the nuclear-structure-dependent corrections, δ_{NS} and δ_C, in the derivation of the $\mathcal{F}t$ values in the latter. Since these corrections were determined [3] completely independently of the superallowed decay data, the consistency of the $\mathcal{F}t$ values is also a powerful validation of these calculated corrections: obviously they act very well to remove the considerable "scatter" that is apparent in the left panel and is effectively absent in the right one.

The 2005 survey [1, 2], which considered a body of world data comprised of more than 125 individual measurements, presented a remarkably consistent picture for the nuclear results. Even so, it is still possible for well selected experiments to make real improvements. For example, the validation of the nuclear-structure-dependent correction terms can be improved by the addition of new 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. At TAMU we have just completed half-life [6] and branching-ratio [7] measurements for ^{34}Ar decay. This adds ^{34}Ar to the select group of transitions whose $\mathcal{F}t$ values are known to 0.1% or better. Its nuclear-structure-dependent correction is also larger than for any other well known transition with A<40, where the nuclear models used in the calculation are expected to be the most reliable. Conformity of the corrected $\mathcal{F}t$ value for ^{34}Ar with the average result from the other cases provides strong confirmation of the validity of the correction calculations.

We are also studying another superallowed decay with a large calculated correction, ^{38}Ca. We have made some preliminary measurements of both its half-life [8] and branching ratio. Measurements of other new cases with large calculated corrections, such as ^{18}Ne and ^{30}S, are planned.

Another area of potential improvement is in the limit set on scalar currents, the presence of which would manifest themselves as a curvature either up or down in the locus of $\mathcal{F}t$ values at low Z. Thus this limit, currently $f_S < 0.0013$ in electron rest-mass units, is particularly sensitive to the $\mathcal{F}t$-value for ^{10}C. We have re-measured and improved the half-life of ^{10}C [9], with the goal of improving the scalar-current limit.

The nuclear-structure-dependent correction terms can also be tested by tightening the uncertainties on already well-known transitions. Considering the overall quality of world data on superallowed decays, no dramatic surprises were expected as new data appeared. However, two years ago came our measurement with the CPT Penning trap at Argonne National Lab of the Q_{EC} value of the ^{46}V superallowed beta-decay branch [10]. This was the first time a Penning trap had been used for any of the well-known superallowed transitions and the one chosen was the transition whose Q_{EC} value was least precisely known, with the expectation that it would simply improve the precision of the average. Indeed, it shrunk the error bar but it also changed the result considerably.

This raised the question of whether there could be a systematic difference between on-line Penning-trap and reaction-based measurements? In collaboration with the JYFLTRAP Penning-trap group at the University of Jyväskylä we have settled this issue. We measured the Q_{EC} values for ^{46}V, ^{42}Sc and ^{26}Al^{m}[11], confirming the Savard *et al.* [10] result for ^{46}V but finding that the Q_{EC} values for ^{42}Sc and ^{26}Al^{m} agree well with the survey results, which depend entirely on reaction-based measurements. Thus there is no indication of a systematic shift between Penning-trap and reaction measurements.

There still remains the fact that the corrected $\mathcal{F}t$ value for ^{46}V is now significantly higher than that for any other well known superallowed transition (see Fig. 1). The most obvious explanation of its unusual value is that the correction for isospin symmetry-breaking, which depends upon the nuclear structure of the parent and daughter nuclei, is missing some important components, and we have begun to examine this possibility theoretically [12]. What we have found so far is that by including the *sd*-shell with the *fp*-shell in our configuration space, we could remove the shift in the ^{46}V result but not without introducing shifts in the $\mathcal{F}t$ values for ^{50}Mn and ^{54}Co as well. The currently accepted Q_{EC} values for ^{50}Mn and ^{54}Co are averages, each with an important contribution from a 30-year-old (^{3}He,t) Q-value measurement, which appeared in the same paper in which the now-discredited value for the ^{46}V Q_{EC} value also appeared. Perhaps their results for ^{50}Mn and ^{54}Co were wrong as well. With the Jyvaskyla group, we have re-measured the Q_{EC} values for ^{50}Mn and ^{54}Co [13].

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