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 three 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 $\mathscr{F}t$, were obtained.

In the three 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]; also isospin-symmetry-breaking corrections were improved significantly [5]. Figure 1 shows the raw *ft* values and corrected $\mathscr{F}t$ values for the most precisely known superallowed $0^+ \rightarrow 0^+$ transitions as they are now known in mid 2008. The constancy of the $\mathscr{F}t$ values is evident, their average being 3072.3(8) s, with a normalized χ^2 of 0.3.

There have been important changes in these results since last year. It all began three years ago with our re-measurement of the Q_{EC} value of the ^{46}V superallowed beta-decay branch [6] using the CPT Penning trap at Argonne National Lab. 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 settled this issue. We measured the Q_{EC} values for ^{46}V, ^{42}Sc and ^{26}Al^m [7], confirming the Savard *et al.* [6] result for ^{46}V but finding that the Q_{EC} values for ^{42}Sc and ^{26}Al^m agreed well with the survey results, which depended entirely on reaction-based measurements. This demonstrated that there is no systematic shift between Penning-trap and reaction measurements in general.

There still remained the fact that the new corrected $\mathscr{F}t$ value for ^{46}V was significantly higher than that for any other well known superallowed transition. The most obvious explanation of its unusual value was that the correction for isospin symmetry-breaking, which depends upon the nuclear structure of the parent and daughter nuclei, was missing some important components, and last year we succeeded in improving our previous calculated corrections [3] by including the effects of core states [5]: *eg.* in the case of ^{46}V this meant including the *sd*-shell with the *fp*-shell in our configuration space. The new corrections completely removed the anomaly in the $\mathcal{F}t$ value for ^{46}V but introduced equivalent anomalies for ^{50}Mn and ^{54}Co. However the accepted Q_{EC} values for ^{50}Mn and ^{54}Co at that time were averages, each with an important contribution from a 30-year-old (^{3}He,t) Q-value measurement by Vonach *et al.* [8], which appeared in the same paper in which the newly discredited value for the ^{46}V Q_{EC} value also appeared. Perhaps their results for ^{50}Mn and ^{54}Co were wrong as well.

Last year with the Jyvaskyla Penning trap, we also re-measured the Q_{EC} values for ^{50}Mn and ^{54}Co [9]. Our results differ from the values published by Vonach *et al.* [8] by more than 2.5 keV (5 or more of the latter's standard deviations). Evidently, whatever problem these authors had with their measurement of the ^{46}V Q_{EC} value extended to ^{50}Mn and ^{54}Co as well: all three of these values are lower than the modern more-precise values by approximately the same amount. Using our new Q_{EC} values for ^{50}Mn and ^{54}Co, we find that the apparent anomaly in their $\mathcal{F}t$ values completely disappears. With the new experimental results and the re-calculated isospin-symmetry-breaking corrections the $\mathcal{F}t$ values are completely consistent with one another as shown in the right panel of Figure 1.

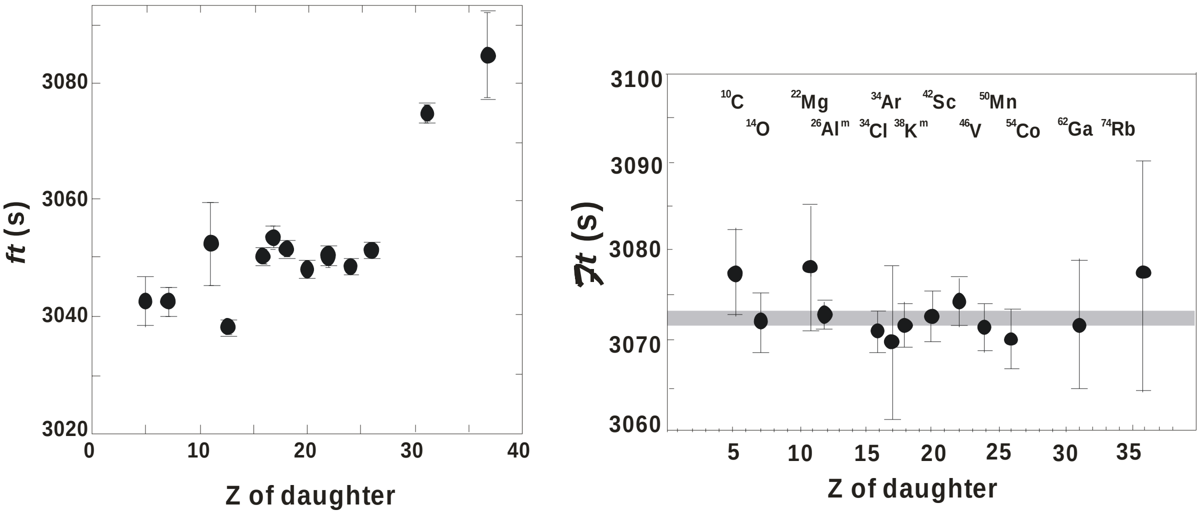

Figure 1. Results from the 2005 survey [1] updated with more recent published results. The uncorrected *ft* values for the thirteen best known superallowed decays (left) are compared with the same results after corrections have been applied (right). The grey band in the right-hand panel is the average 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]. 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 0.97402(26)

For several decades, the top-row unitarity sum 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 0.9997(10). 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 $\mathscr{F}t$ values in the latter. Since these corrections were determined [3,5] completely independently of the superallowed decay data, the consistency of the $\mathscr{F}t$ 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 $\mathscr{F}t$ 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 a half-life measurement for ^{10}C decay [10] and are also at the analysis stage of a similar measurement for ^{38}Ca [11].

We continue to focus on improving and securing our analysis procedures for precise branching-ratio measurements. We have introduced a new laser-based system to determine the source-to-HPGe-detector distance for each sample delivered by our tape-transport system [12]; and we have continued our source measurements and Monte Carlo calculations to thoroughly characterize our beta detector [13-15]. We continue to use ^{34}Ar decay as a test case to which we apply these improvements [16].

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