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 last year [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. The results are shown in Figure 1.

Since these corrected $\mathcal{F}t$ values are directly proportional to the vector coupling constant, G_V, the bottom panel of the figure demonstrates the constancy of G_V to better than three parts in 10^4, and also limits any possible induced scalar current to $f_S < 0.0013$ in electron rest-mass units. This confirms – to unprecedented precision – two out of three of the necessary consequences of the Conserved Vector Current (CVC) hypothesis. Since the nuclear-structure-dependent corrections, δ_{NS} and δ_C, 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 top panel and is effectively absent in the bottom one, where the corrections have been applied.

Once the consistency of the $\mathcal{F}t$ values – and, with them, G_V – has been established, the average value obtained for G_V can be used to test a fundamental principle of the electroweak standard model, the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The up-down 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], and the possible failure of that test at the 0.35% level has focused considerable experimental attention on another element of the top row, V_{us}, which is determined from kaon decays.

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.

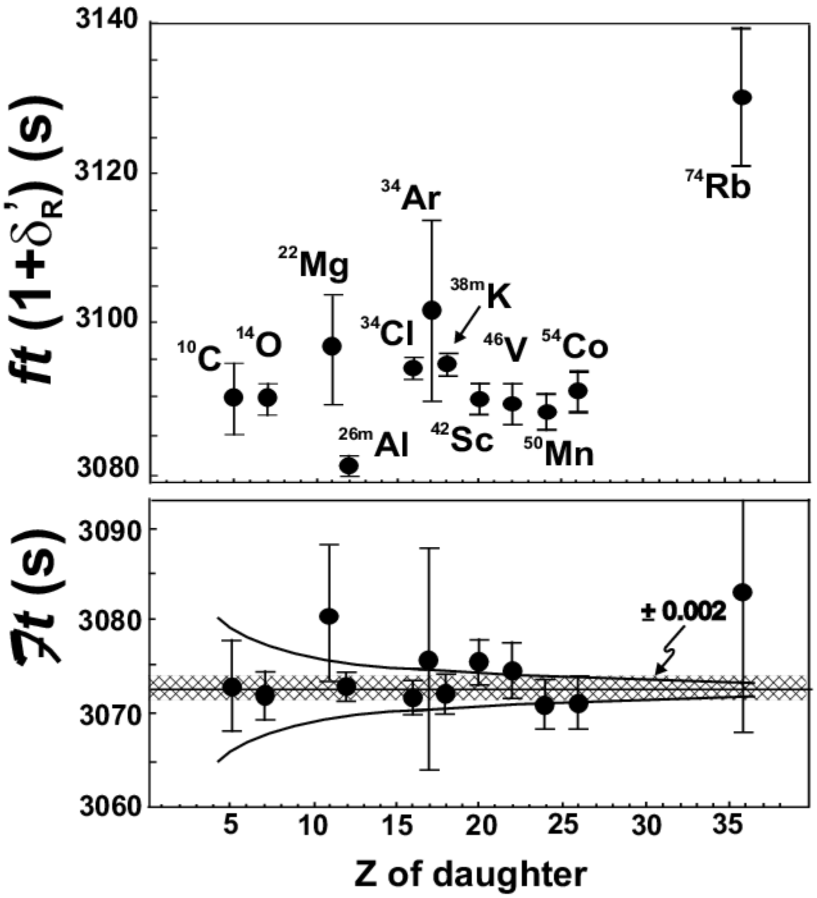

Figure 1. In the top panel are plotted the experimental ft values corrected only for δ_R', those radiative corrections that are independent of nuclear structure. In the bottom panel, the corresponding $\mathcal{F}t$ values are given; they differ from the top panel simply by the inclusion of the nuclear-structure-dependent corrections, δ_{NS} and δ_C. The horizontal crosshatched band indicates the average $\mathcal{F}t$ value with its uncertainty. The curved lines show the approximate loci the $\mathcal{F}t$ values would follow if the induced scalar coupling constant were $f_S = \pm 0.002$.

The 2005 survey [1, 2] presented a remarkably consistent picture for the nuclear results, one that naturally challenges us to improve our precision still further in order to better constrain critical weak-interaction parameters. Even though the body of world data already comprises the results of more than 125 individual measurements, 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. Currently at TAMU we are studying the decays of ^{34}Ar [4] and ^{38}Ca for this reason; their precision can certainly be improved, and 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, which is particularly sensitive to the $\mathcal{F}t$ values for ^{10}C and ^{14}O. We are now re-measuring the half-life of ^{10}C [5] and have re-visited an old measurement of the ^{14}O branching ratio [6] with this goal in mind.

Considering the overall quality of world data on superallowed decays, no dramatic surprises were expected as new data appeared. However, last year 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 [7]. 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. Instead, as can be appreciated from Figure 2, it indeed shrunk the error bars but it also changed the result considerably.

This raised a number of important questions:

- Could there be a systematic difference between on-line Penning-trap and reaction-based measurements? If so, which type of measurement is at fault? (See ref. [8] for a fuller discussion of this issue.)
- If the Penning-trap measurement for ^{46}V is correct, then the most precise previous determination of the Q_{EC} value, from a Munich (^{3}He, t) measurement [9], is seriously in error. Does that mean that the other six Q_{EC} measurements quoted in the same reference should be discarded too? (See Fig. 2.)
- If all the Q_{EC} values in ref. [9] were to be discarded and new Penning-trap results turn out to differ significantly from the remaining reaction results, then the excellent agreement among the $\mathcal{F}t$ values in the lower panel of Fig. [1] might well be destroyed. Will the calculated nuclear-structure-dependent corrections thus prove to be flawed?
- Will all this change the nuclear result for V_{ud}?

Our very recent measurements [10] with the Penning trap, JYFLTRAP, at the University of Jyväskylä appear to have settled the most important of these questions. We confirm the Savard *et al.* [7] result for ^{46}V but also find 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. Apparently ^{46}V was an anomalous case, for which only a single dominant measurement had previously been available [9], a measurement that appears simply to have been wrong.

We plan to continue these Q_{EC}-value measurements of superallowed decays with the Penning traps at both Argonne and Jyväskylä. Of particular interest are the cases of ^{50}Mn and ^{54}Co. The survey results for both these cases are strongly influenced by ref. [9] and they could change significantly if the results of that reference were to be eliminated.

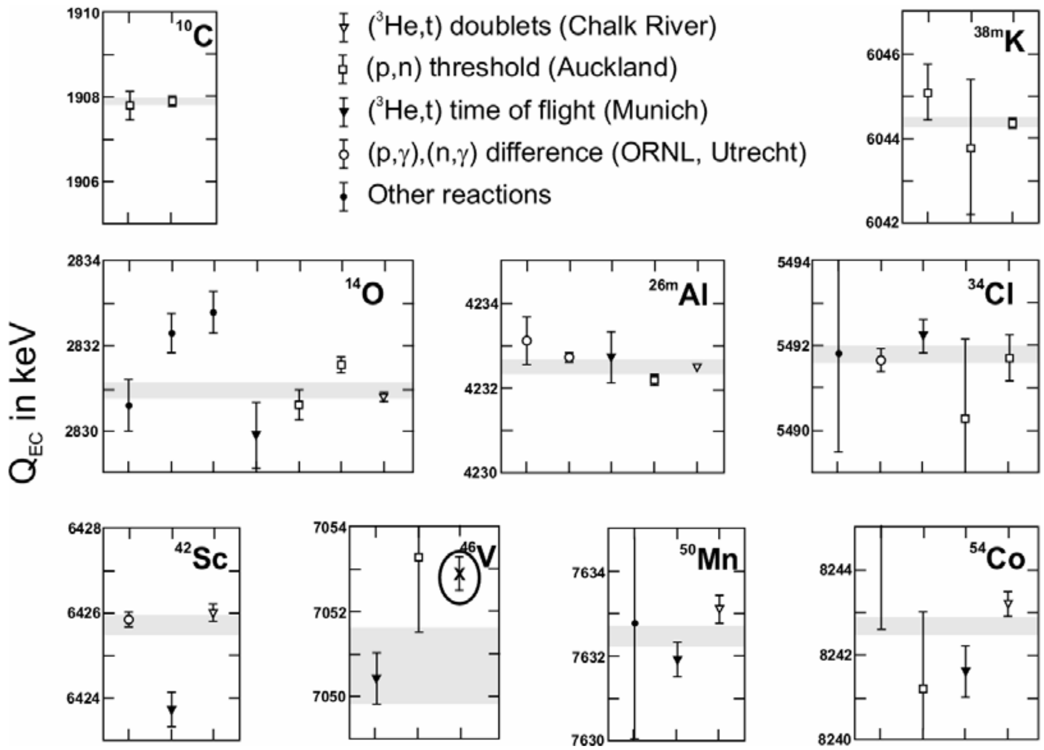

Figure 2. All Q_{EC}-value measurements that contribute to the 2005 survey of world data [1, 2] are plotted in chronological order, and identified by the type of reaction(s) employed. The shaded bands indicats the average values. The only Penning trap measurement is the recent ^{46}V result of Savard et al. [7]; it is indicated by an "X" and is circled.

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