

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 Ft (see Fig. 1). 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 Ft 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 2010 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 [1,3,4] is 0.97425(22), a result that yields the most up-to-date CKM unitarity sum of 1.0008(56) [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

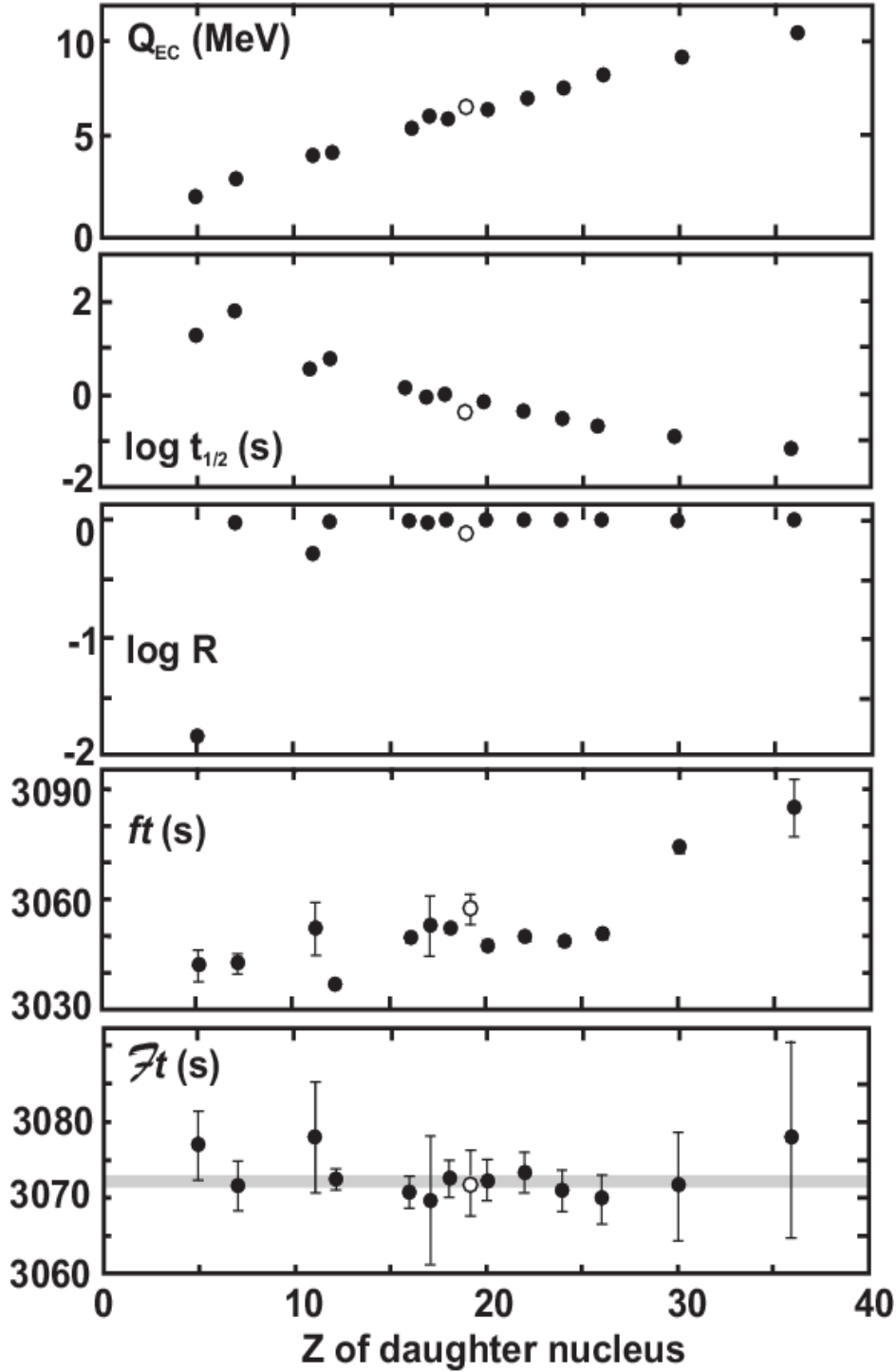


FIG. 1. Results from the most recent survey of 13 precisely measured superallowed $0^+ \rightarrow 0^+$ β transitions appear as solid black circles. The parents of these transitions, from left to right, are ^{10}C , ^{14}O , ^{22}Mg , $^{26}\text{Al}^m$, ^{34}Cl , ^{34}Ar , $^{38}\text{K}^m$, ^{42}Sc , ^{46}V , ^{50}Mn , ^{54}Co , ^{62}Ga and ^{74}Rb . The top three panels present the average of measured Q_{EC} , $\log t_{1/2}$ and $\log R$ (branching ratio) values for each transition. The bottom two panels give the corresponding ft and Ft values. The shaded horizontal line in the bottom panel represents the overall average Ft value for all transitions. All error bars are shown: in the cases where none are visible, they are smaller than the data point. Recent results for ^{38}Ca are shown as open circles.

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 [1,3,4] 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 Ft values. Though these corrections are only of order 1%, their effect is very significant: The bottom two panels of Fig. 1 show 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 second panel from the bottom, replacing it with the consistent set of corrected Ft values appearing in the bottom panel. Since these corrections were determined [2] completely independently of the superallowed decay data, this consistency in Ft 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 Ft 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, we believe that we have achieved a major milestone this past year: After many years of incremental improvements we have finally reached our goal of determining the branching-ratio for a superallowed β -branch to a precision of 0.1% in the presence of other strong branches. This is crucial for the characterization of $T_z = -1$ parent decays, which – unlike $T_z = 0$ decays – exhibit a number of strong Gamow-Teller branches that compete with the superallowed Fermi branch. After making considerable improvements to our electronics and data-acquisition system [5] using off-line sources to generate β - γ coincidences, in September 2012 we made an on-line measurement of the decay of ^{38}Ca ($t_{1/2} = 444$ ms), the analysis of which is now nearly complete [6].

We expect that we will be able to quote the branching ratio for the Gamow-Teller branches from ^{38}Ca to a relative precision of about 0.3%. Since these branches represent $\sim 23\%$ of the decays from ^{38}Ca , the relative precision on the superallowed Fermi branch, which is determined by subtraction from 100%, will be at or below 0.1%. It thus would be the first measurement of a $T_z = -1$ emitter with significant non-superallowed branches to be measured with a precision of 0.1%, and will complete all the data required for a precise ft -value result for ^{38}Ca .

To our knowledge, this promises to be the most precise branching-ratio measurement ever made for short-lived beta emitter. It will also provide the first mirror pair of $0^+ \rightarrow 0^+$ superallowed emitters (^{38}Ca and $^{38}\text{K}^m$) and will make possible a more demanding test of the isospin symmetry-breaking correction, δ_C , used to extract V_{ud} from the measured ft values. By improving our ability to discriminate among the different calculations of δ_C , measurements of $T_Z = -1$ emitters like ^{26}Si , ^{34}Ar and ^{38}Ca , can potentially lead to reduced uncertainties on δ_C and ultimately to reduced uncertainties on V_{ud} as well as the unitary sum for the Cabibbo-Kobayashi-Maskawa matrix. This approach to testing δ_C calculations was first proposed by us and has been discussed in detail in Ref. [7] and in this progress report [8].

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, which allows us to determine half-lives by time-interval analysis [9], and a digital-pulse-analysis system for the signals from our 4π proportional gas counter, with which we have now measured a new more precise value for the half-life of $^{26}\text{Al}^m$ [10]. We have worked to eliminate spurious pulses and to reduce, or improve our handling of our system dead time. We have achieved some modest success towards this goal, as evidenced by the improved $^{26}\text{Al}^m$ result, but have had to conclude that our count-rate will now be limited, not by our electronics, but by the inherent properties of our gas counter.

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