Superallowed $0^+ \rightarrow 0^+$ Beta Decay

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At present, the most exacting test of the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix is provided by nuclear beta decay. Precise measurements of beta-decay transitions between analog 0^+ states are used to determine G_V, the vector coupling constant; this, in turn, yields V_{ud}, the up-down element of the CKM matrix. To date, the *ft*-values for nine 0^+-to-0^+ transitions have been determined to a precision of ~0.1% or better; this spans a wide range of nuclear masses from ^{10}C, the lightest parent, to ^{54}Co, the heaviest. As anticipated by the Conserved Vector Current hypothesis, CVC, all nine yield consistent values for G_V, but the value of V_{ud} derived from their average yields a more provocative result. The unitarity test of the CKM matrix fails by more than two standard deviations: *viz* $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9968$ (14). This result would have far-reaching consequences if it were to be confirmed with improved statistical definition.

The uncertainty attributed to V_{ud} is dominated by two theoretical correction terms [1]: the charge correction, δ_C, which is nuclear-structure dependent, and the radiative correction, Δ_R, which is not. Both corrections are themselves rather small (~ 1%) and their associated uncertainties are an order of magnitude smaller still. Nevertheless, the experimental *ft*-values are now known so precisely that any improvement in either theoretical uncertainty would directly affect the precision of the unitarity test.

We have implemented an experimental and theoretical program aimed at reducing the uncertainty of the unitarity test by improving our knowledge of δ_C. The experimental components of the program currently comprise the determination of *ft*-values for the superallowed beta decays of ^{22}Mg ($t_{1/2}$ = 3.9 s), ^{30}S (1.2 s) and ^{34}Ar (0.8 s); and the observation of non-analog 0^+-to-0^+ transitions from ^{62}Ga (0.1 s), and ^{74}Rb (0.06 s). The ^{74}Rb decay experiments are being undertaken with the new ISAC facility at TRIUMF; the others are taking place at Texas A&M, where we use the MARS spectrometer and the fast tape-transport system. The mass measurements required for precise determination of each Q_{EC}-value are being undertaken with the Canadian Penning Trap at the Atlas facility at Argonne. All five cases are additional to the nine already well-known superallowed transitions. Each has been selected because its calculated δ_C value is either particularly high (1-2%) or particularly low (<0.3%). If experiments confirm these extreme transition-to-transition differences, then the uncertainty in all δ_c values will be reduced accordingly.

Our initial emphasis is on the three lighter cases, ^{22}Mg, ^{30}S and ^{34}Ar. These nuclides share the same nuclear shell-model space as the nine currently contributing to the unitarity test and, particularly in the *sd*-shell, that model is extremely successful in calculating a wide range of nuclear properties. Thus, any discrepancies observed between theory and experiment for these cases would directly reflect on the δ_C values now being used in the extraction of V_{ud}. None of these decays has previously been accessible to precise *ft*-value measurements since each parent decays by several beta transitions of comparable strength and the branching ratio for the superallowed transition must be determined from photo-peak intensities in the spectrum of beta-delayed gamma-rays. To be useful in the present context, these intensities are required to a precision approaching 0.1% over energy ranges from 70 to 1300, 670 to 2350 and 460 to 3130 keV, for ^{22}Mg, ^{30}S and ^{34}Ar, respectively. This is a very demanding requirement never previously achieved!

In subsequent reports we describe our recent results and current status. The data-taking phase of our branching-ratio measurement for the decay of ^{22}Mg is now complete, and analysis of the data is well advanced [2]. Our result for its half-life, which has the anticipated 0.03% precision, is now final [3], and the measurement of its mass has begun [4]. We have also measured the half-lives of the ^{34}Ar and ^{34}Cl decays [5]. Because ^{34}Ar decay feeds ^{34}Cl, and both have comparable half-lives, the precision with which the latter's half-life is known affects directly the precision achievable for the half-life of the former. The superallowed transition from ^{34}Cl is actually one of the nine well known 0^+-to-0^+ transitions on which the current unitarity test is based; our new result for its half-life, which is precise to 0.03%, turns out to be a significant improvement on the currently accepted world-average value.

Our branching-ratio measurements, in which we record extremely clean beta-coincident gamma-ray spectra from pure source samples, have only become possible as a result of our success in efficiency-calibrating a HPGe detector to sub-percent precision with a combination of source measurements and Monte Carlo calculations. Our calibration has been improved considerably during the past year [6] with three new sources, two of them prepared with the cyclotron [7]; these latter two, ^{48}Cr and ^{120m}Sb, involve γ-ray cascades that provide precise relative efficiency calibration around 100 keV, where one of the ^{22}Mg γ-rays appears.

The short-term goals in our studies of the decays of the heavier N=Z nuclei, ^{62}Ga [8,9] and ^{74}Rb [10, 11], are necessarily more modest. The Q_{EC}-values for such exotic nuclei are unlikely to be known with sufficient precision to determine a useful *ft*-value for some years to come. However, a less-precise measure of the *ft*-value for the non-analog 0^+-to-0^+ transition to the lowest excited 0^+ state in their daughters is definitely feasible. Such a transition can only occur through the effects of charge-dependent mixing, effects that also determine δ_c. The measured *ft*-value should then provide a valuable constraint on δ_c. However, the β-delayed γ-rays observed from the decays of these nuclei [8, 11] show more complexity than had been anticipated. This has prompted us to a theoretical examination of such decays [12]. The results will have considerable influence on how the study of superallowed decay from heavier N=Z nuclei will proceed in future.

Finally, our complete and consistent set of calculations for the nuclear-dependent parts of the radiative and charge corrections has been completed [13]. It is these calculations which will ultimately be tested by our experiments and, if verified, will be used to determine an improved value of V_{ud}.

References

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