Precision Absolute Branching-Ratio Measurements: the Superallowed $\beta$-Decay of $^{34}$Ar

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For some years now, we have been embarked on an experimental and theoretical research program to test CKM (Cabibbo-Kobayashi-Maskawa) unitarity via precision measurements of $f\ell$-values for superallowed $\beta$-transitions. The thrust of this program is to determine and validate the nuclear-structure-dependent correction terms that must be applied to the experimental $f\ell$-values for $0^+ \rightarrow 0^+$ transitions in order to extract a value for the vector coupling constant, $G_V$. From $G_V$, the up-down mixing element of the CKM matrix can be determined and the unitarity of that matrix tested. We intend to study a number of superallowed transitions that have not previously been precisely characterized. The cases are being chosen to cover a relatively wide range of calculated correction terms in order to test if the experimentally observed variations among them confirm the theoretical calculations [1]. Aspects of this work have been described in previous progress reports and also appear elsewhere in this report [2].

![Beta-decay schemes for $^{22}$Mg and $^{34}$Ar, illustrating the important difference between them: the absence or presence of a ground-state $\beta$-transition. Note the different energy scale in the two schemes.](image)

**Figure 1.** Beta-decay schemes for $^{22}$Mg and $^{34}$Ar, illustrating the important difference between them: the absence or presence of a ground-state $\beta$-transition. Note the different energy scale in the two schemes.

The experimental component of this program reached its first milestone with the completion and publication a year ago of our study of $^{22}$Mg decay [3]. After several years of work, we had completed the calibration of the relative efficiency response of our HPGe detector to an unprecedented 0.15% precision between 50 and 1500 keV. With this detector, we then successfully determined the superallowed branching ratio for $^{22}$Mg with comparable precision. However, we chose $^{22}$Mg decay to be our first case for a good reason: all its decay branches feed excited states in its daughter, $^{22}$Na, and are thus followed by at least one $\gamma$-ray transition (see Fig 1). The $\beta$-branching ratios for $^{22}$Mg can all be determined from the relative $\gamma$-ray intensities as observed in our detector. This is the only one of our targeted superallowed decays where that simplification exists. In all other cases of interest, the ground state in the daughter
nucleus is also populated by β-decay so any determination of the β-branching ratios requires absolute γ-ray intensities to be determined. In anticipation of this requirement, we have already established the absolute efficiency of our detector [4] to 0.2% precision, only slightly less stringent a limit than the one we assign to its relative efficiency.

The most favorable case with which to begin our absolute branching-ratio measurements is the decay of $^{34}$Ar. As illustrated in Fig. 1, unlike $^{22}$Mg, $^{34}$Ar does have a branch to the ground state of its daughter. In fact, that branch is the superallowed transition, and it alone accounts for 94.6% of the total β-decay of $^{34}$Ar. Although, in this case, the absolute branching ratios must be determined for the allowed branches to excited states, their total can then be subtracted from 100% to yield the value for the superallowed branch. To obtain 0.1% precision on the latter, one need only determine the former to a combined uncertainty of ±0.1%. Since these other branches total to a mere 5.4%, an uncertainty of ±0.1% actually constitutes a precision of ~2%, a rather modest goal for our equipment. Even though this goal is very easy for us to achieve, we have chosen to use the decays of both $^{22}$Mg and $^{34}$Ar as a means to investigate the limits to our precision for absolute measurements in general. Much higher precision than 2% will be required in subsequent measurements.

Two methods for determining absolute branching ratios are open to us: 1) we can relate the number of γ-rays observed from a sample at our counting location to the number of source atoms observed exiting the MARS spectrometer on their way to being collected in that sample; and 2) we can relate the number of γ-rays observed in coincidence with β-particles at the counting location, $N_\beta - \gamma$, to the β-singles rate, $N_\beta$. Since

$$N_\beta = N_{\text{decays}} \times \epsilon_\beta$$
$$N_\beta - \gamma = N_{\text{decays}} \times \epsilon_\beta \times \epsilon_\gamma \times BR_\gamma,$$

then

$$N_\beta - \gamma / N_\beta = \epsilon_\gamma \times BR_\gamma,$$

where $\epsilon_\beta$ and $\epsilon_\gamma$ are the detector efficiencies for detecting β’s and a particular γ-ray, respectively, and BRγ is the branching ratio for producing that γ-ray – the quantity to be measured. The first of these two methods is, in principle, independent of the absolute HPGe detector efficiency if the relationship between detected atoms and observed γ-rays is determined first from a measurement on $^{22}$Mg, where the absolute branching ratios are now known; this, of course assumes that there is no change in conditions between the $^{22}$Mg calibration and the subsequent measurement of an unknown decay. The second method relies on knowledge of the absolute detector efficiency, but is independent of uncertainties associated with atom counting and collection on a tape.

We are currently testing both these methods on the known decay of $^{22}$Mg, and on the “unknown” decay of $^{34}$Ar. A spectrum of γ-rays observed in coincidence with β-particles for the latter decay is shown in Fig. 2. The $^{34}$Ar was produced by a 30.4 MeV $^{35}$Cl beam on a cooled hydrogen target, initiating the $^1\text{H}(^{35}\text{Cl}, \text{p}2\text{n})^{34}\text{Ar}$ reaction. Fully stripped reaction products were separated in the MARS spectrometer. The experimental method was the same as that described in reference [3]. So far, the results are promising but we require further study of the energy-dependence of our beta-detection efficiency, which influences the relative intensities of γ-rays in the coincidence spectrum. This was not an issue in the $^{22}$Mg-decay study, where the key γ-rays to be compared followed β-transitions of nearly
Figure 2. Spectrum of $\gamma$-rays observed in coincidence with $\beta$-particles following the decay of a sequence of pure collected samples of $^{34}$Ar.

identical end-point energies. We are using Monte Carlo simulations to help understand and ultimately control this aspect of our measurement technique.