Precise half-life measurements for the superallowed β^+ emitters ^{34}Ar and ^{34}Cl

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As part of our program to test the Standard Model *via* the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1] we have measured the half-lives of ^{34}Ar and ^{34}Cl with the principal aim of extracting a precise *ft* value (±0.1% or better) for the superallowed $0^+ \rightarrow 0^+$ β branch of ^{34}Ar. The *ft* value is determined from three experimental quantities: the half-life, branching ratio and Q_{EC} value. For the experimental results to contribute significantly to the CKM unitarity test, the required precision for each quantity must be better than 0.1%, making the experiment very demanding.

Before the measurement reported here, the half-life of ^{34}Ar was only known to 0.4% and its branching ratio to 0.3% [2]. Our new branching-ratio measurement, which has a precision of 0.08%, is described elsewhere in this report [3]. The half-life measurement described here has a precision of 0.05%. It has already been published [4].

The ^{34}Ar radioactive beam was produced from the ^{35}Cl(p,2n) reaction with the primary beam at 30*A* MeV impinging on a liquid-nitrogen cooled gas target at 1.6 atm. A ^{34}Ar beam at 26*A* MeV was separated by the Momentum Achromat Recoil Spectrometer (MARS). The beam exited the vacuum chamber through a thin Kapton window and then passed through a 0.3-mm-thick plastic scintillator and a series of Al degraders, which were adjusted to ensure the implantation of the ^{34}Ar nuclei at the center of a 76-μm-thick aluminized Mylar tape, part of our fast tape transport system. With an ^{34}Ar beam intensity of about 3×10^4 particles/s, we collected a radioactive sample (>99.8% pure) for either 0.7 or 1 s, then turned off the beam and transported the activity in 180 ms to the center of our 4π proportional gas counter. Signals from the counter were multiscaled for a period of 12 s. These cycles were repeated until the desired statistics were achieved.

We collected a total of about 400 million decay events in two separate experiments. The first one included about 180 million events from 20,800 tape cycles, which were split into 40 separate runs. In the second experiment another 220 million events were collected in 14,700 cycles split into 24 separate runs. For both experiments, each run was characterized by different settings of the adjustable detection parameters: dead-times, detector biases and discrimination thresholds. The main difference between the two experiments was the purity of the beam in the focal plane of MARS: the only significant impurity, ^{33}Cl ($t_{1/2}$ = 2.51 s) -- as identified by a position-sensitive detector at the MARS focal plane -- was at a level of 0.3% relative to ^{34}Ar in the first experiment, but increased to 0.7% in the second. A series of runs with longer collection times determined how much of this ^{33}Cl impurity actually survived the range-purification of the degrader. From these runs, we determined that we had 0.1% ^{33}Cl in the collected samples in the first experiment and 0.2% in the second. This was incorporated into our analysis.

We processed the data run-by-run by summing the dead-time-corrected spectra from all the cycles included in each run. The total time-decay spectrum obtained from the combined experiments is presented in Fig. 1, where we also show the separate contributions from the ^{34}Ar parent and ^{34}Cl daughter. This breakdown into components comes from a calculation based upon our final analysis and is presented

here simply to illustrate the problems we faced in analyzing the data. Clearly the decay of ^{34}Ar is almost completely masked by the growth of its daughter. The experimental decay curve only differs very slightly from a single exponential with the daughter's half-life. We can easily understand this situation by examining the coupled decay equations for combined parent-daughter decays. The combined ^{34}Ar and ^{34}Cl activity is given by

$$\Lambda_{tot} = C_1 e^{-\lambda_1 t} + C_2 e^{-\lambda_2 t}, \tag{1}$$

where

$$C_1 = N_1 \lambda_1 \frac{2\lambda_2 - \lambda_1}{\lambda_2 - \lambda_1}$$

$$C_2 = \left(N_2 - \frac{N_1 \lambda_1}{\lambda_2 - \lambda_1} \right) \lambda_2, \tag{2}$$

where t is the time elapsed after the end of the collect period, $N_{1,2}$ are the numbers of ^{34}Ar and ^{34}Cl nuclei present in the source at $t = 0$, and $\lambda_{1,2}$ are the corresponding decay constants. Note that when $\lambda_1 = 2\,\lambda_2$ the coefficient C_1 vanishes, leaving a single exponential term having the decay constant of ^{34}Cl. Although not related exactly by a factor of 2, the actual half-lives of ^{34}Ar and ^{34}Cl are close enough that, for our measurements, the coefficient C_1 was more than six times smaller than the coefficient C_2, and was negative. This is a serious limitation for any conventional two-component fit of the data.

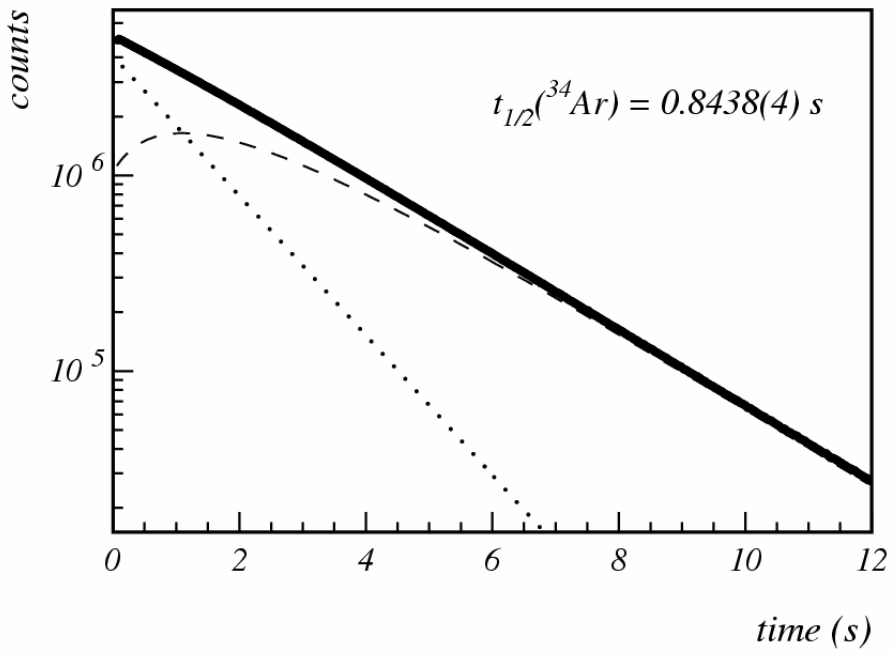

Figure 1. Total time-decay spectrum obtained for the β^+ decay of ^{34}Ar and it daughter ^{34}Cl. The dotted/dashed lines represent the calculated ^{34}Ar/^{34}Cl contributions.

Instead, we recognized that the near cancellation of the C_1 coefficient could actually be turned to our advantage: instead of solving for the two components independently, we could focus on the difference between the experimental data and a one-component decay, and use that difference to determine the amount by which the ratio of the two half-lives deviates from 2. However, for this type of analysis to be effective, we needed an independent determination of the value of N_2/N_1 from our experiment. If the ^{34}Ar-sample collection rate had been constant, this ratio could have been determined from a simple calculation of the production of ^{34}Cl (via ^{34}Ar decay) over the collection period.

Unfortunately, although the collection rate was very nearly constant over most of the collection period, it was evident from the measured rate in the scintillator at the exit of MARS, which detected the separated ^{34}Ar ions as a function of time, that there were noticeable variations at the beginning of the collection period. With the collection profile actually measured, however, we could perform numerical integrations over the measured ^{34}Ar accumulation and the calculated decay-production of ^{34}Cl during the collection period in order to obtain the N_2/N_1 ratio for each cycle.

Naturally the half-life used for ^{34}Cl, also influenced the result we extracted for ^{34}Ar from fitting the data. We therefore dedicated another independent experiment to measuring its half-life. We produced it directly with a 25A-MeV ^{35}Cl beam initiating the ^{35}Cl(p,pn) reaction; no significant impurities were observed and otherwise conditions were similar to the ^{34}Ar measurement. Our result, $t_{1/2}(^{34}\text{Cl}) = 1.5268(5)$ is consistent with the most precise previous results cited in a recent survey of world data [5], but its precision is more than a factor of two better than any of them.

In our analysis of the experimental data collected in both the ^{34}Cl and ^{34}Ar experiments, we tested for the stability of the fitted half-lives as a function of various detection settings: the results showed no systematic dependence on detector bias, discriminator threshold or circuit dead time. Our final result for ^{34}Ar thus represents a self-consistent analysis of more than 400 million combined ^{34}Ar and ^{34}Cl decay events. We determine the final half-life to be $t_{1/2}(^{34}\text{Ar}) = 843.8(4)$ ms, a result that is consistent with, but significantly more precise than, the only comparable previous result for the ^{34}Ar half-life, 844.5(34) ms [2].

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