High precision half-life measurement of the superallowed β-emitter ^{38}Ca

H. I. Park, J. C. Hardy, V. E. Iacob, A. Banu, L. Chen, V. V. Golovko, J. Goodwin, V. Horvat,
N. Nica, E. Simmons, L. Trache, and R. E. Tribble

We have now analyzed the results obtained from our half-life measurement of ^{38}Ca. In that measurement, we produced ^{38}Ca via the ^{1}H(^{39}K, 2*n*) reaction at a primary beam energy of 30*A* MeV. A 99%-pure ^{38}Ca beam was obtained at the focal plane of the MARS spectrometer, from which it exited the vacuum system through a 50-μm thick Kapton window, passed through a 0.3-mm-thick BC404 scintillator and a stack of aluminum degraders, and finally stopped in the 76-μm thick aluminized Mylar tape of our fast tape-transport system. The combination of *q/m* selectivity in MARS and range separation in the degraders provided implanted samples that we determined to be better than 99.6% pure. After ^{38}Ca was collected on the tape for 1 s, the cyclotron beam was interrupted and the collected sample was moved in 198 ms to the center of a 4π proportional gas counter. Multiscaled signals from the counter were recorded for 15 s into two separate 500-channel time spectra, each corresponding to a different pre-set dominant dead-time. This "collect-move-count" cycle was repeated until high statistics were obtained. In its shielded location, the gas counter had a background rate of about 0.5 counts/s, which was 3-4 orders of magnitude lower than the initial count rate for each collected sample.

In all, we recorded over 125 million β events from 11,271 cycles divided into 32 separate runs. The total time-decay spectrum obtained from the combined runs is presented in Fig. 1, where we also show the separate contributions from the decays of the ^{38}Ca parent and the ^{38}K^{m} daughter.

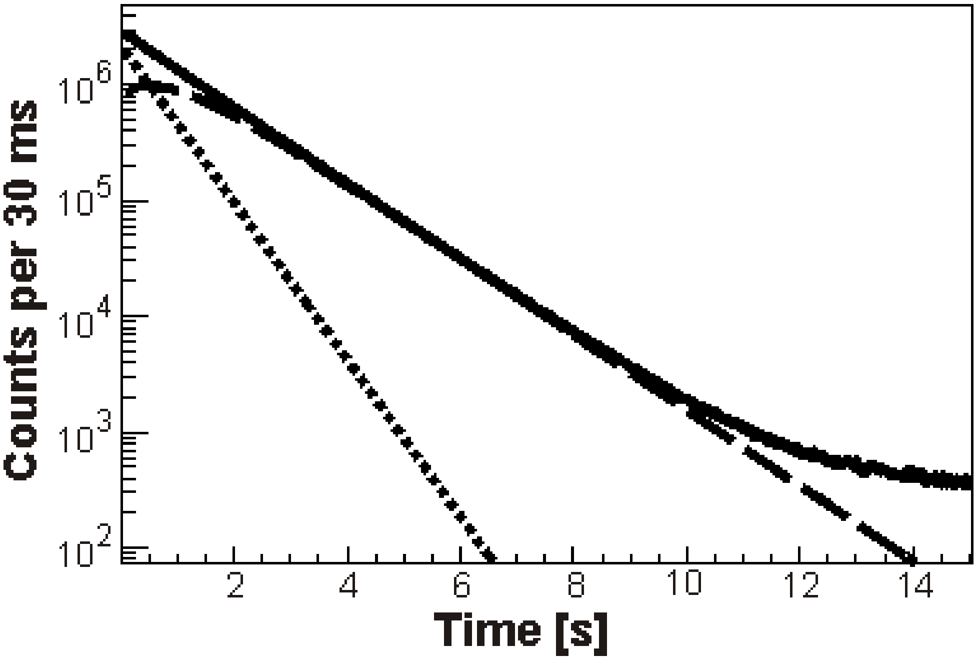

FIG. 1. Measured time-decay spectrum (solid line) obtained for the total of all data obtained from the β^{+} decay of ^{38}Ca and its daughter ^{38}K^{m}. The dotted/dashed lines represent the derived ^{38}Ca/^{38}K^{m} contributions.

As our detection system does not disentangle the two components, the only information that can be processed is the combined parent-daughter decay. A detailed analysis of the coupled ^{38}Ca and ^{38}K^{m} decay equations gives for the total detected rate as

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

with

$$C_1 = N_1 \varepsilon_2 \lambda_1 \left(\frac{\varepsilon_1}{\varepsilon_2} - \frac{\lambda_2}{\lambda_1 - \lambda_2} \right) \tag{2}$$

$$C_2 = N_1 \varepsilon_2 \lambda_2 \left(\frac{N_2}{N_1} + \frac{\lambda_1}{\lambda_1 - \lambda_2} \right), \tag{3}$$

where *t* is the time elapsed after the end of the collect period; $N_{1,2}$ are the numbers of ^{38}Ca and ^{38}K^{m} nuclei present in the sample at $t = 0$; $\varepsilon_{1,2}$ are the experimental efficiencies for detecting the positrons from the respective decays; and $\lambda_{1,2}$ are the corresponding decay constants. Note that if $\varepsilon_1 = \varepsilon_2$ and $\lambda_1 = 2\lambda_2$, the coefficient C_1 vanishes and the total decay rate is fully determined by $C_2 e^{-\lambda_2 t}$. This is very nearly the case for ^{38}Ca and ^{38}K^{m}, which have decay constants that are related by a factor of 2.1. Consequently for our measurements, the coefficient C_1 is more than a factor of 10 smaller than C_2. The impact is clearly evident in Fig. 1, where the total spectrum deviates very little from a one-component decay curve with the daughter's decay-constant. This is similar to the situation we encountered for our ^{34}Ar [1] and ^{26}Si [2] experiments.

As we did in those previous measurements, we calculated the ratio N_1/N_2 from the production of ^{38}K^{m} (via ^{38}Ca decay) over each collection period, based on the rate of deposit of ^{38}Ca as measured with the scintillator located just before the degraders at the exit to MARS. For these coupled decays it might easily be assumed that the efficiency ratio, $\varepsilon_1/\varepsilon_2$, equals unity since both activities were observed with identical geometry, a very low electronic threshold and nearly 100% overall efficiency. However, there is also a threshold energy arising from the fact that low-energy positrons are stopped in the aluminized Mylar transport-tape (half-thickness, 38 μm) and in the Havar windows of the gas counter (1.5 μm thick), never reaching the active volume of the detector. The impact of this effective threshold on the efficiency ratio becomes significant when the end-points and/or shapes of the parent and daughter β spectra are significantly different from one another. By Monte Carlo simulations we determined this ratio to be $\varepsilon_1/\varepsilon_2 = 1.00042(5)$ for this mass-38 measurement.

To test the robustness of our results, each run was obtained with a different combination of critical detection settings: detector bias, discriminator threshold and major dead-time combination. As seen in Fig. 2, the half-life results show no systematic dependence on detector bias or discriminator threshold. Although not illustrated, the results were also found to be independent of both the imposed circuit dead time and the length of time for which the sample was collected.

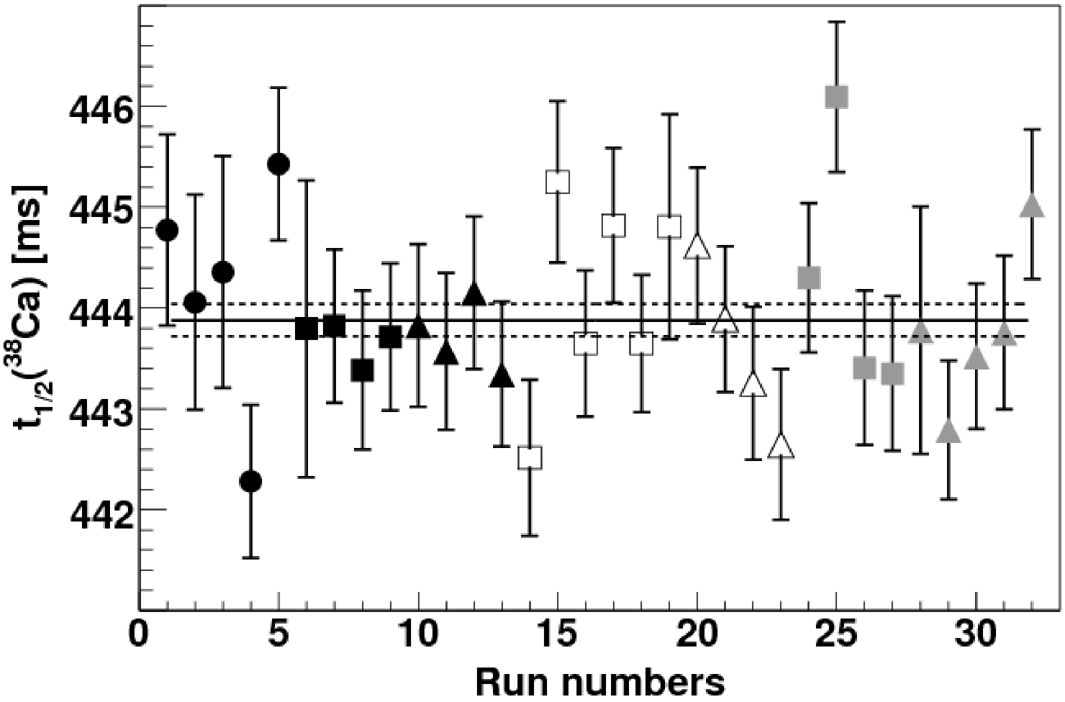

FIG. 2. Test for possible systematic bias in the ^{38}Ca half-life measurement due to discriminator threshold or detector voltage. The three detector biases, 2600 V, 2700 V and 2800 V are represented by the symbol shapes O, □, and Δ, respectively; black/open/grey symbols represent the three discriminator settings, 150 mV/200 mV/250 mV. The average value for the half-life is 443.88(16) ms (statistical uncertainty only) with λ^2/ndf = 39/31. The average value appears as the solid line, with dashed lines as uncertainty limits

Further tests of the half-life stability versus undetected short-lived impurities or rate-dependent counting losses were performed by the standard “front-channel-chopping” technique, which involves separate fits to subsets of the data with successively longer time periods removed from the beginning of the counting cycle. Here too the derived half-life proved to be stable: no statistically significant change was observed as the starting time for the fit was systematically changed.

The error budget and final result for the ^{38}Ca half-life is given in Table I. Four out of the five previous measurements of the ^{38}Ca half-life were made before 1980 and with quoted uncertainties more than thirty times

Table I. Error budget for the 38Ca half-life measurement.

Source	Uncertainty (ms)
statistics	0.16
sample impurity (^{35}Ar)	0.23
$t_{1/2}$ ($^{38}K^m$)	0.22
Efficiency ratio, $\varepsilon_1/\varepsilon_2$	0.01
Total	0.36
38Ca half-life result (ms)	443.88(36)

larger than ours: 470(20) ms [3], 439(12) ms [4], 450(70) ms [5] and 430(12) ms [6]. These were each obtained by observation and analysis of the decay of β-delayed γ-rays from the daughter, ^{38}K. The first result lies about one-and-a-half of its error bar away from our quoted half-life; the other three agree well within their error bars. There is a much more recent measured value, 443.8(19) ms [7], which was obtained in a similar manner to ours, from a measurement of the decay positrons in a gas counter; in their case, though, sample purity was achieved by collecting the ^{38}Ca first in a Penning trap. Our half-life result agrees well with theirs but with an uncertainty five times smaller.

[1] V.E. Iacob, J.C. Hardy, J.F. Brinkley, C.A. Gagliardi, V.E. Mayes, N. Nica, M. Sanchez-Vega, G. Tabacaru, L. Trache and R.E. Tribble, Phys. Rev. C **74**, 055502 (2006).

[2] V.E. Iacob, J.C. Hardy, A. Banu, L. Chen, V.V. Golovko, J. Goodwin, V. Horvat, N. Nica, H.I. Park, L. Trache and R.E. Tribble, Phys. Rev. C **82**, 035502 (2010).

[3] R.W. Kavanagh, A. Gallmann, E. Aslanides, F. Jundt and E. Jacobs, Phys. Rev. **175**, 1426 (1968).

[4] A. Gallmann, E. Aslanides, F. Jundt and E. Jacobs, Phys. Rev. **186**, 1160 (1969).

[5] J. Zioni, A.A. Jaffe, E. Friedman, N. Haik, R. Schectman and D. Nir, Nucl. Phys. A **181**, 465 (1972).

[6] H.S. Wilson, R.W. Kavanagh and F.M. Mann, Phys. Rev. C **22**, 1696 (1980).

[7] B. Blank, A. Bey, I. Matea, J. Souin, L. Audirac, M.J.G. Borge, G. Canchel, P. Delahaye, F. Delalee, C.-E. Demonchy, R. Domnguez-Reyes, L.M. Fraile, J. Giovinazzo, Tran Trong Hui, J. Huikari, D. Lunney, F. Munoz, J.-L. Pedroza, C. Plaisir, P. Delahaye, F.L. Serani, S. Sturm, O. Tengblad and F. Wenander, Eur. Phys. J. A **44**, 363 (2010).