Precise half-life measurement of the superallowed β^+ emitter $^{38}K^m$

G. C. Ball, G. Boisvert, P. Bricault, R. Churchman, M. Dombsky, T. Lindner, J. A. Macdonald,* and E. Vandervoort
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3

S. Bishop
Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6, and Physik Department, Technische Universität München, D-85748 Garching, Germany

J. M. D'Auria
Department of Chemistry, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6

J. C. Hardy and V. E. Iacob
Cyclotron Institute at Texas A&M University, College Station, Texas 77843, USA

J. R. Leslie and H.-B. Mak
Department of Physics, Queen's University, Kingston, Ontario, Canada K7L 3N6
(Received 27 July 2010; published 4 October 2010)

The half-life of $^{38}K^m$ has been measured to be 924.46(14) ms, a result that is a factor of two more precise than any of the five previous measurements of this quantity. The previous results are not consistent with one another, but our result agrees well with the two most recent ones. The derived ft value for $^{38}K^m$ is now one of the three most precisely known superallowed ft values.

DOI: 10.1103/PhysRevC.82.045501 PACS number(s): 21.10.Tg, 23.40.−s, 27.30.+t

I. INTRODUCTION

Precise measurements of superallowed $0^+ \to 0^+$ β^+ transitions have led to increasingly precise tests of several key ingredients in the electroweak standard model: the conserved vector current (CVC) hypothesis, the absence of scalar currents, and the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The most recent survey of world data on superallowed decays, published in 2009 [1], demonstrates that the vector coupling constant has the same value for all 13 precisely measured transitions to within ±0.013% as required by CVC, sets an upper limit on a possible scalar current at 0.2% of the vector current, and confirms CKM unitarity to ±0.06%. These are fundamentally important results, and they can be further improved by even more precise measurements of the input data.

The ft value that characterizes any β transition depends on three measured quantities: the total transition energy, Q_{EC}; the half-life, $t_{1/2}$, of the parent state; and the branching ratio, R, for the particular transition of interest. The Q_{EC} value is required to determine the statistical rate function, f, while the half-life and branching ratio combine to yield the partial half-life, t. Without the measurement reported here, the ft value for the superallowed decay of $^{38}K^m$ was only determined to 0.06% precision, a value dictated almost entirely by the $t_{1/2}$ value, which itself was uncertain to ±0.06%. The uncertainties on f and R are only ±0.01% and ±0.004%, respectively. Thus, any improvement in the half-life uncertainty has a direct impact on the final ft value for the transition.

*Deceased.

In this article we report a new and improved half-life value, which reduces the uncertainty on the ft value of $^{38}K^m$ by a factor of two, to ±0.03%. It should be noted, however, that this new half-life value was already incorporated into the most recent survey [1] as a reference "to be published," so the improved ft value appears there as well.

II. HALF-LIFE DETERMINATION

A. Experiment

The measurement was carried out at the Isotope Separator and Accelerator (ISAC) facility at TRIUMF in Vancouver, Canada. A radioactive beam of $\sim 5 \times 10^5$ ions/s was obtained from a production target of 42 gm/cm^2 $CaZrO_3$ bombarded with 0.5–1.0 μA of 500-MeV protons. The spallation products were ionized with a surface-ionization source. Unfortunately the short-lived ($t_{1/2} = 924$ ms) isomeric state of interest for this measurement, $^{38}K^m$, was produced with ∼50 times less yield than the long-lived ($t_{1/2} = 7.6$ min) ground state of the same nucleus, ^{38}K. To optimize the ratio of initial activities in favor of $^{38}K^m$, we collected samples for only 0.3 s and, in addition, pulsed the proton beam on the ISAC target with a duty cycle of 6%–11%; that is, the beam was on for only 4 s of every 30–60 s. As a result, it was possible to increase the ratio of initial activities for $^{38}K^m/^{38}K$ to 60–80:1.

The high-precision β-decay half-life measurements were carried out using techniques developed previously by one member of this collaboration in experiments elsewhere (see Ref. [2] for the most refined version). The low-energy, 29-keV radioactive ion beam from ISAC was implanted into the

25-mm-wide aluminized mylar tape of a fast tape-transport system [3]. After a collection period of 0.3 s, the ISAC beam was interrupted and the samples were moved out of the vacuum chamber through two stages of differential pumping, finally being positioned in the center of a 4π continuous-gas-flow proportional β counter [2,4]. The signals from the 4π counter were then multiscaled for about 25 half-lives and the data stored. This collect-move-count cycle was repeated continuously until sufficient statistics had been accumulated.

Special care was taken to ensure that systematic effects, if any, would be revealed. The amplified signals from the detector were passed to a discriminator, the output from which was split and sent to two fixed-width nonextendable gate generators. The durations of the gates were set to different times—3 and 4 μs—both being significantly longer than any series dead time in the circuit preceding it and each thus establishing a single dominant dead time in its branch. The gate signals from each branch were then routed simultaneously to two different and completely independent CAMAC multichannel scaler modules (MCS1 and MCS2) with dwell times of 0.1 s per channel. A 1 MHz $\pm$ 2 Hz laboratory clock was used to provide a time standard for the experiment. The dead times in both branches of the electronics were measured with an uncertainty of ± 0.01 μs using the source-plus-pulser technique [5]. By comparing the dead-time corrected results from both branches, we could check for any systematic dead-time effects not already accounted for.

We also explored for possible systematic errors associated with the other key equipment parameters by grouping cycles into separate runs, each with different settings for these parameters. The detector bias voltage was altered within the plateau region (2600–2800 V); the lower-level-discriminator threshold was varied between 100 and 200 mV; the proton beam on/off cycle was changed from 4/30 s to 4/60 s; and the fixed 3- and 4-μs dead times were interchanged. The run-to-run consistency in the measured half-life values then provided a sensitive test for any unwanted dependence on these parameters.

In addition, we monitored sample purity using a 40% HPGe detector located just outside the 4π β counter. The surface-ionization source used to produce $^{38}K^m$ is very specific to alkali elements, but small quantities of other elements are produced at high temperatures. At ISAC the radioactive ion beams from the source are subsequently mass analyzed, first by a low-resolution preseparator and then by a high-acceptance mass analyzer operating in the low-resolution mode with a resolving power of $M/\Delta M \cong 1000$. This is more than sufficient to eliminate any nuclides with a different mass number from the one of interest, but not neighboring isobars. An upper limit on the possible contribution from such isobars could be determined from examining the HPGe-detector spectrum for their characteristic β-delayed γ rays.

B. Analysis and results

Altogether, 31 runs, each consisting of 100–300 cycles, were recorded in this experiment. The initial $^{38}K^m$ activity for each cycle was in the range 8000–25 000 Hz and resulted in 2–10 $\times$ 10^6 decays being counted per run. In our off-line analysis, a threshold was set to reject any cycles for which the total number of counts was substantially below the average value. This rejection criterion removed cycles during which the primary proton beam or the ISAC beam had tripped off. A second cycle-rejection criterion used the ratio of the number of counts recorded by the 4π gas counter to that of a scintillation detector located at the beam implantation site. A low value for this ratio indicated that the $^{38}K^m$ sample had not been accurately centered by the tape-transport system within the gas counter. On average, $\sim$2% of the cycles were rejected by these two criteria.

The decay data from each accepted cycle were dead-time corrected according to the precisely measured, dominant dead time in each branch of the electronics. Then all the accepted cycles were summed into two decay curves for each run, one curve from the MCS1 branch and one from the MCS2 branch. All decay curves were then fitted with a function that contained two exponentials, corresponding to the decays of ^{38}K and $^{38}K^m$, and a constant background. The half-life of ^{38}K was fixed at its known value, 7.636 $\pm$ 0.018 min [6]. The data obtained from one typical run are shown in the top panel of Fig. 1; the bottom panel shows the results obtained for the $^{38}K^m$ half-life from the MCS1 data in each of the 31 runs. The statistical uncertainty on the half-life determined from the analysis of each decay curve was 0.4–0.9 ms, and the weighted average half-life from all the data is 924.44 $\pm$ 0.11 ms, with a reduced χ^2 of 0.74.

A consistent result, 924.46 $\pm$ 0.11 ms, was obtained from the analysis of the data from MCS2. Because the two multichannel scalers independently bin the same decay data, these are not independent measurements of the $^{38}K^m$ half-life,

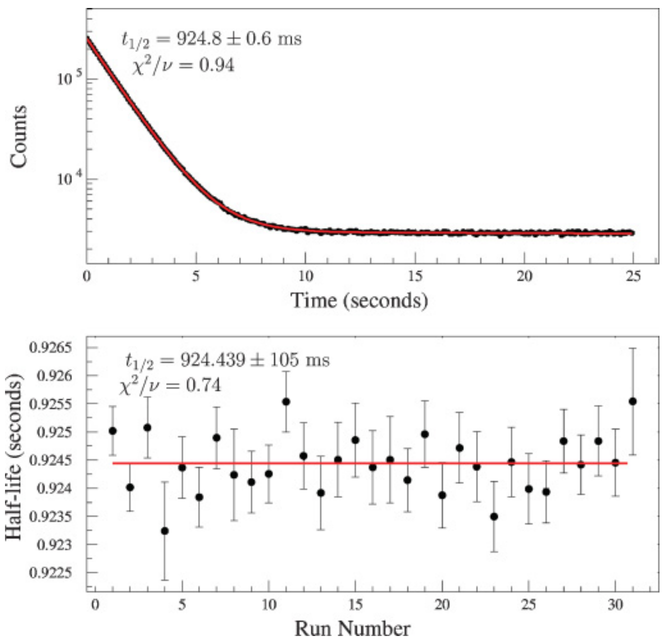

FIG. 1. (Color online) The $^{38}K^m$ half-life results. The top panel shows a typical dead-time-corrected decay curve from a single run summed over 128 cycles. The bottom panel shows the half-life results (with statistical errors) obtained with MCS1 for all 31 runs.

but instead provide an important consistency check of the dead-time corrections. With consistency established we adopt the unweighted average, 924.45 ± 0.11 ms.

As already noted, we tested for potential systematic uncertainties by altering equipment parameters from run to run. A summary of the $^{38}K^m$ half-life values obtained as a function of each of these parameters is shown in Fig. 2. In computing the weighted average of the values obtained for each grouping, we found the reduced χ^2 to be less than one in all cases. There is no identifiable systematic uncertainty associated with the experimental parameters in this measurement.

Next, to probe for otherwise undetected rate dependence in our measurements, we removed leading channels from the data set in increments of five channels (0.5 s), with a new half-life fit being performed for each successively reduced data set. This was continued until a maximum of 40 channels had been removed—4.3 half-lives of $^{38}K^m$—without any statistically significant change in the extracted half-life: The half-life remained consistent even when 95% of the data had been removed from the analysis.

Finally, to test for a possible correlation in the fitted half-life of $^{38}K^m$ with the initial activity of ^{38}K determined in each run, we removed the last 125 channels from each run in steps of 25 channels and refit each successively reduced data set. No systematic shift was observed in the extracted half-life of $^{38}K^m$ nor in the ratio of the initial activities of $^{38}K^m/^{38}K$.

In parallel with this TRIUMF-based analysis, we carried out a completely independent analysis of the same data at Texas A&M University using unrelated analysis software. For this analysis, in addition to fitting the summed data from each run, we also made a separate determination of the half-life by simultaneously fitting the data cycle by cycle within a given run, using a common half-life value (see Table II in Ref. [2]). The half-life for $^{38}K^m$ obtained from this analysis was 924.47 ± 0.10 ms, and no evidence for any systematic effects was observed. Combining the results of both analyses,

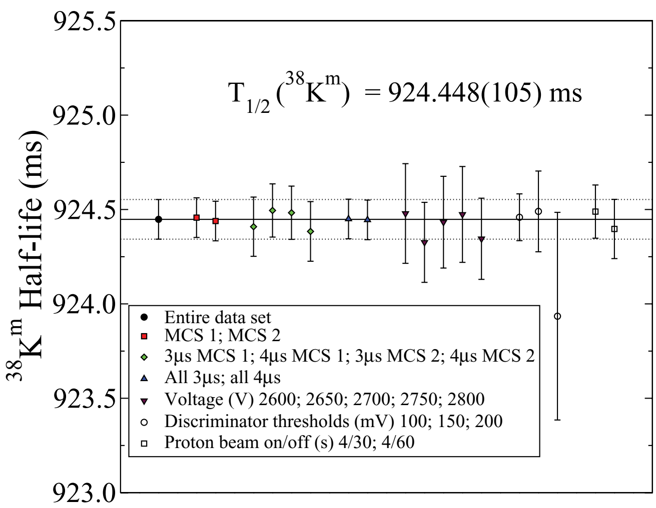

FIG. 2. (Color online) Half-life measurements of $^{38}K^m$ (with statistical uncertainties) sorted by adjustable electronic and experimental settings. All reduced χ^2 values for the independent groups are less than unity.

TABLE I. Uncertainty budget for $^{38}K^m$ half-life measurement.

Source	Uncertainty (ms)
Statistics	0.11
$t_{1/2}$ (^{38}K), 7.636 ± 0.18 min	0.05
Dead-time, ± 0.01 μs	0.06
^{38}Ca contaminant, $\leqslant 1/5000$	0.01
Total uncertainty	0.14

we adopt an average value of 924.46 ± 0.11 ms as the half-life of $^{38}K^m$ with its statistical uncertainty.

There are, of course, other contributions to the overall uncertainty budget. These are listed in Table I. The half-life of ^{38}K, though much longer than that of $^{38}K^m$, carries with it an uncertainty of $\pm 0.2\%$ [6], which has a small impact on the uncertainty in the $^{38}K^m$ half-life, as do the uncertainties in the measured 3- and 4-μs dead times (± 0.01 μs). We determined the effects of these input-parameter uncertainties by finding the difference between the best-fit half-life when the parameters were fixed at their central values and the results obtained when the parameters were fixed at their $\pm 1\sigma$ uncertainties.

The final contribution to the uncertainty budget comes from the observed upper limit on possible isobaric contaminants in the mass-separated $A = 38$ beam as determined from the HPGe detector located adjacent to the 4π gas counter. The only such contaminant that could possibly be produced (though in small quantities) with a surface ion source is ^{38}Ca, which has a half-life of 440 ms. With the detector's efficiency established from standard γ-ray sources placed at the center of the 4π β counter, we could set an upper 1σ limit of 1 part in 5000 deduced from the intensity of the 1567-keV γ ray (21% branch), which follows the β-decay of ^{38}Ca, as recorded during the first 1 s of the decay cycle. More recent yield measurements at ISAC using a TiC production target gave a relative intensity of 1 part in 25 000 for ^{38}Ca relative to $^{38}K^m$ and 1 part in 642 000 relative to ^{38}K. If a ^{38}Ca contaminant at the most conservative 1/5000 level is included in our fit of the data, the $^{38}K^m$ half-life increases by 0.011 ms. It is this value that we incorporate into the full uncertainty budget in Table I. Our final result for the $^{38}K^m$ half-life is 924.46 ± 0.14 ms, including all sources of uncertainty.

TABLE II. Summary of all $^{38}K^m$ half-life measurements with quoted uncertainties that are within a factor of 10 of the present measurement.

Reference	Year	$t_{1/2}$(ms)
G. T. A. Squier *et al.* [7]	1975	925.6 ± 0.7
D. H. Wilkinson *et al.* [8]	1976	922.3 ± 1.1
D. H. Wilkinson *et al.* [9]	1978	921.71 ± 0.65
V. T. Koslowsky *et al.* [4]	1983	924.15 ± 0.31
P. H. Barker *et al.* [10]	2000	924.4 ± 0.6
Present work	2010	924.46 ± 0.14
Weighted average (scale factor = 2.3)		924.33 ± 0.27
Excluding Refs. [8,9] (scale factor = 1.1)		924.44 ± 0.14

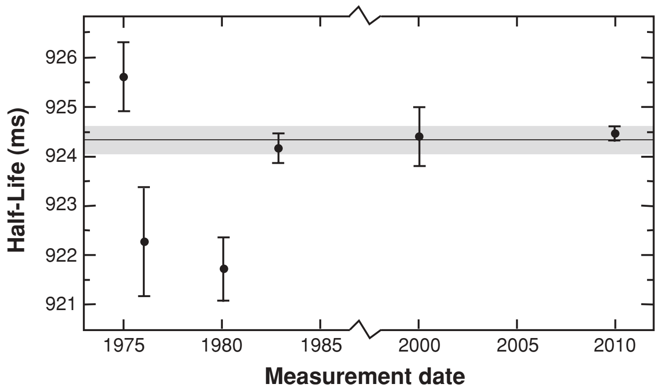

FIG. 3. The data points represent all published measurements of the ^{38}K^{m} half-life with quoted uncertainties that are within a factor of 10 of the present measurement. The results are plotted in chronological order from left to right in the same order as they appear in Table II. The weighted average, 924.33 ms, is given by the horizontal line, with its scaled uncertainty, ±0.27 ms, represented by the gray band. Note that the uncertainty on the average has been increased by a scale factor equal to the square root of the reduced χ^2 for all six results, which is 4.83.

C. Comparison to previous results

There have been five previous measurements of the half-life of ^{38}K^{m} that have been quoted with uncertainties within a factor of ten of the present measurement [4,7–10]. As can be seen in Table II and Fig. 3, our result is a factor of two more precise than any of the previous ones. The weighted average of all six measurements is 924.33 ± 0.12 ms but with a unsatisfactory reduced χ^2 of 4.83. As is the usual practice in the periodic surveys of superallowed β decay (e.g., Ref. [1]), we follow the method of the Particle Data Group [11] and inflate the uncertainty quoted on the average by a "scale factor," which is essentially equal to the square root of the reduced χ^2. This result for the average, 924.33 ± 0.27 ms, is the one shown as a horizontal band in Fig. 3.

From that figure it can also be seen that the three most recent measurements agree well with one another, while the two Wilkinson measurements [8,9] are significantly below the average, the most recent of the two being four of its standard deviations from the average. Although there is no obvious reason from the original articles to disregard these two measurements, it can be noted that if they are removed from the averaging process, the weighted average becomes 924.44 ± 0.14 ms with a scale factor of 1.1.

III. CONCLUSIONS

The result from this measurement considerably improves the world-average value for the ^{38}K^{m} half-life, although the apparently discrepant Wilkinson results [8,9] prevent the uncertainty on the average from being reduced to the experimental precision that we claim to have achieved. We have remarked earlier that our result has already been incorporated into the most recent survey of superallowed β decay [1]. The following analysis has been adopted from that survey: If we combine the value 924.33 ± 0.27 ms for the half-life of ^{38}K^{m} together with the branching ratio for the superallowed transition from that state, $99.967 \pm 4\%$ [12], and the calculated electron-capture fraction, $P_{\rm EC} = 0.085\%$, we obtain a partial half-life for the transition of $t = 925.42 \pm 0.27$ ms. With the statistical rate function, $f = 3297.88 \pm 0.34$, as calculated from the measured $Q_{\rm EC}$ value [1], the final ft value becomes 3051.9 ± 1.0 s, one of the most precisely known of all superallowed emitters.

Finally, we remark that if the two Wilkinson half-life measurements [8,9] were removed from the world average, then the partial half-life of the ^{38}K^{m} superallowed decay would become $t = 925.53 \pm 0.14$ s and its ft value would shift slightly and carry a significantly smaller uncertainty: $ft = 3052.3 \pm 0.6$ s. There is no objective reason to follow this approach, but this outcome may perhaps provide some motivation for attempting in the future an even more precise measurement of the ^{38}K^{m} half-life with the goal of making the suspect Wilkinson measurements statistically irrelevant.

ACKNOWLEDGMENTS

The authors thank the TRIUMF ISAC and cyclotron beam delivery teams for their contributions toward the production of a high-quality ^{38}K^{m} beam. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada, the US Department of Energy under Grant No. DE-FG02-93ER40773, and the Robert A. Welch Foundation under Grant No A-1397. TRIUMF receives federal funding via a contribution agreement through the National Research Council of Canada.

[1] J. C. Hardy and I. S. Towner, Phys. Rev. C **79**, 055502 (2009).
[2] V. T. Koslowsky, E. Hagberg, J. C. Hardy, G. Savard, H. Schmeing, K. S. Sharma, and X. J. Sun, Nucl. Instrum. Methods Phys. Res. A **401**, 289 (1997).
[3] E. Hagberg *et al.*, Nucl. Phys. A **571**, 555 (1994).
[4] V. T. Koslowsky, E. Hagberg, J. C. Hardy, R. E. Azuma, E. T. H. Clifford, H. C. Evans, H. Schmeing, U. J. Schrewe, and K. S. Sharma, Nucl. Phys. A **405**, 29 (1983).
[5] A. P. Baerg, Metrologia **1**, 131 (1965).
[6] J. A. Cameron and B. Singh, Nucl. Data Sheets **109**, 1 (2008).
[7] G. T. A. Squier, W. E. Burcham, J. M. Freeman, R. J. Petty, S. D. Hoath, and J. S. Ryder, Nucl. Phys. A **242**, 62 (1975).
[8] D. H. Wilkinson and D. E. Alburger, Phys. Rev. C **13**, 2517 (1976).
[9] D. H. Wilkinson, A. Gallmann, and D. E. Alburger, Phys. Rev. C **18**, 401 (1978).
[10] P. H. Barker and M. S. Wu, Phys. Rev. C **62**, 054302 (2000).
[11] C. Amsler *et al.* (Particle Data Group), Phys. Lett. B **667**, 1 (2008).
[12] K. G. Leach *et al.*, Phys. Rev. Lett. **100**, 192504 (2008).