Internal γ Decay and the Superallowed Branching Ratio for the β^+ Emitter ^{38}K^m

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The branching ratio for the superallowed β^+ decay of ^{38}K^m was measured at TRIUMF's ISAC radioactive ion beam facility. The $M3$ internal transition between the isomer and the ground state of ^{38}K^m was observed with a branching ratio of 330(43) ppm. A search for the nonanalogue β-decay branch to the first excited 0^+ state in ^{38}Ar was also performed and yielded an upper limit of ≤ 12 ppm at 90% C.L. These measurements lead to a revised superallowed branching ratio for ^{38}K^m of 99.967(4)%, and increase the ^{38}K^m ft value by its entire quoted uncertainty to $ft = 3052.1(10)$ s. Implications for tests of the nuclear-structure dependent corrections in superallowed β decays and the extraction of the Cabibbo-Kobayashi-Maskawa matrix element $V_{\rm ud}$ are discussed.

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Through precision measurements of ft values, studies of superallowed $0^+ \rightarrow 0^+$ nuclear β decays provide rigorous tests of the Standard Model description of electroweak interactions [1]. These pure Fermi decays between nuclear isobaric analogue states allow for a direct measurement of the vector coupling constant for semileptonic weak interactions, G_V. This vector coupling constant, together with the Fermi coupling constant G_F for purely leptonic decays, determines the first element ($V_{\rm ud} = G_V/G_F$) of the Cabibbo-Kobayashi-Maskawa (CKM) matrix relating the weak interaction and mass eigenstates of the quarks. To achieve high precision, corrections to the almost nucleus-independent ft values for superallowed β decays must be made for radiative effects as well as isospin symmetry breaking by Coulomb and charge-dependent nuclear forces. Accounting for these corrections gives the transition-independent $\mathcal{F}t$ value [1]:

$$\mathcal{F}t \equiv ft(1+\delta'_R)(1+\delta_{\rm NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R)} \quad (1)$$

where f and t represent the statistical rate function and partial half-life, respectively, and are obtained through measurements of the Q values, branching ratios, and half-lives for the superallowed decays. The δ_C and $\delta_{\rm NS}$ corrections depend explicitly on nuclear structure and account for isospin symmetry breaking and a nucleus-dependent component of the radiative correction, respectively [2]. The correction terms δ'_R and Δ_R represent nucleus-dependent and nucleus-independent radiative corrections. In Ref. [3], a significant advance in controlling hadronic uncertainties in the calculation of Δ_R reduced the uncertainty of $V_{\rm ud}$ by nearly a factor of 2. Using the experimental ft values from Ref. [4], the authors of Ref. [3] obtained $V_{\rm ud} = 0.97377(11)(15)(19)$, a value that has recently been updated to $V_{\rm ud} = 0.97418(13)(14)(18)$ through the incorporation of more recent experimental results and updated calculations of the nuclear-structure dependent corrections δ_C and $\delta_{\rm NS}$ [2]. The uncertainties quoted for $V_{\rm ud}$ are associated with (i) the experimental ft values together with the nucleus-dependent radiative corrections δ'_R, (ii) a systematic difference between two independent calculations of the δ_C corrections [5,6], and (iii) the remaining uncertainty in the nucleus-independent radiative correction Δ_R. The redistribution of terms between δ'_R and Δ_R in Ref. [2] is primarily responsible for the shift of uncertainties between the first and third term quoted above. The value of $V_{\rm ud}$ thus determined from the superallowed β-decay data is the most precisely measured element of the CKM matrix by more than an order of magnitude. We note, however, that the significant (1.5σ) shift in the central value of $V_{\rm ud}$ between Refs. [2,3] is the largest change in this quantity in 20 years and arises almost entirely from the new theoretical calculations of the nuclear-structure dependent corrections presented in Ref. [2]. Precision tests of these corrections are therefore essential.

In this Letter, we revisit the superallowed β decay of ^{38}K^m, representing the most precisely determined experimental ft value. In particular, we note that the adopted superallowed branching ratio for ^{38}K^m, $100^{+0}_{-0.002}$% [1], assumes negligible competition from the internal γ-ray transition between the isomer ($I^\pi = 0^+$, $E^* = 130.4$ keV) [7] and ground state ($I^\pi = 3^+$) of ^{38}K. A shell model calculation for this pure $M3$ transition in ^{38}K [8] predicted a heavily quenched $B(M3)$ value of $0.025\ \mu_N^2\ \mathrm{fm}^4$ (1.2×10^{-4} W.u.) that would yield a $0^+ \rightarrow 3^+$ internal γ-ray branching ratio of only 0.14 ppm. A footnote of Ref. [9], however, briefly references an alternate calculation which predicted a $B(M3)$ of 0.25 W.u. and would yield a significant branching ratio of 390 ppm when corrected for internal conversion. In this Letter, we report a measurement of the branching ratio for this internal decay of the isomeric state by an $M3$ γ-ray transition to the ground state. This result represents the first measurement of a nonsuperallowed branch in the decay of $^{38}\mathrm{K}^m$ and significantly alters the superallowed branching ratio (by more than 16 times the previously quoted uncertainty). The $^{38}\mathrm{K}^m$ ft value is thereby increased by its entire quoted uncertainty.

The experiment was conducted at the Isotope Separator and Accelerator (ISAC) facility at TRIUMF in Vancouver, Canada. A 65 μA, 500 MeV proton beam induced spallation reactions in a 22 g/cm^2 Ta target. The reaction products were surface ionized and mass separated to produce a 30 keV beam comprised of $\sim 7 \times 10^5$ ions/s of ^{38}K and $\sim 4 \times 10^4$ ions/s of $^{38}\mathrm{K}^m$. This beam was implanted into a mylar tape at the mutual centers of the Scintillating Electron Positron Tagging Array (SCEPTAR) [10], an array of 20 plastic scintillators used for β detection, and the 8π γ-ray spectrometer comprised of 20 HPGe detectors in a truncated icosahedron geometry [11]. The beam was cycled in order to optimize the ratio of $^{38}\mathrm{K}^m$ to ^{38}K decays. The tape was moved during the first 0.3 s of each cycle to transport the previously deposited activity behind a lead shielding wall, and background was measured in the time interval from 0.6 s to 1.6 s after the start of each cycle. The ions were then implanted on the tape for 3.5 s to allow the $^{38}\mathrm{K}^m$ ($t_{1/2} \approx 0.924$ s) activity to nearly saturate while the ^{38}K ($t_{1/2} \approx 458$ s) activity had an approximately linear increase over this time. The beam was subsequently deflected at the ion source, and the activity observed for 1.0 s ($\sim$ 1 half-life of $^{38}\mathrm{K}^m$). The cycle was then repeated. List mode data comprised of γ ray and β energies and times, as well as an event time stamp relative to the start of the cycle, derived from a 10 MHz ± 0.1 Hz SRS-SC10 precision oscillator, were recorded to disk for all γ-ray singles events, all $\beta\gamma$-coincidence events, and, to reduce system dead times, every 10th β-singles event. Shown in Fig. 1(a) is the β-activity curve consisting of summed data for 59 381 tape cycles. The number of β decays from each of the beam components was determined by a fit to these data using a maximum likelihood technique and accounted for the small (<3%) bin-by-bin dead time. The result of this fit is shown in Fig. 1(a) and yields a total of $1.96(1) \times 10^9$ $^{38}\mathrm{K}^m$ β decays detected during the experiment.

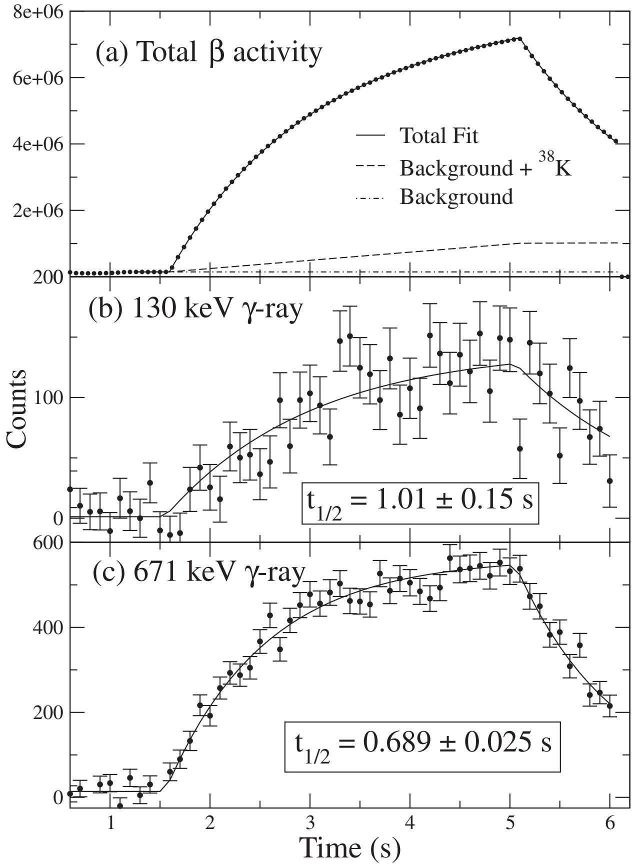

FIG. 1. (a) Total β activity for all 59381 good cycles. The data are in 10 ms bins and consist of prescaled β singles (only every fifth data point is shown for clarity). Activity of (b) the $^{38}\mathrm{K}^m$ 130-keV γ ray (100 ms bins), and (c) the $^{38}\mathrm{Cl}^m$ 671-keV γ ray (100 ms bins). Figures (b) and (c) represent the energy gated activity projections for the background-subtracted photopeaks in the $\bar{\beta}\gamma$ energy spectrum (see text for details).

The total γ-ray spectrum recorded by the 8π spectrometer for cycle times between $t = 1.6$ s (beam on) and $t = 6.1$ s (tape move), as well as the $\beta\gamma$-coincidence spectrum with bremsstrahlung suppression [10] achieved by vetoing the HPGe detector behind the SCEPTAR β detector that was triggered, are shown in Fig. 2(a). These spectra are dominated by the 511-keV annihilation radiation and the 2167-keV γ ray populated in 99.9% of ^{38}K β decays. To search for the $M3$ internal γ-decay of $^{38}\mathrm{K}^m$, a β anticoincidence ($\bar{\beta}\gamma$) γ-ray spectrum [Fig. 2(b)] was constructed. In addition to known background γ rays, a 130-keV γ ray is clearly observed in this spectrum and the measured energy of the transition, 130.1(2) keV, is in excellent agreement with the tabulated excitation energy for the isomeric state, 130.4(3) keV [7]. Confirmation that this peak represents the internal decay of $^{38}\mathrm{K}^m$ is obtained from the background-subtracted activity projection of the 130-keV γ ray shown in Fig. 1(b). A fit to these data yields $t_{1/2} = 1.01(15)$ s, in good agreement with $t_{1/2} = 0.92433(27)$ s for $^{38}\mathrm{K}^m$ decay [1]. For comparison, the 671-keV γ ray from the internal decay of a small $^{38}\mathrm{Cl}^m$ contaminant in the $A = 38$ beam was also observed in the $\bar{\beta}\gamma$ spectrum and a corresponding analysis [Fig. 1(c)]

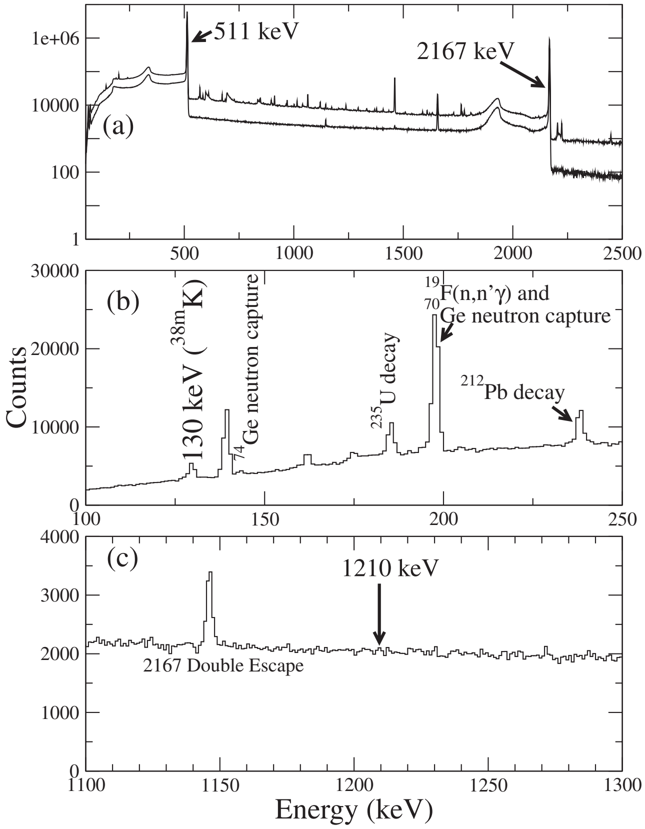

FIG. 2. (a) The total γ-ray spectrum (upper), and the $\beta\gamma$ coincidence and bremsstrahlung suppressed spectrum (lower). (b) Enlarged low-energy region of the $\bar{\beta}\gamma$ energy spectrum. (c) Enlargement of the $\beta\gamma$ and bremsstrahlung suppressed γ-ray spectrum showing the 1210 keV region.

yielded $t_{1/2} = 689(25)$ ms for this transition, in good agreement with the literature value of 715(3) ms [7]. All other γ-ray peaks in the $\bar{\beta}\gamma$ spectrum arose from known backgrounds and had activities that were constant in time, as expected.

The measured peak area of 4100(164) counts for the 130 keV transition, along with (a) the absolute γ-ray efficiency at 130 keV of 0.74(9)% determined by a relative γ-ray efficiency calibration from ^{56}Co, ^{133}Ba, and ^{152}Eu sources scaled to an absolute efficiency using calibrated sources of ^{60}Co ($\pm 1.9\%$) and ^{137}Cs ($\pm 3.7\%$), (b) the total number of observed ^{38}K^m β decays, $1.96(1) \times 10^9$, (c) the β detection efficiency, $\epsilon_\beta = 84(2)\%$, deduced from the ^{38}K $\beta\gamma$ coincidence and γ-singles data, (d) the calculated internal conversion coefficient, $\alpha = 0.392(6)$ [12], for a 130 keV $M3$ transition in ^{38}K, and (e) the calculated superallowed electron-capture fraction $P_{\text{EC}} = 0.085\%$ [1] combined to yield an $M3$ γ-ray branching ratio of 237(31) ppm. The total internal decay branching ratio, including internal conversion, is therefore 330(43) ppm. This branching ratio corresponds to a $B(M3)$ value of 44(6) $\mu_N^2\,\text{fm}^4$ [0.21(3) W.u.], larger than the theoretical prediction of Ref. [8] by more than 3 orders of magnitude, but in good agreement with the alternate prediction of 0.25 W.u. mentioned in Ref. [9].

We have also searched for a nonanalogue Fermi β-decay branch of ^{38}K^m to the first excited 0^+ state of the daughter ^{38}Ar at excitation energy 3377.45(12) keV [7]. The subsequent γ decay of this state to the 2_1^+ state occurs via a transition of energy 1209.96 keV [7]. An enlargement of the $\beta\gamma$ coincidence and bremsstrahlung suppressed spectrum in this region [Fig. 2(c)], shows no discernable peak at this energy. A fit to the expected location of the 1210 keV peak with fixed width and centroid yielded an area of 43(96) counts. As the negative counts are unphysical, the assumed Gaussian probability distribution function (P.D.F.) associated with this mean and standard deviation was truncated at zero counts and renormalized to unit probability. This P.D.F. was then scaled using the total number of detected β decays from ^{38}K^m [$1.96(1) \times 10^9$] along with the γ-ray detection efficiency at 1210 keV [0.847(15)%]. Integrating the scaled P.D.F. yields an upper limit of 8 ppm for the nonanalogue β-decay branch at 67% confidence level (C.L.), and 12 ppm at 90% C.L. The only previous measurement quoted an upper limit for this branch of 19 ppm at the 1σ level [13]. With the ratio of the phase-space factors for the decay of ^{38}K^m to the ground state and first excited 0^+ state of ^{38}Ar, $f_0/f_1 = 148$, limits on the isospin-mixing correction at the 67% and 90% confidence levels are $\delta_{C1}^1 = (f_0/f_1)B_1 \leq 0.12\%$ and $\leq 0.17\%$, respectively. These results are in good agreement with the theoretical prediction $\delta_{C1}^1 = 0.085(30)\%$ [2] for ^{38}K^m that would yield a nonanalogue branching ratio of 6(2) ppm. As we set only an upper limit for the nonanalogue Fermi branch, 8 ppm at 67% C.L., which is negligible compared to the uncertainty in the 330(43) ppm internal branch, we subtract the latter from unity to obtain a revised superallowed branching ratio for ^{38}K^m of 99.967(4)%.

Using $P_{\text{EC}} = 0.085\%$ and $t_{1/2} = 0.92433(27)$ s from Ref. [1], the superallowed branching ratio of 99.967(4)% reported here yields a partial half-life of $t = 0.92542(27)$ s. Together with $f = 3298.10(33)$ [1], $ft = 3052.1(10)$ s is obtained, which is larger than the previously adopted value by 1σ. Applying the calculated corrections for ^{38}K^m of $\delta_R' = 1.440(39)\%$, $\delta_{\text{NS}} = -0.100(15)\%$, and $\delta_C = 0.655(59)\%$ from Ref. [2] yields a corrected $\mathcal{F}t$ value of 3072.7(24) s. These revised values for ^{38}K^m are shown in Fig. 3, together with the data for the other 12 high-precision superallowed ft values from Ref. [2].

The revised superallowed branching ratio for ^{38}K^m presented in this work increases the world-averaged $\overline{\mathcal{F}t}$ value by 0.12 s from $\overline{\mathcal{F}t} = 3071.4(8)$ s [2] to $\overline{\mathcal{F}t} = 3071.5(8)$ s. The reduced χ^2 of the fit to the world superallowed data in Fig. 3(b) increases marginally from 0.59 to 0.61 but remains in excellent agreement with the conserved vector

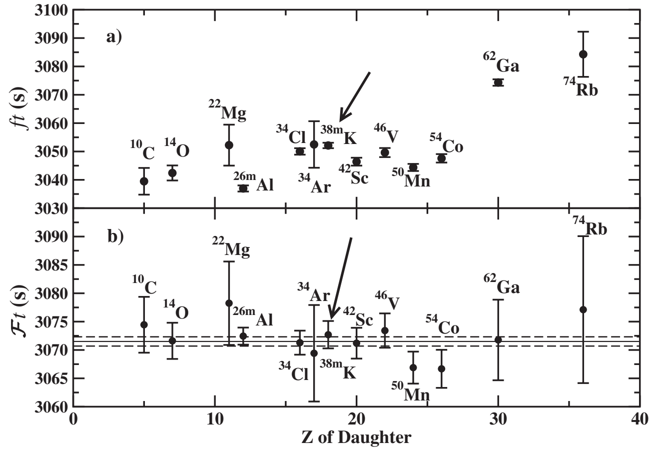

FIG. 3. The 13 most precisely measured superallowed (a) ft and (b) $\mathcal{F}t$ values using the corrections of Ref. [2]. The world average $\overline{\mathcal{F}t} = 3071.5(8)$ s with these corrections includes the current results for ^{38}K^m as well as recently published results for ^{62}Ga [14]. Very recent Q value measurements for ^{50}Mn and ^{54}Co [15] that bring these points into better agreement with the average are not yet included in the evaluated data.

current (CVC) hypothesis, which continues to be supported by the superallowed data at the level of 1.3 parts in 10^4 [2]. Following the procedures adopted in Ref. [2], the corresponding value for the up-down element of the CKM quark mixing matrix is reduced to $V_{\mathrm{ud}} = 0.97416(13)(14)(18)$.

More significant than the shift in the central value of V_{ud} is the importance of accurate ft values to probe the case-by-case variations in the nuclear-structure dependent corrections [2]. Assuming the validity of the CVC hypothesis, we can substitute the average of the other 12 $\mathcal{F}t$ values in Eqn. (1) to extract an experimental value of $\delta_C - \delta_{\mathrm{NS}} = 0.79(6)\%$ for ^{38}K^m. With an uncertainty of only 7% of its own value, this is the most precise relative measurement of the nuclear-structure dependent corrections for any $A < 62$ superallowed decay, and is in excellent agreement with the prediction of 0.76(6)% in Ref. [2]. The $\delta_C - \delta_{\mathrm{NS}}$ values for all 13 precise superallowed decays are shown in Fig. 4. While the average agreement with theory is enforced by the adoption of the CVC hypothesis and the use of $\overline{\mathcal{F}t}$, the case-by-case variations provide real tests of theory and are in impressive agreement with Ref. [2]. The difference $(\delta_C - \delta_{\mathrm{NS}})(^{38}\mathrm{K}^m - {}^{26}\mathrm{Al}^m) = 0.46(6)\%$, for example, has the highest relative precision for any pair of $A < 62$ superallowed decays and is in excellent agreement with the prediction of 0.45(6)% in Ref. [2].

To conclude, this Letter reports a revised superallowed branching ratio for ^{38}K^m based on the measurement of the internal $M3$ γ decay between the isomer and the ground state of ^{38}K. The resulting superallowed branching ratio, 99.967(4)%, leads to revised ft and $\mathcal{F}t$ values of 3052.1(10) s and 3072.7(24) s, respectively. The revised world average $\overline{\mathcal{F}t}$ value yields $V_{\mathrm{ud}} = 0.97416(26)$ for the up-down element of the CKM quark mixing matrix.

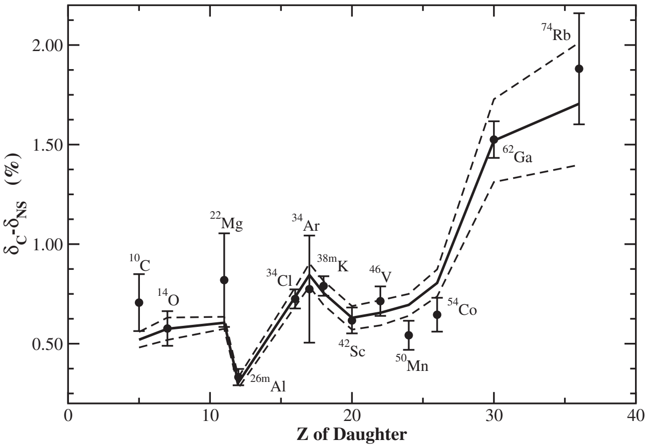

FIG. 4. Experimentally extracted nuclear-structure dependent corrections for the 13 high-precision superallowed decays. The solid line represents the theoretically calculated values from Ref. [2], and the dashed lines their uncertainties.

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