The β decay of ^{38}Ca: Sensitive test of isospin symmetry-breaking corrections from mirror superallowed $0^+ \rightarrow 0^+$ transitions

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We have measured for the first time precise branching ratios for the β decay of ^{38}Ca (see Fig. 1), which includes a superallowed $0^+ \rightarrow 0^+$ branch not previously characterized. Our result sets a new benchmark for such measurements: ±0.35% systematic experimental uncertainty. With the corresponding Q_{EC} value and half-life [1] already known, the transition's *ft* value can now be determined to ±0.2%. This is the first addition to the set of well-known superallowed transitions in nearly a decade and, being from a $T_Z = -1$ parent nucleus, it provides the opportunity to make a high-precision comparison of the *ft* values from a pair of mirror superallowed decays, $^{38}Ca \rightarrow ^{38}K^m$ and $^{38}K^m \rightarrow ^{38}Ar$. The ratio of mirror *ft* values is very sensitive to the model used to calculate the small isospin symmetry-breaking corrections that are required to extract V_{ud} from the data. Since the uncertainty in these corrections contributes significantly to the uncertainty both on V_{ud} and on the unitarity sum, experimental constraints imposed by mirror *ft*-value ratios can serve to reduce those uncertainties by up to 10%.

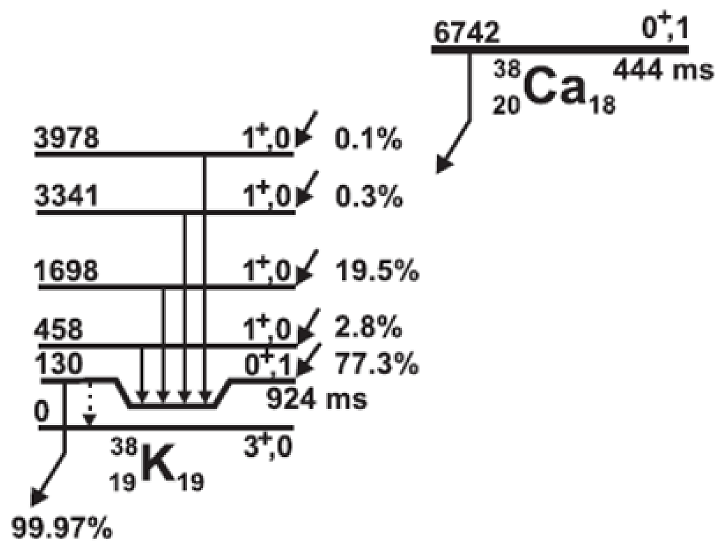

FIG. 1. Beta-decay scheme of ^{38}Ca showing the most intense branches, For each level, its (J^π,T) is given as well as its energy expressed in keV relative to the ^{38}K ground state. Branching percentages come from this measurement.

We produced 444-ms ^{38}Ca using a 30*A*-MeV ^{39}K primary beam from the K500 superconducting cyclotron to initiate the $^1H(^{39}K, 2n)^{38}Ca$ reaction on a LN_2-cooled hydrogen gas target. The fully stripped ejectiles were separated by their charge-to-mass ratio in the MARS recoil separator, producing a ^{38}Ca beam at the focal plane, where the beam composition was monitored by the periodic insertion of a position-sensitive silicon detector. With the detector removed, the ^{38}Ca beam exited the vacuum system through a 50-μm-thick Kapton window, passed successively through a 0.3-mm-thick BC-404 scintillator and a stack of aluminum degraders, finally stopping 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 were 99.7% pure ^{38}Ca, with the main surviving trace contaminants being ^{34}Ar, ^{35}Ar and ^{36}K. Approximately 24,000 atoms/s of ^{38}Ca were implanted in the tape.

During the measurement, each ^{38}Ca sample was accumulated in the tape for 1.6 s, with its rate of accumulation being measured by the scintillation detector located ahead of the degrader stack. Then the beam was turned off and the tape moved the sample in 200 ms to a shielded counting location 90 cm away, where data were collected for 1.54 s, after which the cycle was repeated. This computer-controlled sequence was repeated continuously for nearly 5 days.

At the counting location, the sample was positioned precisely between a 1-mm-thick BC-404 scintillator to detect β^+ particles, and our specially calibrated 70% HPGe detector for γ rays. The former was located 3 mm from one side of the tape, while the latter was 15.1 cm away on the other side. We saved β-γ coincidences event-by-event, recording the energy of each β and γ ray, the time difference between their arrival, and the time that the event itself occurred after the beginning of the counting period. For each cycle we also recorded the rate of accumulation of ^{38}Ca ions in the tape as a function of time, the total number of β- and γ-ray singles, and the output from a laser ranging device that recorded the distance

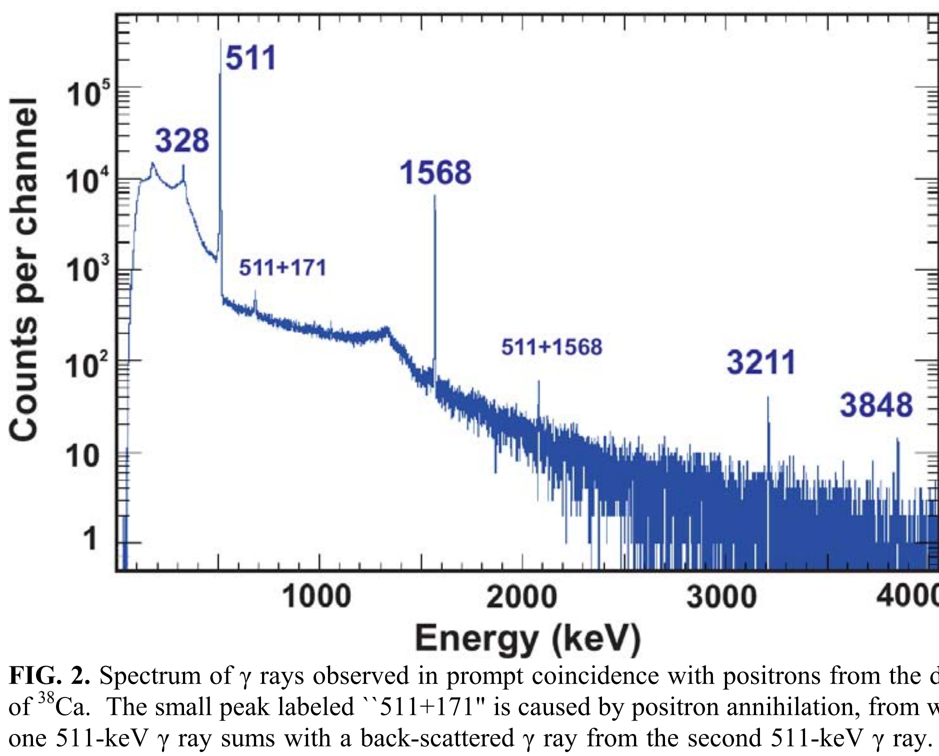

FIG. 2. Spectrum of γ rays observed in prompt coincidence with positrons from the decay of ^{38}Ca. The small peak labeled ``511+171" is caused by positron annihilation, from which one 511-keV γ ray sums with a back-scattered γ ray from the second 511-keV γ ray. The ``511+1568" peak is the result of coincidence summing between a 1568-keV γ ray and annihilation radiation from the positron decay that preceded it.

of the stopped tape from the HPGe detector. From cycle to cycle that distance could change by a few tenths of a millimeter, enough to require a small adjustment to the HPGe detector efficiency. Our recorded spectrum of β-coincident γ rays appears in Fig. 2.

It can be seen from Fig. 1 that all β transitions from ^{38}Ca populate prompt γ-emitting levels in ^{38}K, except for the superallowed branch. To obtain the superallowed branching ratio, our approach is first to determine the number of 1568-keV γ rays relative to the total number of positrons emitted from ^{38}Ca. This establishes the β-branching ratio to the 1^+ state in ^{38}K at 1698 keV. Next, from the relative intensities of all the other (weaker) observed γ-ray peaks, we determine the total Gamow-Teller β-branching to all 1^+ states. Finally, by subtracting this total from 100%, we arrive at the branching ratio for the superallowed transition.

More specifically, if the γ ray de-exciting state *i* in ^{38}K is denoted by γ_i, then the β-branching ratio, R_i, for the β-transition populating that state can be written:

$$R_i = \frac{N_{\beta\gamma i}}{N_\beta \varepsilon_{\gamma i}} \frac{\varepsilon_\beta}{\varepsilon_{\beta i}} \qquad (1)$$

where $N_{\beta\gamma i}$ is the total number of β-γ coincidences in the γ_i peak; N_β is the total number of beta singles corresponding to ^{38}Ca β decay; $\varepsilon_{\gamma i}$ is the efficiency of the HPGe detector for detecting γ_i; $\varepsilon_{\beta i}$ is the efficiency of the plastic scintillator for detecting the betas that populate state *i*; and ε_β is the average efficiency for detecting the betas from all ^{38}Ca transitions.

After correction for dead time, pile-up and other small factors [2], we found the branching ratio for the β transition to the 1698-keV state in ^{38}K to be 0.1949(13). Then, by analyzing the full γ-ray spectrum of Fig.2 and making provision for weak $1^+ \rightarrow 1^+$ γ transitions, we obtained the total of all Gamow-Teller branches relative to this transition. Our final result for the total Gamow-Teller branching from ^{38}Ca is 0.2272(16), and this leads to a superallowed branching ratio of $0.7728 \pm 0.0014_{stat} \pm 0.0009_{syst}$ or, with the uncertainties combined in quadrature, 0.7728±0.0016.

The half-life of ^{38}Ca is 443.77(35) ms [3,4] and the Q_{EC} value for its superallowed branch is 6612.12(7) keV [5]. Taking these results with our new value for the branching ratio and correcting for electron capture, we arrive at an *ft* value for the ^{38}Ca superallowed branch of ft^a = 3062.3(68) s. The *ft* value for the mirror transition from $^{38}K^m$ is ft^b = 3051.5(9) s, a value that comes from our 2009 survey [1] updated for a more recent Q_{EC} measurement reported by Eronen *et al.* [6]. The ratio of the two, ft^a/ft^b = 1.0036(22), appears in Fig. 3, where it can be compared with the calculated results, which appears in Table I of the Progress Report by I.S. Towner and J.C. Hardy [7].

Although our experimental result favors the Woods-Saxon (WS) calculation of δ_C (see [7]), it is not yet definitive. Nevertheless, it clearly points the way to a potential reduction of the uncertainty on V_{ud} through the elimination of alternatives to the WS-calculated corrections currently used. The lack of precise branching-ratio measurements has so far prevented the T_Z = -1 decays of ^{26}Si, ^{34}Ar, ^{38}Ca and ^{42}Ti from being fully characterized with high precision. Now that we have demonstrated the capability to make such a measurement on ^{38}Ca, the other three cases should not be far behind. Together, if all four convey a consistent message, they can have a major impact by sensitively discriminating among the models used to calculate the isospin-symmetry-breaking corrections.

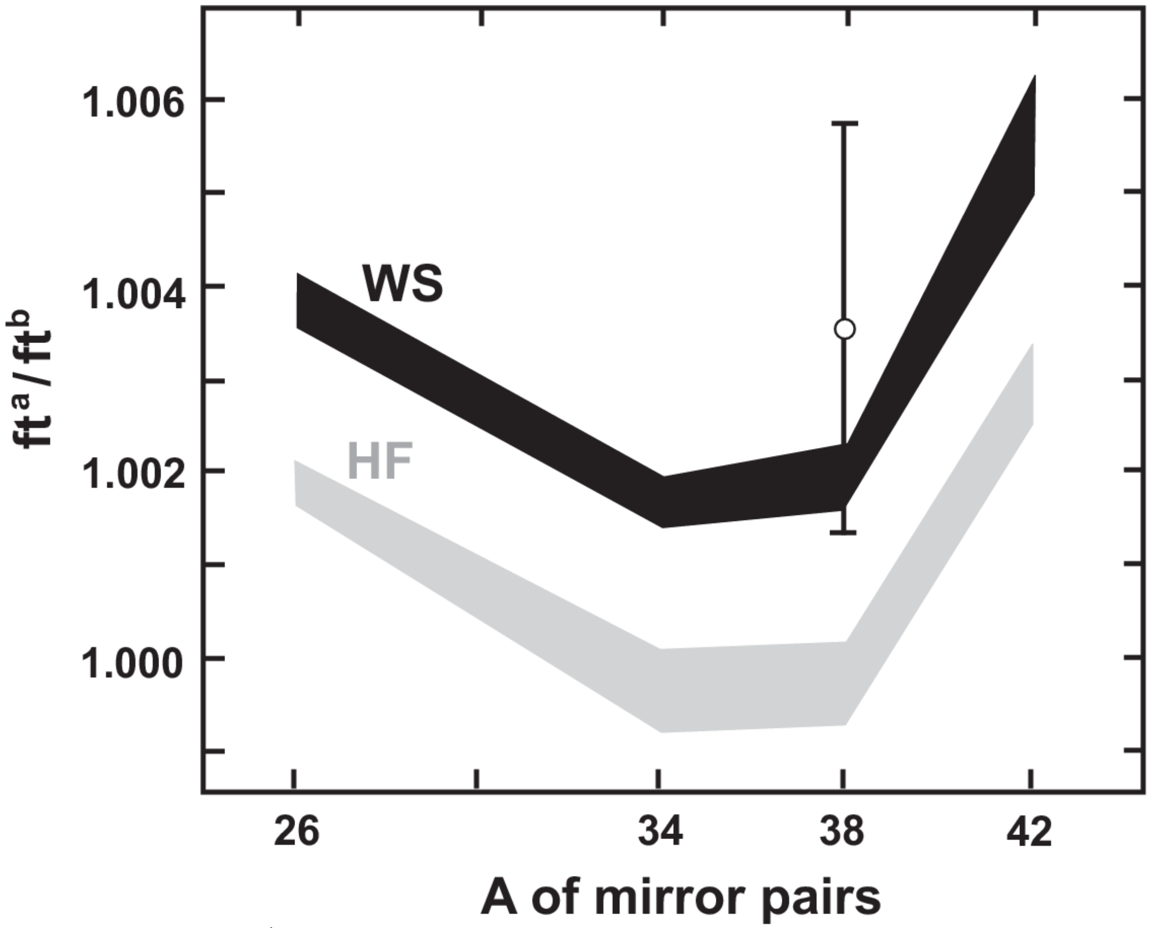

FIG. 3. Mirror-pair ft^a/ft^b values for A = 26, 34, 38 and 42, the four cases currently accessible to high-precision experiment. The black and grey bands connect calculated results that utilize Woods-Saxon (WS) and Hartree-Fock (HF) radial wave functions, respectively (see [7]). Our measured result for the A=38 mirror pair is shown as the open circle with error bars.

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