

Q_{EC} Values of the Superallowed β Emitters ^{50}Mn and ^{54}Co

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Using a new fast cleaning procedure to prepare isomerically pure ion samples, we have measured the beta-decay Q_{EC} values of the superallowed β emitters ^{50}Mn and ^{54}Co to be 7634.48(7) and 8244.54(10) keV, respectively, results which differ significantly from the previously accepted values. The corrected $\mathcal{F}t$ values derived from our results strongly support new isospin-symmetry-breaking corrections that lead to a higher value of the up-down quark mixing element V_{ud} and improved confirmation of the unitarity of the Cabibbo-Kobayashi-Maskawa matrix.

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Precise measurements of superallowed $0^+ \rightarrow 0^+$ nuclear β transitions yield several important tests of the electro-weak standard model [1,2], including the most demanding one available for the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. These tests have by now reached the $\pm 0.1\%$ level, with the dominant uncertainty coming not from experiment but from the radiative and isospin-symmetry-breaking corrections that must be applied to the experimental results. Though small, these theoretical corrections sensitively impact the CKM unitarity test and the limit that it sets on possible physics beyond the standard model. The measurements we report here constitute a crucial test of new calculations of the isospin-symmetry-breaking corrections [3].

Any β -decay transition is characterized by an experimental ft value, which depends on three measurable quantities: the total transition energy Q_{EC} , the half-life of the parent state, and the branching ratio 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 . Currently, there are 13 superallowed $0^+ \rightarrow 0^+$ transitions with ft values that have been measured to a precision of between 0.03% and 0.3%. According to the standard model, once the calculated transition-dependent correction terms have been applied to each ft value, the corrected quantities—denoted $\mathcal{F}t$ —should be identical for all cases since the $\mathcal{F}t$ value is proportional to G_V^{-2} , where G_V is the vector coupling constant. In fact, in 2005 the most important validation of the existing isospin-symmetry-breaking corrections [4] was their success in converting the substantial scatter in the uncorrected ft values into a remarkable consistency among the corrected $\mathcal{F}t$ values [2].

This agreement was somewhat clouded soon after by precise Penning-trap Q_{EC} -value measurements for the ^{46}V superallowed decay [5,6], which shifted that transition's $\mathcal{F}t$ value more than 2 standard deviations above the average of all other well-known transitions and prompted a

close reexamination of its isospin-symmetry-breaking corrections. What ultimately resulted was a new calculation of those corrections, not just for ^{46}V but for the other superallowed transitions as well [3]. For the first time, the calculations included core orbitals, the effects of which were small but sufficient to decrease the $\mathcal{F}t$ values of ^{46}V , ^{50}Mn , and ^{54}Co relative to the average. Impressively, the ^{46}V anomaly disappeared, but at the same time the $\mathcal{F}t$ values for both ^{50}Mn and ^{54}Co were shifted down far enough that they now disagreed with the average.

Is this a sign that the new calculations are flawed or does it mean that the accepted Q_{EC} values of ^{50}Mn and ^{54}Co are incorrect just as the ^{46}V Q_{EC} value had been found to be incorrect? Supporting the latter possibility is the fact that the key measurements for ^{50}Mn and ^{54}Co were reported in the same reference [7] as was the original now-discredited ^{46}V measurement. We settle the question in this report where we present the first Penning-trap Q_{EC} -value measurements for ^{50}Mn and ^{54}Co .

All ions of interest were produced at the IGISOL facility [8] with 13–15 MeV protons initiating (p, n) and (p, p) reactions on enriched ($>90\%$) ^{50}Cr and ^{54}Fe targets. Since ^{50}Mn ($t_{1/2} = 283$ ms) and ^{54}Co ($t_{1/2} = 193$ ms) have much longer-lived (>1 min) isomeric states at ~ 200 -keV excitation, in each case the ground and isomeric states were both produced in the former reaction; the β -decay daughter, either ^{50}Cr or ^{54}Fe , was produced in the latter. All recoil ions were thermalized, extracted, reaccelerated, and mass separated in a dipole magnet having a mass resolving power of ~ 500 . Ions with the selected mass number, either $A = 50$ or $A = 54$, then entered the JYFLTRAP setup.

This setup consists of a radio frequency quadrupole (RFQ) cooler and buncher [9], which is used to bunch the beam, followed by two cylindrical Penning traps—the purification trap and the precision trap—housed inside the same superconducting 7-T magnet. Once a sufficient number of ions has accumulated in the RFQ, the bunch is transferred to the purification trap for isobaric cleaning

[10]. In our previous Q_{EC} -value measurement [6], we successfully used the purification trap alone to prepare isomerically clean samples of $^{26}\text{Al}^m$ and ^{42}Sc ions. However, in those cases the difference in cyclotron frequencies between the ground and isomeric states was ~ 40 Hz. For ^{50}Mn and ^{54}Co the separation is only ~ 10 Hz so we developed a new cleaning scheme—visualized in Fig. 1—in which the ions were transferred to the precision trap where an electric dipole excitation was applied with time-separated oscillatory fields. By choosing an appropriate pattern of excitation with time, we could excite ions in the undesired state to a large orbit while leaving the orbit of the desired ions unaffected. After this excitation, the ion sample was transferred back to the purification trap, removing the undesired ions on the way since they could not pass the 2-mm diaphragm electrode. The cleaned bunch was then recentered in the purification trap and sent again to the precision trap for its final cyclotron frequency determination. Because this cleaning method is rather fast, requiring less than 200 ms to complete, the decay losses were acceptable.

To determine the cyclotron frequency of the ion of interest, we first applied a magnetron excitation for a short duration in order to establish a magnetron radius of ~ 0.8 mm. Then an electric quadrupole excitation was applied to mass-selectively convert the magnetron motion to cyclotron motion. Finally, the resonance was detected using the time-of-flight ion cyclotron-resonance (TOF-ICR) technique [11,12]. There is an alternative and more-precise approach and, since the fitting function for excitation with time-separated oscillatory fields has recently become available [13,14], we took the opportunity to measure part of our data with this so-called Ramsey excitation scheme. Examples of time-of-flight resonance curves taken with this scheme for $^{54}\text{Co}^m$ and ^{54}Co are shown in Fig. 2.

The Q_{EC} values for ^{50}Mn and ^{54}Co were each obtained directly from the frequency ratio of the mother and daughter nuclei. As consistency checks, we also measured the isomer-daughter and isomer-to-ground-state pairs: for example, $^{50}\text{Mn}^m/^{50}\text{Cr}$ and $^{50}\text{Mn}^m/^{50}\text{Mn}$. In all cases, we determined the frequency ratio by interleaving resonance measurements of one pair member with measurements of

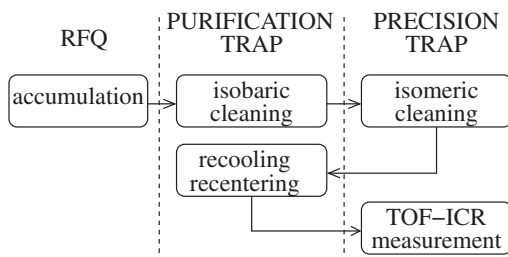


FIG. 1. Schematic of the full cycle to perform a cyclotron frequency measurement with an isomerically clean sample of ions.

the other until ~ 10 successive measurements of both had been recorded under identical conditions. For every mass pair we obtained several such sets of measurements, each set taken with a different timing scheme. We recorded about 4000 ions for each resonance measurement with a bunch-size distribution maximum kept to 1–2 ions/bunch. This allowed us to perform a count-rate class analysis and correct for any possible shift due to contaminating ions [15]. Typical results are shown in Fig. 3.

Since our isomer cleaning technique was completely new, we controlled it carefully and checked to ensure that it worked properly. For consistency, when measuring a mother-daughter pair we cleaned both the mother, which required it, and the daughter, which did not. Then we tested the result by also measuring the pair with the isomeric state purified not by cleaning but by delaying it several half-lives for the ground state to decay away. It was found that if the delay took place in the purification trap the resonances were of much worse quality, but if it happened in the RFQ trap the quality was excellent. The latter result for the resonance frequency agreed well with the result obtained when the cleaning procedure was applied.

Since all our measurements were of mass doublets with the same A , any uncertainty arising from mass-dependent frequency shifts was negligible. Also, since we interleaved the measurements of each frequency, we eliminated the effects of any linear drift in the magnetic field. We accounted for possible nonlinear drifts by adding a relative

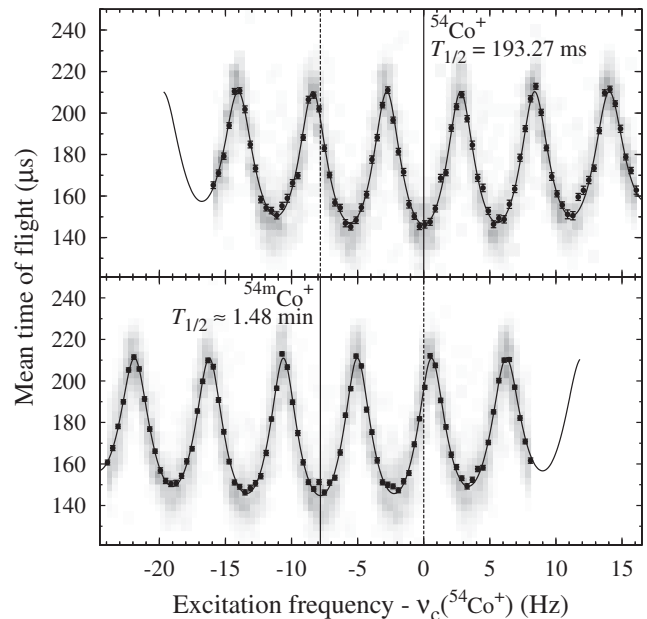


FIG. 2. Time-of-flight cyclotron resonances obtained using excitation with time-separated oscillatory fields. An excitation time pattern of 25-150-25 ms (on-off-on) was used. The vertical bars denote the cyclotron resonance frequencies ν_c . Gray shading around the data points indicates the number of ions in each time-of-flight bin: the darker the gray, the more ions.

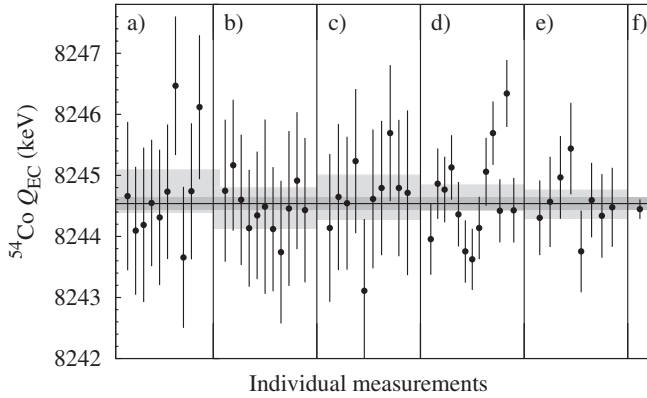


FIG. 3. Individual measurements for the ^{54}Co - ^{54}Fe Q_{EC} value. Sets (a)–(c) were obtained with conventional 200-ms rf excitation but with different cleaning settings for each set. Sets (d) and (e) were both obtained with an excitation time pattern of 25-150-25 ms (on-off-on) but with different magnetron excitation amplitudes. The result labeled (f) is the Q_{EC} -value result from the isomer-daughter and isomer-to-ground-state pairs. The light gray bands denote the average of each set; the dark gray band is the final average including all the data.

uncertainty of $3.2 \times 10^{-11} \text{ min}^{-1}$ multiplied by the time in minutes between successive frequency measurements [16].

We measured every possible pair (mother-daughter, isomer-daughter, and isomer-to-ground state) for both $A = 50$ and 54 . This way we could determine the superallowed Q_{EC} values, not only directly but also via the isomeric states. As illustrated in Fig. 3, several sets of measurements, each including ~ 10 pairs of frequency scans, were obtained for each frequency ratio. The final result was derived from the weighted mean with the quoted uncertainty always being the larger of the inner and outer errors [17]. The results for all six pairs are compiled in Table I, where the final Q_{EC} values for the two superallowed transitions are weighted averages of the direct mother-daughter frequency ratio and two-step result linked via the isomer. We have not added an additional systematic uncertainty since the systematic shift is expected to be common for all

TABLE I. Results of the present measurements. “No.” denotes the number of A - B pairs used in determining the frequency ratio. The superallowed decay branches are given in boldface. The reference mass excesses (Ion B) were taken from Ref. [18].

| Ion A | Ion B | No. | Frequency ratio, $\frac{\nu_B}{\nu_A}$ | Q_{EC} or E_{ex} (keV) |
|--|------------------|-----------|--|--|
| ^{50}Mn | ^{50}Cr | 42 | 1.000 164 097 1(21) | 7634.44(10) |
| $^{50}\text{Mn}^m$ | ^{50}Cr | 58 | 1.000 168 941 2(13) | 7859.81(6) |
| $^{50}\text{Mn}^m$ | ^{50}Mn | 38 | 1.000 004 841 3(20) | 225.28(9) |
| Final superallowed ^{50}Mn - ^{50}Cr Q_{EC} | | | | 7634.48(7) |
| ^{54}Co | ^{54}Fe | 52 | 1.000 164 091 4(25) | 8244.59(13) |
| $^{54}\text{Co}^m$ | ^{54}Fe | 55 | 1.000 168 022 2(17) | 8442.09(9) |
| $^{54}\text{Co}^m$ | ^{54}Co | 39 | 1.000 003 933 0(27) | 197.64(13) |
| Final superallowed ^{54}Co - ^{54}Fe Q_{EC} | | | | 8244.54(10) |

ion species with the same mass number and makes a relatively negligible contribution to the frequency ratio uncertainty.

As an additional check, we measured under identical conditions—including Ramsey cleaning—the double β -decay Q value of ^{76}Ge , which is known to very high precision from an off line Penning-trap measurement with SMILETRAP [19]. The details of our measurement will be published elsewhere [20], but our result, 2039.04(16) keV, agrees completely with 2038.997(46) keV, the SMILETRAP result.

In Fig. 4, our Q_{EC} values are compared with previous measurements [7,21,22] and with the average value adopted in the 2005 survey of superallowed β decay [1]. Obviously our results are significantly higher than the adopted averages, principally because the latter were dominated by the measurements published by Vonach *et al.* [7], with which we disagree by more than 2.5 keV (5 or more of their standard deviations). Evidently, whatever problem Vonach *et al.* had with their measurement of the ^{46}V Q_{EC} value extended to ^{50}Mn and ^{54}Co as well: all three of these results are lower than the modern more-precise values by approximately the same amount.

Our results can also be compared with a previous measurement of the difference in Q_{EC} values between ^{50}Mn and ^{54}Co , 610.1(5) keV [23]. Our present results yield the value 610.06(12) keV, in fine agreement. Less satisfactory is a comparison with the Q_{EC} value difference between ^{42}Sc and ^{54}Co , which was previously determined [23] to be 1817.2(2) keV. If we use our present result for ^{54}Co combined with our recent Penning-trap measurement of the ^{42}Sc Q_{EC} value [6], we obtain a difference of 1818.4(2) keV. Perhaps the previous measurement [23], which depended upon ($^3\text{He}, t$) reactions, included an undetected target impurity in this case.

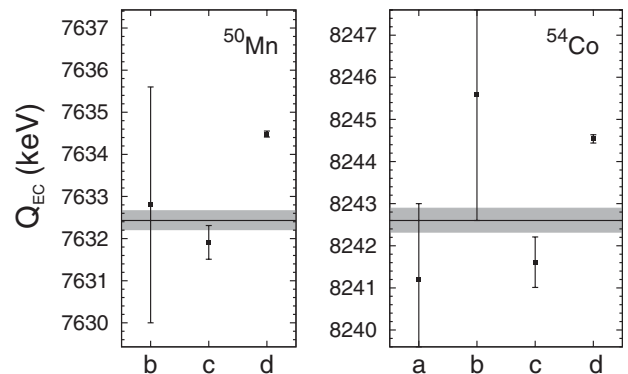


FIG. 4. Previous measurements of the Q_{EC} values of ^{50}Mn and ^{54}Co compared to the present results. The letters on the horizontal scale refer to the sources: (a) Hoath *et al.* [21]; (b) Hardy *et al.* [22]; (c) Vonach *et al.* [7]; and (d) this work. The gray bar is the value adopted in [1], including not only the data shown but also the measurements of Q_{EC} -value differences [23].

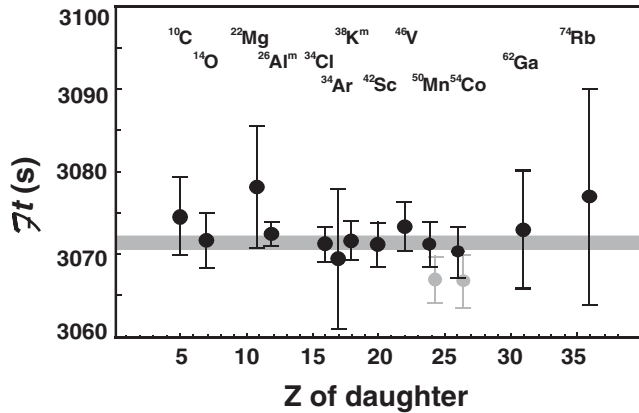


FIG. 5. $\mathcal{F}t$ -value results for the 13 best known superallowed decays, to which the new isospin-symmetry-breaking corrections [3] have been applied. For the ^{50}Mn and ^{54}Co cases, the points shown in gray are the values that were obtained using the previously accepted Q_{EC} values; those in black result from the new Q_{EC} values reported in this work.

Do our new Q_{EC} values remove the discrepancy between the ^{50}Mn and ^{54}Co $\mathcal{F}t$ values and the average $\mathcal{F}t$ value for the whole set of 13 precisely measured superallowed transitions? The answer is clearly yes. The results are shown in Fig. 5, where the old values for ^{50}Mn and ^{54}Co are shown in gray and our new results are in black. In determining the $\mathcal{F}t$ values for ^{50}Mn and ^{54}Co —3071.2(28) and 3070.4(32) s, respectively—we combined our new Q_{EC} values with the half-lives and branching ratios from the 2005 survey of world data [1], and applied the new calculated correction terms reported in Ref. [3]. The consistency is now excellent ($\chi^2/N = 0.22$), an outcome that strongly supports those recent calculations and their inclusion of the effects of core orbitals.

In supporting the new isospin-symmetry-breaking corrections [3], our results also reinforce the higher value of V_{ud} , the up-down quark mixing element of the CKM matrix, that those corrections led to. Incorporating our new $\mathcal{F}t$ values with the 11 others quoted in Ref. [3], we obtain the result that $|V_{ud}| = 0.974\,08(26)$. With the values of the other two top-row elements of the matrix taken from the 2006 Particle Data Group review [24], the unitarity sum becomes

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9998(10), \quad (1)$$

in perfect agreement with standard model expectations.

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