Q_{EC} Values of the Superallowed β Emitters ^{34}Cl and ^{38}K^m

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The superallowed β-decay Q_{EC} values of ^{34}Cl and ^{38}K^m have been measured with an online Penning trap to be 5491.662(47) keV and 6044.223(41) keV, respectively. The new values are more precise than the previous high-precision reaction-based values but are consistent with them and establish that there are no significant systematic differences between the two types of measurements.

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Precise measurements of superallowed $0^+ \rightarrow 0^+$ nuclear β transitions yield several important tests of the electroweak standard model [1], including the most demanding one available for the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. With these tests now at the $\pm 0.1\%$ level or better, any further improvement demands a thorough understanding of all systematic effects that may impact the input data. We address here one of the most important questions: in the determination of β-decay Q_{EC} values, is there a systematic difference between results obtained from nuclear reactions and those derived from Penning-trap measurements of the parent and daughter atomic masses?

Until recently, the total β-decay energy for each superallowed transition could only be determined from a reaction-based measurement, typically a (p, n) threshold, a $(^3\mathrm{He}, t)$ Q value, or a combination of (p, γ) and (n, γ) measurements. Over the years, specialized techniques were developed for these experiments until their quoted uncertainties in the best cases reached the ± 100-eV level. Then, shortly after the year 2000, online Penning traps made short-lived radioactive nuclei accessible to precise mass measurements and it became possible to obtain Q_{EC} values of comparable precision from mass-difference measurements. Two different types of measurements, with quite different sources of possible systematic error, opened up the opportunity for consistency checks.

Early results were startling. First with the ^{46}V Q_{EC} value [2,3] and then with the Q_{EC} values for ^{50}Mn and ^{54}Co [4], Penning traps produced results that were significantly different—by about 2 keV—from the previously accepted values. Questions arose about whether there might be a systematic discrepancy between Penning-trap and reaction-based measurements [5]. By now, though, it has become evident [1,6] that the problems with ^{46}V, ^{50}Mn, and ^{54}Co came from a single set of flawed $(^3\mathrm{He}, t)$ Q-value measurements made 30 years ago [7] rather than from a generic property of reaction-based measurements.

However, even with the 2-keV problem solved, there still remains the broader question of whether few-hundred-eV-level systematic differences could remain between the two types of measurement techniques. Even such small differences would have a noticeable effect on the extraction of weak-interaction parameters from superallowed decays. To be sure, the Penning-trap results for ^{26}Al^m and ^{42}Sc [3] both agreed with earlier values from (p, n) and $(p, \gamma) + (n, \gamma)$ measurements, but in both cases the Penning-trap results had larger uncertainties than the reaction-based ones.

Here we report Penning-trap measurements for the ^{34}Cl and ^{38}K^m transitions, which yield Q_{EC} values with less than ± 50-eV uncertainties, the most precise yet obtained for any superallowed transition. In both cases, the Q_{EC} values have been determined previously from (p, n) threshold measurements to ± 540 eV in the case of ^{34}Cl [8] and to ± 120 eV for ^{38}K^m [9]. For ^{34}Cl, the Q_{EC} value has also been determined previously, to ± 260 eV, from a combination of (p, γ) and (n, γ) measurements [10–12]. Not only do the new results lead to improvements in the ft values for the two transitions but they also test more sensitively for any possible systematic differences between the two types of measurement techniques.

All ions of interest were produced at the IGISOL facility [13] with proton-induced fusion-evaporation reactions. For both β-decay transitions being studied, the parent and daughter ions were simultaneously produced in the reaction, thus enabling a direct measurement of the decay energy. In fact, for both cases the parent nucleus had a low-lying isomeric state so we included it in our measurements as well. For ^{34}Cl and ^{34}Cl^m, we employed the ^{34}S(p, n) reaction, with a 15-MeV proton beam impinging on a natural zinc-sulphide target that had been evaporated onto a nickel backing. With this beam and target combination, the beta-decay daughter ^{34}S was also readily available as an ion beam via the (p, p) reaction channel. Similarly, ^{38}K^m and ^{38}K were produced from a natural potassium-chloride target with 20-MeV protons initiating the ^{39}K(p, pn) reaction. The beta-decay daughter ^{38}Ar ions were available through the $(p, 2p)$ reaction channel and also from ionization by the primary proton beam of residual argon atoms in the helium of the IGISOL gas cell.

The reaction products were thermalized in helium gas of 150 mbar pressure, extracted with a radio frequency sextupole [14], and accelerated to $30q$ keV. After coarse mass separation in a dipole magnet with a mass resolving power of ~500, the selected isobars with charge state $q = 1$ and mass number either $A = 34$ or $A = 38$ were injected into a radio frequency quadrupole [15] for cooling and bunching. Next, the bunched beam was delivered to a double Penning-trap system, in which both traps are housed inside the same superconducting 7-T magnet. The first Penning trap is filled with dilute helium gas and is used for mass purification and ion cooling [16,17], while the second is operated in vacuum for high-resolution beam purification and for high-precision cyclotron-frequency determination.

As the cyclotron-frequency differences between the ground and isomeric states in ^{34}Cl and ^{38}K are only about 15 Hz and 11 Hz, respectively, the purification trap alone was not sufficient to entirely remove the undesired state. To achieve complete purity, an extra step was added: the ions were transferred to the precision trap, where the cyclotron orbit of the undesired ions was expanded with a radio frequency electric-dipole excitation accomplished by Ramsey's method of time-separated oscillatory fields [18]. After excitation, the ion bunch was extracted back towards the purification trap but, since the channel between the traps is only 2 mm in diameter, only the nonexcited ions of interest survived. The isomerically cleaned bunch was then recaptured in the purification trap, where additional cooling and centering took place. Finally, the bunch was released back to the precision trap for cyclotron-frequency determination.

To determine the cyclotron frequency of the ion of interest, we first applied an electric-dipole excitation at the magnetron frequency (about 160 Hz), which was phase locked with the time the ion bunch was injected into the trap [19]; this increased the radius of the ion magnetron orbit to about 0.8 mm. Next, a quadrupole excitation was switched on to mass selectively convert magnetron motion to cyclotron motion. Here, time-separated oscillatory fields (the Ramsey method) were also used to enhance the precision of the frequency determination [20,21]. The resonances were obtained with a (25-250-25) ms (on-off-on) excitation-time pattern for $A = 34$ ions and with (25-350-25) ms for $A = 38$ ions. The duration of the ion excitation-time pattern was chosen to be short because of the rather strong ion-motion damping caused by the rest gas in the precision trap. The effect is more pronounced with lighter ions due to a velocity-dependent damping.

The frequency of the quadrupole excitation was scanned over the sideband frequency $\nu_+ + \nu_-$ of the ions. When the excitation frequency matches the sideband frequency, the conversion from magnetron to cyclotron motion is maximal. Thus, since the ions had been prepared with only magnetron motion to begin with, at resonance they have only cyclotron motion and, upon extraction from the trap, they arrive sooner to the detector that registers the time-of-flight of the ions from the trap [22]. A sample resonance for ^{38}K^m ions is shown in Fig. 1. Since we only measure mass doublets, the invariance theorem given by Brown and Gabrielse [23,24] proves that the sideband frequency actually corresponds to the cyclotron frequency $\nu_c = qB/(2\pi m)$ with a precision of the order of 10^{-10}. This is by far smaller than the quoted statistical uncertainties for any mass-difference results reported in this Letter.

To minimize the effects of temporal fluctuations in the magnetic field, we revised the frequency scanning procedure that we have followed in the past. Instead of continuously scanning one ion species for about 30 min and then switching to another, we switched after every scan: approximately once per minute. Typically this interleaved scanning was continued for about 10 h for each ion pair. In analyzing the data, we split the total 10-h measurement into roughly 40-min intervals, and the time-of-flight resonance result obtained for each interval was fitted separately for both ion species to get a frequency ratio. The final frequency ratio for a particular doublet was then obtained from the weighted average of its interval results.

To account for possible shifts in the resonance frequency due to multiple ions being stored in the trap, we fitted all resonances using the method of "count-rate class analysis" [25]. We classified the result from each filling of the trap according to how many ions were detected, and then separately fit the data in each class: all of the results with four detected ions in one class, all of those with three in another, and so on. This yielded the cyclotron frequency as a function of the number of detected ions, from which we obtained a final frequency value by extrapolation to the single-ion value. This worked effectively for $A = 38$ but the frequency extrapolation turned out to be rather unreliable for $A = 34$ since the average number of ions per bunch was low. Therefore, for that case we limited the

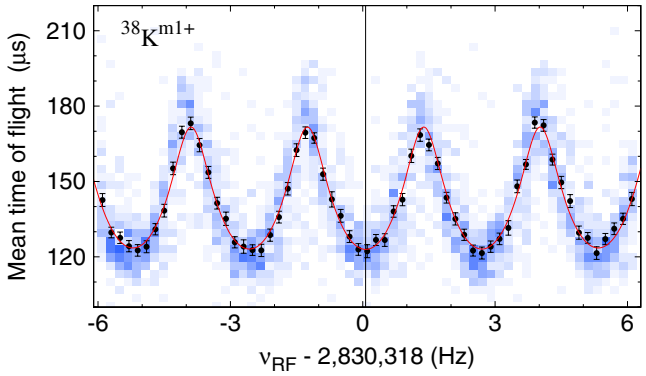

FIG. 1 (color online). Time-of-flight ion-cyclotron resonance of ^{38}K^m obtained with singly charged and isomerically cleaned ions. The resonance was obtained with a (25-350-25) ms (on-off-on) Ramsey excitation-time pattern. The pixels represent detected ions: the darker the pixel, the more ions it represents. The solid (red) line is a fit to the experimental data.

analysis to bunches containing 1–3 ions to obtain the quoted central value; the uncertainty was taken from the count-rate analysis. As an example of the quality of results, Fig. 2 shows the individual cyclotron frequencies obtained for the $^{38}K^m$-^{38}Ar pair, together with the deviations of the frequency ratios from the average value. It can be seen that, although the magnetic field fluctuates, the cyclotron-frequency ratios are consistent over a 12-h span.

The Q_{EC} value, or mass difference, is given by

$$Q_{EC} = M_m - M_d = \left(\frac{\nu_d}{\nu_m} - 1\right)(M_d - m_e) - \Delta B_{m,d}, \quad (1)$$

where M_m and M_d are the masses of the parent and daughter atoms, respectively; ν_d/ν_m is their cyclotron-frequency ratio with singly charged ions; m_e is the electron mass; and $\Delta B_{m,d}$ is the electron binding-energy difference between the parent and daughter atoms: +2.6 eV for chlorine-sulfur and −11.4 eV for potassium-argon [26]. In extracting Q_{EC} values from Eq. (1), we took the masses of the daughter atoms from Ref. [27].

Not only did we determine the mass differences for the superallowed parent-daughter pairs ^{34}Cl-^{34}S and $^{38}K^m$-^{38}Ar but, as consistency checks, we also did so for the $^{34}Cl^m$-^{34}S, $^{34}Cl^m$-^{34}Cl, ^{38}K-^{38}Ar, and $^{38}K^m$-^{38}K pairs as well as the $^{26}Al^m$-^{26}Al pair, which we produced with an enriched ^{26}Mg target. The results are presented in Table I, where the final Q_{EC} values for the superallowed transitions have been derived from both the direct and the indirect—i.e., double-mass differences.

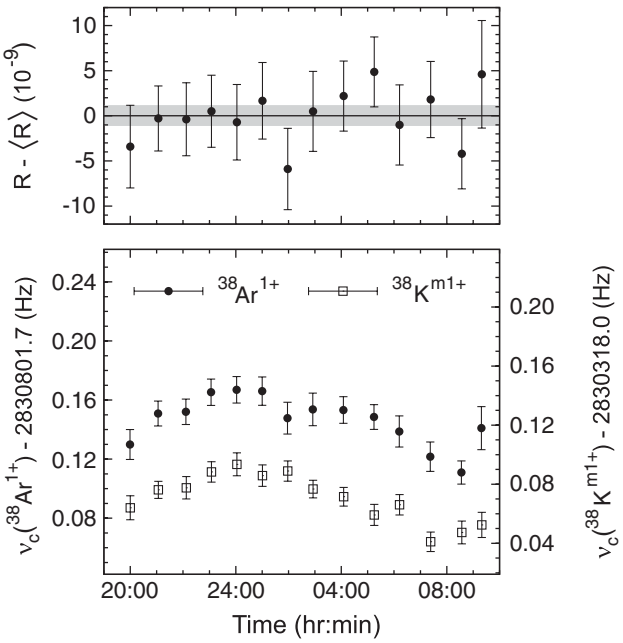

FIG. 2. Series of fitted cyclotron frequencies for $^{38}K^m$ and ^{38}Ar (lower panel). Each frequency point includes the results of 40 interleaved scans. The top panel shows the deviation of the individual frequency ratios, ν_d/ν_m, from the average frequency ratio.

The excitation energy of $^{34}Cl^m$ has previously been determined precisely from its decay γ ray to be 146.36(3) keV [28] and that of $^{26}Al^m$ from a (p, γ) measurement [29] to be 228.305(13) keV. For both states, our results in Table I agree with these values within statistical uncertainties, demonstrating consistency at the level of a few tens of eV. The excitation energy of $^{38}K^m$ was previously known only to relatively modest precision, 130.4(3) keV [30]. Our result agrees with, but is much more precise than, this value.

With the measurements reported here, there are now four superallowed $0^+ \rightarrow 0^+$ transitions for which both Penning-trap and comparably precise reaction-based measurements exist. It is instructive to examine the differences among them, as illustrated in Fig. 3. The agreement between the reaction-based values (points with error bars) and Penning-trap ones (gray bands) is very good, with one exception: the (p,n) threshold measurement for the $^{26}Al^m$ transition [31]. That case is a particularly difficult one to measure by the (p,n) reaction since there is a pronounced resonance in yield within a few keV of threshold, and a target impurity added further complications to the published measurement. Although great care was obviously taken in the experiment, the difficulties were apparently not fully overcome in this particular case. Clearly, though, it is not indicative of any systematic problem.

The other two (p, n) measurements and all three of the $(p, \gamma) + (n, \gamma)$ ones agree with the Penning-trap results within their uncertainties. Their weighted average difference (reaction result minus Penning-trap result) is 15(85) eV. Any systematic difference between reaction and trap measurements, if it exists at all, must be below 100 eV, which is below—and usually well below—the uncertainties quoted on the reaction-based measurements themselves. At the level of precision currently required in dealing with world data for the evaluation of weak-interaction parameters, it appears that one can safely combine the results of both types of measurements without including any additional systematic uncertainties.

The previously accepted Q_{EC} values for ^{34}Cl and $^{38}K^m$ obtained from world data in the most recent survey of

TABLE I. Results of the present measurements. The final Q_{EC} values for superallowed branches are given in boldface.

Ion A	Ion B	Frequency ratio $\frac{\nu_B}{\nu_A}$	Q_{EC} or E_{ex} (keV)
^{34}Cl	^{34}S	1.000 173 565 3(17)	5491.665(52)
$^{34}Cl^m$	^{34}S	1.000 178 188 2(20)	5637.935(64)
$^{34}Cl^m$	^{34}Cl	1.000 004 622 7(31)	146.289(98)
Final superallowed ^{34}Cl-^{34}S Q_{EC} value			**5491.662(47)**
$^{38}K^m$	^{38}Ar	1.000 170 926 5(13)	6044.237(46)
^{38}K	^{38}Ar	1.000 167 244 7(18)	5914.044(63)
$^{38}K^m$	^{38}K	1.000 003 679 3(17)	130.126(61)
Final superallowed $^{38}K^m$-^{38}Ar Q_{EC} value			**6044.223(41)**
$^{26}Al^m$	^{26}Al	1.000 009 432 4(19)	228.323(46)

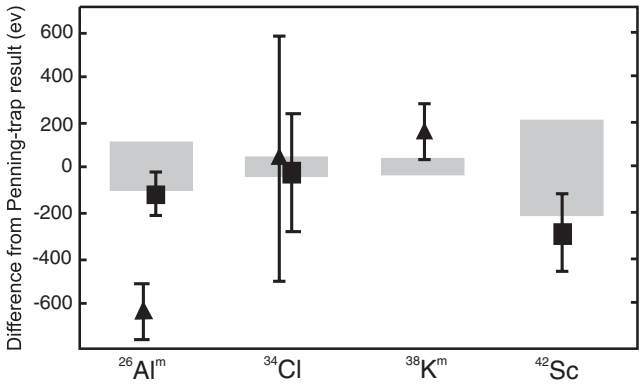

FIG. 3. Differences between precise reaction-based and Penning-trap Q_{EC} value measurements for $^{26}Al^m$, ^{34}Cl, $^{38}K^m$, and ^{42}Sc. Only measurements with uncertainties ≤ 540 eV are included. The (p, n)-threshold measurements are shown as triangles and are from Refs. [8,9,31] (in order from $A = 26$ to $A = 38$). The $(p, \gamma) + (n, \gamma)$ measurements appear as squares and are from groups of references, which are given in Ref. [1]. The gray bands about the zero line represent the uncertainty of the Penning-trap measurements, which are taken from an average of Refs. [3,32] for $^{26}Al^m$, from this work for ^{34}Cl and $^{38}K^m$, and from [3] for ^{42}Sc.

superallowed $0^+ \rightarrow 0^+$ β decay [1] are 5491.64(23) and 6044.40(11) keV, respectively. All of the existing measurements on both nuclei were reaction based. In the case of ^{34}Cl, our Penning-trap result is 5 times more precise than, and lies well within the uncertainties of, the survey value. The survey value for $^{38}K^m$ has a smaller uncertainty than that for ^{34}Cl and differs by one and a half of its standard deviations from our Penning-trap result, which is nearly 3 times more precise.

Obviously the present results tighten the uncertainties on the Q_{EC} values for ^{34}Cl and $^{38}K^m$, whose world averages now become 5491.662(46) and 6044.240(39) keV. These improved values leave the uncertainties in the ft values for the corresponding superallowed transitions totally dependent on the uncertainties of their measured half-lives. It should be noted that the ft-value uncertainties would now be reduced by nearly an order of magnitude if the half-life measurements were to be improved by that factor. That would provide a useful new check on the efficacy of the isospin symmetry breaking corrections used in the CKM unitarity test [1].

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