Q Values of the Superallowed β Emitters ^{26}Al^m, ^{42}Sc, and ^{46}V and Their Impact on V_{ud} and the Unitarity of the Cabibbo-Kobayashi-Maskawa Matrix

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The β-decay Q_{EC} values of the superallowed beta emitters ^{26}Al^m, ^{42}Sc, and ^{46}V have been measured with a Penning trap to a relative precision of better than 8×10^{-9}. Our result for ^{46}V, 7052.72(31) keV, confirms a recent measurement that differed from the previously accepted reaction-based Q_{EC} value. However, our results for ^{26}Al^m and ^{42}Sc, 4232.83(13) keV and 6426.13(21) keV, are consistent with previous reaction-based values. By eliminating the possibility of a systematic difference between the two techniques, this result demonstrates that no significant shift in the deduced value of V_{ud} should be anticipated.

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A recent critical survey of superallowed $0^+ \to 0^+$ nuclear β decays [1] presented a remarkably consistent picture, from which it was possible to obtain precise values and demanding limits on a number of fundamental weak-interaction parameters [1,2]. In particular, the value of the up-down element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix was determined from the superallowed data to be $V_{ud} = 0.9738(4)$. Since V_{ud} is a key component of the most demanding available test of the unitarity of the CKM matrix, the precision and reliability of the value for V_{ud} has a direct impact on the search for physics beyond the standard model.

Shortly after the survey was published, a new Q_{EC}-value measurement was reported by Savard *et al.* [3] for the superallowed β decay of ^{46}V. This was the first time that the Q_{EC} value for any of the nine most-precisely known superallowed transitions had been measured with an on-line Penning trap. All previous results had been obtained from reaction Q values: generally from (p, n) or $(^3\mathrm{He}, t)$ reactions, or from a combination of (p, γ) and (n, γ) reactions. Stunningly, the Penning-trap result differed by more than 2 keV from the survey result and left the $\mathcal{F}t$ value for the ^{46}V transition anomalously high with respect to the $\mathcal{F}t$ values for the other superallowed transitions. There was understandable concern that this could be signaling a previously undetected systematic error in all the reaction measurements, which, when corrected, might lead to a significant shift in V_{ud} from the value obtained in the survey.

Since systematic changes of only a few hundred eV in the Q_{EC} values could have an appreciable effect on V_{ud}, this concern prompted a careful study [4] of whether such systematic errors could be excluded in past measurements of (p, γ) and (n, γ) reaction Q values. The study's authors concluded that systematic effects up to at least 200 eV could not be excluded, and they proposed that a Penning-trap measurement of the superallowed transition from ^{26}Al^m would provide an excellent case to test for systematics since the corresponding reaction-based Q value was particularly soundly based.

We report here Penning-trap measurements of the Q_{EC} values for three superallowed β transitions. The first, the decay of ^{46}V, was chosen to confirm (or not) the recent unexpected Penning-trap result [3]. The second, ^{26}Al^m, is the case proposed [4] as a test for systematic effects. The third, ^{42}Sc, is another case in which high-quality (p, γ) and (n, γ) reaction measurements have previously been performed. The measurements were specifically aimed at establishing whether undetected systematic effects were present in earlier measurements and whether a significant change in V_{ud} might be anticipated as a result.

All ions of interest were produced at the IGISOL facility [5]. We produced ^{46}V and ^{26}Al^m via (p, n) reactions, with 20- and 15-MeV proton beams incident on enriched ^{46}Ti and ^{26}Mg targets, respectively. For ^{42}Sc, we used a ^{3}He beam of 20 MeV on $^{\mathrm{nat}}$Ca. In these bombardments, not only were the superallowed emitters of interest produced in the primary reactions but ions from the target material itself—the β-decay daughters of these emitters—were also released by elastic scattering of the cyclotron beam. The recoil ions were slowed down and thermalized in the gas cell of an ion guide filled with 150 mbar of helium [5]. These were then transported by gas flow and electric fields through a differentially pumped electrode system into a high-vacuum region, accelerated to 30 keV and passed through a 55° dipole magnet for a coarse mass selection with resolving power of 300–500.

The mass-separated ion beam was then transferred to the JYFLTRAP setup. This consists, first, of an rf quadrupole cooler [6], which is used to improve the quality of the beam and bunch it for efficient injection into the Penning-trap system. The latter consists of two cylindrical traps housed inside the same superconducting 7-T magnet. The first trap is filled with helium buffer gas to allow for purification of the ion sample. A mass resolving power of up to a few $\times 10^5$ [7] can be achieved in this first trap, which is enough to resolve the isomeric and ground states in ^{26}Al and ^{42}Sc.

After purification, the ion ensemble was injected into the second Penning trap for the actual mass measurement. A dipole electric field was used to establish a magnetron orbit of ≈ 0.8 mm in radius with a fixed frequency and amplitude. Then, the ions were exposed to an rf quadrupole electric field for a given time. The amplitude of the rf electric field was tuned so that, when the frequency corresponded to the cyclotron frequency of the ion of interest, the whole magnetron motion was converted to cyclotron motion. After the quadrupole excitation, the ions were extracted from the trap and their time of flight to the microchannel plate detector recorded. The frequency corresponding to the shortest time of flight is the true cyclotron frequency [8,9]. To locate the precise resonance frequency, we scanned the frequency and recorded the time of flight over a range that spanned the resonance. Examples of these frequency scans appear in Fig. 1.

The Q_{EC} value of each ion of interest was obtained directly from the frequency ratio of the mother and the daughter nuclei. The cyclotron frequency measurements were interleaved: first, we recorded a frequency scan for the daughter, then for the mother, then for the daughter, and so on. This way, the slow drift of the magnetic field, mostly due to drifts in the room temperature, could be treated properly by interpolation of the reference frequency to the instant of measurement for the ion of interest. In the cases of ^{26}Al^m and ^{42}Sc we also measured the resonance frequencies of the nearby high-spin, long-lived states to check for consistency.

For each measurement, data were collected in several sets. Each set comprised ~10 pairs of parent-daughter frequency scans taken under the same conditions. Between sets, the excitation time was changed. Each of the resonance curves was fitted with a realistic function, described in Ref. [9], which yielded values for the resonant frequency and its statistical uncertainty.

For ^{46}V, a total of 40 resonances were obtained with ^{46}Ti as a reference ion; these were grouped in three sets with excitation times of 700, 500, and 300 ms. For ^{42}Sc we used ^{42}Ca as a reference and obtained 52 resonances in 5 different sets covering three different excitation times, 300, 400, and 600 ms (see Fig. 2). As a consistency check for ^{42}Sc, we also measured the Q_{EC} value of ^{42}Sc^m, referenced to both ^{42}Ca and ^{42}Sc.

The ^{26}Al^m measurement followed the same pattern as for ^{42}Sc. The resonances of ^{26}Al^m and ^{26}Al were both measured with respect to the ground state of ^{26}Mg and, in addition, we measured the excitation energy of ^{26}Al^m directly by using ^{26}Al(g.s.) as a reference. In each of these three ratio measurements, excitation times of 200, 300, and 400 ms were used. As a further consistency check, the frequency ratios for ^{26}Al^m and ^{26}Al were also obtained with ^{25}Mg as the reference ion; however, in this latter case only a 200-ms excitation time was used and relatively few resonances were obtained. Our final measured frequency ratios for all cases are given in Table I.

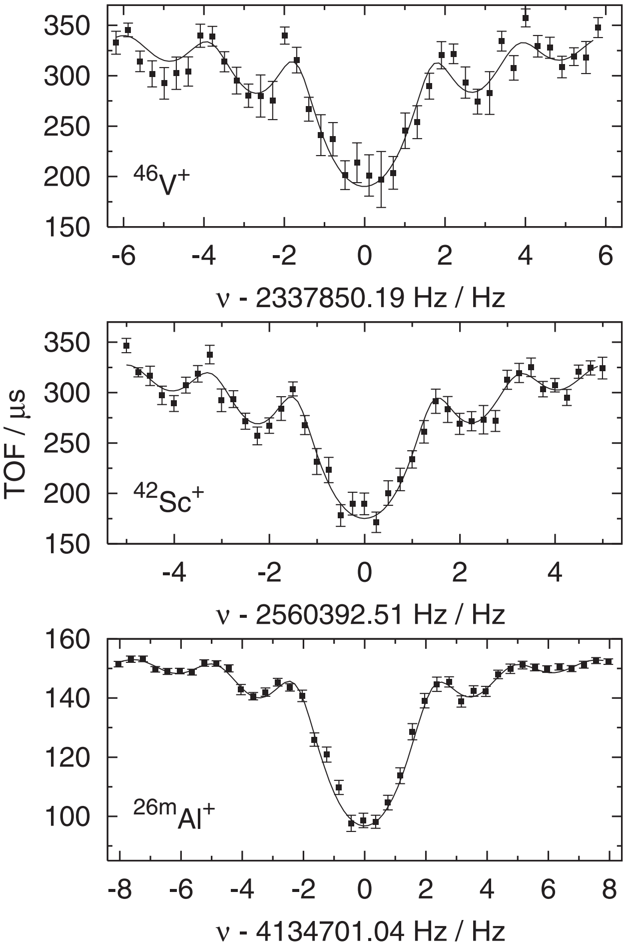

FIG. 1. Examples of the time-of-flight (TOF) resonances measured for each of the superallowed beta emitters. The solid curves are fitted functions (see text).

With the frequency ratios thus determined, we derived the Q_{EC} value between mother-daughter pairs from the following equation:

$$Q_{\mathrm{EC}} = m_m - m_d = \left(\frac{\nu_d}{\nu_m} - 1\right) m_d, \tag{1}$$

where m_m and m_d are the masses of the singly charged mother and daughter ions and $\frac{\nu_d}{\nu_m}$ is their frequency ratio. In our experiment, all measured ions were singly charged and the mass excess values for the reference ions, m_d, were obtained from Ref. [10]. Since the term inside parenthesis is small ($<10^{-3}$), the uncertainty contribution from m_d to

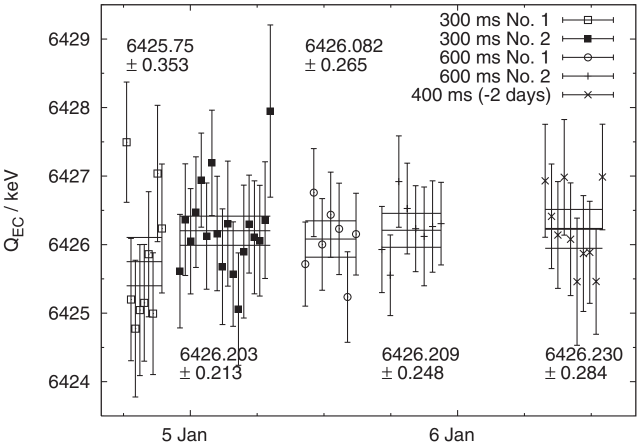

FIG. 2. Individual Q_{EC} values obtained for ^{42}Sc in January 2006 by using ^{42}Ca$^+$ as a reference ion. Each set of measurements corresponds to a different excitation time (see legend). The values given (in keV) for each set contain only statistical uncertainties from fitting and those arising from short-term magnetic field fluctuations. The 400 ms set was shifted earlier by 2 days for plotting convenience.

the Q_{EC} value is negligible. The final Q_{EC} value (or, where appropriate, the excitation energy, E_{ex}) for each pair was obtained from the weighted average of the results from each relevant set. The results from successive sets of scans in our ^{42}Sc measurement are shown in Fig. 2.

In obtaining a final uncertainty on the frequency ratios (and derived Q_{EC} values), we considered more than just the statistical uncertainties in the fitted resonance frequencies. Although the slow drift of the magnetic field was accounted for by the interpolation process already described, short-term field fluctuations may also exist, so we quadratically added an uncertainty of 47, 20, and 34 mHz to the individual frequency uncertainties for ions with $A = 46$, 42, and 26, respectively. These numbers were derived from the observed scattering in the reference frequencies and have a relatively small impact on the final uncertainties.

An important source of systematic uncertainty is the number of ions stored simultaneously in the trap, which can cause shifts in the resonance frequency. There are two ways to deal with this effect. The first is simply to keep the number of ions stored simultaneously in the trap small. We took this approach in the cases of ^{46}V and ^{42}Sc, for which we filtered the data during analysis, only including time-of-flight results from bunches that included 2 ions or less. Since the ideal number would be 0.6, corresponding to 1 ion stored per bunch corrected for the known detection efficiency of 60%, we took account of any possible remaining systematic shift due to our nonideal bunch size by including an additional uncertainty of 0.008 Hz to both the reference and the ion of interest: i.e., $\sqrt{2} \times 0.008$ Hz on the Q_{EC} value (see [11]).

The second way of dealing with the count-rate effect is to divide the data into different groups depending on the number of ions per bunch that were detected. Each group is fitted separately and a resonance frequency obtained. The resonant frequencies obtained for the various numbers of detected ions are then extrapolated back to 0.6 detected ions per bunch [12]. Only in the case of ^{26}Al^m did we have high enough statistics to allow us to analyze the data following this procedure.

Finally, because most of our measurements were of mass doublets, each partner having the same mass number, mass-dependent systematic effects in such cases are expected to cancel out. However, when the reference mass number is different from the one of interest, the uncertainty typically applied for heavier nuclei is 7×10^{-10} per mass unit difference. To be conservative, we adopted an uncertainty of 1×10^{-8} in the case where ^{25}Mg was used as a reference for ^{26}Al.

Our results for the Q_{EC} (or E_{ex}) values are given in Table I for each measured doublet. Also given are the derived mass excesses for each identified ion. Our data for both $A = 26$ and $A = 42$ allow us to obtain the superallowed Q_{EC} values by two routes: via the direct doublet

TABLE I. Results of the present measurements. "No." denotes the number of doublet measurements made. The superallowed decay branches are indicated in boldface. The reference mass excesses were taken from Ref. [10].

Ion	Reference	No.	Frequency ratio, $\frac{\nu_{ref}}{\nu_{ion}}$	Q_{EC} or E_{ex} (keV)	Mass excess (keV)
^{46}V	**^{46}Ti**	**40**	**1.000 164 767 4(71)**	**7052.72(31)**	**−37 070.68(86)**
^{42}Sc	**^{42}Ca**	**52**	**1.000 164 419 9(52)**	**6426.14(22)**	**−32 120.93(32)**
^{42}Sc^m	^{42}Ca	29	1.000 180 196 1(54)	7042.73(23)	−31 504.34(33)
^{42}Sc^m	^{42}Sc	23	1.000 015 774 3(58)	616.62(24)	−31 504.64(35)
Final superallowed ^{42}**Sc—**^{42}**Ca** Q_{EC} value				**6426.13(21)**	
^{26}Al^m	**^{26}Mg**	**22**	**1.000 174 893 4(64)**	**4232.79(15)**	**−11 981.79(16)**
^{26}Al	^{26}Mg	18	1.000 165 466 0(64)	4004.63(15)	−12 209.95(16)
^{26}Al^m	^{26}Al	18	1.000 009 431 4(64)	228.30(16)	−11 982.01(17)
Final superallowed ^{26}**Al**^{m}**—**^{26}**Mg** Q_{EC} value				**4232.83(13)**	
^{26}Al^m	^{25}Mg	3	1.040 075 606(21)		−11 981.36(49)
^{26}Al	^{25}Mg	4	1.040 065 775(19)		−12 210.15(45)
^{26}Al^m—^{26}Al using ^{25}Mg as reference				228.79(62)	

measurement and via the combination of the other two doublets involving the non-0^+ state in the mother nucleus. In both cases the two routes led to statistically consistent results, and it is their average that we quote for our final Q_{EC} values.

We note as well that for both $A = 26$ and $A = 42$, we obtain the excitation energies of the isomeric states in the mother nuclei. In the case of $^{26}Al^m$ we obtain this energy via three different routes, giving an average result of 228.27(13) keV. This compares very favorably with the accepted value [13] of 228.305(13) keV, which is based on γ-ray measurements. For $^{42}Sc^m$ the two paths we have available yield an average excitation energy of 616.61(22) keV, which also is in tolerable agreement with 616.28(6) keV, the accepted value [13]. These results provide a gratifying confirmation of the consistency of our measurements.

There are three important conclusions we can draw from our Q_{EC}-value results. First, our result for the superallowed Q_{EC} value for ^{46}V, 7052.72(31) keV, confirms the recent Savard *et al.* [3] measurement of 7052.90(40) keV, and disagrees with the previously accepted value of 7050.71(89) keV, a survey result [1] principally based on a 30-year-old $(^3He, t)$ Q-value measurement by Vonach *et al.* [14].

Second, we can effectively rule out widespread systematic differences of more than ~200 eV between reaction-based Q-value measurements and those obtained with an on-line Penning trap. In their study of past measurements of (p, γ) and (n, γ) reaction Q values near ^{26}Al, Hardy *et al.* [4] derived a "best" reaction-based result for the mass excess of ^{26}Al of $-12\,210.27(11)$ keV. By comparing reaction Q values with much more precise *off-line* Penning-trap measurements of stable nuclei in this same mass region, the authors cited evidence for possible systematic effects in the former of ~100 eV. They then derived a second mass excess for ^{26}Al of $-12\,210.21(22)$ keV, a value that they state has been "adjusted for possible systematics." Our measurement of the ^{26}Al mass excess—the first one made with a Penning trap—is $-12\,209.95(16)$ keV and does not differ significantly from either of the values presented by Hardy *et al.*; however, it certainly agrees more closely with their systematics-adjusted value. We cannot therefore exclude systematic differences of up to ~200 eV between reaction-based and *on-line* trap measurements but anything significantly greater is ruled out. This conclusion is further supported by our Q_{EC}-value result for ^{42}Sc, 6426.13(21) keV, which agrees well with the most precise previous result, 6425.84(17) keV, obtained from (p, γ) and (n, γ) reaction Q values [1].

This leads to our third conclusion, that no significant shift in the value of V_{ud} should be anticipated as more and more on-line Penning-trap measurements of the superallowed Q_{EC} values become available. With our Penning-trap results for the Q_{EC} values of $^{26}Al^m$ and ^{42}Sc in good agreement with the previously accepted values [1] and no evidence now of significant systematic differences between reaction and Penning-trap measurements, it can reasonably be concluded that ^{46}V was an anomalous case, for which only a single dominant measurement had previously been available [14], a measurement that appears simply to have been wrong. For all other "well-known" superallowed transitions, several precise reaction-based measurements already exist and new Penning-trap Q_{EC}-value measurements, when they appear, can safely be averaged on an equal footing with those previous results. To date, on-line Penning-trap results are being quoted with uncertainties comparable to the best of the earlier measurements, so no large changes should be expected in the resultant averages.

Although our result for ^{46}V confirms that there is a small anomaly in the $\mathcal{F}t$ value for this transition [3], if we incorporate our three new Q_{EC} values and the one from Ref. [3] into the 2005 survey data [1] (and include improved radiative corrections [15]) we find $V_{ud} = 0.9737(3)$, only marginally changed—and slightly improved—from the value 0.9738(4) quoted in the survey.

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