Q Value of the Superallowed Decay of ^{46}V and Its Influence on V_{ud} and the Unitarity of the Cabibbo-Kobayashi-Maskawa Matrix

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The masses of the radioactive nuclei ^{46}V and its decay daughter ^{46}Ti have been measured with the Canadian Penning Trap on-line Penning trap mass spectrometer to a precision of 1×10^{-8}. A Q_{EC} value of 7052.90(40) keV for the superallowed beta decay of ^{46}V is obtained from the difference of these two masses. With this precise Q value, the $\mathcal{F}t$ value for this decay is determined with improved precision. An investigation of an earlier Q-value measurement for ^{46}V uncovers a set of 7 measurements that cannot be reconciled with modern data and affects previous evaluations of V_{ud} from superallowed Fermi decays. A new evaluation, adding our new data and removing the discredited subset, yields new values for G_{V} and V_{ud}. When combined with recent results for V_{us}, this yields modified constraints for the unitarity of the Cabibbo-Kobayashi-Maskawa matrix and other extensions of the standard model.

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Superallowed $0^+ \rightarrow 0^+$ decays, with their inherent simplicity, are an invaluable probe of possible extensions of the electroweak sector of the standard model. The nuclear matrix element for these transitions is almost independent of nuclear structure: a Clebsch-Gordan coefficient corrected at the percent level for isospin symmetry breaking. The ft value for these decays, obtained from measurements of the lifetime, Q value, and branching ratio, yields, after correction for radiative effects, a corrected $\mathcal{F}t$ value which has the simple form [1]

$$\mathcal{F}t \equiv ft(1 + \delta_R')(1 + \delta_{NS} - \delta_C) = \frac{K}{2G_{\mathrm{V}}^2(1 + \Delta_{\mathrm{R}}^{\mathrm{V}})}, \quad (1)$$

with f being the statistical rate function, t the partial half-life, G_{V} the weak vector coupling constant, and K a numerical constant. The small correction terms include δ_C, the isospin symmetry-breaking correction, δ_R' and δ_{NS}, the transition-dependent parts of the radiative correction, and $\Delta_{\mathrm{R}}^{\mathrm{V}}$, the transition-independent part. Only δ_C and δ_{NS} depend on nuclear structure.

The conserved vector current (CVC) hypothesis states that the same value of G_{V} should be obtained for all superallowed decays. A recent review of the superallowed decay data indicates that, from the set of 12 most precisely determined decays, this CVC expectation is confirmed at the 3×10^{-4} level [1]. The resultant average value of G_{V}, together with the Fermi coupling constant from the pure-leptonic decay of the muon, yields the most precise available value for V_{ud}, the up-down quark mixing element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. This matrix is a rotation matrix connecting the weak and mass eigenstates of the quarks. Currently, the most demanding test of CKM unitarity comes from the top-row sum which, when taken from the latest Particle Data Group (PDG) survey [2], yields a result that violates unitarity at the 2.3 sigma level. The main contributors to this unitarity test are V_{ud} and V_{us}. Recent work yields a higher value of V_{us} and a much better agreement with unitarity; this in turn fuels the need for a more precise V_{ud} value to obtain a tighter unitarity test.

The data on the superallowed Fermi decays used to obtain V_{ud} come from over 100 different experiments. They contribute less than 20% of the total uncertainty on V_{ud}, the remainder coming from the small theoretical corrections that must be applied to the data. In particular, the corrections for nuclear structure effects, though not the largest contributors, have a significant impact on the uncertainty. One test of the latter corrections is to examine how precisely they convert the scatter in experimental ft values to the CVC-predicted constancy of the $\mathcal{F}t$ values. Improved precision for individual transitions sharpen that test. Of the nine most precisely known cases, ^{46}V has the largest uncertainty associated with the Q value. We report here a Q-value measurement for the ^{46}V decay, which yields a more precise $\mathcal{F}t$ value for this superallowed transition. This new Q value disagrees with a previous measurement and uncovers a total of seven inconsistent Q-value measurements from the same reference that should be removed from the previously accepted data set. This leads to a significant change in the average of all $\mathcal{F}t$

values and produces a change in V_{ud}. It also impacts the derived limits on new physics.

The mass measurements were performed at the Canadian Penning Trap (CPT) mass spectrometer located on-line at the ATLAS accelerator of Argonne National Laboratory. The CPT mass spectrometer has been used previously for high-precision measurements on other superallowed decay cases [3], and a detailed description of the device can be found elsewhere [4,5]. The ^{46}V and ^{46}Ti isotopes were created by a 3.3 MeV/u beam of ^{36}Ar impinging on a 0.8 mg/cm^2 rotating target of natural carbon. Reaction products recoiling out of the target are separated from the primary beam and transported to a gas catcher system via a focusing magnetic quadrupole triplet, a velocity filter, and an Enge magnetic spectrograph. The gas catcher system, described in [6], thermalizes these fast recoil ions in high-purity helium gas and extracts them as a low-energy doubly charged ion beam, suitable for injection into ion traps. The extracted ions are accumulated for 300 ms in a linear rf trap and transferred in a bunch to a gas-filled Penning trap where mass-selective cooling [7] is applied. The ions are mass selected there with a resolving power of 1000 before being transported to the CPT spectrometer itself.

The transport is performed in pulsed mode, which allows further selection of the $A/q \sim 23$ ions by time of flight. At the end of the time-of-flight system, the purified ions with $A = 46$ and $q = +2$ are captured in a second linear rf trap and further cooled by buffer-gas collisions before being transferred via a differential pumping section to the precision Penning trap where the mass measurements take place.

In the Penning trap, a mass measurement is performed as a frequency scan. The ions are first loaded into the trap. Remaining contaminant ions (in this case, either mostly ^{46}Ti^{2+} when ^{46}V^{2+} is being measured or the reverse) are removed from the trap by a strong mass-selective rf excitation. The ions of interest are then excited to a finite magnetron orbit by a fixed-frequency dipole rf excitation and are subjected to a quadrupolar rf field, which couples the magnetron and the reduced cyclotron motion when the frequency applied corresponds to the true cyclotron frequency. The ions are subsequently ejected and allowed to drift towards a microchannel-plate detector, where a time-of-flight spectrum is recorded. The process is repeated with the injection of another bunch of ions into the trap, repetition of the ion cleaning and preparation, and quadrupolar excitation at the next frequency. At the true cyclotron frequency, the ions will have their magnetron motion converted to reduced cyclotron motion and hence will have higher energy, leading to a reduced time of flight to the detector [8,9]. Frequency scans for the isotopes ^{46}V^{2+} and ^{46}Ti^{2+} are shown in Fig. 1.

The experiment interleaved measurements of the mass of ^{46}V^{2+} and ^{46}Ti^{2+} with calibrations of the magnetic field via measurements of ^{22}Ne$^+$ (see Fig. 2). A small magnetic-field drift (about 8×10^{-10} per hour) was observed during the experiment. This shift is negligible at the level of accuracy required since calibration and measurements on radioactive species were interleaved; nevertheless, all measurements were corrected for it. The results of the different measurements are then averaged with the proper statistical weights to yield the final values for the cyclotron frequencies and statistical uncertainties. The resulting cyclotron frequency ratios are $\nu(^{46}\mathrm{V}^{2+})/\nu(^{22}\mathrm{Ne}^{1+}) = 0.956974161(12)$, $\nu(^{46}\mathrm{Ti}^{2+})/\nu(^{22}\mathrm{Ne}^{1+}) = 0.957131846(10)$, and $\nu(^{46}\mathrm{V}^{2+})/\nu(^{46}\mathrm{Ti}^{2+}) = 0.999835252(9)$.

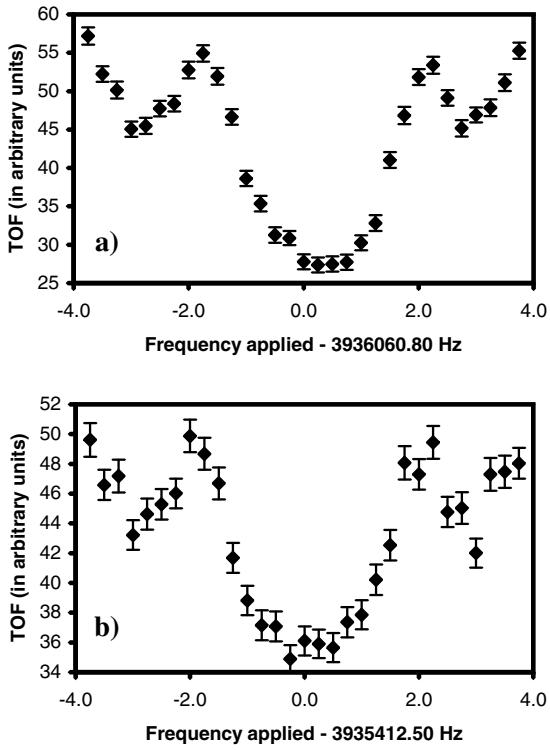

FIG. 1. Time-of-flight (TOF) spectra obtained for ^{46}Ti^{2+} (a) and ^{46}V^{2+} (b) using a quadrupole excitation of 500 ms duration. The mass resolution is $\sim 5 \times 10^{-7}$.

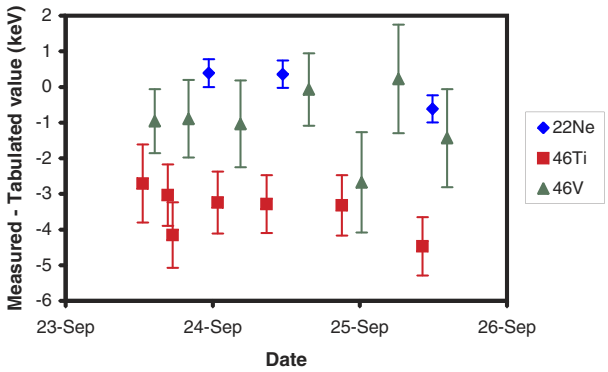

FIG. 2 (color online). Measured mass values (plotted as deviations from the tabulated mass values [10]) for the isotopes of interest versus time during the experiment.

Measurements on the ^{46}V, ^{46}Ti, and ^{22}Ne isotopes were performed with an average of 0.34, 1.02, and 1.18 ions detected per cycle, respectively. Shifts in cyclotron frequency due to ion-ion interactions for different number of ions in the trap were measured with ^{22}Ne isotopes to be $-1.7(2.7)$ ppb per detected ion, under the conditions used during the experiment. Corrections to the three frequency ratios given above of $1.4(2.3) \times 10^{-9}$, $0.3(4) \times 10^{-9}$, and $1.2(1.8) \times 10^{-9}$, respectively, were applied to account for this effect. The spatial extent probed by the ions in the trap is determined by the ion preparation and the conditions of injection. Optimization of the injection conditions to minimize possible systematic errors is performed following a procedure outlined in [3]. For measurements of isotopes with different A/q ratios, this procedure yields an accuracy better than 10^{-8}; for species with the same A/q ratio, the conditions are identical and no uncertainty is introduced. We use the demonstrated 1 part per 10^8 accuracy as a conservative value for our systematic uncertainty for the new mass values obtained below from ratios of isotopes with different mass number. The masses of the two $A = 46$ isotopes can be obtained from the frequency ratios to the well-known mass of ^{22}Ne, after correction for the missing electron mass (or two electron masses) and the electronic binding energies. This yields mass values of m(^{46}V) = 45.96019909(69) amu and m(^{46}Ti) = 45.95262748(62) amu. Our result for ^{46}Ti differs substantially from the value in the 2003 mass tables [10]. It should, however, be noted that this latter value depends on a 30-year-old unpublished (p, γ) measurement [11].

The Q value for the decay can be obtained more precisely from the ratio of the cyclotron frequencies for ^{46}V and ^{46}Ti directly since most systematic effects (with the exception of the ion number dependency which is corrected for) cancel out for such a close doublet of masses. The measured ratio yields, after corrections, a Q value for the superallowed decay of 7052.90(40) keV, which differs by 2.19 keV from the value determined in the latest compilation [1] [from the average of two mutually inconsistent results: 7053.3(1.8) [12] and 7050.41(60) keV [13]]. The present measurement agrees with the first of those but is in strong disagreement with the second one, which claims smaller error bars. This second result originated from (^{3}He, t) reaction measurements in a Q3D spectrometer calibrated with a beam whose energy was measured with a time-of-flight system. These measurements actually included results [13] on a total of seven high-precision Q values of superallowed emitters and we therefore undertook a reassessment of all seven. In Fig. 3 we compare the Q values obtained in [13] to those we obtain using all data from a recent compilation [1], including our new measurement, but excluding [13]. The deviations average more than 2σ and peaks at 5σ. The probability that the deviations of the results from [13] are due to statistical fluctuations is below 0.000 000 1%. Since the energy calibration used in [13] cannot be traced back and the deviations appear not only to be large but also predominantly in one direction, we have opted to remove these measurements from the high-precision data set.

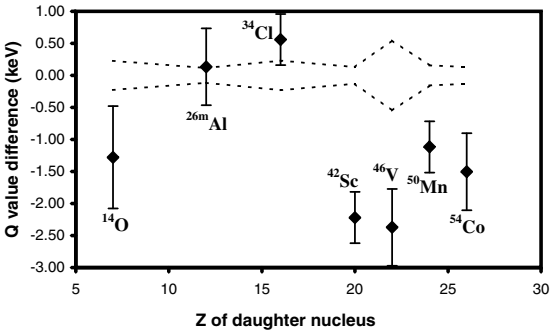

FIG. 3. Difference between the Q values measured in [13] and the values obtained from all other data. The lines indicate the uncertainty on the relevant Q values from the other existing data.

The resulting precision data set (Table I) yields the $\mathcal{F}t$ value plot shown in Fig. 4. The agreement amongst the various emitters is still remarkable. The average $\mathcal{F}t$ value for the most precise 12 cases is now shifted to 3073.66(75), 1 standard deviation above the latest evaluation, with a reduced χ^2 of 1.12. The increase in the reduced χ^2 is due mainly to the new $\mathcal{F}t$ value for ^{46}V, $\mathcal{F}t(^{46}\text{V}) = 3079.9(23)$ s, with the neighboring decays ^{42}Sc and ^{34}Cl also contributing slightly. This might be a first clear indication of deviations from the calculated isotope-to-isotope variation in nuclear-structure-dependent corrections that we ultimately aim to test. This poorer reduced χ^2 is also reflected in a slightly weaker scalar current limit than that obtained in [1], the Fierz interference term now being $b_F = 0.0024(28)$. For the ^{46}V decay, the Q value and lifetime measurements now have roughly similar contributions to the total experimental error, both being smaller than the uncertainty in the nuclear-structure-dependent corrections. The $\mathcal{F}t$ values for both ^{46}V and ^{42}Sc are significantly above the average, and in both cases the values were raised with respect to the other emitters by

TABLE I. New values for the ft values and corrected $\mathcal{F}t$ values for the 12 most precisely known cases obtained with the modified data set.

Emitter	ft value	$\mathcal{F}t$ value
^{10}C	3039.5(47)	3073.0(49)
^{14}O	3043.3(19)	3072.0(26)
^{22}Mg	3052.4(72)	3080.9(74)
^{26m}Al	3036.8(11)	3073.0(15)
^{34}Cl	3050.0(12)	3071.2(19)
^{34}Ar	3060(12)	3076.6(123)
^{38m}K	3051.1(10)	3072.2(21)
^{42}Sc	3046.8(12)	3076.4(24)
^{46}V	3050.7(12)	3079.9(23)
^{50}Mn	3045.8(16)	3072.4(27)
^{54}Co	3048.4(11)	3072.2(28)
^{74}Rb	3084.3(80)	3083.3(154)

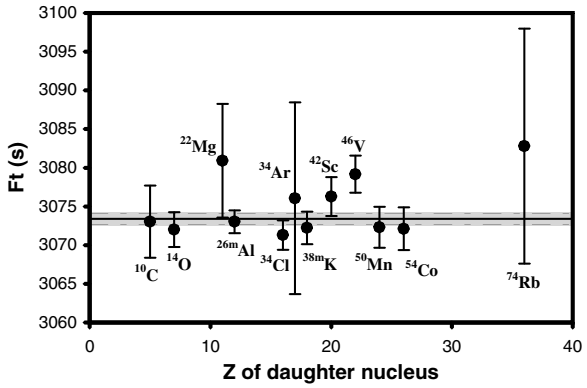

FIG. 4. $\mathcal{F}t$ values for the most precisely known superallowed beta emitters with the modified data set.

the calculated corrections. An independent calculation of these nuclear-structure-dependent corrections exists [14] that yields a slightly higher average $\mathcal{F}t$ value but the same general variations from emitter to emitter. A reevaluation of the variations in these calculations may be warranted, but at present we follow [1] and use the mean value for these corrections for the nine most precise cases (for which both calculations are available), assigning a systematic uncertainty equal to half the mean difference. This yields a new average $\mathcal{F}t = 3074.4(12)$ s.

With the new average $\mathcal{F}t$ value and the transition-independent radiative corrections, one obtains a new value for the weak vector coupling constant of $G_V/(\hbar c)^3 = 1.1356(5) \times 10^{-5}$ GeV^{-2}. Combining this value with the Fermi coupling constant, one obtains a new value of $V_{ud} = 0.9736(4)$. This value is lower than that obtained in the latest evaluation of superallowed decay data [1] but is still within the previously quoted uncertainty.

Before proceeding to the unitarity sum of the top row of the CKM matrix, we must first decide on an appropriate value for V_{us}. Recent results from BNL-E865 [15], KTeV [16], NA48 [17], and KLOE [18] yield values for $|V_{us}|f_+(0)$ consistently higher than the values quoted by the Particle Data Group [2]. Various calculations are available for $f_+(0)$, but following [19,20] we use the value from [21] which yields, with the weighted average of the above experimental results, $V_{us} = 0.2248(19)$. Using this value together with our new value for V_{ud} and the PDG value for V_{ub}, we obtain

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9985 \pm 0.0012, \qquad (2)$$

with equal contributions to the uncertainty coming from V_{ud} and V_{us}. For both elements, the uncertainty is dominated by uncertainty in theoretical calculations [$f_+(0)$ for V_{us} and Δ_R^V for V_{ud}].

In conclusion, a high-precision determination of the Q value of the superallowed decay of ^{46}V has resolved a discrepancy in that value and uncovered a set of seven measured Q values that systematically disagree with this and other precise results from the data set used for the most precise determination of V_{ud}. A new evaluation has been performed with a revised data set that includes the present measurement and excludes the seven faulty values. It yields a lower value for V_{ud} that, when combined with the recently improved value for V_{us}, almost satisfies CKM unitarity in the top-row test. The precision of that test is now dominated by theoretical uncertainties in the determination of both V_{ud} and V_{us}. The CVC test connected to the constancy of the $\mathcal{F}t$ values measured in superallowed decays has been worsened slightly by the changes to the data set, as has been the limit on scalar currents. An extension of the precision measurement techniques used here to the other superallowed emitters is necessary to shed more light on this situation.

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