Direct Mass Measurements on the Superallowed Emitter ^{74}Rb and Its Daughter ^{74}Kr: Isospin-Symmetry-Breaking Correction for Standard-Model Tests

A. Kellerbauer,[1,*] G. Audi,[2] D. Beck,[3] K. Blaum,[1,3] G. Bollen,[4] B. A. Brown,[4] P. Delahaye,[1] C. Guénaut,[2] F. Herfurth,[3]
H.-J. Kluge,[3] D. Lunney,[2] S. Schwarz,[4] L. Schweikhard,[5] and C. Yazidjian[3]
[1]*Department of Physics, CERN, 1211 Genève 23, Switzerland*
[2]*CSNSM-IN2P3-CNRS, 91405 Orsay-Campus, France*
[3]*GSI, Planckstraße 1, 64291 Darmstadt, Germany*
[4]*NSCL, Michigan State University, East Lansing, Michigan 48824-1321, USA*
[5]*Institut für Physik, Ernst-Moritz-Arndt-Universität, 17487 Greifswald, Germany*
(Received 8 March 2004; published 12 August 2004)

The decay energy of the superallowed β decay $^{74}\text{Rb}(\beta^+)^{74}\text{Kr}$ was determined by direct Penning trap mass measurements on both the mother and the daughter nuclide using the time-of-flight resonance technique and was found to be $Q = 10\,416.8(4.5)$ keV. The exotic nuclide ^{74}Rb, with a half-life of only 65 ms, is the shortest-lived nuclide on which a high-precision mass measurement in a Penning trap has been carried out. Together with existing data for the partial half-life as well as theoretical corrections, the decay energy yields a comparative half-life of $Ft = 3084(15)$ s for this decay, in agreement with the mean value for the series of the lighter nuclides from ^{10}C to ^{54}Co. Assuming conserved vector current, this result allows for an experimental determination of the isospin-symmetry-breaking correction δ_C.

DOI: 10.1103/PhysRevLett.93.072502 PACS numbers: 21.10.Dr, 07.75.+h, 23.40.–s, 32.10.Bi

According to the conserved-vector-current (CVC) hypothesis, a postulate now incorporated into the standard model, the vector-current part of the weak interaction is not influenced by the strong interaction. The comparative half-life ft of a superallowed β transition between analog states should therefore be only a function of the matrix element $\langle M_V \rangle$ that connects the two states and the vector coupling constant G_V [1–3]:

$$ft = \frac{K}{\langle M_V \rangle^2 G_V^2}, \tag{1}$$

where f is the statistical rate function, t is the partial half-life, and K is a product of fundamental constants. The nuclear matrix element, which depends on the isospins T_i and T_f of the initial and final states, is $\langle M_V \rangle^2 = 2$ for $T = 1$ analog states. As the β decay occurs within the nuclear volume, theoretical corrections must be applied to f and $\langle M_V \rangle^2$ [2], such that the corrected ft value, denoted by the symbol Ft, is expected to be truly constant, i.e., independent of the nuclear charge Z of the decay pair. This leads to the following overall expression for the Ft value:

$$Ft \equiv ft(1 + \delta_R)(1 - \delta_C) = \frac{K}{2G_V^2(1 + \Delta_R^V)}, \tag{2}$$

where δ_R is the nucleus-dependent radiative correction, δ_C is the isospin-symmetry-breaking correction, and Δ_R^V is the nucleus-independent radiative correction. Experimentally, Ft is accessible via the following measured quantities: the decay energy Q, which enters to the fifth power into the calculation of the statistical rate function f [4], the half-life $T_{1/2}$, and the branching ratio R. The latter two yield the partial half-life $t = T_{1/2}(1 + P_{EC})/R$, where P_{EC} is the calculated electron capture fraction.

The most precise value for V_{ud}, the up-down quark mixing element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, can be extracted from the mean Ft value of nuclear β decay, in conjunction with the Fermi coupling constant from muon decay G_μ [5]:

$$V_{ud}^2 = \frac{G_V^2}{G_\mu^2}. \tag{3}$$

Together with particle-physics data from K and B meson decay [6], this can be used to test CKM unitarity.

In this Letter we report on high-precision mass measurements on short-lived nuclides which reduce the uncertainty of the decay energy of the superallowed β decay $^{74}\text{Rb}(\beta^+)^{74}\text{Kr}$ by almost 2 orders of magnitude. These data extend the nuclear-physics contribution to tests of the CVC hypothesis and the unitarity of the CKM matrix to a new nuclear-shell region. They permit an experimental determination of δ_C and should provide important input for an improvement of theoretical calculations of that correction parameter. With a half-life of only 65 ms, ^{74}Rb is the shortest-lived nuclide on which a high-precision mass measurement in a Penning trap has been carried out.

A recent compilation of all existing data on comparative half-lives from superallowed β decays [3] catalogs high-precision data on nine light nuclides from ^{10}C to ^{54}Co. It represents the status of 2002 and comprises more than 100 separate measurements. Figure 1 in Ref. [3] illustrates the fact that the Ft value is constant in the region covered by these data and within the current uncertainty. With $\chi_\nu^2 = 0.6$, the CVC hypothesis is clearly confirmed in this mass region.

Using these nuclear-physics data, along with particle-physics results for V_{us} and V_{ub} [6], the unitarity test of the first row of the CKM matrix currently fails by more than 2 standard deviations:

$$\Delta \equiv 1 - (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) = 0.0032(14). \quad (4)$$

This is corroborated by data from neutron β decay [7], with which an even stronger deviation from unity of $\Delta = 0.0083(28)$ is found.

Measurements of Ft in higher-mass regions are required to substantiate the high-precision results for the light nuclides, in particular because δ_C is not well known beyond $A = 56$ and is expected to rise sharply [2,8]. A previous direct mass measurement on ^{74}Rb [9] achieved a mass uncertainty of 720 keV, resulting in an uncertainty of the Ft value of about 1400 s when using the most recent values for all other input data.

For the experiments reported here, the Penning trap mass spectrometer ISOLTRAP [10] was used, which is installed at the online isotope separator facility ISOLDE [11] at CERN. It is dedicated to measuring the masses of short-lived radionuclides with high resolving power and precision and has so far been used to measure the masses of more than 250 radioactive nuclides [12,13].

The ISOLTRAP apparatus consists of a linear Paul trap for beam preparation [14], a cylindrical Penning trap for the cooling and isobaric cleaning of the ions, and a hyperbolical precision Penning trap for the precision mass measurements [10]. Figure 1 shows a sketch of these main components. A mass measurement is carried out via a determination of the true cyclotron frequency $\nu_c = qB/(2\pi m)$ of the ion in the precision Penning trap using the time-of-flight (TOF) cyclotron resonance technique [15], where q and m are the charge and the mass of the ion and B is the magnetic-field magnitude. The mass of the ion of interest is obtained from the comparison of its cyclotron frequency with that of a well-known "reference mass." The mass resolving power in the precision Penning trap is the product of the cyclotron frequency of the ion and the duration of the radio frequency (rf) excitation [16] and can reach 10^7 for medium-heavy nuclides and an excitation time of 10 s. After recent upgrades and improvements [16], calibration measurements using a carbon cluster ion source have shown that the limit of ISOLTRAP's overall relative uncertainty is now 8×10^{-9} [17].

The radiative correction is customarily expressed as the sum of a nuclear-structure-independent part δ'_R and a small nuclear-structure-dependent part δ_{NS}, which is due to spin-flips induced by axial-vector and electromagnetic interactions. δ'_R can be evaluated to first order in α with standard quantum electrodynamics [18]. An analytical expression for the second-order term (order $Z\alpha^2$) was calculated by two groups [19,20], who agree on the result, including the estimated third-order correction, which is also used as the uncertainty. Towner and Hardy [2] use the formulas of Ref. [19], but additionally incorporate a Fermi charge density distribution for the nucleus.

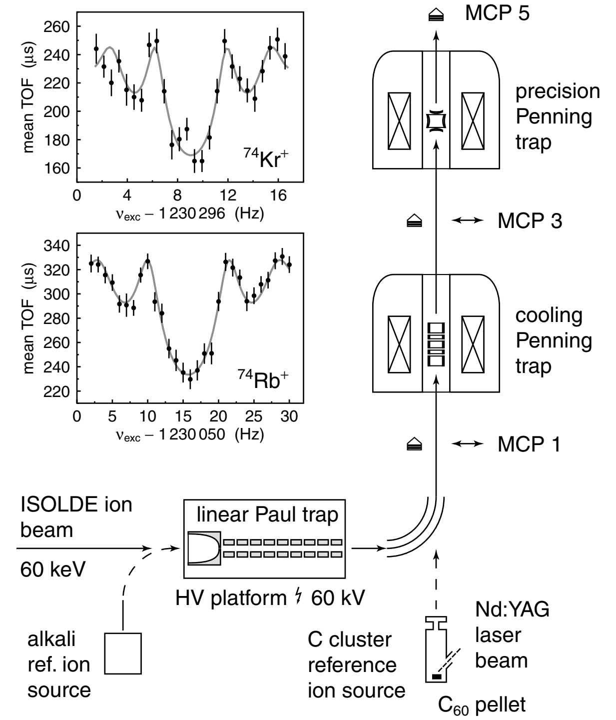

FIG. 1. Sketch of the ISOLTRAP mass spectrometer used for the ^{74}Kr and ^{74}Rb mass measurements, consisting of a linear Paul trap located on a high-voltage (HV) platform, a cooling Penning trap, a precision Penning trap, an alkali reference ion source, and a carbon cluster ion source. Micro-channel-plate (MCP) detectors monitor ion transfer and record the time-of-flight (TOF) cyclotron resonances (MCP 5). The insets show typical TOF cyclotron resonances of ^{74}Kr$^+$ and ^{74}Rb$^+$. The solid lines are fits of the theoretically expected line shape [15] to the data.

The first calculations for the isospin-symmetry-breaking correction δ_C for $A = 74$ were carried out by Ormand and Brown [8]. The most important contribution comes from the mismatch in the radial wave functions of the valence protons and neutrons. The calculations labeled "WS" and those of Ref. [2] in Fig. 4 employ a Woods-Saxon potential where the addition of the Coulomb potential for protons pushes out the protons relative to the neutrons. The overlap is reduced more for the low-l orbits $p_{3/2}$ and $p_{1/2}$ than for high-l orbits $f_{7/2}$ and $f_{5/2}$ due to the lower centrifugal barrier for low l. Below $A = 56$, mainly the $f_{7/2}$ orbit is occupied and δ_C is on the order of 0.40% (see Table V in Ref. [8]). Above $A = 56$, the p orbits are more important and there is a dramatic increase in δ_C to 1.4%–1.7% for $A = 74$. Towner and Hardy [2] also used the WS model and obtained a value of 1.3(4)%. The calculations labeled "HF" and those of Ref. [21] in Fig. 4 employ self-consistent Hartree-Fock potentials where the attractive proton-neutron interaction has the effect of pulling the protons and neutrons together relative to the WS calculation. This reduces the value of

δ_C from 1.7% to about 0.9% [8]. The HF results obtained by Sagawa *et al.* [21] are similar to but slightly smaller than those of Ref. [8]. For our calculations below and the comparison with the existing Ft values, we adopt $\delta_C = 1.43(40)\%$ [this is the value of 1.3(4)% above plus the smaller configuration mixing correction δ_{C1}] as well as $\delta_R = 1.45(12)\%$ of Ref. [2], and $P_{EC} = 0.19(2)\%$.

The masses of ^{74}Kr and ^{74}Rb were measured with ISOLTRAP during four data taking periods in 2000 and 2001 (^{74}Kr) [22] and 2002 and 2003 (^{74}Rb) [23]. For the production of radioactive krypton isotopes, a ZrO target was used in combination with a plasma ion source with a cooled transfer line. Rubidium isotopes were produced from a Nb foil target in conjunction with a W surface ionization ion source. Both targets were bombarded with proton pulses containing up to 3×10^{13} protons each at kinetic energies of 1.0 or 1.4 GeV. ISOLDE's high-resolution separator, which was used in all of the measurements discussed here, was operated at a mass resolving power of $m/\delta m \approx 4000$. Because of the extremely low production yield of ^{74}Rb of only a few 100 ions per proton pulse, a total measurement time of more than 54 h was required to record 10 000 ions. The duration of the rf excitation was 300–600 ms for the rather long-lived ^{74}Kr ($T_{1/2} = 11.5$ min) and 120–150 ms in the case of the short-lived ^{74}Rb ($T_{1/2} = 65$ ms), corresponding to a mass resolving power of about 2×10^5 for the latter. Typical TOF cyclotron resonances of ^{74}Kr$^+$ and ^{74}Rb$^+$ are shown as insets of Fig. 1. For the results reported in this Letter, a total of 15 resonances were recorded for ^{74}Kr and 18 for ^{74}Rb. They were carefully analyzed with respect to systematic and statistical uncertainties by following the data analysis procedure described in Ref. [17]. Figure 2 shows the ISOLTRAP results of the four data taking periods and the weighted means in comparison with the previous literature values [24]. As is illustrated by the figure, the data from the different data taking periods agree well with each other within their uncertainties. A detailed discussion of these data in comparison with previous experiments and an account of their treatment for the atomic-mass evaluation is given in Refs. [22,23].

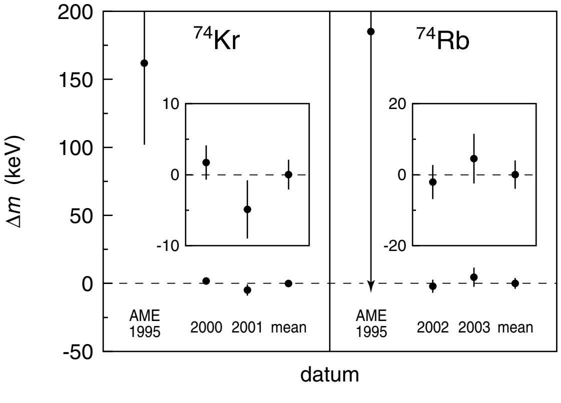

FIG. 2. Mass deviation between the measurements reported here and the literature values (data points labeled "AME1995") [24] for ^{74}Kr (left) and ^{74}Rb (right). The zero line is defined by the weighted means of the two ISOLTRAP measurements for each of the nuclides (data points labeled "mean"). In the case of ^{74}Rb, the 720-keV error bar of the literature value is too large to be fully displayed. The insets show our data and their weighted means at a finer scale.

Our mass measurements on ^{74}Kr and ^{74}Rb yield the mass excesses $D(^{74}\text{Kr}) = -62\,332.0(2.1)$ keV [22] and $D(^{74}\text{Rb}) = -51\,915.2(4.0)$ keV [23]. The decay energy is therefore $Q = 10\,416.8(4.5)$ keV which, using the formula of Ref. [4], yields a statistical rate function of $f = 47\,285(110)$ [25]. The two most precise ^{74}Rb lifetime measurements [26,27] yield a mean half-life of $T_{1/2} = 64.776(29)$ ms, and a recent spectroscopic study of the β decay of ^{74}Rb [28] found the branching ratio of the analog transition to be 99.5(1)%. Using these experimental results, along with the values for the theoretical corrections discussed above, we obtain $Ft = 3084(15)$ s, the first meaningful Ft value for nuclides with $A > 54$. Figure 3(a) shows this value in comparison with the data

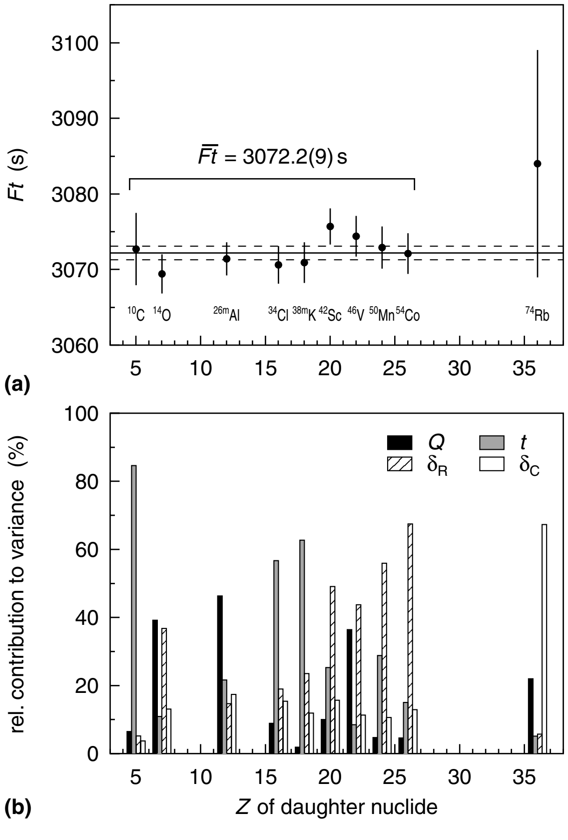

FIG. 3. (a) Ft value for the decay ^{74}Rb(β^+)^{74}Kr, compared to the data from Ref. [3]. The dashed lines represent the confidence interval of the weighted mean $\overline{Ft} = 3072.2(9)$ s for the nine lighter nuclides. (b) Relative contributions to the variance of the Ft values by the four input parameters Q (decay energy), t (partial half-life), δ_R (radiative correction), and δ_C (isospin-symmetry-breaking correction).

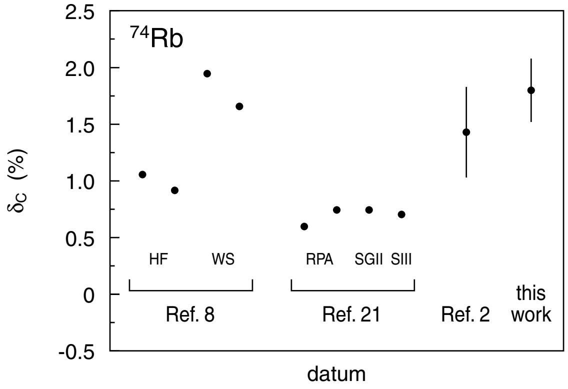

FIG. 4. Isospin-symmetry-breaking parameter δ_C calculated by use of the Q value measured by ISOLTRAP under the assumption of vector current conservation, compared with calculated values [2,8,21]. See the discussion in text.

for the nine lighter nuclides. Our result agrees with the mean $\overline{Ft} = 3072.2(9)$ s of the other data within 0.8σ, but the uncertainty is still too large to make a definitive statement on vector current conservation in this nuclear-shell region and to have a noticeable effect on the unitarity sum of the CKM matrix. However, an examination of the error budget [Fig. 3(b)] reveals that the uncertainty of Ft is now mainly due to the isospin-symmetry-breaking parameter δ_C (67% relative contribution to the variance). The decay energy Q contributes only 22% to the variance of Ft, all other input parameters 6% or less.

Assuming the vector current is conserved, one can predict any of the six experimental and theoretical parameters for $Ft(^{74}\mathrm{Rb})$ from the other five parameters and the average Ft of the other nuclides by solving Eq. (2) accordingly. Since δ_C is the least certain of these, we have extracted it in this way and obtained $\delta_C = 1.81(29)\%$. This result is shown in Fig. 4 next to results of theoretical calculations of three groups [2,8,21]. The experimental value of δ_C is larger than most of the calculated values. This appears to favor the non-self-consistent WS approach. However, the value of δ_C obtained from WS or HF is sensitive to the relative occupation of the p and f orbits. In this respect the wave functions obtained in Refs. [2,8] are rather uncertain since they are based on pf shell Hamiltonians obtained for the $A = 41$–56 mass region. In addition, the low-lying 0^+ state in ^{74}Kr cannot be reproduced within the pf model space and it requires the addition of at least the $g_{9/2}$ orbit [2]. Better pf shell Hamiltonians are becoming available [29], and the computational ability to include $g_{9/2}$ more completely than was possible in Ref. [2] is becoming feasible. Thus we should expect more refined calculations for δ_C in the next few years. In addition, the calculations of δ_R for such high-Z and neutron-deficient nuclei need to be checked. The accuracy obtained in the present work is well suited to check our understanding of the Z dependence of δ_C. Definitive conclusions and comparisons with theory will require an improved shell model description of the nuclei in this mass region.

The authors thank the ISOLDE Technical Group for their assistance. This work was supported by the German Federal Ministry for Education and Research (BMBF) under Contracts No. 06MZ962I, No. 06LM968, and No. 06GF151, by the European Commission under Contracts No. FMRX-CT-97-0144 and No. HPRI-CT-2001-50034, by the French IN2P3, as well as by the U.S. National Science Foundation (NSF) under Grant No. PHY-0244453.

---

*To whom correspondence should be addressed.
Electronic address: a.kellerbauer@cern.ch

[1] W. E. Ormand *et al.*, Phys. Rev. C **40**, 2914 (1989).
[2] I. S. Towner and J. C. Hardy, Phys. Rev. C **66**, 035501 (2002).
[3] I. S. Towner and J. C. Hardy, J. Phys. G **29**, 197 (2003).
[4] I. S. Towner and J. C. Hardy, Nucl. Phys. **A205**, 33 (1973).
[5] R. E. Shrock and L.-L. Wang, Phys. Rev. Lett. **41**, 1692 (1978).
[6] K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).
[7] H. Abele *et al.*, Phys. Rev. Lett. **88**, 211801 (2002).
[8] W. E. Ormand and B. A. Brown, Phys. Rev. C **52**, 2455 (1995).
[9] G. Audi *et al.*, Nucl. Phys. **A378**, 443 (1982).
[10] G. Bollen *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **368**, 675 (1996).
[11] E. Kugler, Hyperfine Interact. **129**, 23 (2000).
[12] F. Herfurth *et al.*, J. Phys. B **36**, 931 (2003).
[13] K. Blaum *et al.*, Nucl. Phys. A (to be published).
[14] F. Herfurth *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **469**, 254 (2001).
[15] M. König *et al.*, Int. J. Mass Spectrom. Ion Process. **142**, 95 (1995).
[16] A. Kellerbauer, Int. J. Mass Spectrom. **229**, 107 (2003).
[17] A. Kellerbauer *et al.*, Eur. Phys. J. D **22**, 53 (2003).
[18] A. Sirlin, Rev. Mod. Phys. **50**, 573 (1978).
[19] A. Sirlin, Phys. Rev. D **35**, 3423 (1987).
[20] W. Jaus and G. Rasche, Phys. Rev. D **35**, 3420 (1987).
[21] H. Sagawa, N. Van Giai, and T. Suzuki, Phys. Rev. C **53**, 2163 (1996).
[22] D. Rodríguez *et al.* (to be published).
[23] A. Kellerbauer *et al.* (to be published).
[24] G. Audi and A. H. Wapstra, Nucl. Phys. **A595**, 409 (1995).
[25] I. S. Towner and J. C. Hardy (private communication).
[26] M. Oinonen *et al.*, Phys. Lett. B **511**, 145 (2001).
[27] G. C. Ball *et al.*, Phys. Rev. Lett. **86**, 1454 (2001).
[28] A. Piechaczek *et al.*, Phys. Rev. C **67**, 051305(R) (2003).
[29] M. Honma *et al.*, Phys. Rev. C **65**, 061301(R) (2002).