Precise Half-Life Measurement for the Superallowed $0^+ \rightarrow 0^+$ β Emitter ^{74}Rb: First Results from the New Radioactive Beam Facility (ISAC) at TRIUMF

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Presently, the world data for superallowed β decay leads to a result in disagreement (at the 98% confidence level) with the predictions of the minimal standard model for the unitarity of the Cabibbo-Kobayashi-Maskawa matrix. Precise data for the superallowed $0^+ \rightarrow 0^+$ β decay of ^{74}Rb would provide a critical test of the nucleus-dependent isospin symmetry-breaking corrections that must be calculated for these superallowed Fermi β decays. The present work reports the first precise measurement of the half-life for ^{74}Rb ($t_{1/2} = 64.761 \pm 0.031$ ms). The data were obtained at the radioactive beam facility (ISAC) at TRIUMF using a beam of $\sim$4000 ^{74}Rb ions s^{-1}.

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Precise measurements of the intensities for superallowed Fermi $0^+ \rightarrow 0^+$ β decays between analog states provide demanding tests of the conserved vector current (CVC) hypothesis and the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, two fundamental tenets of the electroweak standard model. So far, such measurements have been restricted to nuclei with $A \leq 54$, where the world data currently disagree with CKM unitarity by more than 2 standard deviations [1]. Measurements in heavier nuclei are now required to substantiate these results, since small but crucial nuclear corrections are Z dependent and thus become larger and more accessible to investigation there. The need for measurements among odd-odd, $N = Z$ nuclei with $A > 54$ has featured prominently for nearly a decade in proposals for new radioactive beam facilities. This Letter reports the first time that a precision measurement has actually been accomplished on such a nucleus: we report the half-life of ^{74}Rb to $\pm 0.05\%$.

Our result represents two experimental advances. First, and most significant, it is the first result from ISAC, the new generation radioactive beam facility that recently began operation at TRIUMF. The ^{74}Rb ion beam provided by the facility for this experiment was more intense than any previously available elsewhere and, as demonstrated in feasibility tests, can be increased to substantially higher levels in the future. Second, this is the first time that the techniques for precision half-life measurement have been extended to an activity with a half-life substantially under 100 ms; the shortest previously measured was $\sim$200 ms.

Since the axial-vector decay strength is zero for superallowed Fermi $0^+ \rightarrow 0^+$ β decays, the intensities are directly related to the weak vector coupling constant, G_V. Indeed, the CVC hypothesis implies that G_V is an absolute constant with the consequence that the measured ft values for Fermi decays between isospin $T = 1$ states should all be the same irrespective of the nucleus studied. A practical demonstration of this, however, is constrained by a couple of complications. First, bremsstrahlung and related processes must be accounted for through calculated radiative corrections and, second, Coulomb and other charge-dependent forces break isospin symmetry, resulting in a small and calculable shift in the nuclear matrix element. Thus, the test of the CVC hypothesis becomes modified to read

$$ft(1 + \delta_R)(1 - \delta_C) \equiv \mathcal{F}t = \frac{K}{2G_V^2(1 + \Delta_R)} = \text{const}, \tag{1}$$

where f is the statistical rate function, t is the partial half-life for the transition, Δ_R and δ_R are, respectively, the nucleus-independent and nucleus-dependent parts of the radiative correction, and δ_C is the isospin symmetry-breaking (Coulomb) correction. Presently nine transitions have been determined with sufficient precision [1–3] to confirm CVC at the level of 3×10^{-4}. The average value of $\mathcal{F}t$ is $3072.3 \pm 0.9 \pm 1.1$, where the first error is the statistical error of the fit and the second is an error related to the systematic difference between two calculations of δ_C [1].

These data together with the muon lifetime also provide the most accurate value for the up-down quark mixing matrix element of the CKM matrix, V_{ud}. The current status of V_{ud} is reviewed by Towner and Hardy in Ref. [1]. In particular, the value of V_{ud} is given by

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$$V_{ud}^2 = \frac{K}{2G_F^2(1 + \Delta_R)\overline{\mathcal{F}t}}, \quad (2)$$

where G_F is the weak coupling constant from muon decay: $G_V = G_F V_{ud}$, and $\overline{\mathcal{F}t}$ is the average $\mathcal{F}t$ from the nine precision Fermi superallowed β decays measured so far. The result obtained is $|V_{ud}| = 0.9740 \pm 0.0005$. It is important to note that the error associated with $|V_{ud}|$ is not predominantly experimental in origin; the largest uncertainties come from Δ_R (± 0.0004) and δ_C (± 0.0003).

The unitarity test as it relates to the elements in the first row of the CKM matrix,

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1, \quad (3)$$

can be examined using the recommended [4] values for V_{us} and V_{ub} (i.e., 0.2196 ± 0.0023 determined from K_{e3} decay and 0.0036 ± 0.0010, respectively). The result becomes

$$\sum_i V_{ui}^2 = 0.9968 \pm 0.0014, \quad (4)$$

which fails to meet unity by 2.2 standard deviations.

The value of V_{ud} can also be determined from the decay of the free neutron and pion beta decay. These decays have an advantage over nuclear decay in that there are no nuclear-structure-dependent corrections. However, at the present time experimental uncertainties result in values for $|V_{ud}|$ that agree with that obtained from superallowed Fermi β decay but are factors of 4 and 30 less precise, respectively [1]. Ultimately, both will also be limited by the theoretical uncertainty in Δ_R.

Since the failure in the unitarity of the CKM matrix would imply physics beyond the minimal standard model, it is important to eliminate all possible "trivial" explanations for the apparent discrepancy. To restore unitarity, the calculated radiative corrections for all nine nuclear transitions would have to shift downwards by 0.3% (as much as one-quarter of their current value), or the calculated isospin symmetry-breaking corrections shift upwards by 0.3% (over one-half of their value), or some combination of the two. However, because the leading terms in the radiative corrections are so well founded, attention has focused more on the Coulomb corrections. Although smaller than the radiative corrections, the Coulomb corrections are clearly sensitive to nuclear structure because the Coulomb and charge-dependent nuclear forces destroy isospin symmetry between the initial and final analog states in superallowed beta decay. As a result, there are different degrees of configuration mixing in the two states and the radial wave functions of the converting proton and the corresponding neutron differ because their binding energies are not identical. Both effects are accommodated by writing $\delta_C = \delta_{C1} + \delta_{C2}$.

Methods to calculate δ_C have been developed by Towner *et al.* [5] and Ormand and Brown [6]. Both methods employ the shell model to calculate δ_{C1} but derive δ_{C2} by two different methods: (i) from full-parentage expansions in terms of Woods-Saxon radial wave functions and (ii) from a self-consistent Hartree-Fock calculation. The values of δ_C predicted by the two methods are in reasonable relative agreement for the nine well-known transitions with $A \leq 54$ but differ absolutely by $\sim 0.07\%$. This difference is much less than the 0.3% required to resolve the unitarity problem.

The δ_C corrections are predicted to be much larger for the heavier fp-shell nuclei [6]. In addition, the differences between the results from the two methods of calculating δ_{C2} increase by nearly a factor of 10. At ISAC a program has been initiated to measure the half-lives and branching ratios for odd-odd, $T_z = 0$ nuclei with $A \geq 62$. These data, together with accurate Q_{EC} values, will provide a critical test of these theoretical calculations for analog-symmetry breaking.

The new generation radioactive beam facility ISAC [7] produces high-quality beams of short-lived isotopes by the ISOL (on-line isotope separation) method using a beam of protons at 500 MeV to bombard thick production targets. When completed the ISAC facility will be able to accelerate these isotopes up to 6.5 MeV/u for $A = 150$. The facility has been constructed with the capability to handle proton beam intensities of up to 100 μA on a thick uranium target. Protons from the TRIUMF cyclotron are extracted into a new beam line which feeds the ISAC hall. Activated target modules are handled remotely and serviced in hot cells. The target is coupled to the ion source by a small transfer tube. Several types of ion sources will be available; the first operation has used a surface ionization source. Development of a compact microwave ECR (electron-cyclotron resonance) ion source to produce beams of volatile elements is near completion. Plans to develop a laser ion source are being formulated. After extraction from the ion source the radioactive beam is mass analyzed and transported vertically eight meters to the experimental hall located at grade level.

ISAC is ideally suited to precision nuclear β-decay studies and it should be possible to study the series of odd-odd, $T_z = 0$ nuclei from ^{62}Ga to ^{86}Tc. The nucleus ^{74}Rb was chosen for the first experiments since it is the easiest to produce with the surface-ionization source. A Nb foil target (11.5 g/cm^2) optimized for the production of short-lived isotopes was used to produce ^{74}Rb. At proton beam currents above 3 μA the yields of radioactive Rb isotopes were found to increase nonlinearly [8]. The yield of ^{74}Rb obtained at a beam current of 10 μA was $\sim$440 ions μA^{-1} s^{-1}; comparable to the yield previously observed at ISOLDE [9]. During a one day test run when the beam current was increased to 20 μA, the yields of all Rb isotopes increased by a factor of 4. The Nb target was bombarded for several weeks at a proton beam current of 10 μA ($\sim 2 \times 10^{20}$ protons) with no noticeable decrease in yield.

In a previous measurement of the half-life of ^{74}Rb, carried out by D'Auria *et al.* [10] in 1977, a value of

64.9 ± 0.5 ms was obtained. During the run at ISAC we obtained over 100 times more data which allowed us to reduce the error in the lifetime by more than a factor of 10.

The high-precision β-decay half-life measurements were carried out at ISAC using techniques that were established by members of this collaboration in previous experiments (see Ref. [11] for more details). Although the measurements are simple in principle, great care must be taken to achieve the required precision ($\sim$0.05%). Several improvements were made to optimize the experimental setup for short-lived ($\sim$100 ms) radioactive isotopes. The low-energy (29 keV) radioactive ion beam from ISAC was implanted into a 25 mm wide aluminized Mylar tape of a fast tape-transport system [12] modified to operate at double the speed. After a collection period of $\sim$4 half-lives, the ISAC beam was interrupted and the samples were moved out of the vacuum chamber through two stages of differential pumping and positioned in a 4π continuous-gas-flow proportional counter [11,13]. The counting period began 100 ms after the collection period. After signals from the 4π counter were multiscaled for about 25 half-lives, the data were stored and the cycle was repeated.

A 1 MHz $\pm$ 2 Hz laboratory clock was used to provide a time standard for the experiment. A LeCroy model 222 gate generator was used to give a well-defined, nonextendable dead time (preset to 3 or 4 μs) that was significantly longer than any series dead time preceding it. Systematic errors introduced by the measurement techniques (e.g., as a result of discriminator thresholds or detector bias) were determined by our making on-line measurements under a variety of different conditions. The signals were also routed simultaneously to two different and completely independent CAMAC multichannel scaler modules, whose dwell times were also varied.

Sample purity was monitored with a 40% HPGe detector located just outside the 4π β counter. The surface-ionization source used to produce the ^{74}Rb is very specific to alkali elements but small quantities of other elements are produced at high temperatures. The radioactive ion beams are mass analyzed by a low-resolution preseparator followed by a high-acceptance mass analyzer with a resolving power of $M/\Delta M \cong 1000$. (This will be increased by a factor of 5 in the future when the mass analyzer becomes operational in the high-resolution mode.) As expected, no evidence of contaminants from adjacent mass isotopes was observed.

We analyzed the data from each measurement using a method described elsewhere [11]. After the data had been prescreened to eliminate low statistics and noisy samples, the remaining data were dead time corrected, summed, and then fitted with a single short-half-life component and a long-lived background. A total of 38 runs each consisting of $\sim 4 \times 10^5$ events was carried out. The data obtained from one run are shown in Fig. 1. A small ($\sim$2%) long-lived background component was observed in the decay curves which was identified in the gamma-ray spectra as ^{74}Ga ($t_{1/2} = 8.12$ m). The nuclei ^{74}Ni and ^{74}Cu are the only known short-lived ($t_{1/2} \sim 1{-}2$ s) isobars. Limits on these contaminants estimated from calculated production yields corrected for surface-ionization efficiencies are $\sim 1 \times 10^{-5}$ and 6×10^{-5}, respectively, consistent with the limit from the gamma-ray spectra for ^{74}Cu of $<2 \times 10^{-4}$.

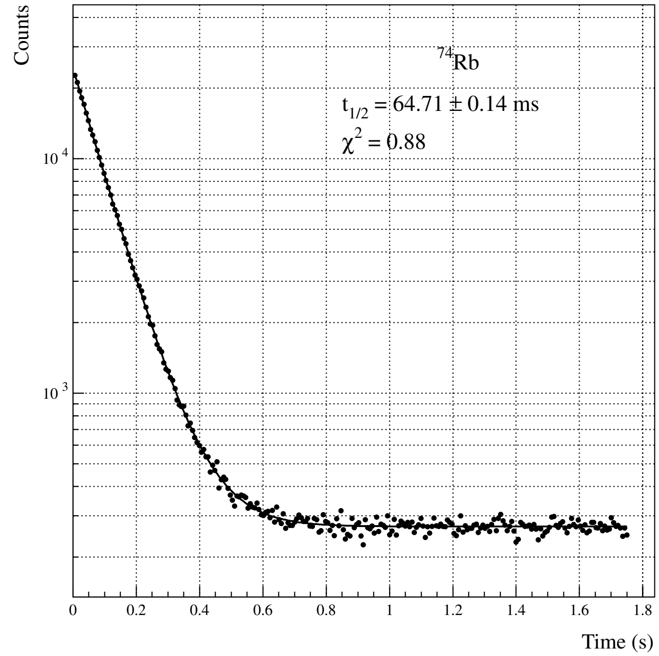

FIG. 1. Typical decay curve obtained for ^{74}Rb. The dwell time was 7 ms per channel (see text for details).

The statistical error in the half-life of ^{74}Rb obtained by fitting each decay curve was $\sim$0.14 ms. No evidence of any systematic error was observed as illustrated by the fit to the full data set shown in Fig. 2, which gives a normalized $\chi^2 = 1.06$. The weighted average of all measurements is 64.768 ± 0.026 ms; the error quoted is statistical only. To estimate the bias introduced in the half-life determination by the possible ^{74}Ni and ^{74}Cu contaminants, these additional decay components were included in a reanalysis of the full data set. In all cases the half-life of ^{74}Rb decreased by less than 0.01%. Two additional tests were carried out to look for possible systematic errors. First of all, to test the effect of the longer-lived background component, the data were refitted after excluding the data above channel 150 in steps of 25 channels. Second, to test for possible unknown very short-lived contaminants, the data from the first 20 channels were eliminated from the fit in steps of 5 channels. In both cases no systematic shifts in the fitted half-lives were observed. Finally, a similar but completely independent analysis of the same data was performed with different prescreening criteria and unrelated analysis software: it yielded a weighted average of 64.754 ± 0.028 ms. As a result we conclude that the

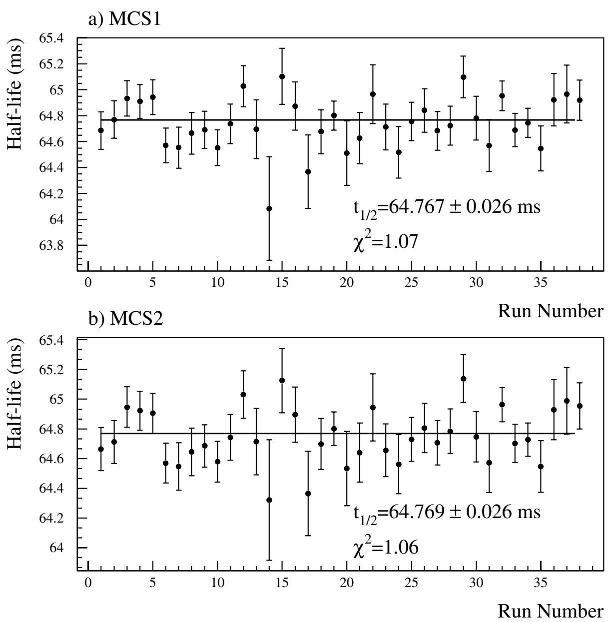

FIG. 2. Half-life results for ^{74}Rb obtained simultaneously with two independent multichannel scaler modules.

half-life of ^{74}Rb is 64.761 $\pm$ 0.031 ms; this error includes a systematic error of 0.015 ms added in quadrature.

As mentioned previously, the present measurement of the half-life of ^{74}Rb is only one of three quantities that must be measured with high precision before the transition strength for the superallowed β decay of ^{74}Rb can be determined; the others are the branching ratio and the Q_{EC} value. High precision branching ratio measurements are presently under way at ISAC. The preliminary results indicate that the superallowed branch is the dominant transition (>99%) [14], similar to those observed previously for odd-odd, $T_z = 0$ superallowed decays. A precise measurement of the Q_{EC} value for the β decay of ^{74}Rb should be possible in the near future using Penning traps such as the Canadian Penning Trap [15].

In conclusion, the present result demonstrates the potential of the new second-generation radioactive-beam facility ISAC to deliver the beams required to extend precision superallowed β-decay studies to heavier short-lived $T_z = 0$ emitters.

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