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High precision branching ratio measurement for the superallowed β decay of ^{74}Rb: A prerequisite for exacting tests of the standard model

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Nonanalog Fermi and Gamow-Teller branches in the superallowed β decay of ^{74}Rb have been investigated using γ-ray and conversion-electron spectroscopy. Nine observed transitions, in conjunction with a recent shell model calculation, determine the branching ratio of the analog transition to be 99.5(1)%. The experimental upper limits for the Fermi decay to the 0_2^+ and (0_3^+) levels are in agreement with recent theoretical predictions. The Q_{EC} value for the ^{74}Rb β decay is predicted to be 10405(9) keV.

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Studies of superallowed nuclear β decays support the validity of the conserved vector current hypothesis that postulates the existence of a universal, constant $\mathcal{F}t$ value for all superallowed β decays (see Ref. [1] and references quoted therein). The existence of a universal $\mathcal{F}t$ value has been established to an accuracy of 3×10^{-4}. The current best value $\overline{\mathcal{F}t}=3072.2(8)$ s [1] is the average of individual $\mathcal{F}t$ values of the superallowed $0^+\rightarrow0^+$ β decays of nine nuclei between ^{10}C and ^{54}Co [1]. This average $\mathcal{F}t$ value also provides the most accurate result for the up-down quark flavor mixing matrix element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, $V_{ud}=0.9740(5)$, which in turn can be used for a precise test of CKM unitarity [1]. The result for the sum of the elements in the first row is 0.9968(14), corresponding to a $2.2-\sigma$ disagreement with unitarity. A recent measurement of the neutron β decay asymmetry [2] leads to an even smaller unitarity sum. If the observed nonunitarity is a real effect, it would show the presence of "new physics" beyond the minimal standard model.

It is important to note that the main uncertainty in $\overline{\mathcal{F}t}$, and hence the unitarity sum, is not due to experimental shortcomings, but results from uncertainties in several calculated correction terms [1] which are applied to the experimental ft values in order to obtain $\mathcal{F}t$, viz.,

$$\mathcal{F}t=ft(1+\delta_R')(1+\delta_{NS}-\delta_C)=\frac{\text{const}}{2G_F^2V_{ud}^2(1+\Delta_R^V)}, \quad (1)$$

where G_F is the fundamental weak-interaction coupling constant, f is the statistical β-decay rate function that is calculated using the experimental Q_{EC} value, and $t=[T_{1/2}\times(1+P_{EC})]/B_0$ is the partial half-life for the transition to the isobaric analog state with $T_{1/2}$ the half-life, B_0 the branching ratio of the analog transition, and P_{EC} the electron capture probability. The calculated correction terms are: a nucleus-independent radiative correction Δ_R^V, of order 2.4%; a nuclear-structure-independent (but Z-dependent) radiative correction δ_R', of order 1.5%; a nuclear-structure-dependent radiative correction δ_{NS}, which is less than 0.1% for $T_z=0$ β emitters; and a nuclear-structure-dependent correction δ_C, accounting for analog-symmetry breaking. For the nine well-investigated lighter emitters, the calculated nuclear-structure dependent correction, $\delta_C-\delta_{NS}$ varies between 0.261(24)% and 0.720(47)% [1], while for ^{74}Rb the correction is predicted to be larger: $\delta_C-\delta_{NS}=1.50(40)$%. Similar large values are obtained for other $T_Z=0$ β emitters with mass $A\geqslant62$. As a result, precise measurements for these superallowed β emitters would provide an important test of theoretical calculations for analog-symmetry breaking.

We report here on the first detailed and precise study of the superallowed β decay of ^{74}Rb, employing γ-ray and conversion-electron spectroscopy. We have experimentally identified a total non-superallowed feeding of 336(20) $\times10^{-5}$ per ^{74}Rb decay. From a comparison of these data with recent shell-model predictions [1] we estimate the unobserved nonsuperallowed feeding to be $(50-250)\times10^{-5}$ resulting in a deduced ground-state β branch of 99.5(1)%.

The aim of this experiment was to determine the branching ratio B_0 of the superallowed $0^+\rightarrow0^+$ transition from

^{74}Rb to the ground state of ^{74}Kr. However, the ground-state branch cannot be measured directly, but is determined by subtracting the (nonsuperallowed) feeding to excited levels from the total intensity of the decay. This strategy has been succesfully applied [3] to several of the lighter emitters. In these cases, the Q_{EC} values and level densities in the Q_{EC} window were comparatively low and the competing Gamow-Teller (GT) decays comprised few decay branches, which were measured experimentally [3] or predicted to be negligibly small [4]. The problem for the β decay of ^{74}Rb (and other emitters with masses $A \geqslant 62$) was illustrated recently by Hardy and Towner [5] using results of a shell-model calculation. In particular, because of the high Q_{EC} value of more than 10 MeV, an abundant number of high lying 1^+ states are predicted to be populated through GT transitions. These transitions, together with nonanalog Fermi (F) branches, must be taken into account to determine the partial half life of the superallowed transition. Yet, their individual intensities are very small, and many of them cannot be detected with high resolution γ-ray spectroscopy. Therefore, in Ref. [5] it was concluded that the measurement of the Gamow-Teller branches using high resolution spectroscopy alone is not viable for the $A \geqslant 62$ nuclei and new techniques must be found to determine B_0, or theory should be used to correct the experimental results. We show in this paper that the problem of abundant, weak GT branches can, in fact, be overcome with the help of theory. It is not necessary to reconstruct the GT strength function of the ^{74}Rb decay, only the total amount of nonsuperallowed feeding, must be determined. The low-lying levels in ^{74}Kr act as *collector states* for a large fraction of the nonsuperallowed feeding and by observing their deexcitation, the larger part of their feeding can be determined. The remaining component, which directly feeds the ^{74}Kr ground state, can be estimated from the shell-model calculation [1], provided it reproduces well the relative feeding to excited levels in ^{74}Kr.

The experiment was performed at the ISAC facility at TRIUMF, where the ^{74}Rb half-life was previously measured to be 64.761(31) ms [6]. The ^{74}Rb nuclei were produced in spallation reactions between a 500-MeV proton beam of $10-20$ μA intensity and an electrically heated ^{nat}Nb stacked-foil target of 22 gm/cm^2 thickness. The nuclei were ionized in a surface ionization source and mass separated in the ISAC on-line separator. The strongest contaminant was the $T_{1/2}=8.12$ min ^{74}Ga. A sketch of the experimental setup can be found in Ref. [7]. At the experimental station, the activity was implanted into a 1/2-inch-wide conducting collector tape that was moved with a cycle time of 4 s to prevent the buildup of long-lived activities. During tape movement, the separator beam was interrupted. The implantation spot on the tape was viewed by two 5-mm-thick liquid-nitrogen-cooled Si(Li) diodes. The use of these conversion-electron detectors was motivated by the observation [8,9], see also [10] for recent results, of the 0_2^+ level of ^{74}Kr at 509 keV, which mainly decays via an $E0$ transition to the ground state. Special care was taken to achieve a low trigger threshold of $\sim$10 keV for the Si(Li) detectors to enable the detection of the strongly converted 53 keV, $0_2^+ \rightarrow 2_1^+$ transition. An 80% high-purity Ge (HPGe) detector served for γ-ray detection. Two fast plastic scintillators of 2 and 55 mm thickness registered β particles and triggered the list-mode data acquisition if a coincidence with a Si(Li) or the HPGe detector occurred within a 800 ns time window. In addition, the numbers of βs detected in the plastic scintillators per cycle and in three time windows distributed over the cycle were recorded to determine the total number of ^{74}Rb decays and to correct for long-lived background which was 5–8 %. A total of 1.4×10^8 ^{74}Rb decays were observed in the plastic scintillators. The energy-independent efficiency of the Si(Li) detectors for conversion electrons was determined to be 2.33(25)% in singles mode with ^{207}Bi and ^{133}Ba conversion-electron calibration sources. The absolute efficiency of the HPGe detector (0.82% at 1.332 MeV) was measured in singles mode with standard sources; the precision obtained in the region of interest was $\sim$5%. An on-line test of the detection system was performed with the β-γ emitter ^{80}Rb [$T_{1/2}=34(4)$ s]. The intensity of the 617-keV $E2$ transition in the daughter ^{80}Kr was measured to be 0.245(15) per decay, in good agreement with the literature value of 0.25(3) [11]. Its conversion coefficient was measured to be $1.66(22)\times 10^{-3}$, in good agreement with the theoretical value of 1.53×10^{-3} [12].

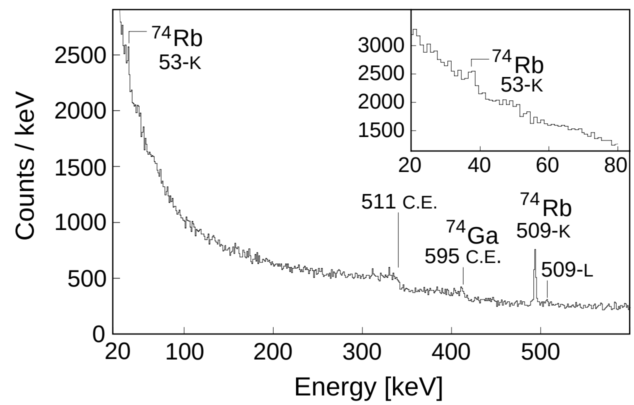

FIG. 1. Conversion-electron spectrum recorded by the Si(Li) detectors. The observed *K*- and *L*-conversion lines are indicated; C.E. = Compton edge.

Figure 1 shows the conversion-electron spectrum recorded by the Si(Li) diodes in coincidence with the plastic detectors. The peaks at 495(1) and 507(1) keV correspond to the emission of *K*- and *L*-shell conversion electrons from the decay of the 0_2^+ level at 509 keV to the ^{74}Kr ground state. The line at 39 keV, also shown in the inset of Fig. 1, corresponds to the *K*-shell conversion of the 53-keV $0_2^+ \rightarrow 2_1^+$ transition. Parts of the γ-ray spectrum from the HPGe detector are shown in Fig. 2. The spectrum is dominated by activity from the ^{74}Ga decay and 511-keV annihilation radiation. Seven γ transitions were attributed to the ^{74}Rb decay, namely, at 456, 695, 748, 1198, 1233, 1286, and 4244 keV. To verify these assignments, high-statistics measurements were performed at mass $A=74$ with a long cycle time, namely, a collection period of 25 s and a decay-measurement period of 134 s. None of the γ rays attributed to the ^{74}Rb decay were present in this sample. Further, in the data taken with the 4 s cycle time, the intensities of the 456- and 1198-

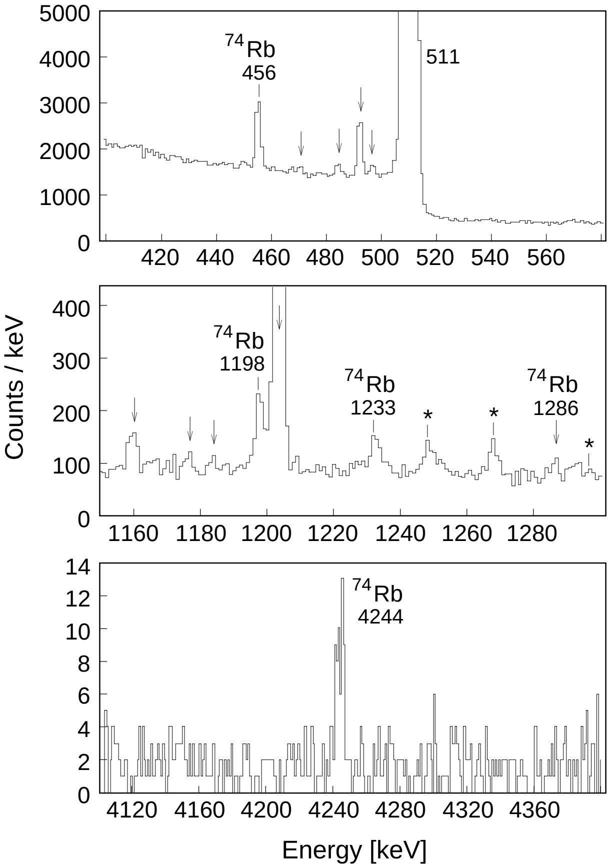

FIG. 2. Spectrum of γ rays from the ^{74}Rb decay. Arrows and stars indicate contaminating radiation from the ^{74}Ga and ^{74}Br decays, respectively.

keV peaks were constant as a function of time, as expected if they come from a very short-lived source. Finally, in an independent β-γ experiment [13], it was found that the 456- and 1198-keV lines decay with the characteristic ^{74}Rb half-life. This $\beta\gamma$ experiment also confirmed the intensities of these two transitions as presented below.

The intensities of the observed transitions per ^{74}Rb decay are given in Table I. The values are corrected for summing effects related to positron emission, which were determined from the experimental γ-ray spectrum to be $\sim$2%. Beyond that, the intensity of each γ ray is corrected for summing with other, coincident, γ rays. The γ-γ summing probabilities were determined from standard calibration sources and range between 5% and 10%. For the $0_2^+\to 0_1^+$ and $2_1^+\to 0_1^+$ transitions, theoretical K/total intensity ratios [14] and conversion coefficients [12] were used to determine the total transition intensities from the measured K-converted radiation.

The decay scheme for ^{74}Rb is shown in Fig. 3. With the exception of the 1198- and 4244-keV γ rays, all of the observed transitions can be attributed to the decay of known levels in ^{74}Kr [8,9,15]. We have tentatively assigned the 4244-keV γ ray as a $(1^+\to 0_1^+)$ transition. The 1204-keV transition from the decay of the 2_2^+ level was not directly observed, since it coincides in energy with a stronger 1204-keV γ ray from the ^{74}Ga decay. Its intensity was inferred from the intensity of the 748-keV γ ray and the intensity ratio of the 1204- and 747-keV γ rays taken from Ref. [15]. The 1742-keV, $(2_3^+)\to 0_1^+$ transition, predicted by the shell-model calculation to have an intensity of one third of the 1286-keV transition, could not be observed because of the presence of the 1745-keV γ ray from the ^{74}Ga decay.

TABLE I. β-Delayed γ transitions in ^{74}Kr.

Energy (keV)	Assignment	Total intensity per decay ($\times 10^{+5}$): Experiment	Theory[a]
53(1)	$0_2^+\to 2_1^+$	32(7)	
509(1)	$0_2^+\to 0_1^+$	48(5)	102[b]
456(1)	$2_1^+\to 0_1^+$	250(14)	252
695(1)	$2_2^+\to 0_2^+$	8(5)	1
748(1)	$2_2^+\to 2_1^+$	19(5)	16
1198(1)	$(0_3^+\to 2_1^+)^c$	52(5)	42
1204	$2_2^+\to 0_1^+$	26(14)[d]	26
1233(1)	$(2_3^+)^c\to 0_2^+$	29(4)	6
1286(1)	$(2_3^+)^c\to 2_1^+$	9(5)	10
4244(1)	$(1^+\to 0_1^+)^c$	12(2)	

[a]Prediction corresponds to column 3 in Table II.
[b]Prediction corresponds to sum of 32(7)+48(5).
[c]Tentative assignments (see text).
[d]Intensity determined indirectly (see text).

From the energy spectrum of the positrons detected in the thick plastic scintillator in coincidence with the observed

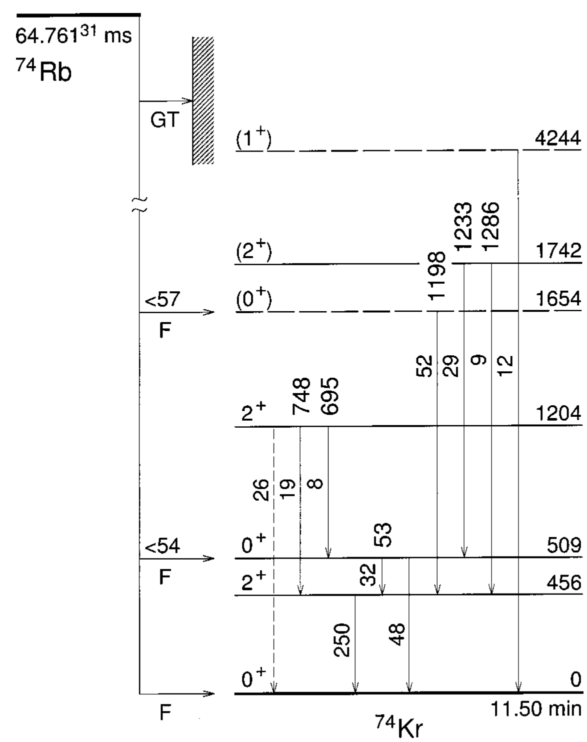

FIG. 3. Partial decay scheme of ^{74}Rb. Intensity of transitions are given in units of 10^{-5} per ^{74}Rb decay.

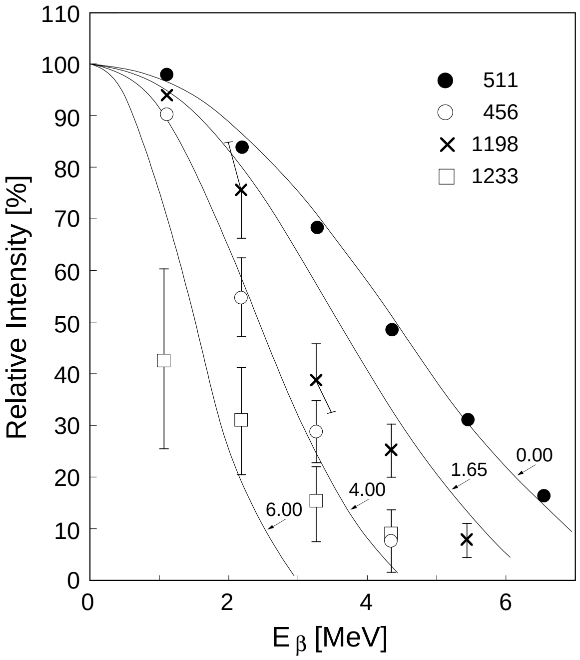

FIG. 4. Intensity of γ rays as a function of the low-energy threshold in the thick plastic detector. Solid lines indicate predicted intensity distributions for β decay to states in ^{74}Kr at 0.0, 1.65, 4.0, and 6.0 MeV.

^{74}Kr γ rays, it is possible to determine the approximate excitation energy of the levels populated in the β decay of ^{74}Rb. This is illustrated in Fig. 4, where the observed intensities of several transitions are plotted as a function of the low-energy threshold in the thick plastic detector. The 511-keV γ ray serves as reference, since it is predominantly associated with the decay to the ground state. The intensity distribution for the 456-keV γ ray closely follows that expected for GT feeding of levels near 4 MeV. Similarily, the 1233-keV γ ray is mainly coincident with low-energy positrons and thus indicates that the 1742-keV level in ^{74}Kr is not directly fed, consistent with a 2^+ assignment [15]. The intensity distribution for the 1198-keV γ ray is consistent with that expected for feeding of a level near 2 MeV. As a result, we suggest that the 1198 keV γ ray comes from the decay of the hitherto unknown 0_3^+ level at 1654 keV, predicted to be at 1918 keV by a recent shell-model calculation [1]. In further support of the (0_3^+) assignment, we note that the (0_3^+) level in ^{74}Se was tentatively identified at 1657 keV [11].

Recently, the ISOLDE Collaboration reported on a study of the nonsuperallowed β decay of ^{74}Rb [16]. The value they obtained for the intensity of the 495-keV conversion electrons from the decay of the 509-keV level in ^{74}Kr was $3.7(11)\times10^{-4}$, in good agreement with the present result of $4.4(5)\times10^{-4}$. The 39-keV conversion electrons corresponding to the $0_2^+\rightarrow2_1^+$ transition in ^{74}Kr were not observed [16], and their 1-σ intensity limit of 1.6×10^{-4} is to be compared with our measured intensity of $2.3(5)\times10^{-4}$. However, the ISOLDE Collaboration did not observe any γ rays that could be attributed to the ^{74}Rb decay. Their 1-σ intensity limit for the 456-keV transition of 81×10^{-5} is in contradiction with our measured intensity of $250(14)\times10^{-5}$.

TABLE II. γ ray and direct nonsuperallowed β feeding to the six lowest states in ^{74}Kr, expressed per ^{74}Rb β decay.

		Theory			
Level	Expt. GT+F ($\times10^{+5}$)	GT [a]+ F ($\times10^{+5}$)	GT [b]+ F ($\times10^{+5}$)	GT [a] (%)	GT [b] (%)
g.s., 0_1^+	12(2)	103	259	26.4	28.2
456, 2_1^+	138(18)	145	324	37.3	35.2
509, 0_2^+	43(11)	60+36	158+36	15.3	17.2
1204, 2_2^+	53(14)	41	87	10.6	9.4
1654, (0_3^+)	52(5)	20+23	46+23	5.0	5.0
1742, (2_3^+)	38(6)	21	46	5.4	5.0
Sum	336(20)	449	979	100	100

[a]Lowest 1^+ level at 3.6 MeV, $g_A=0.8$.
[b]Lowest 1^+ level at 3.2 MeV, $g_A=1.0$.

In Table II, we present the experimental feeding of the lowest six 0^+ and 2^+ levels in ^{74}Kr resulting either from the γ decay of states above the third 2^+ level at 1742 keV (following GT or F decay) or from direct F decay to the lowest two excited 0^+ levels. The sum of the six feedings listed in Table II is equal to the sought branching ratio, namely, the sum of all branchings other than the superallowed branch in the β decay of ^{74}Rb. This experimental sum shown at the bottom of the second column of Table II amounts to 0.336(20)%; however, this sum is incomplete since much of the γ-ray feeding of the ground state from states above 1742 keV likely remains unobserved in the experiment [5]. We will use information from the shell-model calculations of Towner and Hardy [5] (also shown in Table II) to estimate this missing strength.

In these shell-model calculations, two quantities affect the total GT strength, namely, the effective axial-vector coupling constant g_A and the excitation energies of the predicted 1^+ states in ^{74}Kr. In the published calculation [5], g_A was set to 1.0 (a typical quenched value for shell-model calculations in complete $0\hbar\omega$ oscillator model spaces), and the lowest 1^+ state was at 3.2 MeV excitation energy. The results of this calculation appears in the fourth column of Table II, where it can be seen that they give relative feeding intensities in reasonable agreement with experiment, but absolute values that are too large by a factor of 2. Likewise, similar shell-model calculations [5] of ^{62}Ga decay predict that 80% of the GT strength feeds through the 2_1^+ level in ^{62}Zn with an intensity that is more than double the measured value [17]. The purpose of the shell-model calculations is to provide an estimate of the missing strength not seen in the experiment. To this end we have adjusted the calculation to reproduce the intensity of the strongest γ ray seen, the $2_1^+\rightarrow0_1^+$ 456-keV transition. Since the model space used in the calculation is not that of a complete $0\hbar\omega$ oscillator space, it is not clear what an appropriate quenched value of g_A should be; we now choose to use $g_A=0.8$. Further, we raise the spectrum of 1^+ states relative to the 0^+ and 2^+ states such that the lowest 1^+ state occurs at an excitation energy of 3.6 MeV. Again there are very little experimental data to guide us here. In the current experiment one high-energy γ-ray of energy 4.244 MeV is observed. If this is from a $1^+ \rightarrow 0_1^+$ $M1$ transition then that would place a 1^+ state at 4.2 MeV excitation energy, but that does not have to be the lowest-energy 1^+ state. Setting the lowest 1^+ state somewhere between the previously used value of 3.2 and 4.2 MeV seems a reasonable approach: we choose 3.6 MeV for this excitation energy.

In column 3 of Table II we give the γ-ray feeding as provided by the adjusted shell-model calculation. In columns 5 and 6 we give, as a percentage, the relative feedings obtained in both calculations. Notice that between the two shell-model calculations there is little difference in the relative feedings: the adjustments principally altered the absolute intensity. The agreement between the adjusted calculation and experiment is reasonable (see also the comparison of the the predicted γ-ray intensities with experiment given in Table I). From the first row of Table II we can now obtain an estimate of the missing strength—the experimentally unobserved feeding of the ground state from high-lying 1^+ levels, which in their deexcitation do not cascade through any of the five lowest excited states. Our estimate is 0.10%. To place an error on this estimate, we take the spread of the two shell-model calculations to give an upper error, while arguing that the missing strength is unlikely to be less than half of our estimate to get the lower error. Our result is that the missing strength is $0.10^{+0.15}_{-0.05}\%$ or, with symmetrized errors, 0.15(10)%. This missing strength is now added to the observed strength to get the summed branching ratio for all non-superallowed β decays of 0.336(20)+0.150(100) =0.5(1)%. Note that we have assigned a generous error to the missing strength, reflecting the evident inadequacies of the shell-model calculation. As a result, the branching ratio of the superallowed analog transition is determined to be $B_0 = 99.5(1)\%$.

The half-life of the ^{74}Rb decay was earlier determined with an error of better than 0.05% [6]. Having estimated the ground-state branch to a precision of 0.1%, we can now use the average $\overline{\mathcal{F}t}$ value together with the theoretical corrections from Ref. [1] to solve Eq. (1) for the Q_{EC} value of the ^{74}Rb decay. The result, 10 405(9) keV, is in agreement with the measured value of 10 425(18) keV [18]. The error in the predicted Q_{EC} value is dominated by the theoretical uncertainty in the nuclear-structure-dependent correction $\delta_C - \delta_{NS} = 1.50(40)\%$. Similarly, the $\delta_C - \delta_{NS}$ correction can be calculated to be 2.49(92)%, where the error is completely dominated by the uncertainty in the experimental Q_{EC} value. Once the precision of the measured ^{74}Rb mass reaches ~4 keV, the error in $\delta_C - \delta_{NS}$ is reduced to 0.26%, and meaningful tests of this correction become possible. We note that such a mass measurement has recently been completed at the ISOLTRAP [19].

The present experiment also provides a test for part of the analog-symmetry breaking correction δ_C, by obtaining limits on the strength of the Fermi transition to excited nonanalog 0^+ states. For the ^{74}Rb decay, 80% of the nonanalog Fermi strength is predicted to be shared by the two lowest-excited 0^+ levels [1]. The predicted branchings to the 0_2^+ and 0_3^+ levels are 36×10^{-5} and 23×10^{-5}, respectively, in agreement with the experimental upper intensity limits of 54×10^{-5} and 57×10^{-5} (see column 2 of Table II).

Our results show that the precise determination of B_0 in the presence of non-negligible, strongly fragmented GT branches is not a hopeless endeavor and suggests that improved results can be obtained by using refined experimental techniques. Such measurements are presently in preparation. The ISAC separator will be operated in isobaric-resolution mode, and the upgraded Canadian 8π spectrometer, equipped with Si(Li) detectors and plastic scintillator trigger detectors, will serve for γ-ray and conversion-electron detection. This spectrometer system will enable us to identify additional γ rays from the ^{74}Rb decay, especially those directly populating the ground state, and determine a more precise number for the ground-state branch and its error.

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