Eur. Phys. J. A **15**, 229–232 (2002)
DOI 10.1140/epja/i2001-10259-y

THE EUROPEAN PHYSICAL JOURNAL A

Tests of the standard model from superallowed Fermi β-decay studies: The ^{74}Rb β-decay

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Received: 21 March 2002 /
Published online: 31 October 2002 –

Abstract. Precise measurements of the intensities of superallowed Fermi $0^+ \rightarrow 0^+ \beta$-decays have provided a powerful test of the CVC hypothesis at the level of 3×10^{-4} and also led to a result in disagreement with unitarity for the CKM matrix at the 98% confidence level. It is essential to address possible trivial explanations for the apparent non-unitarity such as uncertainties in the isospin symmetry-breaking corrections. We have carefully studied the ^{74}Rb$\rightarrow$^{74}Kr β-decay in order to measure the non-analog β-decay branching to the 0^+ state at 508 keV in ^{74}Kr. We have determined that this branching is $< 3 \times 10^{-4}$, far smaller than any published theoretical estimate. We also show that high-precision, complete spectroscopy, measuring the major β-branches to excited 0^+ and 1^+ states, must be performed if one is to obtain a meaningful branching ratio to the excited 0^+ state and concomitantly deal, in a substantial way, with the possibility of β feeding to an array of 1^+ states.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 23.40.-s Beta decay; double beta decay; electron and muon capture – 27.50.+e $59 \leq A \leq 89$

1 Introduction

The precise determination of β-decay energies, half-lives and branching ratios is essential to testing the Standard Model using superallowed Fermi β-decay. This radioactive decay data, together with muon-decay information, currently provides the most precise values for the up-down quark matrix element $V_{\rm ud}$ in the Cabibbo-Kobayashi-Maskawa (CKM) matrix which connects the weak-interaction and mass eigenstates of the standard model's three-quark generations [1–3]. In that model, the CKM matrix is unitary. The most recent evaluation of experimental results from superallowed β-decay yields a 2.2σ disagreement with unitarity for the top row of the CKM matrix [1,2]. Since this result would have profound implications for the minimal Standard Model, it is essential to exclude *trivial* explanations for the apparent CKM non-unitarity.

Currently, a significant component of the uncertainty in $V_{\rm ud}$ is due to the radial-overlap and charge-dependent corrections to the superallowed ft-values for nuclei from ^{10}C to ^{54}Co, but the corrections themselves are rather small ($< 1\%$). In heavier nuclei, where they are larger, it may be possible actually to validate them [1,2]. With this in mind, a program has been initiated at the ISAC facility at TRIUMF to measure the half-lives and branching ratios for the $T_z = 0$ (odd-odd) β emitters with $A > 60$, where the charge-dependent corrections are predicted to be large ($\sim 1\%$) [2,4]. The nucleus ^{74}Rb was chosen for

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the first experiments. Half-life measurements on ^{74}Rb have yielded values of 64.9(5) [5], 64(10) [6], 64.761(31) [7], and 64.90(9) [8] ms. Clearly, the TRIUMF result [7] of 64.761(31) ms has the requisite accuracy ($\sim 10^{-4}$) for the precise $\log ft$ determination required in Standard Model tests. Information on β-delayed γ emission in the ^{74}Rb decay was also obtained in the TRIUMF measurements [9].

The primary objective of the present study was to determine the non-analog β-branching to the 0_2^+ level at 508 keV in ^{74}Kr using conversion-electron spectroscopy. This low-lying 0^+ level, whose existence was first suggested [10] and then verified [11] by indirect means, was recently observed at 508 keV by an in-beam experiment [12]. It decays primarily by an electric monopole transition (internal conversion) to the ^{74}Kr 0_1^+ ground state. We first observed the 495 keV electrons arising from $E0$, K-shell conversion of the 508 keV $0_2^+ \to 0_1^+$ transition, as well as γ-rays at 456 and 1198 keV in May, 2000. The earlier TRIUMF experiment [9] to look for β-delayed gammas also observed γ-rays at 456 and 1198 keV in the ^{74}Rb β-decay. Around this same time, a collaboration at ISOLDE observed 495 keV electrons but did not identify any γ-rays above a one-σ limit of 0.00081 per ^{74}Rb β-decay other than 511 keV annihilation radiation [8].

We repeated the conversion-electron experiment in May 2001 with an improved spectrometer, re-measured the 495 keV, K-shell, $E0$ electron intensity and, for the first time, its L-shell conversion at 507 keV. We also observed the 39 keV, K-shell, $E2$ electrons (arising from the 52 keV $0_2^+ \to 2_1^+$ transition), and observed ^{74}Rb β-delayed γ-rays at 456, 1198, 1233, and 4244 keV. The observed transitions have been incorporated into the partial decay scheme presented in fig. 4 (see ahead). While the intensity of the γ-rays other than the dominant one at 456 keV are quite small (*e.g.*, 0.0003 per ^{74}Rb β-decay for the 1233 keV γ which directly feeds the 508 keV level), they can nonetheless contribute significant population to the 0^+ state at 508 keV and thus lead to an even smaller value for the already small (0.0005) non-analog β-feeding of that level deduced simply from the intensity of the 495 keV K-shell conversion electrons which depopulate it. Since the ISOLDE Collaboration [8] did not observe any gammas, their determination of an upper limit of 0.00053 for the β-branch to the 0^+ state at 508 keV is too large by a factor of almost two when compared to our value of 0.0003. Our results further show that still unobserved γ-rays may contribute additional intensity to the population of the 508 keV 0^+ level, and that complete spectroscopy at even greater sensitivity is required to get the precision necessary to test the Standard Model using superallowed $0^+ \to 0^+$ Fermi β-decay.

2 Experimental methods

The ^{74}Rb nuclei were produced by a 10–20 μA, 500 MeV proton beam from the TRIUMF cyclotron impacting an electrically heated $^{\rm nat}$Nb target of 10 gm/cm^2 (May 2000) or 20 gm/cm^2 (May 2001) thickness. The ^{74}Rb nuclei were then ionized, mass-separated, and implanted at the ISAC GP2 experimental station onto a moving tape collector that periodically removed the deposit in order to suppress radiation from the daughter products and other isobars. The tape was 40 μm thick and 1/4 inch (May 2000) or 1/2 inch (May 2001) wide. The implantation spot on the tape was viewed by an array of LN_2 cooled Si(Li) diodes (3 in May 2000 and 2 in May 2001) for the detection of conversion electrons, an 80% HPGe detector for γ-ray detection, and 2 plastic scintillators that provided time and energy information of the emitted positrons as well as a normalization of observed non-analog branches to the total number of ^{74}Rb decays. These fast scintillators consisted of NE-102A and BC-403 plastic, 2 mm and 40 mm thick, respectively. These detectors triggered the list-mode data acquisition in coincidence with the Si(Li) or HPGe detectors to provide (β-γ) and (β-e^-) coincidences. A schematic of the spectrometer used in the May 2001 experiment is shown in fig. 1.

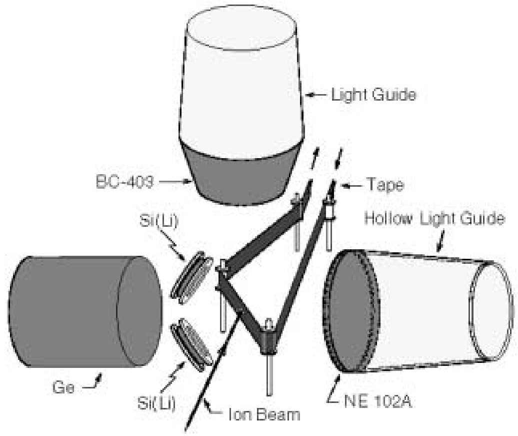

Fig. 1. Sketch of the experimental set-up used in the May 2001 experiment. The transport tape and the Si(Li) detectors are in the center, surrounded by a germanium detector and two plastic scintillators. The scintillators are coupled through light guides to photomultiplier tubes (not shown) located outside the spectrometer vacuum. The tape is 1/2 inch wide and 40 μm thick. It can be moved periodically to prevent the buildup of long-lived contaminating activities. The light guide connected to the 2 mm scintillator was made hollow in order to reduce the 511 keV gamma background that results from the annihilation of positrons.

During the measurements, the tape was moved every 4-6 s. The beam intensity was approximately 3000 ^{74}Rb ions per second. A total of 6.9×10^7 (May 2000) and 1.4×10^8 (May 2001) ^{74}Rb decays were counted in the plastic scintillators. The efficiencies of each Si(Li) and the HPGe detector were on the order of 1% at 500 keV. The most troublesome contaminant was that of ^{74}Ga.

3 Experimental results

Shown in fig. 2 is part of the β-coincident conversion-electron spectrum measured with the Si(Li) diodes. The

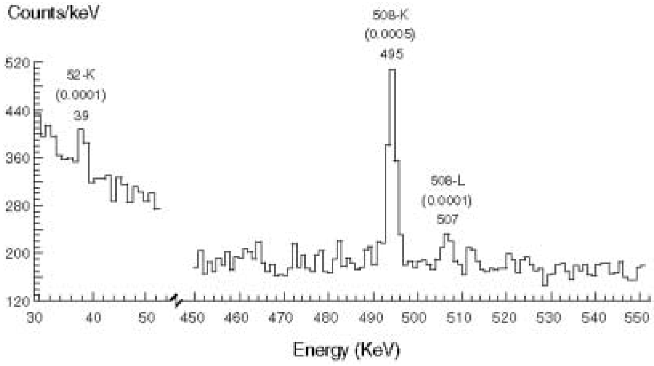

Fig. 2. Parts of the β-coincident conversion-electron spectrum measured with the Si(Li) diodes. The numbers in parenthesis represent the approximate intensity of the transition per ^{74}Rb β-decay. See the text for an explanation of the transitions observed.

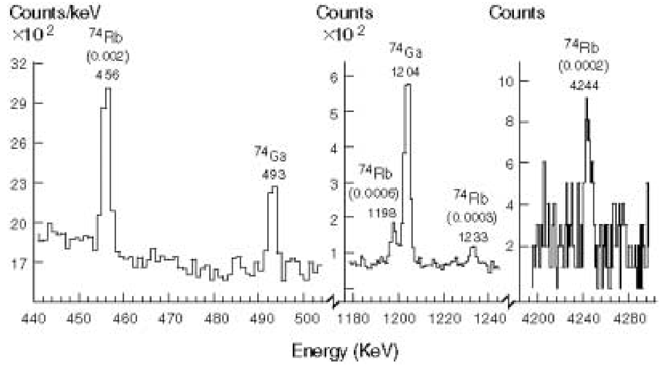

Fig. 3. Parts of the β-coincident γ-ray spectrum measured with the HPGe detector. The numbers in parenthesis represent the approximate intensity of the transition per ^{74}Rb β-decay. See the text for an explanation of the transitions observed.

line at 495 keV corresponds to the emission of $E0$, K-shell conversion electrons from the $0_2^+ \to 0_1^+$ decay of the isomeric level ($\tau = 20$–40 ns [11,12]) at 508 keV in ^{74}Kr. The line at 507 keV corresponds to $E0$, L-shell conversion of the same transition, while the line at 39 keV corresponds to $E2$, K-shell conversion of the 52 keV $0_2^+ \to 2_1^+$ transition. The intensities presented in parentheses are per ^{74}Rb β-decay. They are given to one significant figure and without uncertainties since there has not been sufficient time to fully analyze the data acquired in May 2001. Finalized values with uncertainties will be given in a separate publication [13]. The ISOLDE Collaboration [8] observed only the 495 keV K-shell electrons in their conversion-electron spectrum. For the intensity of the 495 keV K-shell conversion electrons, our result (0.0005) and the ISOLDE result [8] (0.00037) are in good agreement.

Shown in fig. 3 is part of the β-coincident γ-ray spectrum measured by the HPGe detector. This spectrum is dominated by the 511 keV annihilation radiation (not shown) and the ^{74}Ga decay (several lines shown). Only the 511 keV annihilation line was observed in the γ-spectrum of the ISOLDE Collaboration [8]. The line at 456 keV is the $2_1^+ \to 0_1^+$ $E2$ transition in ^{74}Rb that is well known from in-beam data [12,14]. It has an intensity of 0.002 per ^{74}Rb β-decay. We have demonstrated ,that this line belongs to the ^{74}Rb decay by the measurement of its half-life [9] and by an exhaustive analysis of possible sources of contamination. Its observation clearly demonstrates that ^{74}Rb undergoes Gamow-Teller (GT) transitions to higher-lying 1^+ states. Population of these states could also lead to γ-ray population of the 0_2^+ level at 508 keV as well as of the 0_1^+ ground state.

The 1233 keV γ-ray line in fig. 3 corresponds to the $(1^+,\ 2^+) \to 0_2^+$ transition that was also observed in-beam [12]. Look at fig. 4 to see its placement. We also observed coincidences between the 1233 keV γ and the 495 keV electrons that depopulate the 508 keV level as do the authors of ref. [12]. The lines at 1198 and 4244 keV were determined to be associated with the ^{74}Rb decay, but could not be placed in the decay scheme. Coincidences between gammas would be helpful in that regard, but the spectrometer shown in fig. 1 incorporated only one HPGe detector. Coincidence data with the 495 keV electrons, however, show that the 1198 keV transition, unlike the 1233 keV transition, does not directly feed the 508 keV level. Statistics on the 4244 keV transition were too low to draw any conclusions about its population or depopulation channels.

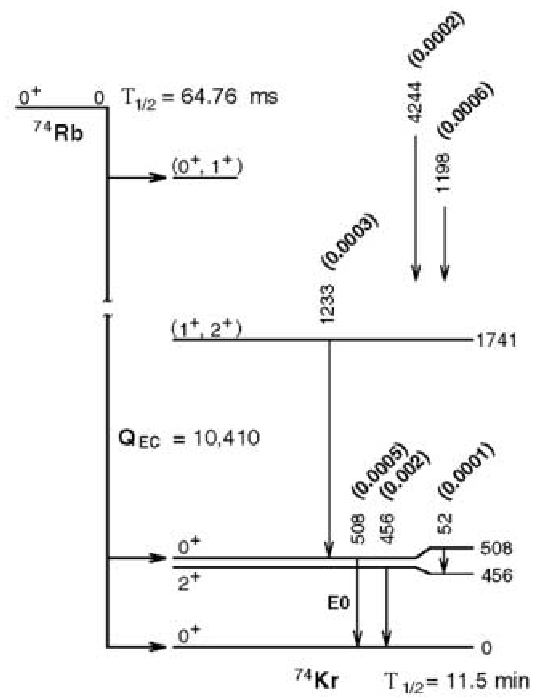

Fig. 4. The ^{74}Rb decay scheme. See the text for a discussion of the transitions, their intensities, and implications for the determination of the non-analog β branch to the 0_2^+ state at 508 keV. The Q_{EC} value was computed [15] using Logft = 3072.3 and a partial half-life of $t = 64.87$ ms.

4 Discussion

The ^{74}Rb decay scheme is presented in fig. 4. The intensities, per ^{74}Rb β-decay, are presented in parentheses. These data indicate an upper limit of 0.0003 for the β population of the 0_2^+ level at 508 keV. Our results clearly show that one cannot compute the non-analog β population of the 508 keV 0_2^+ level, and hence the Coulomb mixing probability, from the intensity of the 508 keV, $E0$ transition alone. One must include the 52 keV $E2$ transition that depopulates the level as well as the 1233 keV gamma-ray that populates it. To get their upper limit of 0.00053, for the population of the 508 keV level, the ISOLDE Collaboration [8] did make an estimate for the 52 keV transition intensity (0.00016) which is in agreement with our measured value, but they did not observe the 1233 keV or any other γ-ray transition. Furthermore, since the total 456 keV 2^+ level depopulation is twenty times that of its feeding by the 52 keV transition, there must exist appreciable GT β-decay to higher-lying 1^+ states (direct β feeding by a 2nd forbidden transition could not possibly account for the difference). This is supported by our observation of γ-rays at 1198 and 4244 keV, which definitely belong to the ^{74}Rb decay but have not been placed in the level scheme, and by the fact that energy gates on the β-spectrum taken with the thick plastic scintillator suggest that the population of the 2_1^+ (456 keV) as well as the 0_2^+ (508 keV) level results from low-energy positrons. While this would be expected for the 456 keV 2_1^+ level, it was not expected for the 508 keV 0_2^+ state. This is consistent, however, with half of the 508 keV intensity coming from the 1233 keV transition and suggests that the non-analog β branch to the 0_2^+ level at 508 keV may be even smaller than the 3×10^{-4} per ^{74}Rb β-decay that would be deduced from the decay scheme presented in fig. 4.

5 Conclusions

We have shown that published theoretical estimates [2,4] of ($\sim$ 1%) overpredict the extent to which the 0_2^+ state is populated in the ^{74}Rb $\rightarrow$ ^{74}Kr Fermi β-decay. More importantly, we have shown that high-precision, complete spectroscopy is required to determine the β-decay branching ratios when using superallowed Fermi β-decay of nuclei like ^{74}Rb to test the unitarity of the CKM matrix and hence the minimal Standard Model.

In addition to measuring the $E0$ (495 keV) and $E2$ (39 keV) conversion-electron intensity depopulating the 0_2^+ state at 508 keV, we have shown that the determination of γ-ray feeding to this level from high-lying 1^+ states, even though weakly fed by GT β-decay, is absolutely essential. In this regard, our identification of 4 γ-rays in the ^{74}Rb β-decay is in stark contrast to the results of the ISOLDE Collaboration [8] where no gammas were observed.

Our upper limit for the non-analog β branch to the 0_2^+ state at 508 keV is 3×10^{-4} per ^{74}Rb β-decay, but energy gates on the β-spectrum ($Q_{\mathrm{EC}} = 10418$ keV) suggest that additional feeding to the 0_2^+ level may come from other γ-rays which are as yet unplaced or unobserved. This would reduce the branching ratio even further. In this regard, Hardy made reference to Pandemonium [16] and indicated that as many as 400 1^+ states were available for population in the ^{74}Rb β-decay [1]. While this may be true, it is unlikely that the β feeding of these levels is evenly distributed. In addition, one might expect that high-energy γ-decay out of these 1^+ states would populate the 0_1^+ (ground) and 0_2^+ (508 keV) levels more or less equally and thus could be estimated by gating on the 495 keV conversion electrons. However, since there is no *a priori* reason to assume that on average nuclear structure effects will not play an important role in the γ-decay of these highly excited 1^+ states, further theoretical and experimental studies are needed to resolve this issue.

We believe we can deal with the concerns raised by Pandemonium through improved spectroscopy. This will be pursued at TRIUMF using the greater statistics afforded by an order of magnitude increase in ^{74}Rb production, by higher mass resolution to reduce isobaric contamination, and by the use of the re-configured 8π γ-ray spectrometer now located at the ISAC facility.

The authors thank the entire TRIUMF-ISAC team whose hard work and dedication led to the availability of high-quality radioactive beams from the ISAC facility. They also gratefully acknowledge the contributions made by the Machine and Electronics Shops at LSU in the design and fabrication of the spectrometer systems.

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