5 July 2001

PHYSICS LETTERS B

Physics Letters B 511 (2001) 145–150

www.elsevier.nl/locate/npe

Non-analog β decay of ^{74}Rb

ISOLDE Collaboration

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Received 15 February 2001; received in revised form 19 April 2001; accepted 16 May 2001
Editor: V. Metag

Abstract

The magnitude of the Coulomb mixing parameter δ_{IM}^{1} has been experimentally deduced, for the first time, for the β decay of ^{74}Rb. The estimated magnitude is derived from the feeding of the non-analog first excited 0^{+} state in ^{74}Kr. The inferred upper limit of 0.07% is small compared to theoretical predictions. The half-life was measured to be 64.90(9) ms. © 2001 Published by Elsevier Science B.V.

PACS: 21.10.-k; 23.40.-s; 27.50.+e
Keywords: Superallowed β decay; Coulomb mixing; On-line mass separation

1. Introduction

Accurate measurements of β-decay energies, half-lives and branching ratios are necessary for studies of superallowed β decay strength. This low-energy nuclear physics input, together with muon-decay data, gives presently the most precise value for the up–down quark mixing matrix element V_{ud} in the Cabibbo–Kobayashi–Maskawa (CKM) matrix [1]. Presently, the systematics of superallowed decays reach ^{54}Co [2–4]. The largest uncertainty in V_{ud}, as determined from β-decay results, is due to charge-dependent and other theoretical corrections [3,4]. Extending the systematics towards higher Z brings data from a new

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0370-2693/01/$ – see front matter
PII: S0370-2693(01)00646-3

realm into the data set and will thus eventually improve on the accepted value for V_{ud}. In addition, it allows for further studies of the charge-dependent effects such as Coulomb mixing.

The Coulomb correction δ_C increases with increasing Z and may reach even a level of 1–2% for isotopes beyond ^{54}Co [5,6]. An important contribution to the Coulomb correction is due to mixing between the involved 0^+ wave functions. The consequences of such an effect are observable in the β decays as transitions feeding the non-analog 0^+ states. The observation of such transitions provides a test for the total Coulomb correction [7] and helps to distinguish between different theoretical values.

In order to improve our knowledge of the superallowed Fermi decays, a program for performing a complete study on the β-decay of ^{74}Rb has been launched at the on-line mass separator facility ISOLDE at CERN [8]. This program aims at high-precision measurements of a half-life, branching ratios and a Q_{EC} value of ^{74}Rb by using decay spectroscopy and atomic mass measurements [9,10]. In addition, extensive shell-model calculations, with realistic effective interactions, are in progress [11] aiming to study the Coulomb effects involved in the decay. The eventual goal of these studies is to extract the strength of the analog transition and to significantly contribute to the superallowed decay systematics. As a first milestone, the measurement of the β-decay half-life and the first observation of non-analog β decay of ^{74}Rb will be reported in this Letter. Based on this observation, the Coulomb mixing between the lowest 0^+ states will be discussed.

2. Experimental methods

^{74}Rb ions were produced in spallation reactions induced by a pulsed 1-GeV proton beam incident on a Nb-foil or a ZrO_2-felt target at the ISOLDE online mass separator at CERN [12]. The 60 keV mass-separated ion beam was implanted in an aluminized Mylar tape with a typical collection time of 150 ms. Any residual long-lived activity was removed by transporting the implantation tape typically after every fifth proton pulse. The only isobaric contaminant was Ga.

Four different types of measurements were performed for ^{74}Rb: the determination of its half-life, a search for a high-spin isomer, a search for β-delayed proton and γ (β–γ) transitions and a search for β-delayed converted transitions (β–e^-). The details of the first two experiments have been described elsewhere [13]. Essentially, the setup for these measurements consisted of a β telescope made of a 2-mm-thick plastic scintillator and a 20-mm-thick planar Ge detector, a 70% HPGe detector for γ-ray detection and a charged-particle detector telescope [14]. In the β–γ experiment a cylindrical scintillator with 70% efficiency was used as a trigger detector for β particles. The γ-rays were detected with three 70% Ge detectors. Each Ge detector was equipped with a veto detector in front of the Ge crystal to reduce β–γ summing. In the β–e^- experiment transitions to excited 0^+ states were searched for with the magnetic conversion electron spectrometer ELLI [15]. In each experiment the data were stored in list-mode and, in addition, data for half-life analysis were collected with a fast multiscaling acquisition system to minimize counting-rate induced effects.

3. Results

3.1. Half-life determination

The existing experimental information on the β decay of ^{74}Rb prior to this work was limited to two half-life measurements [16,17]. Those measurements resulted in a half-life of 64.9(5) and 64(10) ms, respectively. In this Letter, the half-life was determined from the time dependence of the observed events in the thin scintillator detector. Two sets of data were collected: one without conditions and another one with an energy condition of $E_\beta > 5.2$ MeV. After a dead time correction, determined with an intense ^{26}Na sample [13], the time spectra were fitted with a single exponential plus a constant background using a χ^2 method. Weighting of the individual data points was performed using the procedure described in Ref. [18].

The influence of pulse pile-up was negligible since the highest instantaneous count rate was below 2500 cts s^{-1}. The effect of changes in the counting rate during the measurements was estimated to be small and was included into the uncertainty of the deadtime

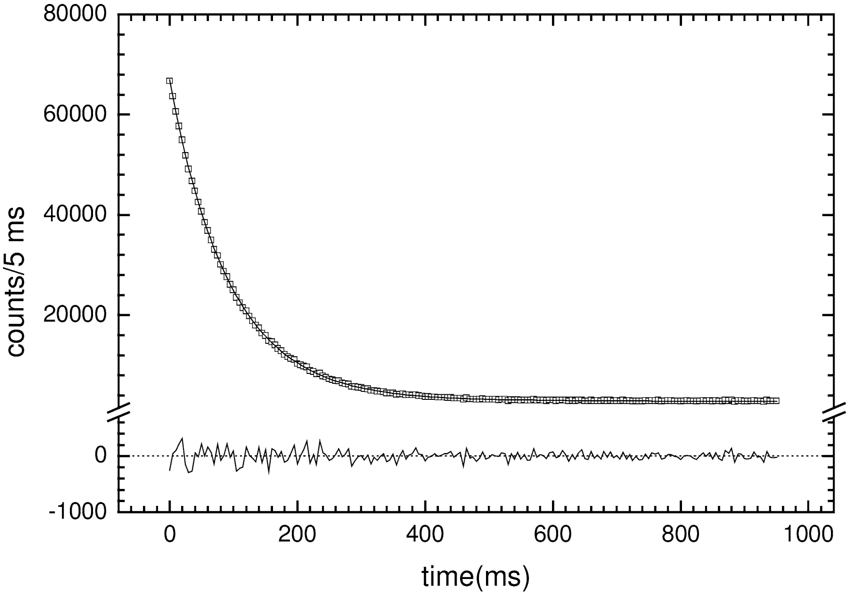

Fig. 1. The decay time spectrum collected at $A = 74$ for the half-life analysis. The open squares show the experimental data and the full line is the fit. The error bars in the data are smaller than the symbols. The residual plot, discussed in the text, is shown in the lower part of the figure.

correction as described in [13]. The systematic error as contributions from contaminant activities was studied using the following procedure. First, a decay curve for ^{74}Rb was generated assuming $T_{1/2} =$ 64.9 ms [16]. Then, decay components taking into account the observed contaminants were added to this curve. The integrals of these components were normalized to correspond to their intensities extracted from the γ spectra. The obtained time spectra were then fitted with a single-component exponential with a constant background. The effect of each contaminant on the final half-life value of ^{74}Rb was deduced as a difference between the half-life value from [16] and the new value given by the fit.

The effects of ^{74}Ga and ^{74m}Ga were found to be less than 0.01% on the half-life value. Another possible effect would be induced by a β-decaying $T = 0$ isomeric state in ^{74}Rb. We could set an upper limit of 0.1% for the production cross section of the isomeric state to that of the ground state of ^{74}Rb [13] assuming $T_{1/2}(^{74m}\text{Rb}) = 2$ s [16]. Even if one assumes a fast Gamow–Teller transition and a half-life of only 0.1 s, the largest possible effect on the half-life of ^{74}Rb would remain below 0.03%.

Table 1
Measured half-lives for ^{74}Rb given in milliseconds

Run	No conditions	$E_\beta > 5.2$ MeV
1	64.86(28)	64.23(49)
2	64.76(22)	64.41(42)
3	64.94(10)	64.96(21)
Weighted average	64.90(9)	64.77(17)

A typical decay-time spectrum is shown in Fig. 1. The residual, defined as a difference between the data and the fit, is plotted in the lower part of the figure and shows no deviation from a single-component exponential decay. The contributions from above discussed sources of systematic uncertainty were quadratically added to the statistical uncertainty of the fit. The results are shown in Table 1. The weighted average of the results are $T_{1/2} = 64.90(9)$ ms for the non-gated and $T_{1/2} = 64.77(17)$ ms for the energy-gated data. Due to its better statistical accuracy we adopt the value of 64.90(9) ms for the final half-life of ^{74}Rb.

3.2. *Non-analog β feeding*

The role of Coulomb-mixing induced corrections can be studied following the procedure described in Ref. [7] by measuring the branching ratio for non-analog β decay to the excited $J^\pi = 0^+$ states. In particular, a strong mixing could be present in the ^{74}Rb–^{74}Kr case since the first excited $J^\pi = 0^+$ state in ^{74}Kr lies energetically low at 508 keV [19,20]. This state decays via a 52 keV $0_2^+ \to 2_1^+$ E2 transition, which subsequently decays by 456 keV E2 γ emission, or a 508 keV $0_2^+ \to 0_1^+$ E0 transition. In addition to the fully-converted ground-state transition, the low-energy E2 transition also largely decays by conversion electron emission with the energy of 38 keV. The relative intensities of these transitions are not known. In the conversion electron measurement our main goal was to search for these decays of the 508 keV 0_2^+ state as a signature of a non-analog Fermi transition, and subsequently, Coulomb mixing.

Fig. 2 shows the conversion electron spectrum measured in coincidence with β-rays during the first 500 ms after proton pulse impact. The peak at 495 keV whose half-life was determined to be 60(17) ms, in agreement with the half-life of ^{74}Rb, was assigned to the K conversion of the 508 keV $0_2^+ \to 0_1^+$ E0 transition. The intensity of the peak compared to the total number of β decays of ^{74}Rb, determined by counting the short-lived decay products, is $(3.7 \pm 1.1) \times 10^{-4}$. In the case of the 38 keV peak, only a 1σ upper limit of 1.6×10^{-4} could be set for its intensity. The above numbers lead to an upper limit of 5.3×10^{-4} for the population of the 508 keV 0_2^+ state in the β decay of ^{74}Rb.

The 508 keV state could be also populated in γ decay following Gamow–Teller (GT) feeding of high-lying $J^\pi = 1^+$ states in ^{74}Kr. Consequently, a search for such γ-rays was performed. The results are shown in Fig. 3. The spectrum is a sum of β-gated, vetoed and background subtracted data collected with the three Ge detectors. The background subtraction was performed by removing the γ spectrum collected during $T = 600$–850 ms after a proton pulse impact from the one collected during $T = 0$–250 ms. No short-lived transitions resulting from the β decay of ^{74}Rb were observed. In particular, the 1σ upper limit for the 456 keV $2_1^+ \to 0_1^+$ γ transition intensity is 8.1×10^{-4}. The branching ratio for β-delayed proton emission, a signature of additional GT feeding, was deduced to be even lower, $< 5 \times 10^{-5}$.

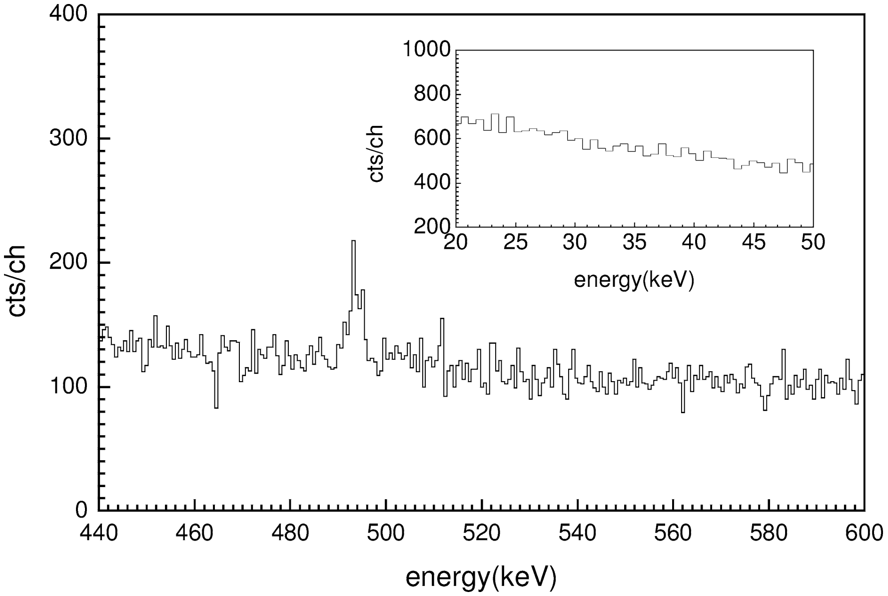

Fig. 2. The conversion electron spectrum collected with the ELLI spectrometer. The inset shows the region around an expected peak at 38 keV.

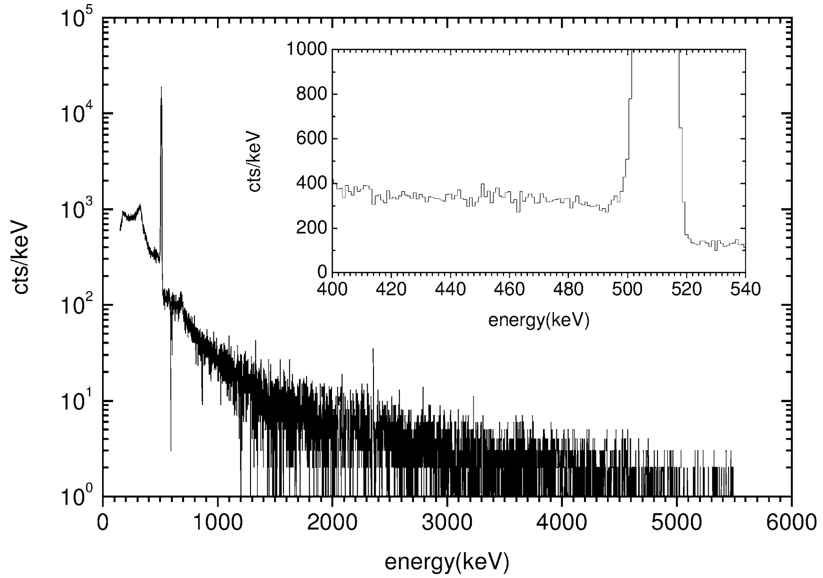

Fig. 3. The sum of the beta-gated and background subtracted gamma spectra collected with the three Ge detectors. The spectra were vetoed with the β-rays observed at the thin scintillators in front of the Ge detectors. The inset shows the expected region of interest for the 456 keV γ-ray.

4. Discussion

Different nuclear shapes have been predicted to exist in the neutron-deficient Kr nuclei [21]. These coexisting structures are usually associated with low-lying $J^\pi = 0^+$ states. A large monopole strength has been considered as an experimental signature of a mixing between these different shapes in a nucleus [22,23]. Assuming $\Omega_K = 2.64 \times 10^{-8}$ [24] and the ratio $\Omega_K/\Omega_L = 9.8$ [25], our results on the decay of the 508 keV state combined with the experimental life-time of the state $T_{1/2} = 33(7)$ ns [26] lead to ten times higher lower limit of $|\rho(\mathrm{E0})| > 0.27$ compared to Ref. [20]. This is also in agreement with the value obtained in Ref. [19], $|\rho(\mathrm{E0})| = 0.30(4)$. Note that a negligible E2 strength was assumed when extracting the latter number.

The result obtained in this work for the production limit of the β-decaying $T = 0$ isomeric state, in addition to its influence on the β-decay half-life, confirms the previous result [16] with an order of magnitude lower value. Also a search for a γ-decaying isomeric state has been performed [27] with a negative result. Thus, the non-existence of a $T = 0$ isomeric state is presently well established.

This measurement improves the accuracy of the half-life of ^{74}Rb with a factor of five compared to the previous result [16]. The relative uncertainty of 1.4×10^{-3} is, however, still five times larger than those measured for the lighter nuclei up to ^{54}Co [2,18]. The largest source of uncertainty is still induced by the statistics. On the other hand, the amount of ^{74,74m}Ga and ^{74m}Rb starts to play a more significant role when the statistical uncertainty decreases. Reducing the amount of these contaminants and, especially, measuring the decay pattern of ^{74m}Ga more carefully will be important goals to further reduce the overall uncertainty.

β-delayed proton emission does not contribute significantly to the branching ratio of the Fermi transition. However, our measurements does not rule out a possibility for the GT β transitions to feed γ-decaying 1^+ states and eventually lead to a population of the 0^+ state at 508 keV. Due to this and since the 38 keV converted E2 transition was not observed our number for the Coulomb mixing probability has to be considered as an upper limit.

Our upper limit of 5.3×10^{-4} for the relative population of the 0_2^+ state is about an order of magnitude larger than those observed for the lower-mass odd–odd $M_T = 0$ nuclei from ^{38m}K to ^{54}Co [4,7]. However, the deduced limit for the Coulomb mixing component $\delta^1_{\mathrm{IM}} < 0.07\%$ (notation from [5]) is only slightly larger than the values obtained for the lower-mass nuclei. The theoretical values for the Coulomb mixing component δ^1_{IM} for ^{74}Rb from [5] are 0.07–0.09% depending on the interaction used in the shell-model calculation. When correcting for the energy difference between the calculated and the experimental 0^+ states, the values increase to 1.4–3.1%. These values seem to be unrealistically large in the light of our experimental upper limit.

Since the total Coulomb correction δ_{C} is expected to increase from about 0.5% for $A < 60$ to about 2% for $A > 60$ [4], the small increase in δ^1_{IM} emphasizes the importance of the radial mismatch of the wave functions in forming the major fraction of the total Coulomb correction for ^{74}Rb.

5. Summary

Beta-decay properties of ^{74}Rb have been studied at the ISOLDE on-line mass separator facility at CERN. A new determination of the β-decay half-life of ^{74}Rb yielded a consistent, though five times more precise, result compared to the previous value. A refined upper limit could be set for the production of a possible β-decaying $T = 0$ isomeric state in ^{74}Rb. The β-delayed proton emission probability was determined to be negligible for the superallowed Fermi decay systematics. A first estimate of the magnitude of the Coulomb mixing involved in the superallowed β decay of ^{74}Rb could be determined in this work. The upper limit for the Coulomb correction due to different degrees of configuration mixing was shown to be of the the same order of magnitude as obtained for the lighter isotopes previously studied. This emphasizes the importance of the radial mismatch part of the total Coulomb correction in the case of ^{74}Rb.

Note added in proof

Recently, the half-life of ^{74}Rb was also remeasured at the ISAC Facility at TRIUMF [28] to be 64.761(31) ms. The result has three times smaller uncertainty compared to our result and differs from our adopted result by 1.5 standard deviations.

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