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Beta-decay half-lives of ^{70}Kr and ^{74}Rb

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Abstract

Beta-decay half-lives of two nuclei close to $N = Z$ line, ^{70}Kr and ^{74}Rb, have been measured at the ISOLDE mass separator facility at CERN. Importance of these half-lives on two ingredients explaining existence and development of the Universe, the astrophysical nucleosynthesis and the Standard Model, are discussed.

Key words: Beta decay; Nucleosynthesis; Superallowed Fermi transitions

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1 Introduction

One of the basic feature of radioactive nucleus is its lifetime. In addition to the importance of the measured lifetimes for testing various nuclear models, two very special areas of modern physics gain from experimental data on half-lives.

The first one, in arbitrary order, is the astrophysical nucleosynthesis. Reaction flows in production of the elements in the universe are defined by a competition of particle capture reactions and radioactive decays, mainly β decays. Thus, the importance of the experimental data on half-lives as input of the network calculations is evident. Recently, Schatz et al. (1) showed that, in the extreme conditions, the rapid proton capture process (2) can be proceed possibly up to $A = 100$ via two-proton (2p) capture reactions bridging the waiting points, for example at ^{68}Se and ^{72}Kr. In this paper we discuss the importance of the experimental half-life of the 2p capture daughter of the former nucleus, ^{70}Kr, for the process path. The half-life was recently measured at the ISOLDE on-line mass separator facility (3).

The second one is the test of the Standard Model via the superallowed Fermi β decays (4). According to the Conserved Vector Current (CVC) hypothesis the transition rates of these β decays expressed as ft values should all be identical (Ft) after small corrections induced by electromagnetic effects. Provided they are, the resulting vector coupling constant of the weak interaction G_V allows determination of the up-down quark mixing matrix element V_{ud} of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The whole CKM matrix describes the quark mixing involved in all the weak interaction processes. The determination of the V_{ud} allows to test the unitarity of this matrix and thus is a test of the Standard Model itself. The determination of the Ft values need precise measurements on half-lives, β-decay energies and branching ratios. One of the most promising candidates to extend the decay systematics beyond ^{54}Co (4) is ^{74}Rb. In addition to its relatively high production rates in present on-line mass separator facilities (5; 6), as a high-Z nucleus it is subject to large Coulomb effects. Observation of isospin-forbidden transitions is a sign of these effects and allows tests of the theoretical Coulomb corrections (7; 8). In this paper we report on one part of this puzzle, namely measurement on the half-life of ^{74}Rb. The detailed results will be found in (9).

2 Experimental details

The studied nuclei were produced in spallation reactions in Nb-foil target induced by 1 GeV pulsed proton beam from PS-Booster, CERN. The Kr and Rb atoms were ionized with cold plasma and W-surface ion sources, respectively and subsequently mass separated using the ISOLDE on-line mass separator facility (5). The resulting ion beam was implanted into movable aluminized Mylar tape. This allowed transportation of the long-lived background activity away from the source position after several successive proton pulses.

The measurement setup around the implantation position was similar in both of the experiments and it is described in ref's. (9; 10). Essentially, it allowed detection of positrons up to 20 MeV, β-delayed γ-rays up to 5 MeV and β-delayed protons up to 6 MeV. Triggering detector was 2-mm-thick plastic scintillator from which the fast time signals were used for half-life analysis for both isotopes.

Yields of these two isotopes differed drastically. While ^{74}Rb nuclei were produced about 800 at/μC in the source position, the yield of ^{70}Kr was possibly the lowest used for spectroscopy at ISOL facilities: 0.03 at/μC.

3 Half-life of ^{70}Kr and the rp process

The β-decay half-life of ^{68}Se, 35.5 s, can be reduced in astrophysical environments if there are competing destruction mechanisms in addition to β decay. Indeed, two-proton capture has been shown to provide such a mechanism for a system involving slightly proton-unbound intermediate nucleus, here ^{69}Br (1). The first step between ^{68}Se and proton-unbound ^{69}Br occurs via resonant scattering of protons in the stellar plasma since the proton decay is the only possible destruction channel for ^{69}Br. The proton-unbound nucleus lives long enough to have a possibility for an additional proton capture leading to ^{70}Kr. At low temperatures below $T_9 = 1.5 - 2$ the rate of the inverse photodisintegration is low (1) and thus the destruction rate of ^{68}Se depends only on the β-decay and 2p-capture rate. However, if the temperature increases to correspond to the typical peak temperatures in X-ray burst scenarios, T_9 >1.5-2, the photodisintegration of ^{70}Kr increases and finally drives the system into (2p,γ)-(γ,2p) equilibrium. Then, the destruction rate of ^{68}Se becomes proportional to the β-decay half-life of ^{70}Kr (1).

The half-life of ^{70}Kr was measured as 57(21) ms (3). The value is clearly shorter compared to the QRPA-value used as an input for the recent extensive network calculation, 390 ms (1; 11). The experimental value agrees well with an estimate assuming pure Fermi β decay, $T_{1/2} = 62$ ms (3). In fact, this explains the inconsistency between the QRPA value and the measured one since Fermi contributions were not taken into account in calculations in ref. (11). The resulting effect into the effective rp-process half-life of the waiting point ^{68}Se is shown in Figure 1.

Under the assumed conditions the shorter half-life of ^{70}Kr induces a factor of 2 faster rp-process flow beyond the waiting point ^{68}Se compared with the result with the QRPA value. This would lead an increased production of $A > 68$ nuclei including possibly p-nuclei ^{92,94}Mo and ^{96,98}Ru for which the solar abundances have been constantly underestimated by standard p-process scenarios (1).

It is interesting to note that the QRPA half-life is relatively long also for ^{74}Sr: 382 ms (11). The main part of its decay is due to Fermi transition between the $J^{\pi} = 0^{+}$ ground states of ^{74}Sr and the daughter ^{74}Rb. If assuming pure Fermi decay and $Q_{EC} = 11.0$ MeV (12), the β decay half-life is about 50 ms. This would enhance the rp process flow beyond the waiting point nucleus ^{72}Kr in a similar manner than in the case of ^{68}Se. In general, it can be noted that for even-even $M_T = -1$ nuclei role of Fermi transitions can not be neglected.

Although the experimental half-lives makes the network calculations more reliable, the major uncertainties are still induced by the unknown atomic masses and level energies, as noted in (1). In the case of the 2p-capture of ^{68}Se, particularly large uncertainty is induced by its proton capture Q-value i.e. the proton separation energy of ^{69}Br. It can be measured via β decay of ^{69}Kr. In fact, the motivation of our studies of light Kr isotopes was actually to measure this quantity (13). Observation of only one event identified as a possible β-delayed proton at an energy of 800 keV allowed only estimation of the yield of ^{69}Kr to be $2.6 \cdot 10^{-4}$ at/μC. This is surprisingly close to the calculated value based on (14): $2.8 \cdot 10^{-4}$ at/μC. Since the observation of β-delayed protons down to 200 keV is rather standard and efficient (15), development towards faster target materials will most likely bring the yield to the same level than observed for ^{70}Kr thus possibly allowing the S_p determination.

4 Half-life determination for ^{74}Rb

Details of the analysis for the half-life and other decay properties of ^{74}Rb will be published elsewhere (9). Here we only present the result and discuss particularly about the difficulties faced in the half-life determination of ^{74}Rb.

The half-life was obtained from a χ^2 fit of a single-exponential decay + a constant background into a time spectrum collected with thin plastic scintillation detector. Intensity, half-life and background level were all treated as free parameters. Weighting of the data was performed following the description in (16). The β-decay half-life was measured to be $T_{1/2} = 64.90(9)$ ms (9). This agrees well with the old value measured at SC-ISOLDE: 64.9(5) ms (17).

The uncertainty in the value includes qudratically added contributions from i) contaminant activities, ii) possible β-decaying $T = 0$ isomer, iii) count-rate changes during the measurement and iv) uncertainty in the dead time. Pile-up effects were estimated to be negligible due to low maximum count rate in the β detector (max. 2400 cts/s) and due to fast pulses taken directly from the anode of the photomultiplier ($\tau < 20$ ns). Behaviour of the multiscaler used for storing the time signals from the PM-tube was tested via measuring the half-life of ^{26}Na. Remarkably good agreement was found with the literature value: $T_{1/2,this\ work} = 1.073(4)$ s compared to $T_{1/2,lit} = 1.072(9)$ s (18). Another check for the behaviour, namely for the differential linearity of the multiscaler, was performed by feeding it by an independent clock pulse of 10^5 Hz. Deviations from the constant value of the count rate per channel were of the order of $3 \cdot 10^{-5}$. Thus, the uncertainties induced by the measurement setup were neglected.

The uncertainty in the half-life of ^{74}Rb is mostly due to counting statistics. Two other contributions deserve special attention: only observed contaminant activity produced on-line, ^{74,74m}Ga, and possible β-decaying $T = 0$ isomer. All the contributions from the contaminants were checked as follows. First, an artificial time spectrum was created for ^{74}Rb based on the old half-life value (17). Then, based on the observed amounts in γ detector, each contaminant contribution was added to this spectrum one by one. Finally, the resulting sum spectrum was fitted with the expression described above. The resulting deviation of the $T_{1/2}$ from the original value was then used as an error contribution of this particular contaminant.

4.1.1 Contribution from ^{74,74m}Ga

The relative uncertainty induced by the decay of the ground state ^{74}Ga was estimated to be $1 \cdot 10^{-4}$. The contribution of the γ rays from ^{74}Ga detected by the thin scintillator was estimated to be negligible based on the absorption considerations.

Lack of information on the decay scheme of isomeric ^{74m}Ga with $T_{1/2} = 9.5$ s (19) impedes the half-life analysis further. The isomer decays possibly by β decay and partly by γ or conversion electron emission. The number of the nuclei in isomeric state at the beginning of the decay period can be estimated assuming the production in the target to be equal for both of the states and taking into account corrections due to tape transport, decay losses and the finite beam-on period used. This results in more or less equal number compared to that of the ground state. Following contributions should then be considered. The internal transition of the isomeric ^{74m}Ga to the ground state is highly converted. The resulting low-energy electrons with $E < 60$ keV do not contribute to the measured time spectra since they are all absorbed in the implantation tape and the 0.2 mm-thick pressure window between the tape and the detector. A harmful component, however, might be due to the successive grow-in of ^{74}Ga during the decay period. This causes a relative uncertainty of $1 \cdot 10^{-4}$. The third contribution is due to the possible β decays of the isomeric state. However we neglect this contribution based on the following arguments: i) branching ratio of the internal transition has been measured to be 75(25)% (19), ii) no component with a half-life of 9.5 s could be fitted to any β spectra observed, iii) observed intensities of the γ peaks which might have contribution from this decay were consistent with the reported decay pattern of ^{74}Ga (19), iv) the amount of the total activity counted in the β detector could all be explained by the observed other activities in the β-delayed γ spectra. We note, however, that experimental information on the decay of the isomeric state in ^{74}Ga would be very welcome in the future.

4.1.2 On the existence of β-decaying $T = 0$ state in ^{74}Rb

Well-known feature of the odd-odd $Z = N$ nuclei is the isomerism due to a competition between $T = 1$ and $T = 0$ states. Such an isomer can be present also in ^{74}Rb. Separate experiment was performed for searching this isomer (20). If existing, it would affect the half-life determination for the ground state. No long-lived β-decaying state was observed and upper limit for the production cross section ratio between the isomer and the ground state can be set to be 10^{-3}. It is realistic to assume that the possible isomer do not have half-life shorter than about 100 ms since it would decay by Gamow-Teller transitions. This, combined with the observed upper limit, leads to an estimate that the relative uncertainty in the half-life of ^{74}Rb induced by the possible isomer is $< 3 \cdot 10^{-4}$. In addition to the importance of this limit for the half-life determination, it provides an order of magnitude lower limit for production of the isomeric state than observed previously in (17).

4.2 Importance of the present accuracy in $T_{1/2}$

Figure 2 illustrates the importance of the present accuracy in the ^{74}Rb half-life concerning the systematics of the superallowed β decays. The uncertainty in the ft value (y-axis) is plotted as a function of the uncertainty in the Q_{EC} value (x-axis) of a Fermi β emitter. Squares in the lower left corner are the values for the 9 isotopes belonging to the present systematics (4). The solid line shows the relation if assuming the present relative accuracy of $1.4 \cdot 10^{-3}$ whereas the dashed line represents the relation deduced assuming the typical relative accuracy of an "official" member of the systematics. The both lines start with the present uncertainty ΔQ_{EC}= 720 keV (12). The present accuracy in the half-life requires the β-decay energy to be determined within 1 keV accuracy to have ^{74}Rb included into systematics. Five times better precision would still need about 3 keV accuracy in the energy. However, this value starts to be within reach with existing Penning trap mass spectrometers, such as ISOLTRAP (21).

4.3 Outlook for ^{74}Rb

Note that the Figure 2 do not include uncertainties induced by the branching ratios. Preliminary analysis for γ-ray intensities resulting from isospin-forbidden or Gamow-Teller transitions restrict their intensities below $1.5 \cdot 10^{-3}$ level (9). Furthermore, branching ratio of the β-delayed proton emission was observed to be negligible: $< 5 \cdot 10^{-5}$ (9). However, more detailed measurements are needed especially for the isospin forbidden transitions and are, in fact, in preparation at various laboratories (22; 23). In addition, determination of masses of ^{74}Rb and daughter ^{74}Kr are still needed to extract the Q_{EC} value within required precision. As discussed above, this requirement is set by the uncertainty in the half-life. Role of the contaminant activity of ^{74,74m}Ga limiting the accuracy of the half-life can be reduced with high-resolution mass separator techniques. However, if taking into account the possible β-decaying $T = 0$ isomer, it remains a considerable limiting factor.

5 Summary

β-decay half-lives of ^{70}Kr and ^{74}Rb have been measured at the ISOLDE on-line mass separator facility. In the point of view of astrophysical nucleosynthesis, the experimental data on even-even $M_T = -1$ nuclei improves the reliability of network calculations considerably. However, masses will be still the largest source of uncertainty. A step towards the extension of the superallowed Fermi β-decay systematics have been taken by the half-life measurement on ^{74}Rb at ISOLDE. Still, higher accuracy in all the crucial parameters: half-life, β-decay energy and branching ratios are needed for this nucleus that it could be considered as an important piece of the puzzle of testing the Standard Model. This half-life measurement has triggered a lot of activity in the field and the near future shows how the low-energy nuclear physics community worldwide succeeds in its efforts.

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Fig. 1. The effective rp process half-life of ^{68}Se as a function of the β decay half-life of ^{70}Kr assuming T_9 =1.5, $\rho = 10^6\ g/cm^3$ and a solar hydrogen abundance.

Fig. 2. Relative uncertainty in ft value of superallowed Fermi β decays induced by the uncertainties in the decay energy and the half-life.