DECAY STUDY OF HEAVY *N~Z* NUCLIDES

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1. Introduction

New physical phenomena associated with nuclear structure and decays along the $Z = N$ line are expected to arise due to the equal filling of the proton and neutron states, as well as due to the increasing of the Coulomb repulsion in heavier nuclei. Nuclei near and at the $Z = N$ line provide an ideal laboratory to study fundamental symmetries in nuclei.

According to the conserved vector current (CVC) hypothesis, the matrix elements of the super-allowed Fermi β-transitions between the $(J^{\pi},T) = (0^{+},1)$ states should all be equal, independent of nuclear structure apart from small terms for nucleus-dependent radiative correction δ_R and for Coulomb correction δ_C. Provided this is true, the experimental *ft* values that include isospin mixing and radiative corrections, allow an accurate determination of the weak vector coupling constant G_V. Up to now, super-allowed $(T = 1)$ $0^+ \rightarrow 0^+$ transitions have been measured to a precision of 0.1% or better in the decays of nine nuclei between ^{10}C and ^{54}Co. This low-energy nuclear physics result, together with the 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. The present nuclear beta-decay result differs at the 98% confidence level from the unitarity condition of the CKM matrix. The uncertainty is largely due to theoretical corrections for δ_R and δ_C.

The Coulomb correction δ_C increases with increasing Z and may reach even a level of 1–2% for isotopes beyond ^{54}Co. The value δ_C can be factored to the contribution due to isospin mixing δ_{IM} and due to the deviation from unity of the overlap between the proton and neutron radial wave functions δ_{RO}. The observation of feeding the non-analog 0_2^+ state transitions provides a test for the total Coulomb correction and helps to distinguish between different theoretical values.

The isobaric doublets have been studied so far with high precision only up to ^{59}Zn. Above ^{59}Zn the experimental information was incomplete. Meanwhile just above $A \sim 60$ due to the increasing importance of the Coulomb interaction, these nuclides are only weakly bound or even proton-unbound. Strong deformation of $N = Z$ nuclides in $A = 70$–80 area enhances uncertainty of Coulomb difference prediction.

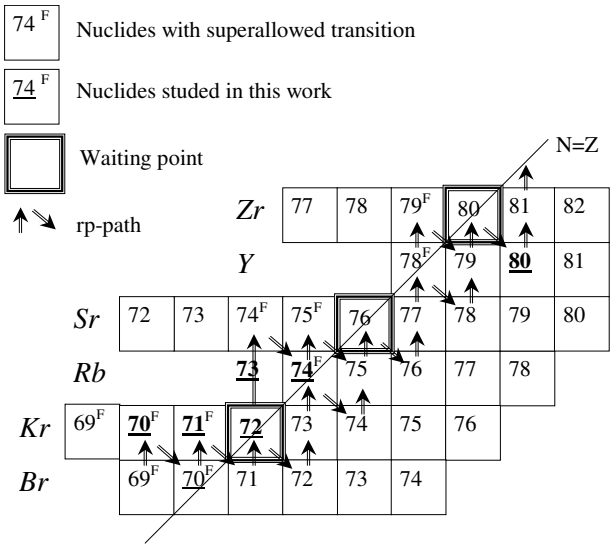


Fig. 1. Nuclear chart area under consideration

Accurate measurements of β-decay energies, half-lives and branching ratios are necessary for studies of superallowed β-decay strength. Aiming at improving 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.

The measurement of the β-decay half-life and the observation of a non-analog transition to the first excited 0^+ state in ^{74}Kr has been carried out [1].

In addition to their nuclear structure interest, nuclei in this region (see Fig. 1) play an important role in astrophysical nucleosynthesis. The path of the rapid proton capture process (*rp*-process) is determined mainly by the competition of proton capture reactions and β-decays along the $N = Z$ line. The critical role play here so called "waiting point" nuclides. The knowledge of nuclides properties nearby waiting points is

essential for correct description of the nucleosynthesis process. Half-life, proton binding, properties of isomers – are the parameters to explore in the present work.

2. Experimental methods

The nuclides in the region under consideration have low production yield and short half-lives. Therefore high efficient and selective methods should be used for nuclides production and decay radiation acquisition.

Nuclides production

Spallation reactions induced by a pulsed 1GeV proton beam on Nb-foil or a ZrO_2-felt target were used for the production of ^{73,74}Rb, ^{70,71,72}Kr at the ISOLDE on-line mass separator. Very clean conditions for Kr were obtained with a plasma ion source connected with target via a cooled transfer line. The Rb - beams have been very selectively obtained in combination with a surface ionization source.

The IGISOL-facility [2] at the Jyvaskyla isochronous cyclotron has been applied for study of the heavy side of A = 80 area. A beam of $^{32}S^{7+}$ with energy of 150 MeV irradiated an enriched ^{54}Fe target was used to produce ^{80m}Y. The reaction products were stopped in a helium gas cell. After extraction from gas cell and mass-separation, the ions were deposited on the moveable collector tape. To suppress the background from highly produced isobaric nuclides we used the high probability of the HIGISOL system [3, 4] to produce the oxide molecules $(YO)^+$ which can be seen at mass number A = 96 without strong contaminations.

Measurement setup

The setup for these measurements is shown in Fig. 2. For accurate half-life measurement and the search for the weak γ-branches the setup /a/ was used. For study nuclides with possible direct or delayed proton emission the setup /b/ have been applied. In the β-e^- experiment the transitions to excited 0^+ states were searched for the conversion electron spectrometer with magnetic transport ELLI (setup /c/).

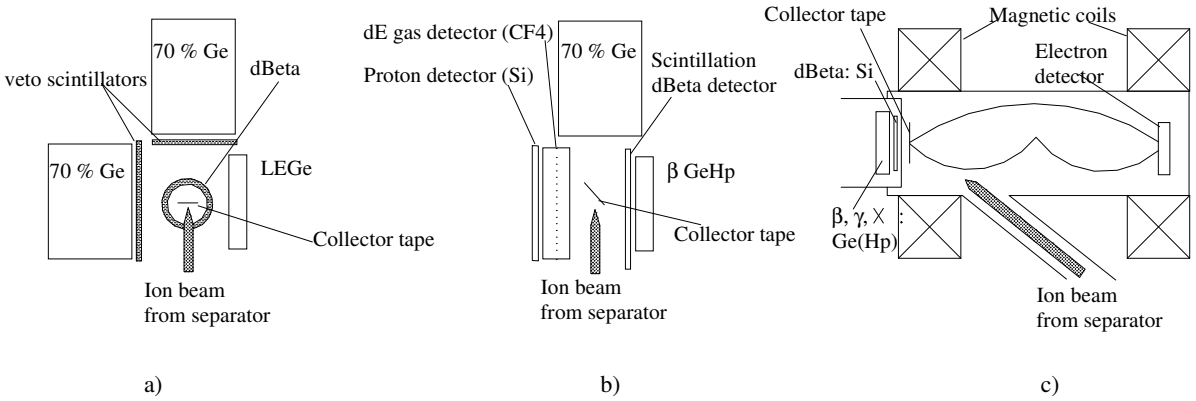


Fig. 2. Detectors set-up in ISOLDE (a, b) and IGISOL (c) experiments

a) Setup for half-life measurements and non-analog decay study of ^{74}Rb. The setup 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. 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.

b) Detectors setup for half-life measurements, and γ, X, p decay study (^{73,74}Rb, $^{69\text{-}72}$Kr). The setup consists of dE(CF_4-gas)–E(Si) telescope for detecting protons, a 70% coaxial and a 20mm thick planar HP Ge detectors for γ- and X-rays and a telescope detector for high energy β-particles

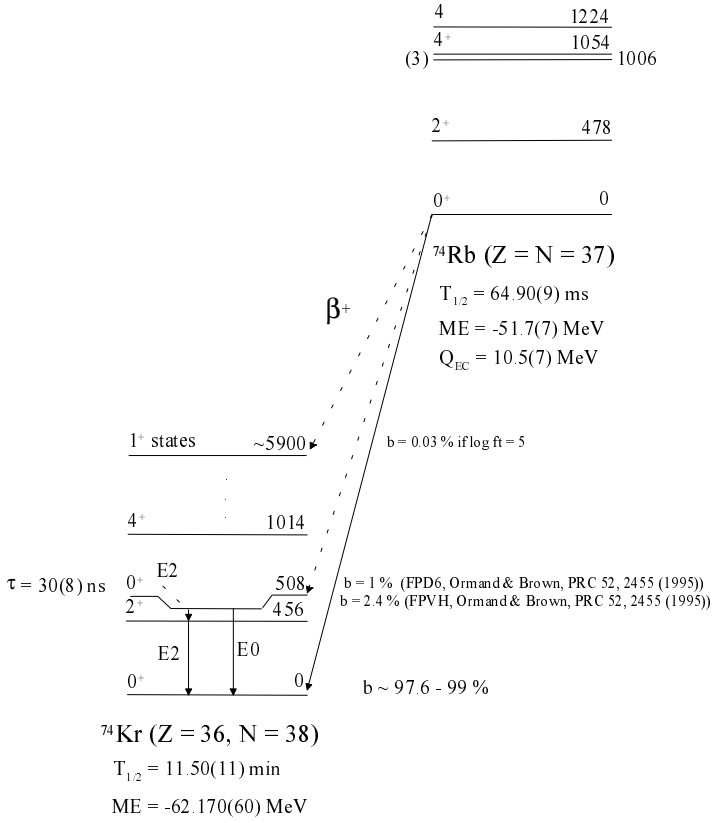
c) Detectors setup for conversion electrons study in non-analog decay study of ^{74}Rb and isomer transitions in A = 80 area. The setup consists of planar low energy germanium detector (LeGe) and Si electron detector with magnetic transport (ELLI).

3. Superallowed decay study

The measurement of the β-decay half-life and the observation of a non-analog transition to the first excited 0^+ state in ^{74}Kr has been carried out [1]. Detection setups are shown in Fig. 2c. 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 $\gamma(\beta\text{-}\gamma)$ transitions and a search for β-delayed converted transitions $\beta\text{-}e^-$.

Precision half-life measurement of ^{74}Rb *($T = 1, T_z = 0$)*

A new determination of the β-decay half-life of ^{74}Rb has been done. This measurement improves the accuracy of the half-life of ^{74}Rb with a factor of five compared to the previous result. The relative uncertainty of $1.4 \cdot 10^{-3}$ is, however, still five times larger than those measured for the lighter nuclei up to ^{54}Co. β-delayed proton emission does not contribute significantly to the branching ratio of the Fermi transition. However, there is still a possibility for the GT β-transitions to feed γ-decaying states at a level of $4 \cdot 10^{-4}$ compared to the ground state feeding.



^{74m}Rb search ($T=0, T_z=0$)

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 with an order of magnitude lower value. Also a search for a γ-decaying isomeric state has been performed with a negative result. Thus, the non-existence of a $T = 0$ isomeric state is presently well established.

Fig. 3. Expected decay scheme for ^{74}Rb. The energy for the 1^+ state is the position of the Gamow-Teller Giant resonance . Branching ratio estimates for the feeding to the first excited 0^+ state are obtained by scaling the calculated result to the experimental energy of 508 keV

Non-analog decay study

A first estimate of the magnitude of the Coulomb mixing involved in the superallowed β-decay of ^{74}Rb has been performed in this work. The value for the Coulomb correction due to different degrees of configuration mixing was shown to be of the same order of magnitude as obtained for the lighter isotopes previously studied. This emphasizes the importance of the binding energy related part of the total Coulomb correction in the case of ^{74}Rb.

Different nuclear shapes have been predicted to exist in the neutron-deficient Kr nuclei. These coexisting structures are usually associated with low-lying $J^\pi = 0^+$ states. The role of Coulomb-mixing induced corrections can be studied 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

0_2^+ state in ^{74}Kr lies as low as 508 keV. This state decays via a 52 keV $0_2^+ \rightarrow 2^+$ E2 transition, which subsequently decays by 456 keV E2 γ-emission, or a 508~keV $0_2^+ \rightarrow 0_1^+$ E0 transition. In addition to the fully converted $0_2^+ \rightarrow 0_1^+$ transition, the low-energy E2 transition also largely decays by conversion electron emission with the energy of 37.5 keV. The relative intensities of these transitions were 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 (see Fig. 4).

Our upper limit of 4.8 10^{-4} for the 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. However, the deduced limit for the Coulomb mixing component δ_{IM}<0.06% is only slightly larger than the values obtained for the lower-mass nuclei. The theoretical values for the Coulomb mixing component δ_{IM} for ^{74}Rb 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 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, the small increase in δ_{IM} emphasizes the importance of δ_{RO} fraction. (*i.e.* the radial mismatch of the wave functions) in the total Coulomb correction for ^{74}Rb.

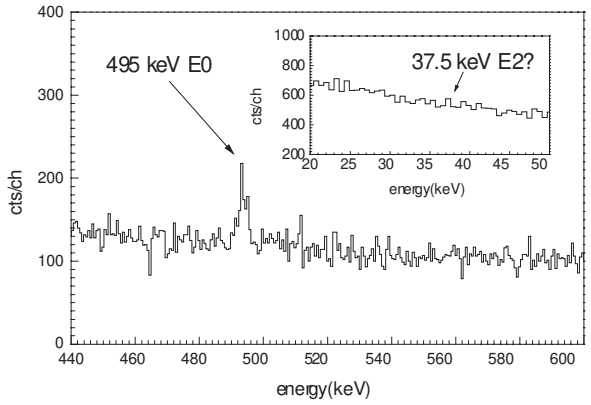
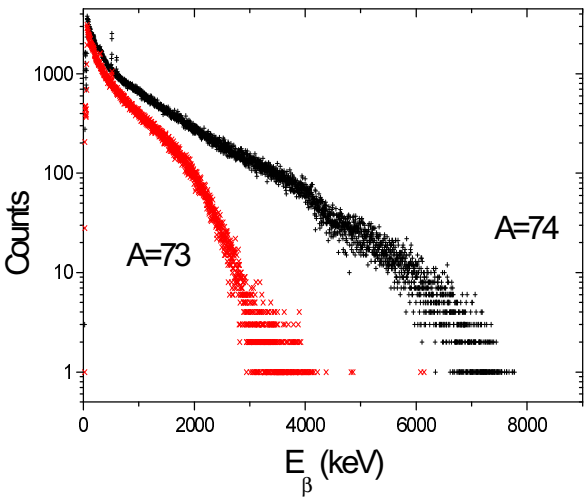


Fig. 4. The conversion electron spectrum. The peak at 495 keV was assigned to the *K*-conversion of the 508 keV $0_2^+ \rightarrow 0_1^+$ E0 transition

The β-decay energy value in the case of ΔT = 0 transition is closely linked to the Coulomb displacement energy. This value can be estimated from mass difference between ^{74}Rb and ^{74}Kr. Recently, such measurements were done with ISOLTRAP and MISTRAL installations and the data are under analysis now.

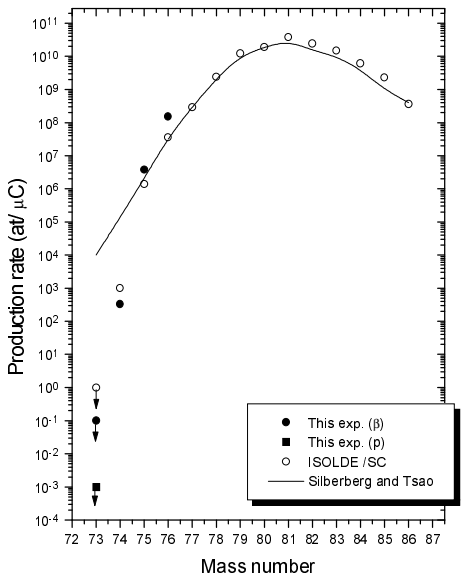


$T_Z = -1/2$ nuclides study

The nuclides ^{71}Kr and ^{73}Rb having T_z = −1/2 belong to the heaviest isobaric doublets which should be characterized by superallowed β-transition between ground states. For these doublets the ground state of daughter T_z = 1/2 nuclide is an analog resonance for mother ground state T_z = 1/2.

The half-life for ^{71}Kr was measured [5] via high-energy β-counting and β-delayed proton counting (Fig. 2b). The value 100(3) s, supports one of the contradictory data in the half-life values for this nuclide. The measured β-feeding of the ^{71}Br ground state which turned out equal to 82(2)% gives a value for GT matrix element $\langle\sigma\tau\rangle$ = 0.33(19).

Fig. 5. The β-spectra obtained with the planar Ge detector at mass A =73 and A = 74. The absence of high energy part of the β-spectrum at A = 73 put the production limit for ^{73}Rb



The mass models predict ^{73}Rb to be proton unbound. However, very large deformation and their change predicted for the ^{73}Rb → ^{72}Kr transition could lead to additional hindrance of the proton decay. To search possible decay via low energy proton emission or high energy β-decay the setup (Fig. 2) has been used [5]. Neither β-particles (Fig. 5), nor γ-rays belonging to ^{73}Rb decay have been observed. The combination of gas telescope with 300 keV threshold for proton identification and thick β-detector gives strict limit for the production rate of ^{73}Rb (Fig. 6).

The most restrictive production limit is equal to $8\cdot10^{-4}$ protons/μC for ^{73}Rb. This limit leads to make the conclusion about proton instability of the ground state of ^{73}Rb [6].

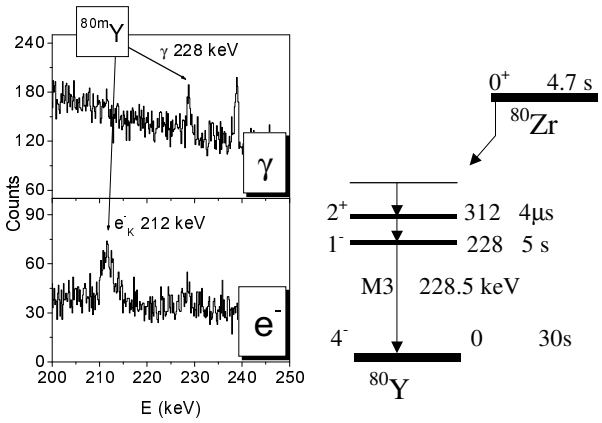
Fig. 6. The behaviour of the yields for various Rb – isotopes. The yields obtained at ISOLDE II installation are also presented there for comparison. The most restrictive production limit is equal to $8\cdot10^{-4}$ protons/μC for ^{73}Rb

4. Astrophysical application

The role of ^{73}Rb and ^{70}Kr

The binding energy and the decay modes are critical for the *rp*-process. The negative proton binding energy of ^{73}Rb have to suppress the consecutive proton capture over this nuclide, then the process can proceed from ^{72}Kr via β-decay or two proton capture. The identification of proton instability of ^{73}Rb means that the slit to produce heavier nuclides became much more narrow.

The two-proton capture is the alternative way to pass the *rp*-process through a proton-unbound nuclide. The role of this mechanism around waiting points ^{68}Se and ^{72}Kr is essentially influenced by half-life of ^{70}Kr. No information about the decay property of ^{70}Kr has been previously published. The superallowed decay chain ^{70}Kr→ ^{70}Br → ^{70}Se has been studded at ISOLDE with setup (Fig. 2b). The measured half-life for ^{70}Kr decay is equal to 60(40) ms, that is consistent with pure Fermi decay. At the same time this value is significantly shorter than the value used in the recent network calculations for rapid capture process. The shorter value results in a higher effective rate for bridging the waiting point at ^{68}Se via two-proton capture at temperatures higher than 1.5–2 GK [7].



Search for ^{80m}Y

A careful investigation of the internal decay modes of the long-lived isomeric state at 228 keV excitation energy in ^{80}Y has been done [8]. The measured conversion electron coefficient for the 228.5 keV isomeric transition $\alpha_K = 0.50(7)$ allows unambiguous 1^- identification for the isomeric state in ^{80}Y. Since we did not observe the 84 keV γ and *e*-line belonging to this transition we can conclude that the 228.5 keV state is the first isomeric excitation in ^{80}Y. The half-life was measured as 5.0(0.5) s in a good agreement with previous value.

Fig. 7. Excited states of ^{80}Y observed in the decay of ^{80}Zr. Energies of states are given in keV. Gamma and conversion electron spectra are shown

The astrophysical *rp*-process in *X*-ray bursts is passing through the nuclide ^{80}Y. In the stellar plasma ^{80m}Y is expected to be fully ionized. A "bare" half-life of this state is determined to be equal to 6.6 s. This bare isomeric state is strongly populated in the rp-process from ^{80}Zr and has therefore to be taken into account in *X*-ray burst model calculations. Because of the similarity of the β-decay half-lives of "bare" ground and isomeric states we find a maximum reduction in the effective β-decay lifetime of ^{80}Y of only 17%.

Our results pave the way for a future investigation of the impact of the isomeric state on the "effective" ^{80}Y proton capture rate.

The full list of PNPI physicists participated in this work is given below:
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