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The β-decay of ^{71}Kr: precise measurement of the half-life

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Abstract. The very proton-rich ^{71}Kr isotope was produced through the in-flight fragmentation of ^{78}Kr on a beryllium target at RIKEN – Nishina Center in order to study its β-decay properties. A stack of double-sided silicon strip detectors, called WAS3ABi, was used as the decay station, where the detection of ion implants, β-decays and β-delayed protons took place. Beta-delayed γ-rays were measured using a system of 84 HPGe detectors, called EURICA, surrounding the decay station. The main goal of the present study was the precise measurement of the half-life of ^{71}Kr, as in the literature there is an almost 10 σ difference between the most precise independent results. Implant–β time correlations, implant–proton time correlations and implant–β–γ time correlations were all used to derive the half-life value, followed by a thorough investigation of systematic uncertainties for each method. As these values were found to be consistent, the weighted average $t_{1/2} = 94.40^{+19}_{-21}$ ms is reported as a new half-life value in this work. Furthermore a total of 26 previously unreported γ-transitions following the β-decay of ^{71}Kr were also identified in the analysis.

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1 Introduction

The origin of p-nuclei is still not fully understood since it is likely that more than one process is responsible for the creation of these isotopes [1]. One of the conceivable candidates is the astrophysical *rp*-process taking place in X-ray bursts [2–4] as the result of hydrogen-rich material accreting from a low-mass star toward a neutron star in such binary systems. During these bursts thermonuclear ignition takes place and via a series of rapid proton capture reactions isotopes up to ^{105}Te can be formed [5]. Near the proton drip-line proton capture starts to compete with photodisintegration and eventually an equilibrium is reached until the relatively slow β-decay of these so called waiting-points takes place. Hence the modeling of the *rp*-process requires a precise knowledge of the β-decay half-lives.

Since it lies on the *rp*-process path, the half-life of ^{71}Kr has been measured in numerous radioactive ion beam experiments using implant-β time correlations, most recently by Sinclair *et al* in 2019 ($t_{1/2}^{\mathrm{Sinc.}}$ = 98.8 ± 0.3 ms) and Waniganeththi *et al* in 2022 ($t_{1/2}^{\mathrm{Wani.}}$ = 94.9 ± 0.4 ms) [6, 7]. As there was a 10 σ difference between these results, they derived the half-life based on the decay-curves of verified γ-transitions as well, leading to $t_{1/2}^{\mathrm{Wani.},\,\gamma}$ = 95.3 ± 2.2 ms. However the results were inconclusive since the statistical uncertainty was too high, as had been the case in the earlier results of $t_{1/2}^{\mathrm{Oin.}}$ = 100 ± 3 ms by Oinonen *et al* and $t_{1/2}^{\mathrm{Rog.}}$ = 92 ± 9 ms by Rogers *et al* [8, 9]. In this work the half-life value was measured using three different methods and better statistics than ever before in order to settle the disagreement between the reported results in literature.

2 Experimental method

The experiment was performed at RIKEN – Nishina Center [10], where a ^{78}Kr primary ion beam with an average intensity of 40 pnA was accelerated to 345 MeV/nucleon kinetic energy and directed on to a 5-mm-thick ^{9}Be target, resulting in the in-flight fragmentation of the ^{78}Kr nuclei. The fragments were separated and identified using the standard ΔE-$B\rho$-ToF method by the BigRIPS separator [11]. 9.8 million ^{71}Kr ions were implanted in the decay station WAS3ABi, consisting of a stack of double-sided silicon strip detectors (DSSSDs) [12], which was used for the detection of implanted ions, β-decays and β-delayed proton emission. The decay station was surrounded by EURICA, an array of twelve EUROBALL cluster germanium detectors, each containing seven crystals. The average distance between the center of the DSSSDs and the front face of the HPGe detectors is 22 cm, corresponding to a total absolute detection efficiency of about 8% at the energy of 1332 keV [13]. The energy spectrum of β-delayed γ-rays recorded by EURICA in coincidence with WAS3ABi signals, after the subtraction of the background and daughter contribution is shown in Figure 1.

Positrons and β-delayed protons were separated using an energy threshold and an exponential function was used to extrapolate and subtract the overlapping high-energy tail of positrons, as in our earlier work on the decay of ^{70}Kr [14], while the event selection criteria is detailed in [15, 16]. The resulting energy spectrum of β-delayed protons is shown in Figure 2.

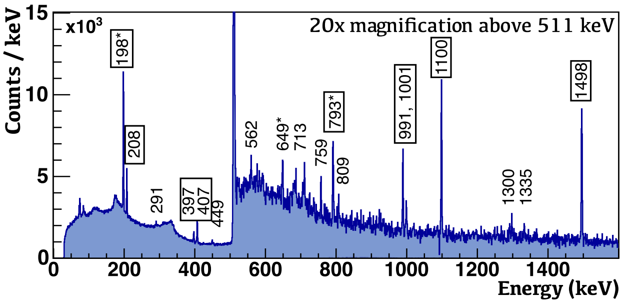

Figure 1. Energy spectrum of γ-rays emitted following the β-decay of ^{71}Kr. Doublets with energy differences within the order of the resolution of the HPGe detectors are marked with an asterisk. Transitions used for the half-life measurement are highlighted with black frames. The region above 511 keV is scaled up with a factor of 20 for the convenience of the reader.

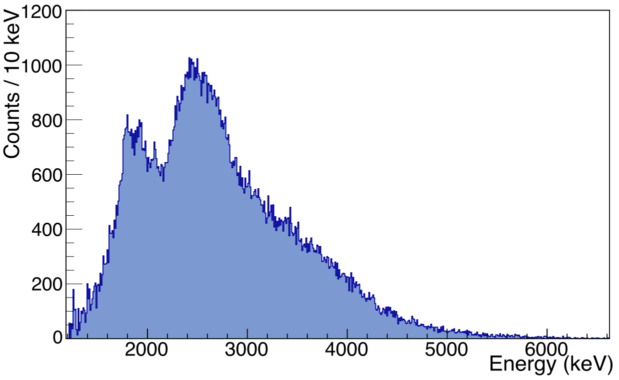

Figure 2. Intensity distribution of the β-delayed protons detected in the DSSSD as a function of the deposited energy. The high energy tail of β-particles was extrapolated by an exponential function, and then subtracted.

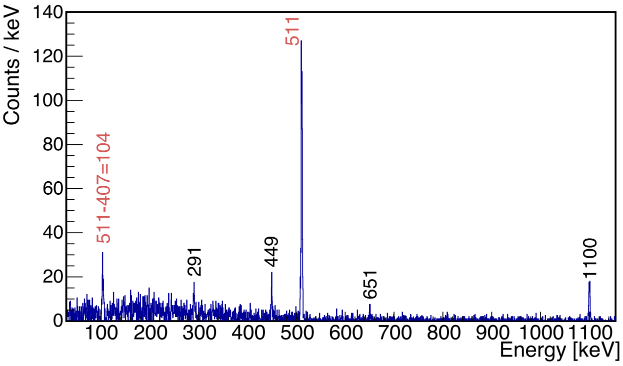

Figure 3. Energy spectrum of γ-transitions in coincidence with the E_γ = 407 keV transition. The peaks at E_γ = 511 keV and E_γ = 104 keV are coincidences originating from 511 keV annihilation photons and their Compton-scattering, respectively.

Coincidences between γ-rays during the same β-event were also analysed in order to look for cascades of γ-rays, used for verifying low intensity γ-rays and building the level-scheme. A fine example of such spectra is shown in

Figure 3, revealing four earlier unseen γ-transitions feeding the $E_x = 407$ keV level of ^{71}Br.

In this study we used three different methods to measure the half-life of the decay of this isotope and evaluated the systematic uncertainties of each method one-by-one, in order to derive a new solid half-life value:

- a fit of the Bateman equation to the the decay-curve of β-decays,
- exponential fit of the decay-curve of β-delayed protons,
- exponential fit of the decay-curve of β-delayed γ-rays.

2.1 Time distribution of β-events

The time distribution of implant–β correlations can be described by the Bateman-equation which is parametrised by the half-lives of the isotopes in the decay chain, the number of parent isotopes and the proton-emitting branching ratio (ε_p). In order to measure the half-life a binned maximum likelihood fit was used, with the two free parameters (the half-life and number of ^{71}Kr isotopes). All other parameters were constrained on a 95% confidence range obtained from literature. The time correlation histogram with the total fit function and its individual decay curves is shown in Figure 4. Systematic uncertainties arise from the Bateman-formula being based on the assumption, that β-detection efficiency is the same for every isotope in the chain and that literature data is accurate for the other isotopes in the decay chain. In this case these effects are expected to be small as all other isotopes in the decay chain have at least 2 orders of magnitude longer half-lives than ^{71}Kr. In order to evaluate any residual systematic uncertainties each *ad hoc* parameter of the fitting method – namely the endpoints of the fitting range, the width of bins and the lower energy threshold – were chosen randomly on a suitable range for every one of the 500 fits performed. Asymmetrical systematic uncertainties were calculated from the distribution of results of the fits.

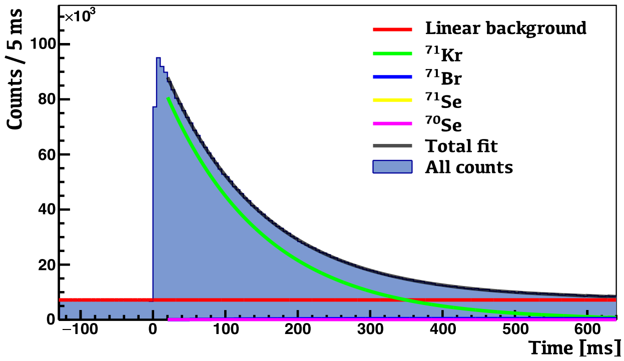

Figure 4. Time correlations of implant events and β-events of ^{71}Kr. The total fit is the sum of a Bateman formula and a linear background, and it is shown by a black line. The individual contributions are represented with colour coded lines. A half-life of $t^{i\beta}_{1/2} = 94.50 \pm 0.06$ (stat.) $^{+0.21}_{-0.23}$ (sys.) ms was derived.

2.2 Time distribution of β-delayed protons

The histogram was built from time correlations between implantation events and β-delayed proton emissions defined by every charged-particle event within the same pixel with deposited energy above a threshold energy (E_{cut}). Systematic uncertainties are effectively suppressed as the only proton emitting decay in this chain is the decay of interest. The time evolution of the overlapping high-energy tail of β-events was estimated through extrapolation and then subtracted from the implant–proton time correlations. The time correlation histogram with the exponential fit to the decay curve plus a linear background is shown in Figure 5 together with the subtracted contribution of high-energy β-events. As the most significant systematic uncertainty is expected to be from the subtraction of the estimated β-contribution, the same *ad hoc* parameters were varied as for the first method, but with the addition of the proton separation threshold being varied between $E_{cut} \in 1300 - 1500$ keV.

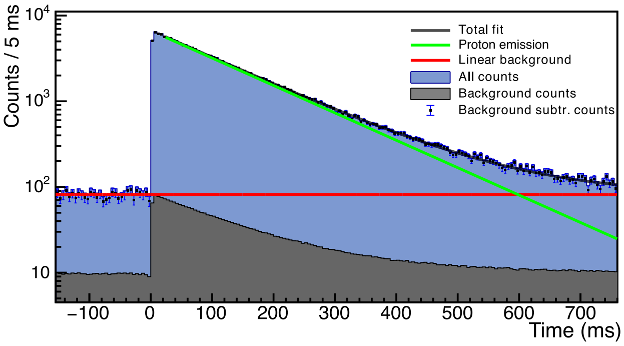

Figure 5. Time correlations of β-delayed proton events and ^{71}Kr implants. The time evolution of the subtracted β-contribution is shown in grey. The total fit is an exponential function with a linear background. A half-life of $t^{ip}_{1/2} = 94.08 \pm 0.22$ (stat.) $\pm$ 0.33 (sys.) ms was derived.

2.3 Time distribution of β-delayed γ-rays

Verified γ-transitions in the daughter nucleus, ^{71}Br, were also used to build decay-curves as well. However, as ^{71}Br has a ground state doublet with a first excited state at $E_\gamma = 9.8$ keV, we see a detailed decay-scheme with many transitions only a few keV from each other (as shown in Figure 1). Thus careful verification of a γ-transition required fulfilling any of the following criteria:

- It was reported in the high quality in-beam spectroscopic study of ^{71}Br by Fischer *et al* [17],
- It was confirmed to be in cascade with such a transition. For example $E_\gamma = 1100$ keV from Figure 3.
- It gave a consistent half-life value with other verified γ-transitions and it was in coincidence with 511 keV annihilation photons from the β^+-decay, but not with any other γ-transition, meaning it was a single transition straight to the ground state doublet.

The time correlation histogram was built using verified γ-transitions with a favourable signal-to-noise ratio, highlighted in Figure 1. Systematic uncertainties are effectively suppressed in principle, since only characteristic γ-rays are used resulting in a purely exponential decay curve. However the β-delayed γ-rays of the other isotopes in the decay chain are also present in the Compton-background. Thus this background was sampled at the proximity of each peak then subtracted after normalisation. The time correlation histogram with the exponential fit to the decay curve plus a linear background is shown in Figure 6. In order to evaluate any unaccounted systematic uncertainties, every *ad hoc* parameter of the fitting method was varied as in the first method, with the addition of the endpoints of the peak and Compton sampling energy gates.

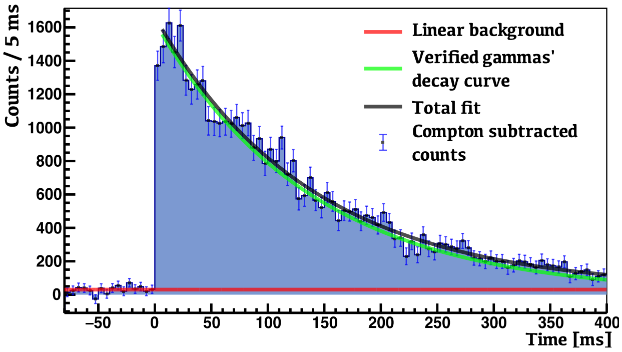

Figure 6. Time correlations of implant events and verified γ-transitions of the β-decay of ^{71}Kr. The total fit is the sum of an exponential function and a linear background, and it is shown by a black line. A half-life of $t^{i\beta\gamma}_{1/2}$ = 94.7 ± 0.5 (stat.) $^{+1.6}_{-1.5}$ (sys.) ms was derived.

3 Conclusion

In this work three half-life values were derived from different methods, $t^{i\beta}_{1/2}$ = 94.50±0.06 (stat.) $^{+0.21}_{-0.23}$ (sys.) ms from the decay-curve of β-events, $t^{ip}_{1/2}$ = 94.08 ± 0.22 (stat.) ± 0.33 (sys.) ms from the decay-curve of β-delayed protons, and $t^{i\beta\gamma}_{1/2}$ = 94.7 ± 0.5 (stat.) $^{+1.6}_{-1.5}$ (sys.) ms from the decay-curve of β-delayed γ-rays, in consistency with each other. The weighted average is $t_{1/2} = 94.40^{+19}_{-21}$ ms, which is consistent with the result of Waniganeththi *et al*, but in strong disagreement, by more than 10 σ difference, with the result of Sinclair *et al.*

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