STUDYING THE EXOTIC DECAY ^{70}Kr → ^{70}Br*

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Beta-decay of the very neutron-deficient Kr isotope, ^{70}Kr, was studied at RIKEN-RIBF using the EURICA cluster array. The experiment significantly increased our knowledge of the beta-decay of this isotope. Namely, 16 new γ-ray transitions were identified and the half-life was derived from time correlations of the beta particles ($t^{i\beta}_{1/2} = (44.99 \pm 0.16)$ ms) and from the decay curves of the observed γ-ray transitions ($t^{i\beta\gamma}_{1/2} = (45.16{\pm}0.71)$ ms), respectively.

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1. Introduction

Type I X-ray bursts, characterized by $T_{\rm peak} = 1$–3 GK and $\rho = 10^6$–10^7 g cm^{-3}, are suggested as possible sites for the astrophysical rp-process [1–3]. In these binary systems, the hydrogen-rich material accretes from a low-mass star, typically from a Main Sequence or a Red-Giant star, toward a neutron star. When the temperature and density in the accreted envelope become high enough to allow breakout from the hot CNO cycle, thermonuclear ignition takes place and via a series of rapid proton capture reactions, isotopes up to ^{105}Te are formed [4]. As the nucleosynthesis path approaches the drip-line, further proton capture is inhibited by strong reverse photodisintegration reactions or by direct proton emission, and the reaction flow has to wait for the relatively slow β-decay process. According to this picture, the modeling of the rp-process requires precise knowledge of the β-decay half-lives and the structure of the involved isotopes.

Presently, very little is known about the β-decay of ^{70}Kr: its lifetime has been determined at CERN ISOLDE by measuring the time distribution of the emitted β particles [5]. Recently the β-decay of ^{70,71}Kr was investigated at RIKEN Nishina Center. In the present contribution, details on the determination of the half-life of the ^{70}Kr isotope are presented.

2. Experimental setup

The ^{70}Kr nuclei were produced at RIKEN Nishina Center by fragmentation of a ^{78}Kr primary beam, with 345 MeV/nucleon energy and ~ 40 pnA average intensity, impinging on a 5 mm thick ^{9}Be target. The nuclei of interest were separated and identified by measuring event-by-event the energy loss (ΔE), magnetic rigidity ($B\rho$) and time-of-flight (TOF) of the ions, in the BigRIPS spectrometer [6]. Figure 1 shows a particle identification matrix, which was used to correlate implantation and decay events.

The fragments were transmitted to the exit of the ZeroDegree spectrometer where a setup for decay studies was installed. It consisted of the EURICA germanium cluster detector array [7] surrounding the WAS3ABi double-sided silicon strip detector (DSSSD) system [8]. The three DSSSD detectors

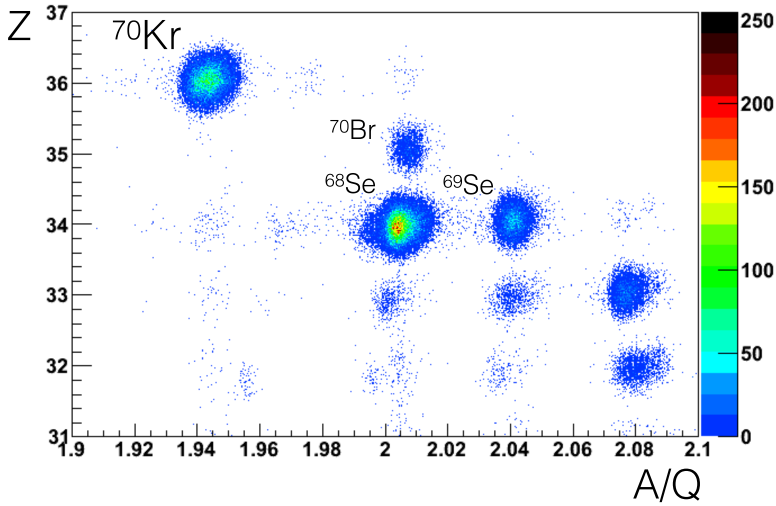

Fig. 1. Identification plot of ions implanted in WAS3ABi, showing the atomic number Z *versus* the mass-to-charge ratio A/Q of the ions.

used in the present experiment were segmented into 60 vertical (X) and 40 horizontal (Y) strips, corresponding to 2400 pixels with an active area of 1×1 mm^2 each. The full range and the resolution of the X and Y strips were 5 MeV/25 keV and 10 MeV/30 keV, respectively.

EURICA is 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.

3. Event selection

The event separation criteria are discussed in detail in Ref. [9], here only a brief summary is given. Namely, we identified events as an implantation of a ^{70}Kr nucleus when a high-energy signal in the plastic scintillator, located after the F11 focal plane of Zero Degree spectrometer, is detected together with an overflow energy signal in a DSSSD, but without an energy signal from the plastic veto detector placed behind WAS3ABi. According to these requirements, about 1.6×10^6 ^{70}Kr nuclei were implanted into the 2$^{\rm nd}$ DSSSD. Each implantation was followed, on average, by saturated signals of 3.4 X strips and 4.3 Y strips, respectively. The strip, where the implantation took place, was identified using the time information of the strips that fired in an implantation event. For that, the strip with the fastest signal was used. Then the selected implantation events in WAS3ABi were correlated in time with decay events taking place in the same strips where the implantation event was observed. The β-delayed γ-ray energy spectra were measured by the EURICA array and the events were selected using the following conditions: the maximum time difference between an implantation and the corresponding detection of a β particle was fixed to 20 s and γ rays were recorded up to 800 ns after the detected β events.

4. Determination of the half-life

The half-life of ^{70}Kr was derived first from the time distribution of implantation-β (i-β) correlations (without any conditions on γ rays). The i-β histogram was fitted with a function including the exponential β-decay and a fixed background extracted from a linear fit to the backward-time distribution of i-β correlations. Figure 2 shows the time distribution of i-β correlations, the lines correspond to the activity of ^{70}Kr (dashed/green), ^{70}Br (dotted/blue) and to the background (long-dashed/red), respectively. The resulting half-life from i-β correlations is

$$t_{1/2} = \left(44.99 \pm \overset{\text{stat}}{0.14} \pm \overset{\text{sys}}{0.06}\right)\ \text{ms} = (44.99 \pm 0.16)\ \text{ms}\,.$$

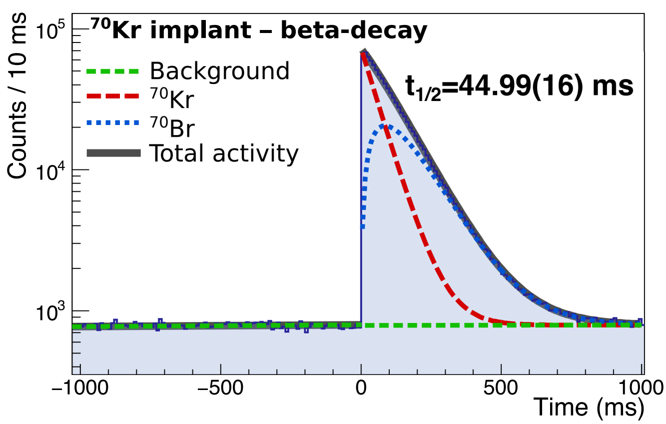

Fig. 2. (Color online) Time distribution of implantation-β correlations. The fitting function includes the Bateman formula and a linear background, determined from a fit to the negative-time distribution.

The background-subtracted β-delayed γ-ray energy spectrum, measured with the EURICA array, is shown in Fig. 3. The $E_\gamma = 933$ keV transition was already assigned to the de-excitation of the 1$^{\text{st}}$ excited state of ^{70}Br [10]. Several other γ-ray transitions are attributed to the β-decay of ^{70}Kr. The $\beta(\gamma$–$\gamma)$ coincidence spectrum gated on the $E_\gamma = 933$ keV γ-ray is shown in Fig. 4.

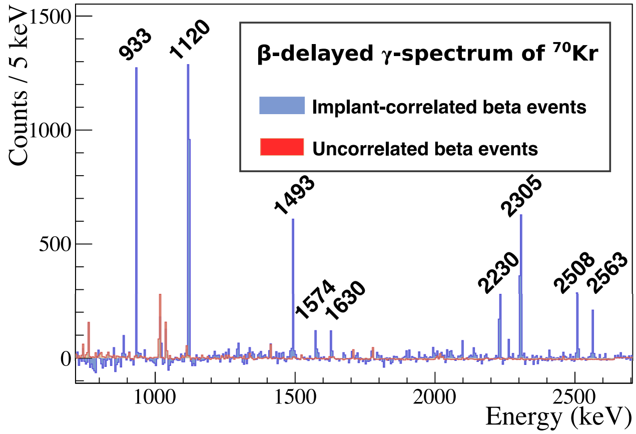

Fig. 3. (Color online) Compton-suppressed γ-ray spectrum. The nine strongest γ rays used to derive the half-life are labeled, and the corresponding energies are given in keV. They were assigned to the β-decay of ^{70}Kr as stated in the text. A spectrum tagged with β particles with negative time correlations with respect to implantation is shown in dark gray/red. These events are interpreted as a possible contamination since they are uncorrelated to implantations.

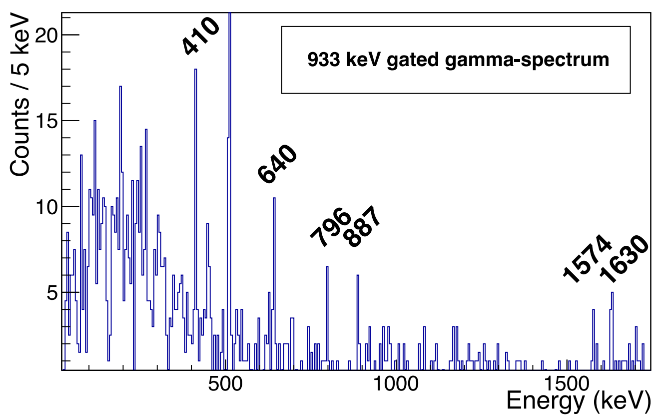

Fig. 4. The energy spectrum of γ-ray transitions in coincidence with the E_γ = 933 keV transition. The transitions in coincidence with the Compton background sampled around the $E_\gamma = 933$ keV peak were subtracted from the spectrum after normalization in order to evaluate the effect of coincidences uncorrelated with the peak, on which the gate was taken. The labeled peaks were all verified via gating back on them as well, and looking for significant $E_\gamma = 933$ keV coincidences in the spectrum.

The half-life of ^{70}Kr was also extracted from the decay curve of the strong β-delayed γ-ray transitions observed at $E_\gamma = 933$ keV, 1120 keV, 1493 keV, 1574 keV, 1630 keV, 2230 keV, 2305 keV, 2508 keV and 2563 keV. These transitions were first used one-by-one to build decay curves, using implantation-β–γ (i-β–γ) time correlations. Then exponential functions with constant background were fitted using maximum likelihood method to obtain half-lives corresponding to the different transitions. This information was used to verify that the γ rays belong to the decay of ^{70}Kr. Finally, these decay curves were summed to increase statistics. Figure 5 shows the time distribution of the i-β–γ correlations and the fitting functions. System-

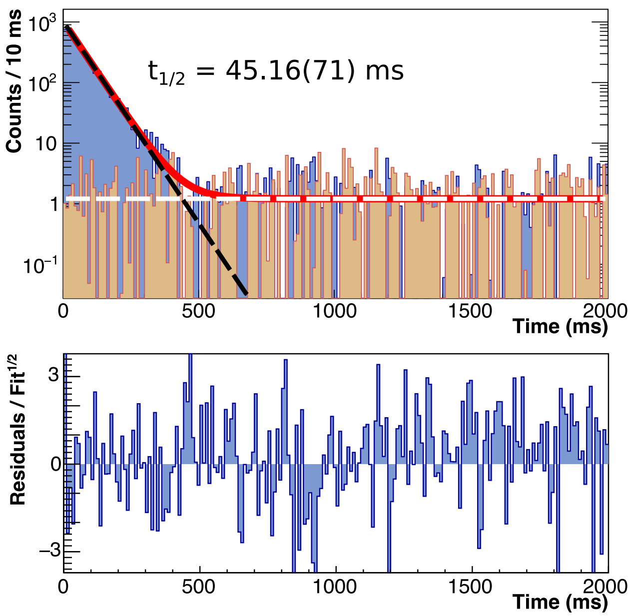

Fig. 5. (Color online) The upper curve shows the β-decay time spectra of ^{70}Kr based on the measurement of i-β–γ correlations. The forward and backward time distributions are indicated with gray/blue and light gray/yellow bars, black and white dashed lines show the fitted exponential and the linear background, respectively. The lower figure shows the normalized residual of the fit, which should be fluctuating randomly with a Gaussian distribution around zero.

atic uncertainties were investigated by varying the fit parameters. Figure 6 shows the resulting ^{70}Kr half-life as the function of the varied fitting parameters (such as bin size, fit ranges and background). The resulting half-life from i-β–γ correlations is

$$t_{1/2} = \left(45.16 \pm \overset{\text{stat}}{0.68} \pm \overset{\text{sys}}{0.20}\right)\ \text{ms} = (45.16 \pm 0.71)\ \text{ms}\,.$$

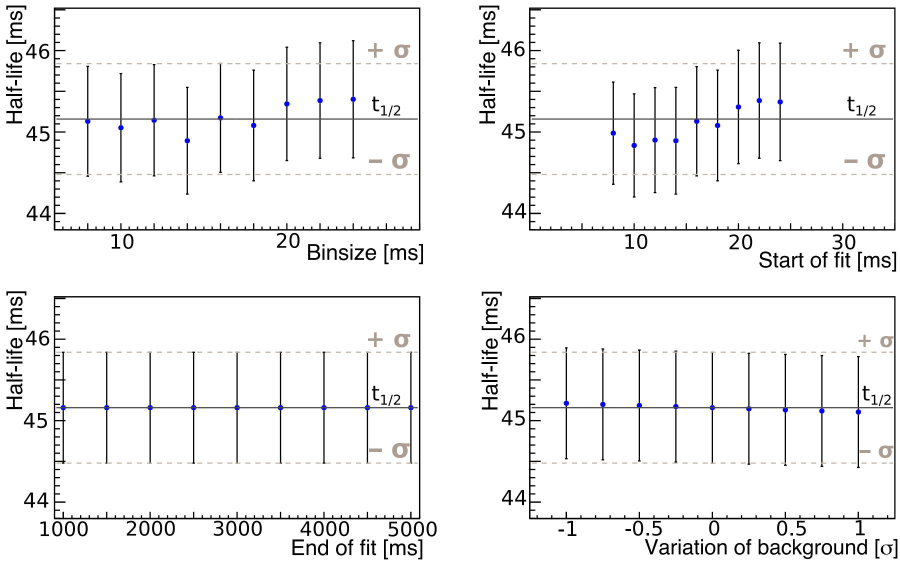

Fig. 6. Error contributions to the half-life of ^{70}Kr: impact of the bin size, fit and background ranges on the fitted half-life values.

5. Summary

Using β–γ and β–γ–γ correlations 16 new γ-ray transitions, assigned to the β-decay of ^{70}Kr were identified, and the half-life was derived from the time correlations of the β particles ($t_{1/2}^{\mathrm{i}\beta} = (44.99 \pm 0.16)$ ms) and the decay curves of the observed γ-ray transitions ($t_{1/2}^{\mathrm{i}\beta\gamma} = (45.16 \pm 0.71)$ ms).

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REFERENCES

[1] R.K. Wallace, S.E. Woosley, *Astrophys. J. Suppl. Ser.* **45**, 389 (1981).

[2] H. Schatz *et al.*, *Phys. Rep.* **294**, 167 (1998).

[3] A. Parikh *et al.*, *Prog. Part. Nucl. Phys.* **69**, 225 (2013).

[4] H. Schatz *et al.*, *Phys. Rev. Lett.* **86**, 3471 (2001).

[5] M. Oinonen *et al.*, *Phys. Rev. C* **61**, 035801 (2000).

[6] N. Fukuda *et al.*, *Nucl. Instrum. Methods Phys. Res. B* **317**, 323 (2013).

[7] P.-A. Söderström *et al.*, *Nucl. Instrum. Methods Phys. Res. B* **317**, 649 (2013).

[8] S. Nishimura, *Prog. Theor. Exp. Phys.* **2012**, 03C006 (2012).

[9] A.I. Morales *et al.*, *Phys. Rev. C* **95**, 064327 (2017).

[10] G. de Angelis *et al.*, *Eur. Phys. J. A* **12**, 51 (2001).