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Beta-decay half-life of ^{70}Kr: A bridge nuclide for the rp process beyond A=70

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Abstract

The β-decay half-life of ^{70}Kr has been measured for the first time at the ISOLDE PSB Facility at CERN. Mass separated ^{70}Kr ions were produced by 1 GeV proton induced spallation reactions in a Nb foil. The measured half-life is 57(21) ms. This value is consistent with the half-life calculated assuming a pure Fermi decay, but is clearly lower than the value used in a recent rp-process reaction flow calculation. The result shows that the reaction flow via two-proton-capture of ^{68}Se is 2.5 times faster than previously calculated assuming an astrophysical temperature of 1.5 GK and a density of 10^6 g/cm^3.

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The nuclei around the $Z = N$ line at $A \sim 70$ have received a lot of interest recently. Large number of valence protons and neutrons filling the same single-particle orbitals induce nuclear deformations. Information on the relationship of deformation and the delicate occupation balance of different single-particle configurations has been obtained through numerous theoretical and experimental studies during the recent years [1, 2, 3, 4, 5, 6, 7]. In addition to their interesting nuclear structure, nuclei in this region play an important role in nucleosynthesis. The abundance flow of the rapid proton-capture process (rp process) on the surface of accreting neutron stars is determined mainly by the competition of proton-capture reactions and β decays along the $Z = N$ line [8].

Recent abundance flow calculations for the rp process show that the process can continue even up to $A = 100$, provided that the time scale in astrophysical events such as X-ray bursts is long enough[9]. This leads to a compositional change in the crust of the underlying neutron star [10]. In addition, the rp process in these systems could produce light Mo and Ru isotopes (^{92}Mo, ^{94}Mo, ^{96}Ru, ^{98}Ru), the large abundance of which in the solar system has so far been underestimated by standard p-process scenarios [9]. It has been shown [9] that the production of nuclei heavier than $A = 68$ in X-ray bursts can be strongly enhanced by the two-proton-capture reaction on ^{68}Se.

In this reaction sequence proton scattering on ^{68}Se produces a small equilibrium abundance of proton-unbound ^{69}Br nuclei, which then capture another proton, producing ^{70}Kr. The β decay out of the $N = 34$ isotone chain occurs then at ^{70}Kr. Two-proton-capture reactions have been proposed originally for lighter nuclei [11], and the mechanism is similar to the 3α reaction bridging ^{8}Be. The two-proton-capture on ^{68}Se reduces the lifetime of ^{68}Se in the rp process as it represents another destruction channel in addition to β decay. This accelerates the rp process towards isotopes above $A = 68$ considerably as ^{68}Se is one of the major rp-process waiting points with a β-decay half-life (35.5 s) of similar order to the event timescale (10-100 s).

A typical X-ray burst reaches peak temperatures of 1.5-2 GK, at which the half-life of ^{70}Kr is important for determining the role of the two-proton-capture on ^{68}Se. At such high temperatures photodisintegration of ^{70}Kr drives ^{68}Se and ^{70}Kr into (2p,γ)-(γ,2p) equilibrium. Then, the net two-proton-capture rate on ^{68}Se, which is defined as the excess of the ^{68}Se(2p,γ)^{70}Kr abundance flow versus the inverse ^{70}Kr(γ,2p)^{68}Se abundance flow, becomes proportional to the β-decay half-life of ^{70}Kr (see equation 43 in [9]). The temperature $T_{\rm eq}$ above which this happens is in good approximation the temperature where the photodisintegration rate on ^{70}Kr exceeds the β-decay rate. $T_{\rm eq}$ depends strongly on the proton separation energy $S_{\rm p}$ of ^{70}Kr, which is not known experimentally. Ref. [9] use the finite range droplet mass model (FRDM) [12], which predicts for ^{70}Kr $S_{\rm p}$ = 2.9 MeV. This results in $T_{\rm eq}$ = 1.6(3) GK, assuming an uncertainty of 0.8 MeV in the proton separation energy. The mass extrapolations of [13] predict for ^{70}Kr much lower $S_{\rm p}$ = 1.86(51) MeV, which gives $T_{\rm eq}$ = 1.2(2) GK.

At temperatures below $T_{\rm eq}$, the ^{70}Kr half-life is still important, as this nucleus represents a waiting point for the fraction of the abundance flow that proceeds via two-proton-capture on ^{68}Se. It can therefore affect the processing time scale and the final production of $A = 70$ nuclei.

The bound character of ^{70}Kr, indicated by the systematics[13] and all the commonly used mass predictions[14], has been confirmed in fragmentation studies of ^{78}Kr at GANIL[4]. However, no information on the decay properties of ^{70}Kr has been previously published due to the low production rate. In this paper, we report on the first observation of the β decay of ^{70}Kr and its half-life determination.

Short-lived Kr isotopes were produced in spallation reactions in a Nb-foil target induced by the 1 GeV pulsed proton beam from the PS Booster at CERN and mass separated using the ISOLDE facility [15]. The PS Booster delivers 1 pulse every 1.2 s with a maximum intensity of 3×10^{13} protons/pulse. Typically 6-7 pulses are sent to the ISOLDE target per 14.4 s supercycle of the PS Booster. The pulse shape of the resulting mass-separated ion beam is described in [16]. In this work, the target was connected to a plasma ion source via a water-cooled transfer line which transmits only volatile elements [17].

The radioactive Kr-ion beam was implanted into a 1/2" aluminized Mylar tape, which was tilted 45 degrees with respect to the beam axis to allow undisturbed proton detection. The ion beam was collected for 150 ms after each proton-pulse impact. The implantation tape was moved 800 ms after the impact of every 10^{th} proton pulse to reduce the long-lived background. The experimental setup is described in [18]. A thin plastic scintillator and a 20-mm-thick planar HPGe detector served as a β telescope. The time interval between the proton pulse impact and the trigger signal from the plastic scintillator was used for determination of the half-life. The time spectrum was obtained by requiring a fast coincidence between the detectors, choosing a narrow energy window for the signals from the plastic scintillator and requiring the beta energy to be above 1.3 MeV in the HPGe detector. About 98 % of positrons due to the decay of ^{70}Kr are above this energy limit. A special gas-Si telescope detector was used for detecting the β-delayed protons[19]. The Si detector thickness of 300 μm allowed detection up to 6 MeV. The data acquisition was triggered by signals either from the plastic scintillator or the Si detector, and data was stored in event-by-event mode.

The total measuring time for $A = 70$ was 27 h with a production rate of 0.03 at/μC for ^{70}Kr. The release parameters for the production system, measured with ^{79}Kr^m, were α = 0.87, τ_r = 90 ms, τ_f = 800 ms and τ_s = 30 s, using the notation of Lettry *et al.*[16]. Uncertainties in the release parameters due to the fitting procedure were below 20 %.

The β decay of ^{70}Kr is expected to be dominated by the superallowed $0^+ \rightarrow 0^+$ decay. The high Q_{EC} value of 10.6(6) MeV[13] could even lead to β-delayed proton decay. The odd-odd $N = Z$ daughter nucleus ^{70}Br is expected to have two β-decaying states: $(J^\pi = 0^+, T = 1)$ and a $(J^\pi = odd, T = 0)$. Indeed, two vastly different half-lives have been reported for ^{70}Br: $T_{1/2}$ = 79.1(8) ms [20] and 2.2(2) s[21]. The shorter half-life points to the superallowed Fermi β decay from the $(J^\pi = 0^+, T = 1)$ state to the isobaric analog ground state of ^{70}Se, while the longer half-life points to the decay of the $(J^\pi = odd, T = 0)$ state of ^{70}Br. From the obtained data set, it is not possible to discriminate positrons following the decay of ^{70}Kr from positrons following the decay of ^{70}Br. Thus, we have to take the 79.1 ms decay with Q_{EC} = 10.4(3) MeV[13] into account in the half-life determination using the β particles. Direct production of short-lived ^{70}Br was assumed to be negligible. Since our result for the half-life of ^{70}Kr is essentially depending on this amount, the assumption needs further discussion.

The water-cooled transfer line between the target and the ion source reduces the amount of contamination due to the elements which are non-volatile at room temperature [17]. In this work, the only observed contaminant activities were ^{70}As and ^{70}Ga. Both of these nuclei are produced in the target with three and six orders of magnitude higher cross sections [22] than ^{70}Br and ^{70}Kr, respectively. The amount of Br was checked in $A = 73$, 72 and 71 where no direct production of Br was observed. The relative amount of Br compared to Kr in $A = 70$ can be estimated based on the non-observation of Br in $A = 71$. The main corrections to be taken into account are decay loss factors due to differing half-lives, and increase in cross section ratio σ_{Br}/σ_{Kr} in $A = 70$ compared to $A = 71$. Due to the low production of Br when a *water-cooled transfer line* is used, the release behaviour of Br has not been measured for such a setup. However, an estimate for the decay losses can be obtained by using the measured release behaviour of Br out of a Nb-foil target equipped with a *hot plasma ion source* without a cooled transfer line, as shown in Fig. 1 [23]. The release of Br is clearly slower than for Kr and this results in higher decay losses for ^{70}Br compared to ^{70}Kr. In the case of the cross sections, the estimate relies on the calculated values[22] due to lack of experimental results. Typical uncertainties in the calculations at the level of one standard deviation are 50% [24]. In particular, the average discrepancy between the calculated and the experimental production cross sections for Br and Kr isotopes for the reaction 1.85 GeV p + ^{nat}Mo has been found to be 63% [25]. We adopt this value for the uncertainty of the individual cross sections. Very close to the proton drip line abrupt changes in proton separation energies between neighboring nuclei may induce some additional uncertainty. However, the ratios of the proton separation energies between Kr and Br are almost equal in $A = 70$ and 71 [13]. Thus, we believe in obtaining a reasonable estimate for the cross section enhancement of ^{70}Br using the Silberberg&Tsao calculation. This give an enhancement factor of $<$4.3 for Br in $A = 70$ compared to $A = 71$.

Using the method described above, it can be estimated that only $<$0.7% of the observed counts might be due to the direct production of ^{70}Br. In the case of ^{70}Br^m, the decay losses are not so significant and the similar estimate gives $<$26% for ^{70}Br^m of the amount of ^{70}Kr. However, this would correspond only to $<$1.4 counts/20 ms in the time spectrum shown in Fig. 2. Thus, the possible contribution from ^{70}Br^m has been neglected. The numbers above include an overall uncertainty of 130% which has been added to the original values. It has to be pointed out that the cooled transfer line used in this work makes the release time even longer for Br[26], thus increasing the decay losses for the short-lived ^{70}Br further and decreasing its estimated amount. Based on the discussion above we assume that the amount of directly produced ^{70}Br is negligible.

Fig. 2 shows the time spectrum of positrons after the 150 ms collection period. Assuming a pure production of ^{70}Kr and a constant background, the time spectrum of the β particles due to the decay chain ^{70}Kr→^{70}Br→^{70}Se can be written as

$$N(t) = y_0 + N_{10}\left[e^{-\lambda_1 t}(1-e^{-\lambda_1 \Delta t}) + \frac{\lambda_1\lambda_2}{\lambda_2-\lambda_1}\left(\frac{e^{-\lambda_1 t}(1-e^{-\lambda_1\Delta t})}{\lambda_1} - \frac{e^{-\lambda_2 t}(1-e^{-\lambda_2\Delta t})}{\lambda_2}\right) + Re^{-\lambda_2 t}(1-e^{-\lambda_2\Delta t})\right] \quad (1)$$

where y_0 = constant for the background, N_{10} = amount of ^{70}Kr in the beginning of the decaying part, R = ratio of ^{70}Br and ^{70}Kr in the beginning of the decaying part, λ_1 = decay constant of ^{70}Kr, λ_2 = the known decay constant of ^{70}Br, and Δt = 0.02 s = width of the time bin in the spectrum. The constant background takes into account the observed long-lived contaminants ^{70}As and ^{70}Ga with the half-lives of 53 min and 14 min, respectively. The parameters λ_1 and R are correlated. The measured release profile for Kr and the half-life of ^{70}Kr determine R. Therefore we adapted the following iterative fitting procedure: i) setting an initial value for $T_{1/2,i}$ for ^{70}Kr, ii) simulation of the Br/Kr ratio R and iii) fitting procedure for the half-life with fixed R to obtain new initial value $T_{1/2,i}$. The procedure described above was repeated until the resulting value for the half-life converged. Initial values of 40 and 90 ms resulted both in the final value of $T_{1/2}$ = 57(21) ms for the β-decay half-life of ^{70}Kr. This leads to a value of R = 1.08. The uncertainty in the half-life includes the statistical uncertainty from the fit and the uncertainty induced by the assumed 20 % uncertainties in the release parameters. The contributions from both were summed quadratically. Only a small contribution of around 2 ms was observed due to the uncertainties in the release parameters. This small effect supports the use of the chosen method for the half-life analysis. Note that this procedure is only valid if the direct production of ^{70}Br is negligible, which was carefully verified.

No evidence for β-delayed γ or proton decay of ^{70}Kr was found in this experiment. An upper limit of 1.3 % for the β-delayed proton branching ratio b_p can be estimated based on two counts seen in the "proton region" in the ΔE-E spectrum of the gas-Si telescope detector.

The β-decay half-lives can also be estimated assuming only superallowed transition to be present in β-decays of ^{70}Kr and ^{70}Br. In the absence of a Gamow-Teller contribution in the β transition the following expression is valid

$$ft = \frac{C}{B(F)} \quad (2)$$

where f = Fermi integral taken from[27], t = partial half-life of the transition, C = 6145(4) s[28], and $B(F)$ = Fermi strength = 2 for the superallowed transitions between $(J^\pi = 0^+, T = 1)$ states. Using a Q_{EC} value from a recent shell model Coulomb-energy calculation[5], the β-decay half-life for ^{70}Br can be estimated to be 78(2) ms. This value is in excellent agreement with the experimental value of 79.1(8) ms for ^{70}Br indicating the reliability of this Coulomb-energy calculation. Assuming for ^{70}Kr Q_{EC} = 10.459(50) MeV based on the same reference [5], one obtains $T_{1/2}$ = 62(2) ms. This estimate agrees well with the result measured in this work. Another prediction by Hirsch *et al.* using a QRPA calculation [29] gives $T_{1/2}$ = 55 ms, also in agreement with our experimental value. The half-life obtained in this work can also be compared with the result from the recent QRPA calculations [30] that take only Gamow-Teller transitions into account. These calculations provided input data for the astrophysical rp-process modelling [9] if experimental or shell-model results were not available. The QRPA value, $T_{1/2}$ = 390 ms, is clearly larger than the value measured in this work. It is evident that Fermi transitions play a significant role in defining the total β-decay rates for certain nuclei near the proton drip line and should not be neglected.

Thermal excitations in a typical X-ray burst environment can affect the rp-process half-lives of the nuclei involved. In the case of ^{70}Kr, assuming mirror symmetry, the first excited state would be around 1 MeV. Even at a temperature of 2 GK the role of the thermal excitations on the lifetime of ^{70}Kr is negligible due to the low thermal population of the states above 1 MeV.

The consequences of implementing the experimental half-life of ^{70}Kr into rp-process calculations are illustrated in Fig. 3, which shows the effective rp-process half-life of ^{68}Se as a function of the assumed β-decay half-life of ^{70}Kr. The effective rp-process half-life is the half-life of ^{68}Se against the proton capture and the β decay and represents the timescale $\tau = T_{1/2}/\ln 2$ for the delay of the rp process caused by the ^{68}Se waiting point. The effective rp-process half-life has been calculated by solving the differential equations describing the abundances of ^{68}Se, ^{69}Br, ^{70}Kr, ^{68}As, and ^{70}Br as a function of time. As an example, we assumed typical X-ray burst model conditions with a temperature of 1.5 GK and a density of 10^6 g/cm^3. The two-proton-capture rate on ^{68}Se has been taken from [9], where an experimental estimate of S_p = -450 keV for ^{69}Br [4] has been used instead of the FRDM mass model [12] used for the other mass values. In these conditions, the destruction rate of ^{68}Se via two-proton-capture based on the old calculated ^{70}Kr half-life [30] reduces the ^{68}Se half-life by only 20% compared to pure β decay (35.5 s). However, with the experimental ^{70}Kr half-life obtained in this work, two-proton-capture reduces the effective rp-process half-life of ^{68}Se drastically by a factor of 2.5 to just 14.4 s. Within the error bars an effective rp-process half-life of ^{68}Se as short as 11 s is possible. The rp-process timescale is given by the sum of the effective rp-process lifetimes of the waiting points along the reaction path. Therefore, under the assumed conditions, the reduced effective rp-process half-life of ^{68}Se will lead to an acceleration of the rp-process abundance flow in X-ray bursts above $A = 68$ compared to [9]. This could result in an increased production of $A > 68$ nuclei, possibly including the p isotopes ^{92}Mo, ^{94}Mo, ^{96}Ru and ^{98}Ru.

The effective rp-process half-life of ^{68}Se depends not only on the ^{70}Kr β-decay half-life but also exponentially on the proton separation energies of ^{69}Br and ^{70}Kr. The uncertainty in the theoretical predictions for these values is certainly the dominant source of uncertainty in the present estimates of the effective rp-process half-life of ^{68}Se.

As a summary, we have measured the β-decay half-life of ^{70}Kr for the first time at ISOLDE On-line Mass Separator, CERN. The value, consistent with a pure Fermi decay assumption, is significantly shorter than the QRPA value used in the recent network calculation for the rapid proton capture process. The shorter value results in a higher effective rate for bridging the waiting point at ^{68}Se via two-proton-capture in typical X-ray burst model conditions.

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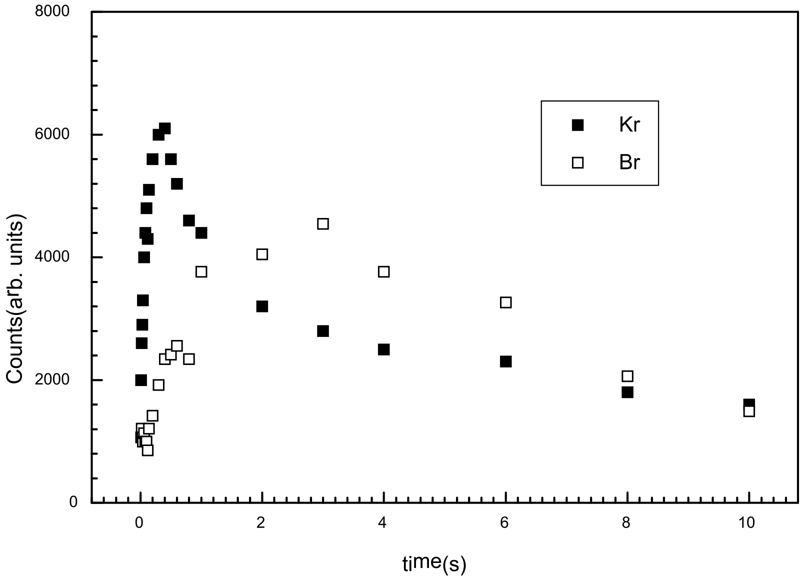

Figure 1: Release time behaviour of Kr and Br measured for a combination of Nb-foil target and hot plasma ion source. The data were obtained by measuring time dependences of the yields of $^{79}Kr^m$ and $^{79}Br^m$ using γ spectroscopy. In the case of water-cooled transfer line at room temperature, as used in this work, the Br atoms are condensed into the wall of the line[17].

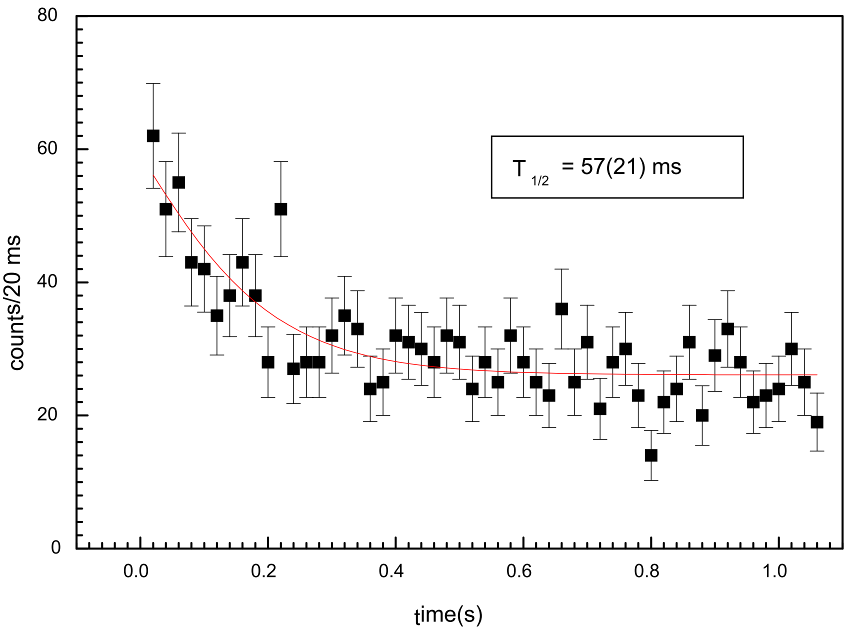

Figure 2: Time spectrum of β particles with energy above 1.3 MeV after 150 ms beam-on period. The solid line shows the fit using the Eq. 1.

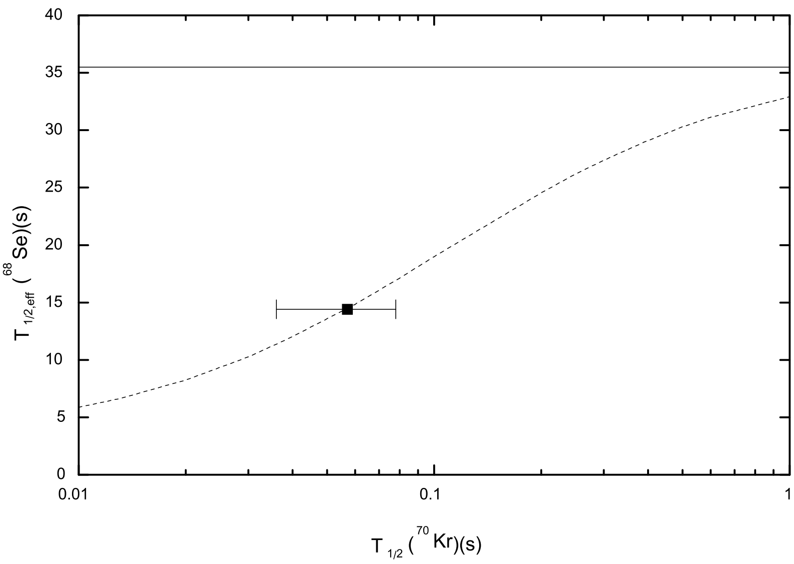

Figure 3: The half-life of ^{68}Se against destruction by β decay and two-proton-capture (effective rp process half-life - dashed line). For comparison the β-decay half-life is shown as well (solid line). The half-life is given as a function of the ^{70}Kr half-life, which defines the destruction of ^{68}Se via 2p capture. The calculation has been performed assuming typical X-ray burst model conditions: a density of 10^6 g/cm^3, a temperature of 1.5 GK, and solar hydrogen abundance.