Physics Letters B 738 (2014) 453–456

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

β-delayed proton emission of ^{69}Kr and the ^{68}Se rp-process waiting point

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ARTICLE INFO

Article history:
Received 29 September 2014
Received in revised form 8 October 2014
Accepted 8 October 2014
Available online 16 October 2014
Editor: W. Haxton

Keywords:
Rp-process
Waiting point
X-ray burst

ABSTRACT

The slow β-decay of the ^{68}Se waiting point in the astrophysical rp-process can in principle be bypassed by a sequential two proton capture. The rate of this reaction sequence depends exponentially on the ^{69}Br proton separation energy. We studied β-delayed proton emission of ^{69}Kr and extracted a proton separation energy of $-641(42)$ keV. In addition, we determined a ^{69}Kr β-decay half-life of $T_{1/2} = 28(1)$ ms and an excitation energy of 3153(55) keV of the ^{69}Kr isobaric analog state in ^{69}Br. X-ray burst model calculations show that regardless of the values of other uncertain masses in the region, the new $S_p(^{69}\text{Br})$ allows for a reaction flow via $^{68}\text{Se}(2\text{p}, \gamma)$ of at most 20%. Uncertainties are sufficiently reduced to conclude that $^{68}\text{Se}(2\text{p}, \gamma)$ has at best a very small effect on burst light curve and composition, and that ^{68}Se is a strong rp-process waiting point. Our results also exclude the possibility of a suggested longer lived, so far unobserved, ^{69}Br ground state.

Astrophysical x-ray bursts are frequently observed and are thought to occur on the surface of accreting neutron stars [1–4]. The bursts are powered by a thermonuclear runaway in the accreted material, triggered by the triple-α reaction and the breakout from the hot CNO cycle through the αp-process. During the burst, temperatures quickly rise and become high enough for hydrogen to burn via the rp-process (rapid proton capture process) [5,6], a sequence of fast (p, γ) reactions and slower β^+-decays reaching Te in some bursts [7].

Waiting point nuclides slow down the rp-process and strongly affect burst observables. They are characterized by long β-decay half-lives of the order of the burst duration, and low or negative proton capture Q values that hamper further proton capture because of strong (γ, p) photodisintegration. Beyond ^{56}Ni, the potential major rp-process waiting points are ^{64}Ge, ^{68}Se and ^{72}Kr with β-decay half-lives of 64, 35 and 17 seconds, respectively. However, the effective half-life of a waiting point can be reduced by the sequential capture of two protons [6] (2p capture). The 2p capture rate and therefore the effective waiting point half-life depends exponentially on the proton separation energy, S_p, of the intermediate nucleus. A quantitative understanding of x-ray burst observations requires the determination of effective half-lives of the potential waiting points ^{64}Ge, ^{68}Se, and ^{72}Kr, and therefore the S_p of ^{65}As, ^{69}Br and ^{73}Rb [8,9].

$S_p(^{65}\text{As}) = -90(85)$ keV has been deduced from direct mass measurements of ^{64}Ge [10] and ^{65}As [11]. ^{65}As is only slightly proton unbound and proton capture on ^{64}Ge reduces the effective half-life of ^{64}Ge such that it is not a major waiting point for most x-ray burst conditions. This raises the important question of

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http://dx.doi.org/10.1016/j.physletb.2014.10.023

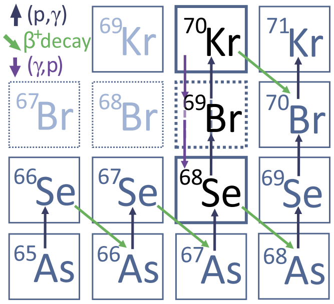

Fig. 1. rp-process reaction sequence around the ^{68}Se waiting point. Isotopes expected to be ground state proton emitters are dashed.

whether the next potential major waiting point, ^{68}Se, imposes a strong delay on the rp-process (Fig. 1).

The mass of ^{68}Se is experimentally known with good precision [12–14]. However, the mass of ^{69}Br cannot be measured directly as the non-observation of this nucleus in fragmentation experiments [15] implies an upper limit on the half-life of 24 ns and a model dependent upper limit of S_p of −500 keV. However, Jenkins [16] argued that this limit is highly uncertain because of the potential population of proton decaying isomers in the fragmentation process that might "shadow" the longer lived ground state.

The first direct measurement of the proton separation energy of ^{69}Br was realized in a complete kinematic measurement of the $^{69}\text{Br} \rightarrow {}^{68}\text{Se} + \text{p}$-decay, and $S_p = -785^{+34}_{-40}$ keV was deduced [17]. However, the sensitivity of this experiment depends on the lifetime of the states, and the interpretation of the results depends on assumptions on level ordering. In principle a "shadowing" effect as discussed by Jenkins [16] could also occur in this case.

A complementary approach to populate ^{69}Br via the β-decay of ^{69}Kr is reported here. The detection of β-delayed protons can constrain the proton separation energy of ^{69}Br. The observation of β-delayed protons from ^{69}Kr has been reported before by Xu et al. [18] and, in parallel to this work, by Rogers et al. [19]. However, neither study was sensitive to β-delayed proton branches from lower energy states in ^{69}Br of interest here.

A radioactive beam containing ^{69}Kr was produced by fragmentation of a 25 pnA ^{78}Kr primary beam on a 142 mg/cm^2 Be target at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The fragments were filtered by the standard $B\rho - \Delta E - B\rho$ method in the A1900 fragment separator [20] using a 173 mg/cm^2 Al wedge at the intermediate image of the device. The Radio Frequency Fragment Separator (RFFS) [21] was used to increase the purity of the radioactive beam by a factor of 60. After purification, the beam was sent to the NSCL Beta Counting System (BCS) [22] and implanted into a 4×4 cm 525 µm thick double-sided silicon strip detector (DSSD) with 40 back and 40 front strips, creating a total of 1600 virtual 1×1 mm pixels. The rate of ^{69}Kr implantations was 0.02 pps with a total implantation rate of 70 pps. Emitted β particles and protons were also detected in the DSSD and were correlated in time with previously implanted ions in the same pixel. Two additional DSSDs with the same specifications and dimensions were placed upstream and downstream of the implantation DSSD to track β particles and to verify all protons were completely stopped in the central DSSD. Three additional 5×5 cm PIN detectors were placed upstream of this array to provide beam energy loss information for particle identification. The BCS was surrounded by sixteen detectors from the Segmented Germanium Array (SeGA) [23] for detection of prompt and β-delayed γ rays. The close-packed arrangement of the detectors gave a photo-peak efficiency of 7% at 1 MeV.

The DSSDs were energy calibrated using a ^{228}Th α-source and a ^{133}Ba conversion electron source to track the calibration down to ∼300 keV. Known β-delayed protons from ^{20}Mg and ^{23}Si were used as additional calibration points. The decays of these isotopes were characterized in the BCS prior to our experiment as part of an experimental campaign. The data were analyzed using the same approach as for ^{69}Kr and known proton branches with energies of 0.806(20) MeV, 1.679(15) MeV and 2.692(41) MeV for ^{20}Mg [24], and energies of 1.32(4) MeV, 2.40(4) MeV, 2.83(6) MeV, 3.02(6) MeV and 3.65(6) MeV for ^{23}Si [25] were used for the energy calibration. Additional systematic errors of 12 and 70 keV for ^{20}Mg and ^{23}Si were included to account for β summing effects.

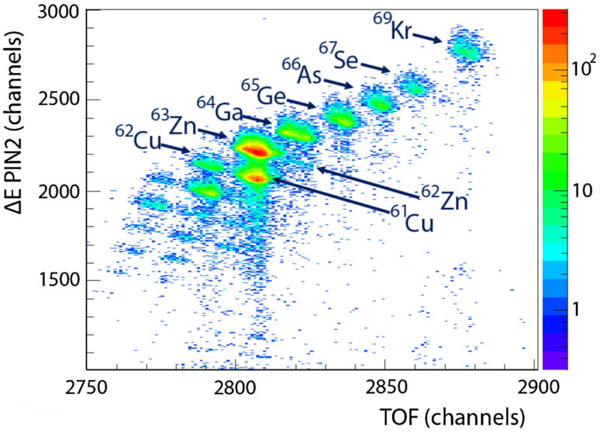

Fig. 2. Particle identification spectrum of implanted ions that were correlated with decays.

^{69}Kr was identified event by event using time of flight TOF measured between a scintillator at the exit of the fragment separator and one of the BCS PIN detectors, and the energy loss ΔE in the BCS PIN detectors. The particle identification (PID) (Fig. 2) was confirmed by detecting γ rays from the known microsecond isomer in ^{66}As [26]. The gap in the PID spectrum between ^{69}Kr and ^{67}Se indicates the absence of the proton unbound ^{68}Br in the secondary beam. A total number of 1726 ^{69}Kr ions were implanted, and 1476 decays were correlated with a ^{69}Kr implantation using a one second time correlation window. To eliminate β particle background in the proton energy spectrum, decays were rejected if another ion was implanted within 200 ms prior to the ^{69}Kr implantation. This reduced the number of ^{69}Kr decay events to 1370. A ^{69}Kr half-life of 28(1) ms was deduced from the time distribution of correlated decay events. The half-life value reported here is consistent with but more precise than previous measurements of 32(10) ms [18] and 27(3) ms [19].

The β-delayed proton spectrum is shown in Fig. 3. As expected for ^{69}Kr, the spectrum does not contain any β only events, which would appear as a low-energy tail near our detection threshold around 0.23 MeV. The energy of decay events in the DSSD is the sum of the proton energy and part of the β energy deposited in a given pixel. This summing effect shifts the peak centroids to higher energies and distorts the shape of the observed spectrum. GEANT4 [27] simulations were used to account for summing and to extract final proton energies. The energy correction depends on the implantation depth distribution in the DSSD. The range distribution was calculated using the code LISE++ [28] and we determined the average implantation depth using observed peak shapes as well as energy shifts observed when gating on β-particles emitted in forward and backward directions. The implantation depth distribution calculations were validated by comparing implantation rates for other isotopes in the radioactive beam that were implanted in more than one DSSD. An average implantation depth of 217(53) µm was obtained for ^{69}Kr, resulting in a β-proton summing energy correction of −79(12) keV. The detector resolution

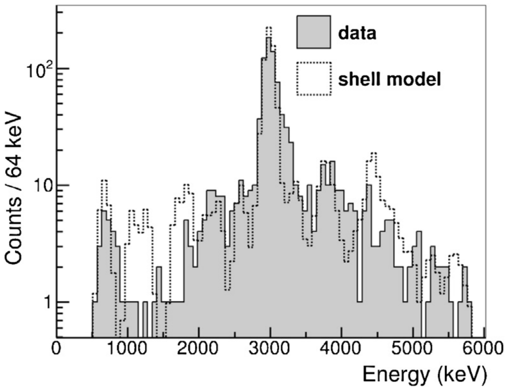

Fig. 3. β-delayed proton spectrum for ^{69}Kr (grey) compared to shell model calculations (dashed line). The shell model results have been folded with the experimental resolution of 60 keV and have been shifted by 79 keV to correct for the shift in peak positions due to β summing.

was $\sigma = 60$ keV. This approach was also applied to the well known β-delayed proton emitters ^{20}Mg and ^{23}Si, and a consistent energy calibration was obtained.

The most intense peak in the β-delayed proton spectrum with a proton energy of 2939(22) keV was assigned to the decay from the isobaric analog state (IAS) in ^{69}Br to the first excited state in ^{68}Se ($E_x = 854$ keV) [29]. These events were in coincidence with the only observed γ-ray line that was present in the delayed γ-ray spectrum with energy 854 keV.

No evidence was found for an IAS decay branch to the ^{68}Se ground state. Using all the counts detected in the relevant proton energy range around 3793 keV, an upper limit of 6.7% was deduced for the ground-state branch. Based on data from the mirror ^{69}As [30], the expected ground state spin and parity of ^{69}Kr are either $J^\pi = 3/2^-$ or $J^\pi = 5/2^-$. The small branch from the IAS to the ^{68}Se ground-state suggests $J^\pi = 5/2^-$ for the ^{69}Kr ground-state, since such an assignment would result in an increased angular momentum barrier for the ground state decay, compared to the decay to the 2^+ state.

The total β-decay branching to the IAS was determined to be $52.5 \pm 6.5\%$. To calculate the ^{69}Kr β-decay Q value to the ^{69}Br IAS, we assumed no isospin mixing and performed shell model calculations using the GPFX1A Hamiltonian [31] to obtain the small Gamow–Teller contribution to the decay, $B(\mathrm{GT}) = 0.048$, resulting in a $\log ft$ value of 3.303. Using the aforementioned $\log ft$ value for the superallowed transition to the IAS, a ^{69}Kr β-decay Q value of 9.90(30) MeV was deduced. Taken in concert with the known ^{68}Se mass [14], a ^{69}Kr mass excess of $-32.42(90)$ MeV was determined, in agreement with $-32.4(1)$ MeV expected from the well known ^{69}As mirror mass and Coulomb shift calculations [9].

Our results are consistent with Rogers et al. [19], who find a proton decay energy from the IAS to the first excited state in ^{68}Se of 2.97(5) MeV and an upper limit of the IAS ground state branch of 10%, but disagree with Xu et al. [18], who reported a proton energy of 4.07(5) MeV from the decay of the IAS. See Fig. 4.

A proton peak was also observed at an energy of 654^{+32}_{-35} keV, after correction for β summing. This proton energy is lower than the 785^{+34}_{-40} keV decay energy reported in the fragmentation experiment of Rogers et al. [17]. A possible explanation for the disparate results is that the experiments observe proton decay from different states. The three lowest ^{69}Br states are expected to have spins and parities of $J^\pi = 3/2^-, 5/2^-$ and $1/2^-$, respectively, based on the low-energy structure of the ^{69}As mirror nucleus. Proton decay is expected to dominate over γ decay for all these expected states in ^{69}Br. The 654 keV protons likely originate from the lowest ^{69}Br state fed in the ^{69}Kr β-decay. Rogers et al. [17] assigned the 785 keV proton energy to the decay of a $3/2^-$ state, since a longer lived $l = 3$ decay of the $5/2^-$ state would lead to broadening of the proton peak in the decay energy spectrum that may have defied detection given the energy resolution of the experiment.

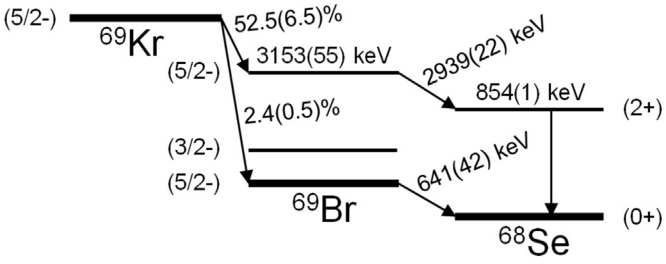

Fig. 4. Proposed ^{69}Br β-delayed proton emission decay scheme (not to scale). The arrows correspond to the transitions identified in this experiment. The level ordering in ^{69}Br was chosen based on the results of this experiment combined with Rogers et al. [17] and the pf-shell model calculation.

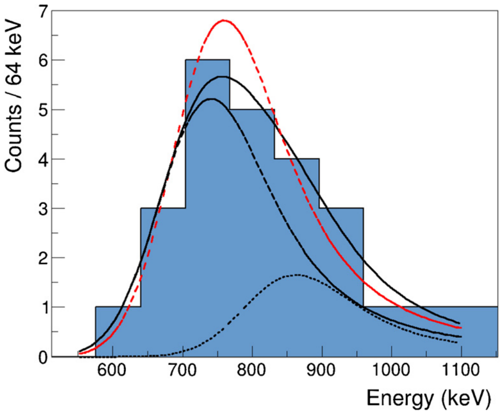

Fig. 5. Lowest energy peak in the β-delayed proton spectrum for ^{69}Kr, uncorrected for β summing. Two fits are shown, the dashed red line assumes one peak and the solid black line assumes two peaks. The solid black line has contributions from the lower-energy $5/2^-$ peak and a higher-energy $3/2^-$ peak, indicated by a long-dashed black line and short-dashed black line.

The suggestion of two proton decaying states at low energy in ^{69}Br is supported by shell model calculations, which were carried out in the $(1f_{5/2}, 0p_{3/2}, 0p_{1/2})^{13}$ model space with GPFX1A Hamiltonian [31]. The shell model calculations predict a low-energy proton (see Fig. 3) with a branching ratio of 2.7% fed from the $5/2^-$ ^{69}Br ground state. The shell model results also predict a significant feeding of 1.5% to the first excited $3/2^-$ state. The DSSD energy resolution was not sufficient to resolve two proton transitions with energies 654 and 785 keV. A maximum likelihood analysis was used to assess the doublet nature of the low-energy peak in Fig. 3. Peak fitting parameters were taken from the shape of the IAS peak, while the centroids and relative branching were free parameters. Proton energies of 641(42) keV and 751^{+132}_{-82} keV were obtained from the analysis (see Fig. 5), the latter being in good agreement with the value reported by Rogers et al. [17]. The relative population of the lower-energy state to the higher-energy state from the maximum-likelihood fit was 4:1. The total branching to the two states was 2.4(0.5)%.

The maximum-likelihood analysis under the assumption of the low-energy proton peak being a doublet provided a better fit to the data, but the single-peak hypothesis cannot be rejected with sufficient confidence. However, the energy determined for the proton assumed to be from the lowest-energy state in ^{69}Br was consistent between analysis methods (the single peak hypothesis yields $S_p = 660(30)$ keV). The doublet analysis is also consistent with

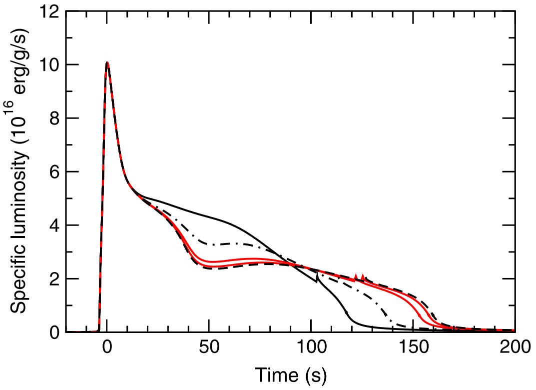

Fig. 6. Calculated x-ray burst light curves for different $S_p(^{69}\text{Br})$ values and for low ^{66}Se and ^{70}Kr masses. The black curves delineate the maximum uncertainty prior to an experimental determination of $S_p(^{69}\text{Br})$ (black solid, black dot-dashed, and black dashed lines correspond to $S_p(^{69}\text{Br}) = -150$ keV, -450 keV, and -750 keV, respectively). The red solid curves reflect the calculations with the $S_p(^{69}\text{Br}) = 641 - 42$ keV and $641 + 42$ keV, the 1σ error bar obtained in this work. Color online.

shell model calculations and with the Rogers et al. [17] measurement. The S_p for ^{69}Br measured here agrees with the experimental limit from the non-observation of ^{69}Br in fragmentation experiments $S_p < -500$ keV [15] indicating the absence of a significant shadowing effect by the population of isomers when producing ^{69}Br in projectile fragmentation reactions. It also agrees well with theoretical calculations of Coulomb displacement energies that together with the experimentally well known masses of ^{68}Se and ^{69}Se, predict $S_p = -636(100)$ keV [10,14].

To explore the impact of the deduced $S_p(^{69}\text{Br})$ on X-ray burst simulations we use a one-zone model [7] with reaction rates from the JINA Reaclib Database v2.0 [32]. Changes in nuclear masses are taken into account by recalculating (γ, p) reactions from the corresponding proton capture reaction rates using detailed balance. The impact of $S_p(^{69}\text{Br})$ on the X-ray burst light curve is highly correlated with other masses in the region. It depends strongly on the ^{70}Kr mass, which together with $S_p(^{69}\text{Br})$ determines the 2p-capture rate on the ^{68}Se waiting point. The importance of $S_p(^{69}\text{Br})$ also depends on the strength of the ^{64}Ge waiting point, in particular on $S_p(^{65}\text{As})$ and $S_p(^{66}\text{Se})$. In this context, the unknown ^{66}Se mass is the dominant uncertainty.

To account for these correlations in mass uncertainties we varied in addition to the ^{69}Br mass (which can be deduced from $S_p(^{69}\text{Br})$ using the well known ^{68}Se mass), the masses of ^{65}As, ^{66}Se, and ^{70}Kr. The masses of ^{66}Se and ^{70}Kr are experimentally unknown and were taken from the extrapolations in AME11 [33] as they agree better with Coulomb shift predictions [9] than the extrapolations of AME12 [34]. For example, the AME12 extrapolated mass of ^{66}Se differs by 460 keV from Coulomb shift predictions, compared to 110 keV for AME11. Similar issues related to AME12 mass extrapolations for neutron deficient nuclei have been reported for ^{56}Cu [35]. We varied all four masses up or down by 3σ and calculated bursts for all possible combinations. This variation accounts for the possibility of large systematic errors in AME extrapolations (for example the extrapolated mass of ^{69}Br changed by more than 3σ from AME11 to AME12).

Fig. 6 shows calculated X-ray burst light curves for different ^{69}Br masses and for low ^{66}Se and ^{70}Kr masses that facilitate 2p capture reaction sequences on ^{64}Ge and ^{68}Se. Clearly in this case $S_p(^{69}\text{Br})$ has a large effect on the burst light curve, even for values below -500 keV. The effect is smaller for a high ^{66}Se mass, but its still significant. However, for a high ^{70}Kr mass, $S_p(^{69}\text{Br})$ would be unimportant. In summary, despite of finding evidence for a lower lying ground state in ^{69}Br than previously observed, our experimental result largely eliminates the light curve uncertainty from $S_p(^{69}\text{Br})$ (see Fig. 6), and implies a reaction flow branching through 2p capture on ^{68}Se of at most 20%, even when considering the remaining uncertainties in other masses in the region. The absence of β-decays from ^{69}Kr without proton emission in our data excludes the possibility for a suggested longer lived ^{69}Br ground state that may have been shadowed in fragmentation reactions and therefore not observed in previous experiments [16]. We can therefore conclude that ^{68}Se is a strong waiting point in the rp-process in X-ray bursts. This provides a robust explanation of occasionally observed long burst durations of the order of minutes, regardless of the remaining nuclear uncertainties along the rp-process in the ^{64}Ge–^{74}Sr region.

Acknowledgements

This project is funded by the NSF through grants PHY 08-22648 (Joint Institute for Nuclear Astrophysics), PHY 11-02511, and PHY 10-68217, and by DFG under Contract No. GE 2183/1-1.

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