Discovery of ^{72}Rb: A Nuclear Sandbank Beyond the Proton Drip Line

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Discovery of ^{72}Rb: A nuclear sandbank beyond the proton drip-line

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In this paper the observation of two previously unknown isotopes are presented for the first time: ^{72}Rb with 14 observed events and ^{77}Zr with one observed event. From the non-observation of the less proton-rich nucleus ^{73}Rb we derive an upper limit for the ground-state half-life of 81 ns, consistent with the previous upper limit of 30 ns. For ^{72}Rb we have measured a half-life of 103(22) ns. This observation of a relatively long-lived odd-odd nucleus, ^{72}Rb, with a less exotic odd-even neighbour, ^{73}Rb, being unbound shows the diffuseness of the proton drip-line and the possibility of sandbanks to exist beyond it. The ^{72}Rb half life is consistent with a $5^+ \rightarrow 5/2^-$ proton decay with an energy of 800–900 keV, in agreement with the atomic mass evaluation proton separation energy as well as results from the Finite Range Droplet Model and shell model calculations using the GXPF1A interaction. However, we can not explicitly exclude the possibility of a proton transition between $9^+(^{72}\text{Rb}) \rightarrow 9/2^+(^{71}\text{Kr})$ isomeric states with a broken mirror symmetry. These results imply that ^{72}Kr is a strong waiting point in X-ray burst *rp*-process scenarios.

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The proton drip-line is one of the fundamental limits of nuclear existence defined by nuclei with such a large

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excess of protons that they are unbound with respect to proton emission. Due to the strong Coulomb repulsion in proton rich nuclei, the proton drip-line lies not far from the region of stability, and the Coulomb mean field also helps to create the conditions for the existence of relatively long-lived resonances beyond the stability limit.

The proton emission half-life is extremely sensitive to the energy and angular momentum of the escaping proton. This sensitivity can serve to blur the drip-line via the appearance and population of ground- and isomeric states [1, 2] at higher spin where the centrifugal barrier is larger. This can create more shallow regions, or sandbanks, in the sea of unbound nuclei, where the life-time is significantly longer than their less exotic neighbours. Such sandbanks could, furthermore, serve to bridge gaps of unbound nuclei along the path of the astrophysical rapid-proton capture (*rp*) process.

From an experimental point of view, proton decay from the ground state has been observed for many nuclei between the Sn ($Z = 50$) and Pb ($Z = 82$), and has been used to determine the sequence of single particle levels beyond the proton drip line, and to study the content of the nuclear wave function [3, 4]. The experimental conditions only allow a definite time interval for the half-lives to be observed. If the decay time is long, proton emission will be superseded by β^+-decay, if it is too short, due to experimental limitations, it will not be sufficient to separate and implant the nuclei in a detector, or keep them in a storage ring, to observe their decay. The time interval can be translated into an energy window. For heavy-nuclei the proton separation energy changes slowly, which results in a greater number of proton decaying nuclei being observed compared to much lighter nuclei. For the latter, the separation energy changes fast, reducing the probability of having a separation energy within the window, and making observation difficult. One-proton radioactivity below $Z = 50$ is therefore extremely challenging to study, and only two nuclei, ^{93}Ag and ^{89}Rh [5], have been identified as ground-state proton emitters, along with the excited states of $^{53\mathrm{m}}$Co [6], $^{54\mathrm{m}}$Ni [7], $^{56\mathrm{m}}$Ni [8], $^{58\mathrm{m}}$Ni [9], $^{59\mathrm{m}}$Cu [10], and $^{94\mathrm{m}}$Ag [11].

As mentioned above, proton radioactivity from nuclei with $Z < 50$ is of particular interest because it serves as an important input to calculate the path of the *rp*-process, which powers thermonuclear explosions on the surface of accreating neutron stars, and is visible as X-ray bursts. This path runs along the proton drip line and its time scale is defined by three main waiting points ^{64}Ge, ^{68}Se, and ^{72}Kr, the latter having a half-life of 17 s. In the stellar environment, however, it is possible for two-proton capture to occur via the ^{72}Kr(2p, γ)^{74}Sr reaction. Depending on the properties of ^{73}Rb, in particular the proton separation energies, S_{p}, the 2p capture process could bypass the waiting point, making the effective half-life shorter. In order to further our understanding, we need to know the proton separation energy in ^{73}Rb. For the other two known waiting points of the *rp*-process beyond ^{56}Ni, ^{64}Ge [12, 13] and ^{68}Se [14], the proton separation energies have been measured with high precision. However, for the last waiting point, ^{72}Kr, none of these properties are constrained by direct measurements. Thus, information about nuclear physics is a cause of significant uncertainties in the X-ray bursts light-curve profile and the subsequent composition of the *rp*-process ashes anticipated by X-ray burst models.

To obtain more nuclear structure information in this region, an experiment was carried out using the accelerator complex and magnetic spectrometers at the Radioactive Isotope Beam Factory (RIBF) of the RIKEN Nishina Center. The accelerator chain up to the SRC cyclotron [15] was used to accelerate a ^{124}Xe beam to an energy of 345 MeV/u with intensity of 30-35 pnA. The xenon beam impinged on a 740 mg/cm^2 beryllium target, inducing fragmentation of the primary beam. After the target, BigRIPS [16–18] and the ZeroDegree Spectrometer [19] was used for separation and tagging of the exotic nuclei of interest, and provided A/q and Z on an event-by-event basis (see Fig. 1) through the magnetic rigidity, time-of-flight and energy loss of the ions (i.e. the $B\rho$–TOF–ΔE technique). The particle identification analysis was carried out using measurements of $B\rho$ in parallel-plate avalanche counter detectors at the F3, F5 and F7 focal points in the BigRIPS separator; the TOF between plastic scintillators placed at F3 and F7; and the energy loss, ΔE, of the ions in an ionization chamber placed at the final focal point, F11. The data were collected in three different sets using the same magnetic fields but with different openings of the slits at F1, F2 and F7 (see supplementary material). For a detailed overview of the different focal planes, see Ref. [16, 19]. The secondary beam was implanted into the active silicon stopper WAS3ABi [20, 21] and subsequent β- and proton-delayed γ-rays were detected within the EURICA [20, 22] high-purity germanium detector array.

For the results presented in this paper, it is critical to discriminate real events from background events with high accuracy. A detailed outline of the analysis procedure can be found in Ref. [18]. In particular, correlations within the parallel plate avalanche counters (PPACs), the positions and angles at the same and different focal planes, energy correlations in the plastic scintillators and ionization chambers and timing and charge deposition in the plastic scintillators were used for background rejection. Proton knock-out events were removed by comparing the A/q values obtained from the F3-F5 and F5-F7 reconstructions. In total, the A/q resolution obtained was 0.04% and the Z resolution at F11 was 0.39%. This procedure gave a very clean separation both in Z and A/q with a very low level of background, as shown in Fig. 1. To deduce the final yields, the events produced from the scraper at F0 were identified and subtracted based on correlations between y-angles and -positions of the beam at the third focal plane, F3. The final $N = 35, 36$ yields are shown in Fig. 2.

14 counts of the isotope ^{72}Rb was unexpectedly observed in the BigRIPS and ZeroDegree combined particle

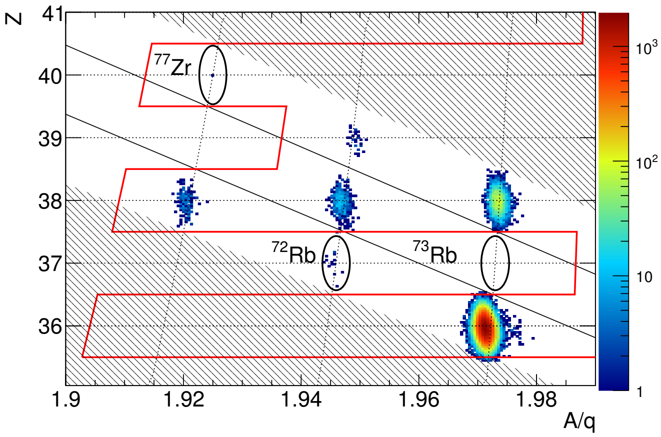

FIG. 1: Particle identification (PID), showing the deduced nuclear charge (Z) versus the mass-over-charge ratio (A/q). The three white bands correspond to the three slit settings used in the experiment, and the red line is the currently known proton drip-line. One can note the absence of counts for ^{73}Rb, beyond the proton drip-line, while 14 counts are visible in ^{72}Rb.

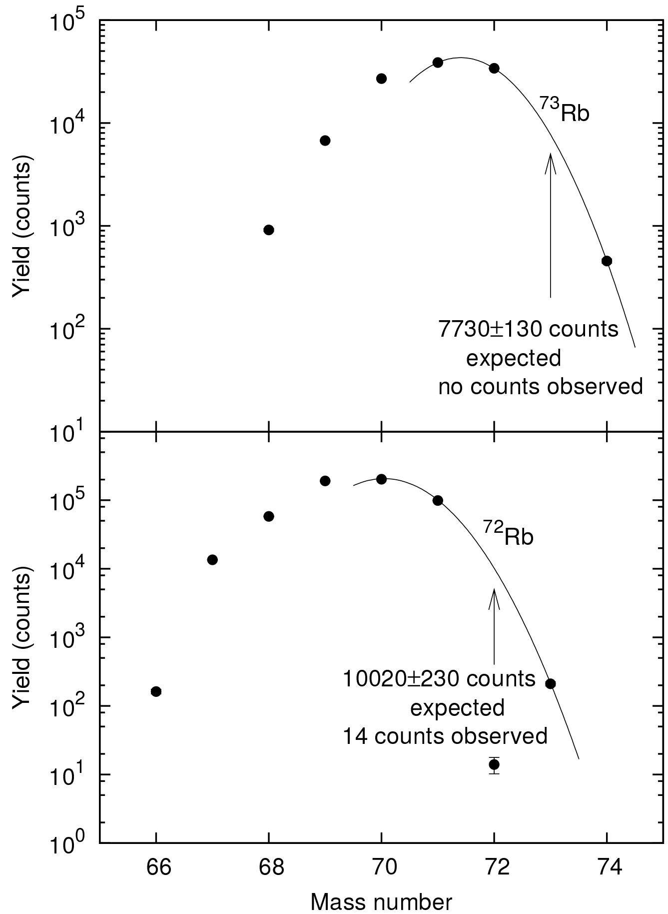

FIG. 2: The number of events of $N = 36$ isotones (top) and $N = 35$ isotones (bottom) identified in BigRIPS and ZeroDegree versus proton number, Z. To determine the half lives of ^{72}Rb and ^{73}Rb, the number of counts expected from a quadratic interpolation of the logarithm of the yields of neighboring nuclei are compared to the number of counts observed.

identification (PID) plot resulting from the procedure described above. However, the gap in the PID in Fig. 1 between ^{74}Sr and ^{72}Kr indicates the absence of ^{73}Rb in the secondary beam. This is consistent with previous work that has suggested that ^{73}Rb is proton unbound [23]. It has, however, been discussed that the non-observation of ^{73}Rb may be due to the population of an isomer that proton decays before the ground state can be reached [1]. It is, however, worth noting that the cross sections measured in this work are well reproduced by the EPAX3.1a cross sections (see supplementary material).

Half-lives were determined by following the procedure outlined in Ref. [18]. These were calculated from the flight paths through BigRIPS and the ZeroDegree spectrometers, 769.0 ns and 779.8 ns for ^{72}Rb and ^{73}Rb, respectively, the initial activity, and the measured yield for ^{72,73}Rb. The initial activities of ^{72,73}Rb were determined by interpolation of the neighbouring yields. The quadratic interpolation shown in Fig. 2 gives an estimated number of produced events as 10020(230). It has been pointed out in Ref. [24] that around the drip-line, the cross sections can be reduced by the weak binding. Thus, we estimate a conservative upper limit of 125 ns, corresponding to a factor of ten in reduction of the quadratic interpolation. With a similar argument, we get an upper limit of 81 ns for the ^{73}Rb half-life, consistent with the upper limit of 30 ns reported in Ref. [23], and a value of 103(22) ns for the new isotope ^{72}Rb. A tentative evidence for the existence of ^{77}Zr was also observed with one count. The measured cross-section for this isotope, $1.2(^{+29}_{-10}) \times 10^{-10}$ mb is consistent with the EPAX3.1a estimate of 4.49×10^{-10} mb.

Using the formalism from Refs. [25, 26], calculations for proton emission from deformed nuclei were performed. In these calculations, a non-adiabatic model for the parent and daughter nuclei wave functions was used. The odd proton in odd-even nuclei or the odd proton and neutron in the case of odd-odd nuclei, are coupled to the experimental spectrum of the even-even core. This guarantees that the rotational excitation of the daughter nucleus is correctly implemented. To take the residual pairing interaction into account, the diagonalisation of the Coriolis interaction has been performed between quasi-particle states. Therefore, pairing is introduced in the calculation in a consistent way, not just as an external spectroscopic factor as in the pure adiabatic model. For the parameterization of the single particle potential Esbensen and Davids paremtrization [27] was used, but also the universal paremtrization [28] gives consistent results. For spectroscopic factors a BCS calculation was used. In this case, the $f_{5/2}$ single particle level in our potential is quite full and below the Fermi surface at zero deformation. This gives a single-particle spectroscopic factor of the order of 0.3.

The proton emission calculations for ^{73}Rb considered a

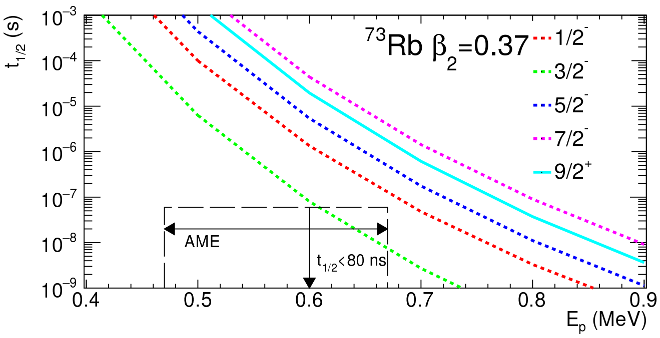

FIG. 3: Theoretical proton emission half-lives for a fixed deformation of $\beta_2 = 0.37$ as a function of the energy of the escaping proton and for different decaying states. The experimental upper limit of the half-life from this work was determined to be 81 ns, which corresponds to a minimum proton energy of 600 keV. The dashed black line shows the upper limit of the half life from this work, and the mass limits from the AME (see text), which translates into a restriction on the proton decay energy of 570(100) keV.

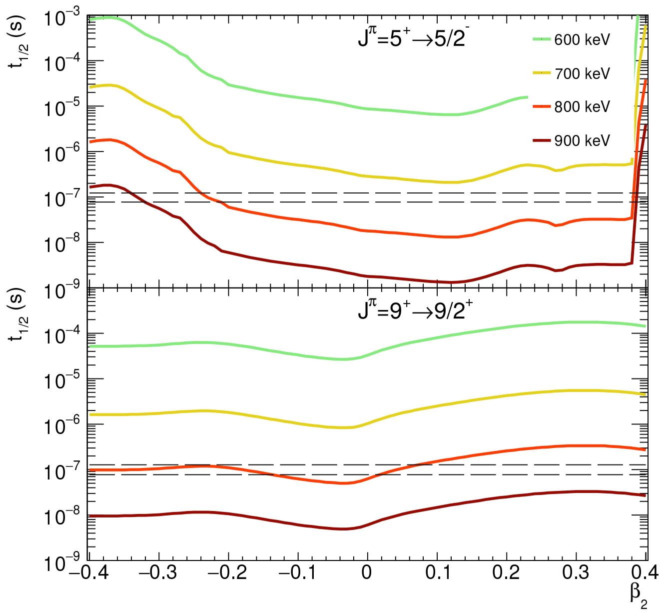

FIG. 4: Theoretical proton emission half-lives as a function of deformation and different proton separation energies for the decay of the 5^+ (main component $\nu 5/2^- \otimes \pi 5/2^-$) (top) and 9^+ (main component $\nu 9/2^+ \otimes \pi 9/2^+$) (bottom) states in ^{72}Rb to the $5/2^-$ and $9/2^+$ states in ^{71}Kr, respectively. The dashed lines show the limits of the half-life measured in this work.

Nilsson proton quasi-particle coupled to the experimentally known excited states of the even-even core ^{72}Kr. The calculations provided the half-life for proton emission as a function of deformation and proton separation energy, for different angular momenta values of the decaying state. An example of this is shown in Fig. 3, for a nuclear deformation of $\beta_2 = 0.37$, as predicted by the finite-range droplet model (FRDM) [29]. The results do not change much in the case of a negative deformation of the same magnitude. The mirror nucleus of ^{73}Rb is ^{73}Kr, where the ground state is suggested of to have a spin-parity of $3/2^-$ [30]. Assuming that mirror symmetry holds, from Fig. 3 one can conclude that there is a lower bound to the energy of the escaping proton, i.e. $E_\mathrm{p} > 600$ keV, in order to fulfill the upper limit of 81 ns for the half-life found in this work. This results is consistent with the atomic mass evaluation (AME) separation energy $S_\mathrm{p} = -570(100)$ keV [31, 32].

In the case of ^{72}Rb, previous calculations have provided a separation energy well beyond the proton drip line. In Ref. [33] the calculated $S_\mathrm{p} = -0.800$ MeV for ^{72}Rb and in Ref. [34] the GXPF1A and Jun45 shell-model interactions resulted in $S_\mathrm{p} = -0.81$ MeV and $S_\mathrm{p} = -1.73$ MeV, respectively. There is, however, a clear staggering in the AME where the odd-odd proton-rich nuclei in the Rb chain consistently have a larger proton-separation energy than their heavier odd-mass neighbour. As ^{72}Rb is an odd-odd nucleus, interpretation is less straightforward than in the ^{73}Rb case as the odd neutron is not a spectator and contributes actively to the decay process [35]. Therefore, to understand the proton emission of ^{72}Rb, the neutron levels in the daughter nucleus ^{71}Kr must be taken into account.

The calculations of the excitation spectrum for ^{71}Kr yield four possibilities for the ground-state spin. For negative parity with large negative deformations, the lowest state is predicted to be $1/2^-$ while for large positive deformations, the lowest state is predicted to be $5/2^-$ or $3/2^-$. Similar calculations for the positive parity states predicts the lowest state to have a spin and parity of $9/2^+$ for all positive and negative values of the deformation. From an experimental point of view, the situation regarding the spin and parity of the ground state of ^{71}Kr is unclear. In Ref. [36] the mirror partner ^{71}Br level scheme is investigated in detail and, assuming that mirror symmetry holds, that experimental data are consistent with a $J^\pi = 5/2^-$ ground state for ^{71}Kr.

In the following discussion we shall focus on the states with $J^\pi = 5/2^-$ and $J^\pi = 9/2^+$. This means that the possible ^{72}Rb dominant components of the wave functions have a $\pi f_{5/2} \otimes \nu f_{5/2}$ and $\pi g_{9/2} \otimes \nu g_{9/2}$ configuration, giving rise to $J^\pi = 5^+$ and $J^\pi = 9^+$ states, respectively [37]. In Fig. 4 the calculated half-lives for different proton separation energies are shown as a function of deformation for the $J^\pi = 5^+ \to 5/2^-$ and $J^\pi = 9^+ \to 9/2^+$ proton decays.

As shown in Fig. 4, the experimental half-life of 103(22) ns suggests a proton decay energy of between 700 and 800 keV for the 5^+ state decaying to the $5/2^-$ state at large positive deformation or between 800 and 900 keV at large negative deformation. For the 9^+ state the proton separation energy is close to 800 keV in most of the deformation range, but is increasing towards 900 keV at large positive deformation. This is in good agreement with the AME where a value of $S_\mathrm{p} = -710(520)$ keV is estimated for ^{72}Rb. This is, however, only valid for the case of 9^+ being the ground state. It is also interesting to compare the np spin-aligned 9^+ state in ^{72}Rb with the corresponding state in the mirror nucleus, ^{72}Br, where the lowest 9^+ state is located at 1448 keV. Such a state could decay to a $9/2^+$ state in the daughter nucleus of ^{72}Rb, ^{71}Kr. The mirror nucleus for ^{71}Kr is ^{71}Br, for which the $9/2^+$ state is known at 759 keV. Such a decay would give an additional energy of 689 keV to the emitted proton, which would be significantly larger than allowed from the observed half life shown in Fig. 4, giving a total energy range of 1089 to 2129 keV for the proton when adding the ground-state to ground-state S_p value of the AME. A similar reasoning around the $f_{5/2}$ states, where the $5/2^-$ state in ^{71}Br is located at 669.56 keV and the 5^+ of ^{72}Br at 543.90 keV, gives an energy range of 274 to 1314 keV for the emitted proton, in good agreement with the half life as indicated in Fig. 4.

Based on these results we have estimated the effect of a value of $S_\mathrm{p} < -600$ keV in ^{73}Rb in a one-zone and one-dimensional model of an X-ray burst, looking for changes in the pathway and the possibility to bypass the ^{72}Kr waiting point. For full details see Refs. [38, 39]. The initial conditions of the burst assume a solar abundance of H, He and and a metallicity of $Z = 10^{-3}$. We have used burst time-scales consisting of a rise time of 4 s and a cooling phase of 200 s [40]. Assuming an upper limit of $S_\mathrm{p} < -600$ keV no two-proton capture was produced, effectively disabling the two-proton bypass of ^{72}Kr in the *rp*-process network as there are virtually no ^{73}Rb nuclei available to undergo proton capture. This result is consistent with, but more stringent than, the more general but less realistic results from Ref. [41] where an upper limit of the reaction rate as 20 % of the β^+ half-life was obtained.

Given the observation of one ^{77}Zr, there is a possibility that this nucleus is proton-bound, or has a bound isomeric resonance, and can be populated in the *rp*-process to create a more exotic pathway, close to the drip-line. The S_p for ^{76}Y and ^{77}Zr were investigated to create such a pathway. However, the ^{77}Zr branch was not populated at 0.5-1 MeV, while at 1.25 MeV the branching is 5-10%. Thus, the S_p for ^{76}Y and ^{77}Zr would need to be at least 1.0 MeV and 1.25 MeV, respectively, for the *rp*-process to proceed in a more exotic manner, which seems unlikely.

In conclusion, we have estimated the proton-decay half-life of ^{72}Rb and obtained an upper limit of the half-life of ^{73}Rb. Based on mirror-symmetry arguments and theoretical calculations within the non-adiabatic quasi-particle model, we have interpreted the proton emission from these nuclei as a decay from the $3/2^-$ and 5^+ states in ^{73}Rb and ^{72}Rb, respectively. However, it can not be excluded that the decay in ^{72}Rb is from a 9^+ isomer. Using the constraints of the new half lives in the calculations, the energies of the protons emitted from these nuclei are expected to be more than 600 keV and around 800 keV for ^{73}Rb and ^{72}Rb, respectively. These values are in good agreement with the predicted values from the AME. Using these results in network calculations of X-ray burst scenarios we conclude that ^{72}Kr is a strong waiting point in the *rp*-process.

Acknowledgments

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