New proton drip-line nuclei relevant to nuclear astrophysics

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Abstract. We discuss recent results on decay of exotic proton rich nuclei at the proton drip line for \( Z < 50 \), that are of great importance for nuclear astrophysics models. From the interpretation of the data, we assign their properties, and impose a constraint on the separation energy which has strong implications in the network calculations.

1. Introduction
Nuclear structure far from stability plays a crucial role in the processes that lead to the formation of the elements [1, 2] In the specific case of the proton drip-line, its location constrains the path of the rapid proton capture reactions (rp) that lead to the nucleosynthesis of medium heavy elements in explosive astrophysical scenarios such as in supernovae, and X-ray bursters [3], and to determine the reaction rates needed for the calculation of the abundances [4].

In such scenarios, the density and temperature are so high, that rapid proton capture can occur, and unstable nuclei will be generated up to and beyond the proton drip-line. The path for these reactions depends on the level structure and existence of specific resonances in proton rich nuclei. The existence of isomeric states, for example, might change to higher masses the location of waiting points that held the process. Therefore, the link between reactions and properties of exotic nuclei and astrophysical observables for explosive scenarios is very strong.

However, direct experiments with unstable nuclei are still challenging, creating an obstacle to our understanding of their structure, and implying that a great part of the nuclear structure at the extremes of stability, still relies on theoretical extrapolations. It is then crucial to have a solid theory, with great independence from parameterizations, which would be capable to interpret the experimental data and predict new features.

The observation of proton radioactivity [5, 6], and its theoretical interpretation [7, 8] has made possible to access the nuclear structure properties in the neutron deficient region of the nuclear chart, for nuclei with charges \( 50 < Z < 81 \). It has also provided an indirect way to determine separation energies [9], an important input in the network calculations, and to the understanding of the rp process.

Proton radioactivity from nuclei with \( Z < 50 \) is also very important to determine the time scale of the (rp) capture path, which in this region runs along the proton-drip line, but up to now, proton emission from the ground state has only been observed in two nuclei, \(^{93}\text{Ag}\) and \(^{89}\text{Rh}\) [10].

The observation and theoretical interpretation of these exotic decays, specially if they encompass the waiting points isotopes will help to understand their nuclear structure, that
controls how the capture process evolves. A good example the nucleus $^{72}$Kr, a waiting point isotope whose properties have not been determined by direct measurements, but where the knowledge of the proton separation energies, and half-lives of the neighbour Rb isotopes recently produced at Riken [11, 12], would allow to establish the most probable path through $^{72}$Kr.

Theoretical models developed to explain decay by proton emission, provide consistent interpretation of the experimental data, helping to determine some nuclear properties. They can explain very well the measured half-lives for spherical as well as deformed nuclei, predicting the nuclear shape parameters and quantum numbers of the decaying states. Microscopic studies of deformed proton emitters allow to test the details of the nuclear wave function to which the half-lives are quite sensitive.

The most consistent non-relativistic theoretical approach for proton emission is the non-adiabatic quasiparticle approach [7], which is very successful in bringing out several interesting features of deformed odd-even proton emitters including the triaxially deformed ones [13]. Its extension to odd-odd nuclei [14], suggested that it is possible to test the residual neutron proton interaction [15] and to determine the neutron Nilsson level even if the neutron does not participate actively in the decay [16]. Electromagnetic transitions can also be described within the model in a consistent way [17, 18].

It is the purpose of this work to discuss recent developments in the study of proton rich nuclei with $Z < 50$, and their relevance to nuclear astrophysics, and to the study of fundamental symmetries. From the interpretation of their decay data by proton emission, we will identify properties of their spectra and shape, and deduce constraints to the astrophysical processes.

2. Decay of $^{73}$Rb

Particle decay is the only way to obtain information on separation energies of very short lived nuclei at the limits of stability, but not always the energy of the escaping nucleon is measured, and only information on the half life is obtained. Therefore, theoretical models can play an important role in providing some hint on the range for these energies.

The case of $^{73}$Rb is an interesting example in this context. In a multi-fragmentation experiment at RIBF Riken [11, 12], where a 124Xe beam of 345 MeV/u was impinged on a

![Figure 1. Nilsson proton resonances in 73Rb as a function of deformation.](image-url)
beryllium target, different neutron deficient nuclei were produced with charges below Z=50. The nucleus $^{73}$Rb was not directly observed, but from the observation of the decay of neighbouring nuclei, it was possible to derive an upper limit for the half-life of the ground-state of this nucleus.

We have performed calculations for decay by proton emission of $^{73}$Rb, within the non-adiabatic quasiparticle model. According to mass formula estimates of Möller-Nix [19], $^{73}$Rb is expected to have a quite large quadrupole deformation, of the order of $\beta_2 \approx 0.37$. As a first step in our calculation we have determined the proton Nilsson resonances in the daughter nucleus $^{72}$Kr, that are shown in Fig 1 as a function of deformation. They were obtained as solutions of the Schrödinger equation with outgoing boundary conditions in the single particle mean field with the parameterization of Ref. [20].

In order to obtain the spectrum of the decaying nucleus, we have to diagonalize the full Hamiltonian, containing the Nilsson contribution, the pairing residual interaction, and the rotational contribution, which includes the spectrum of the core and the coupling of the proton to the experimental spectrum of the even-even core $^{72}$Kr, which is known experimentally [21]. The latter guarantees that the rotational excitation of the daughter nucleus is correctly implemented. The residual pairing interaction is taken into account in the calculation in a consistent way, by diagonalizing the Coriolis interaction between the quasi-particle states.

Following this procedure, the calculation of the spectrum of $^{73}$Rb gives various possibilities for the angular momentum and parity of the lowest states in energy, which are the possible candidates for the ground-state. We found that for positive parity states the $9/2^+$ is the lowest one, for all positive and negative values of the deformation. In the case of negative parity states, and large deformation $\beta > 0.3$ the calculation predicts as the lowest state the $3/2^-$ or the $5/2^-$. The region in the nuclear chart of Rb isotopes, presents drastic changes of deformation oscillating from very large prolate to very large oblate shapes. Whereas $^{70-72}$Rb isotopes are oblate, heavier ones above $^{73}$Rb, and lighter ions below $^{69}$Rb, are prolate. The same occurs in the Kr region where $^{73}$Kr has $\beta \approx 0.38$, and $^{72}$Kr has $\beta \approx -0.35$. Besides these rapid changes

![Figure 2. Theoretical half-lives, as a function of the proton energy, for decay of the lowest energy states, at a fixed positive deformation $\beta_2 = 0.37$](image)
of shape, shape coexistence is also possible, making these region a quite challenging probe for theoretical models.

The next step is the calculation of the half-lives for decay from the lowest states close to the Fermi surface, previously obtained by the diagonalization of the Hamiltonian. these are the states that should have a large spectroscopic factor. We have followed the procedure described in Ref.[7], and the results are presented in Fig.2, and Fig.3.

Since the energy of the emitted proton is not known, the figures are done as a function of the proton escaping energy, and due to the great ambiguity in the attribution of a definite deformation, the calculation was done for the deformation predicted by Möller-Nix [19], and also for a large oblate deformation $\beta = -.37$, which is the deformation of the daughter nucleus. As it can be seen from the figures, for the same deformation and different energies, the half life just scales.

From the RIBF Riken experiment of Ref. [11, 12], an upper limit of 80 ns was found for the half-life. From the analysis of Fig 2., a decaying state consistent with this value, would need that the proton escaping energy should be above 600 KeV. If the prediction of Möller-Nix [19] for the deformation is correct, and $^{73}$Rb has a prolate deformation, the $3/2^-$ would be a good candidate as the decaying state. The conclusions are very much the same, as it can be seen from Fig 3., if the nucleus has instead a large oblate deformation of the same magnitude, or even for large deformations different from the Möller-Nix value.

The lower bound found in our calculation for the proton energy, imposes a constraint on the proton separation energy in $^{73}$Rb, coming directly from the experiment. According to the recent evaluation of atomic masses, AME2016 [22, 23], the proton separation energy in this isotope is $S_p=-570(200)$. Our results are in agreement with these predictions, and are the first time that a direct experimental constraint of $S_p$ is found. This has important implications for nuclear astrophysics, since the half-life of a waiting point depends exponentially on the $S_p$ of the intermediate nucleus.

In x-ray bursts, the temperature is quite high, therefore, the rapid proton capture processes
for the formation of the elements, proceeds through a sequence of fast \((p, \gamma)\) reactions, but the flow can be slowed down if there are nuclei in the path that have very long \(\beta\) decay half-lives, and very small proton separation energies. Then, \(\beta\) decay will compete with the proton capture and the low Q-value, will suppress the p capture rate. The burst observables [24] will be affected by this behavior, but to interpret these observables, the half lives of the waiting points have to be well determined.

The nucleus \(^{72}\text{Kr}\), is one of the waiting points in the sequence, so the proton separation energy in \(^{73}\text{Rb}\) is very important to obtain the half-life of this isotope. Also, since \(^{73}\text{Rb}\) is unbound, it might also be possible a competition between two-proton capture and beta-decay. The constraint on \(S_p\) through network calculations, can tell us if \(^{72}\text{Kr}\) is a strong waiting point with an rp-process flux not larger than expected. X-ray bursts calculations with this limit on \(S_p\) [25], seem to indicate that the two-proton capture thorough \(^{72}\text{Kr}\) is inhibited.

### 3. Conclusions

In conclusion, the theoretical interpretation of the experimental data on proton decay from proton rich nuclei, provides the possibility to predict the properties of the decaying state, and impose directly from the experiment, constraints on the separation energy. This information, is quite relevant for nuclear astrophysics studies, specially when the decay process involves a waiting point, as in the case discussed in this work.

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