Nuclear structure of proton drip-line nuclei as an input to nuclear astrophysics

L.S. Ferreira and E. Maglione
Centro de Física e Engenharia de Materiais Avançados CeFEMA, Instituto Superior Técnico,
Universidade de Lisboa, Avenida Rovisco Pais, P1049-001 Lisbon, Portugal

Abstract. The observation, and the theoretical interpretation of the decay of proton rich nuclei at the proton drip line, are a probe to the nuclear structure at the extremes of stability, with strong implications to nuclear astrophysics models. Nuclear levels, and proton separation energies, can be assigned in these studies, establishing information that could not be obtained otherwise due to very short lifetimes of these nuclei.

1. Introduction
Understanding the structure of nuclei at the proton drip line is vital to the progress of nuclear astrophysics [1, 2]. From the observation of the nuclear chart of the elements, it can be seen that for nuclei with charge Z below 50, the path of the rapid proton capture processes that lead to the nucleosynthesis of medium heavy elements in explosive astrophysical scenarios, like supernovae, and thermonuclear explosions on the surface of accreting neutron stars, seen as X-ray bursters [3], seems to follow the N=Z line up to the neighbourhood of the double shell closure N=Z=50 nucleus $^{100}$Sn, and it is constrained by the proton drip line.

Along the trajectory of the rp capture, there are waiting points, nuclei with a very small proton emission Q-value, which make the half-life for proton emission too long to allow competition of beta decay over p capture. The flow of the rp process will slow down, thus decreasing the production of heavier elements, and will affect strongly the burst observables. There are three possible waiting points, $^{64}$Ge, $^{68}$Se, and $^{72}$Kr, but there are open questions concerning their nature and, also about the existence of possible bottlenecks.

To establish the most probable path through these nuclei, not only their half lives have to be well determined, but the proton separation energies, and half-lives of the neighbouring nuclei need to be known. Details of the nuclear structure, like the possible existence of specific resonances, also play an important role. The observation of proton emission in these nuclei, and the determination of the Q-value, for the process, can answer some of these questions.

The rp process ends up in a loop just above Z=50, due to the presence of an island of alpha emitters, besides the decay by proton emission. The nuclei involved in the cycle are the proton rich Tin, Anthimonium, and Tellurium isotopes, but it is still questionable which are the isotopes that exactly define the trajectory of the termination process. An important ingredient to identify the path, is the knowledge of the proton separation energy $S_p$ in the neighboring isotopes, which might not be obtained directly. However, with the identification of proton and alpha decay branches in some isotopes, relations between Q values due to energy conservation can be found, and one might infer from them unknown Q values.
This was the case for the determination of $S_p$ in $^{105}\text{Sb}$, using the discovery of an $\alpha$ decay branch from the known proton emitter $^{109}\text{I}$ [4]. Since decay of $^{108}\text{Te}$ was already well established, the separation energy was immediately obtained from the relation $Q_{\alpha}(^{109}\text{I}) + Q_p(^{105}\text{Sb}) = Q_p(^{109}\text{I}) + Q_{\alpha}(^{108}\text{Te})$.

Similarly, from a weak proton emission branch recently observed in $^{108}\text{I}$ [5], and the measured $Q_p(^{108}\text{I})$, and $Q_{\alpha}(^{107}\text{Te})$ values, the proton-decay $Q$ value for $^{104}\text{Sb}$ was also indirectly extracted $Q_{\alpha}(^{108}\text{I}) + Q_p(^{104}\text{Sb}) = Q_p(^{108}\text{I}) + Q_{\alpha}(^{107}\text{Te})$.

In both examples, the use of the determined energies in network calculations with a one-zone X-ray burst model [6] could not predict significant branching to the Sn-Sb-Te cycle via the $^{103}\text{Sb}$ or the $^{104}\text{Sb}$ isotopes.

Proton rich nuclei along the drip line have very short half lives to render possible experimenting with them. They are produced in fusion evaporation reactions, and also in multi-fragmentation processes, where the half-life and Q-value are obtained in the first process, and only information about the half-life is available in the second production mechanism. From these experimental observations, and their theoretical interpretation, not only information about the proton separation energy can be obtained, but also, nuclear structure details of the decaying nucleus can be revealed.

Theoretical models have been developed, based on realistic mean field approaches, that can predict the nuclear shape parameters and quantum numbers of the decaying states of axial and non-axial deformed nuclei [7, 8, 9]. Fully selfconsistent calculations, using more fundamental interactions based on relativistic density functionals derived from meson exchange and point coupling models, were also able to account for the experimental data of proton radioactivity from spherical nuclei and deformed [10, 11].

It is the purpose of this work to discuss examples of proton emitters with charge $Z<50$, where a theoretical interpretation of the decay process could provide relevant information for the nucleosynthesis process.

2. Proton emission and the rp-process

Until quite recently, the observation of one proton radioactivity for nuclei with $Z<50$ had only found nuclei decaying from isomeric states [12]. It was only in the last three years that decay from the ground state was observed in the nuclei $^{72}\text{Rb}$, $^{73}\text{Rb}$ [13], $^{93}\text{Ag}$ [14], $^{89}\text{Rh}$ [14], $^{28}\text{Cl}$ [15], and $^{30}\text{Cl}$ [15].

The Rb isotopes were produced in a multi-fragmentation experiment at RIBF Riken [13], by collision of a 124Xe beam of 345 MeV/u on a beryllium target. The nucleus $^{72}\text{Rb}$ was observed and half-life was measured, but the nucleus $^{73}\text{Rb}$ was not directly observed, and only an upper limit for the half-life of the ground-state could be determined. The nucleus $^{73}\text{Rb}$ decays to $^{72}\text{Kr}$, a waiting point in the sequence, that might be overtaken by two proton capture, depending on the proton separation energy $S_p$ in $^{73}\text{Rb}$. However, the proton $Q$ value could not be measured in the experiment, but the theoretical calculation could provide a lower bound for this quantity.

According to mass formula estimates of Möller-Nix [16], both isotopes are expected to have a quite large quadrupole deformation. Therefore, we have performed calculations for decay by proton emission within the non-adiabatic quasiparticle model [7], which treats the proton Nilsson resonances in the field of the daughter nucleus exactly, and describes the structure of the decaying nucleus by the Nilsson contribution, the pairing residual interaction, and the rotational contribution, which includes the spectrum of the core and its coupling to the proton state, thus guaranteeing that the rotational excitation of the daughter nucleus is correctly implemented.

The rotational spectra of the core $^{72}\text{Kr}$, is known experimentally [17]. This is not the case for $^{71}\text{Kr}$, so the spectra of the even-even neighbour was used instead. The parameters of the single-particle potential were the ones derived by Esbensen and Davids [18], but the results were consistent with the ones using the universal parameters [19]. The residual pairing interaction
is taken into account in the calculation in a consistent way, by diagonalizing the interaction between the quasi-particle states.

In the case of decay by proton emission of $^{73}$Rb the experiment gave an upper limit of 80 ns for the half-life. In our calculation [13], considering the prolate deformation predicted by Möller-Nix [16] $\beta_2 \approx 0.37$, we found that the $3/2^-$ would be a good candidate as decaying state, with a proton escaping energy larger than 600 KeV in order to reproduce the experimental half-life. For details see Ref. [13]. A proton separation energy $S_p=600$ keV is consistent with $S_p=-570(200)$ keV suggested in the recent evaluation of atomic masses, AME2016 [20, 21]. A ground state decay from the 3/2$^-$ is also consistent with mirror symmetry, since the mirror of $^{73}$Rb is $^{73}$Kr, where the ground state also has a spin parity of 3/2$^-$.

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, with important implications for nuclear astrophysics, since the half-life of a waiting point depends exponentially on the $S_p$ of the intermediate nucleus, and it can increase by an order of magnitude if the decay Q value decreases by $\approx 100$ keV. The x-ray bursts observables [22] shape and intensity, provide the possibility to see the nature of a waiting point, but to interpret these observables the half lives of the waiting points have to be well determined. Network calculations, can tell us if $^{72}$Kr is a strong waiting point with an rp-process flux not larger than expected. Calculations performed with this limit on $S_p$ [23], seem to indicate that the two-proton capture thorough $^{72}$Kr is inhibited, and the nucleus is a strong waiting point.

The calculation for $^{72}$Rb was more elaborate since it is an odd-odd nucleus, and the emission of one proton is quite dependent on the state of the unpaired neutron. The daughter nucleus in this case has an odd number of nucleons, and its angular momentum is determined by the Nilsson level occupied by the odd neutron. Different values of this angular momentum, will allow different values of the angular momentum of the escaping proton [24, 9]. It was found that the best candidates as decaying state were the 5$^+$ which has a main component of the wave function with both proton and neutron in the 5/2$^-$ state, decaying to the 5/2$^-$ of 71Kr as discussed in Ref. [13]. It was also possible a decay from an isomeric 9$^+$ state, with a main component of proton and neutron in the 9/2$^+$ state, decaying to the 9/2$^+$ of the daughter. Since the escaping energy is not known, a plot of the half-life for decay from these states as a function of energy and assuming the nucleus has the Möller-Nix [16] predicted deformation of $\beta_2 \approx -0.37$, the experimental half-life is reproduced if the proton energy is of order of 800 keV, also consistent with atomic masses evaluation AME2016 [20, 21].

Proton emission in the vicinity of $^{100}$Sn, from $^{93}$Ag and $^{89}$Rh were also observed at Riken[14] with the same reaction used for Rb isotopes. The half-life of $^{93}$Ag was estimated to be $t_{1/2}=228$ (16) ns, and an upper limit of 120 ns was deduced for the half-life of $^{89}$Rh. No information was obtained on the energy of the proton. Both nuclei are almost spherical, so we have performed a relativistic mean-field calculations based on covariant density functional theory (CDFT) [10].

The advantage in relation to the non relativistic microscopic models that are based on parameterizations of the nuclear mean field available in the literature, relies on the fact that, (CDFT) is derived from relativistic quantum field theory, and fulfills Lorentz invariance allowing to describe consistently the spin-orbit coupling. Thus, the number of parameters of the functionals to be adjusted in order to reproduce bulk properties of nuclei are restricted. The nuclear surface is described by the inclusion of a density dependence or by using nonlinear coupling terms. The interactions derived along these lines, as the non-linear meson exchange model the NL3 [26] and the density dependent point coupling models the DD-PC1 [27], describe ground-state properties and collective excitations of stable and exotic nuclei at the extremes of stability, and map the proton drip-line.

We have performed a self-consistent calculation following the procedure described in Ref. [10] with the NL3 and DD-PC1 interactions, of proton emission from $^{93}$Ag and $^{89}$Rh [25]. The
experimental half lives were reproduced for a proton emitted from a $g_{9/2}$ ground state, with an escaping energy of $\approx 1040$ keV in the case of $^{93}$Ag, and with a lower bound of 990 keV for $^{89}$Rh. Consequently, the calculation could determine the proton separation energy for nuclei whose properties are important for the flow of the rp process in the region of $^{100}$Sn. Both interactions gave very similar results.

3. Conclusions

In conclusion, proton emission from proton rich nuclei, is the perfect tool to unveil the structure of nuclei relevant to our understanding of the rp process for the synthesis of the elements in the Universe. The theoretical interpretation of the experimental decay data, gives the possibility to predict the properties of the decaying state, and impose directly from the experiment, constraints on the separation energy. A very solid theory exists for this purpose, that has been applied quite successfully to interpret the available data at the extremes of proton stability.

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