Journal of Physics: Conference Series **580** (2015) 012034 doi:10.1088/1742-6596/580/1/012034

The structure of proton rich nuclei in nuclear astrophysics

L.S. Ferreira

Centro de Física das Interacções Fundamentais, and Departamento de Física, Instituto Superior Técnico, Avenida Rovisco Pais, P1049-001 Lisbon, Portugal

Abstract. The properties of exotic proton rich nuclei are of great importance for nuclear astrophysics models. In the present work, we show how to address many nuclear structure properties of these nuclei at the extremes of stability, from the analysis of proton radioactivity.

1. Introduction

Reaching the limits of bound nuclei is one of the major challenges for modern nuclear physics. Due to the appearance of new experimental facilities and technologies using radioactive ion beams, nuclei with an excess of protons or neutrons are being produced in the laboratory, mapping vast regions of the nuclear chart. The limits of stability for nucleon emission are established for proton rich nuclei almost up to charges equal to 83, and for neutron rich nuclei up to oxygen [1]. The development of new detection techniques and the use of storage rings, and Penning traps, allowed the measurement with high precision of masses, half-lives and branching ratios for decay, and even the energy spectrum in some cases. The availability of these data offered the possibility to test the quality of theoretical model predictions for fundamental properties of the nucleus at the extremes of isospin, where it becomes unstable against nucleon emission.

An overview of the main astrophysical processes shows that the vast majority of reactions encountered in the chains for the formation of the elements, involve quite unstable species. The various scenarios to explain the production of stable heavy nuclei, will go through combinations of (p,γ) and (n,γ) captures, or emission reactions (γ,n), (γ,p) and (γ, α) completed by β-decays and electron captures.

The path for the rapid proton capture processes might involve nuclei close to the proton drip-line[2], and in most cases, a stable p-nuclide will be synthesized through a quite unstable progenitor formed at the end stage of the evolution of massive stars, where there are enough seed nuclei, and high temperatures, for the reactions to take place.

Nuclear astrophysics models strongly depend on a very precise determination of the reaction rates and reaction energies. Since the nuclei involved are very unstable and short-lived, the cross sections for most reactions are unknown, but the energies can be obtained from nuclear masses. Particle-decay spectroscopy is for most of these nuclei the only way to determine their properties, like separation energies and identification of the decaying states. An interesting example[3] is provided by the indirect determination of the separation energy of a proton in ^{105}Sb, relevant for the rapid proton capture in the Sn-Sb-Te cycle at various Sn isotopes. It was achieved through the measurement of the Q-value for a very small α decay branch of the proton radioactive ^{109}I, and this new measurement, imposed strong constraints on the proton capture flow for the various isotopes.

For the calculation of the reaction rates, some of the nuclear ground state properties, like masses, and deformations, need to be known. Many reaction chains along the rp processes can go via direct or resonance capture of the proton, therefore, the properties of the excited states are also required. Moreover, the evaluation of the reverse (γ,p) reaction, is of key importance in the proton capture networks.

The previous discussion points out the strong link between astrophysical properties needed for explosive scenarios, and the properties of exotic proton rich nuclei, short lived and only known from their decay data. Nuclei at the proton drip line tend to be proton radioactive. The theoretical interpretation of this phenomena, can unveil relevant features of the structure of proton rich nuclei.

2. The spectra and shape of proton rich nuclei

The emission of a proton from the ground and excited states of exotic drip-line nuclei, with charges ranging from Z=50 up to Z=83 has been measured extensively in the last two decades [4]. The emission of two protons has been also observed in the decay of ^{45}Fe[5, 6], and afterwards for other lighter nuclei[7].

Theoretical models developed to explain this radioactive decay, provide consistent interpretation of the experimental data, helping to determine some nuclear properties. Realistic mean field models, can predict the nuclear shape parameters and quantum numbers of the decaying states of deformed nuclei[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 [10].

A model that reproduces the experimental half lives and branching ratios for decay to excited states, will also assign the spins and parities of the decaying states, and the nuclear shape parameters. Consequently, these decay modes can be used to probe the wave functions of the nuclear levels involved and to study also nuclear shell effects. The non-adiabatic-quasi-particle model, has been very successful in this context, and was able explain many aspects of the structure of odd-even nuclei, with an odd number of protons[11], as well as odd-odd nuclei[12], including the breaking of axial symmetry. We will discuss below a few cases which might be relevant in the nuclear astrophysics context.

It is difficult to determine experimentally the structure of very proton-rich nuclei due to the small production cross section. A quite recent experiment, provided very good data for the proton radioactive ^{151}Lu nucleus[13]. Using recoil proton tagging, the lifetime of the first excited state above the proton emitting ground state as well as higher-lying longer-lived states have been measured using γ ray coincidence techniques.

Theoretical calculations based on the non-adiabatic quasi-particle model, coupling the quasi-particles with the spectra of the daughter nucleus, suggest that the proton emitting ground state of ^{151}Lu is a h11/2$^-$, and has a mildly oblate quadrupole deformation of $\beta \approx$ - 0.11.The experimental value of the half-life for decay from the ground state is reproduced assuming this deformation, and is also consistent with the calculation of the life time of the first excited state, which decays by an electromagnetic γ-ray transition. These results, provide the best evidence to date for proton emission from an oblate nucleus.

The spectrum of ^{151}Lu is shown in Fig 1. The theoretical calculation of the energy levels were obtained by diagonalizing the interaction between the quasi-particle states and the spectrum of the daughter nucleus. For details see reference[13]. This example, is an interesting determination of shape parameters, and spectrum of drip-line nuclei, through the observation of proton decay.

Another important nucleus for astrophysical calculation is ^{18}Ne, since the breakout path from

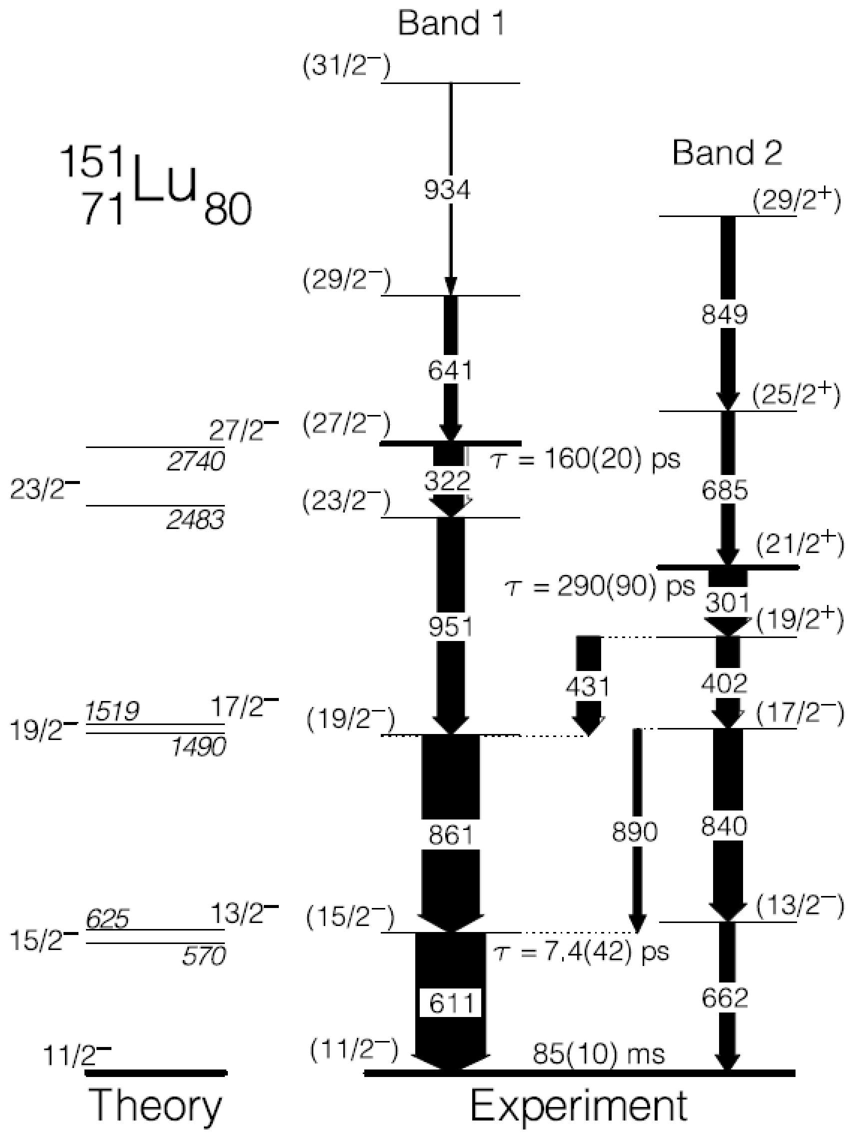

Figure 1. Theoretical and experimental excited states in ^{151}Lu from Ref[13].The widths of the arrows correspond to the intensities of each transition, with the white component of each arrow indicating the calculated internal conversion component.The life times of the states are also shown.

the hot CNO cycle involve sequences of alpha particle reactions that proceed through the ^{18}Ne resonances, above the alpha decay threshold. The determination of resonances in ^{18}Ne is then an important issue to obtain the reaction rates, but they are not easy to observe experimentally [14].

The reaction ^{17}F(p,γ)^{18}Ne is particularly important for the rp-process path, and it is just the inverse of proton decay from resonances in ^{18}Ne, which exhibits two proton radioactivity[15, 16]. The analysis of these experiments, beside finding the simultaneous two proton emission from a 1^- state at 6.15 MeV, that has been discussed together with the sequential decay through the ghost of the $1/2^+$ in reference [17], has also shown at higher excitation energy a strong branch, ≈30%, for sequential emission of one proton after the other, going through excited states of ^{17}F

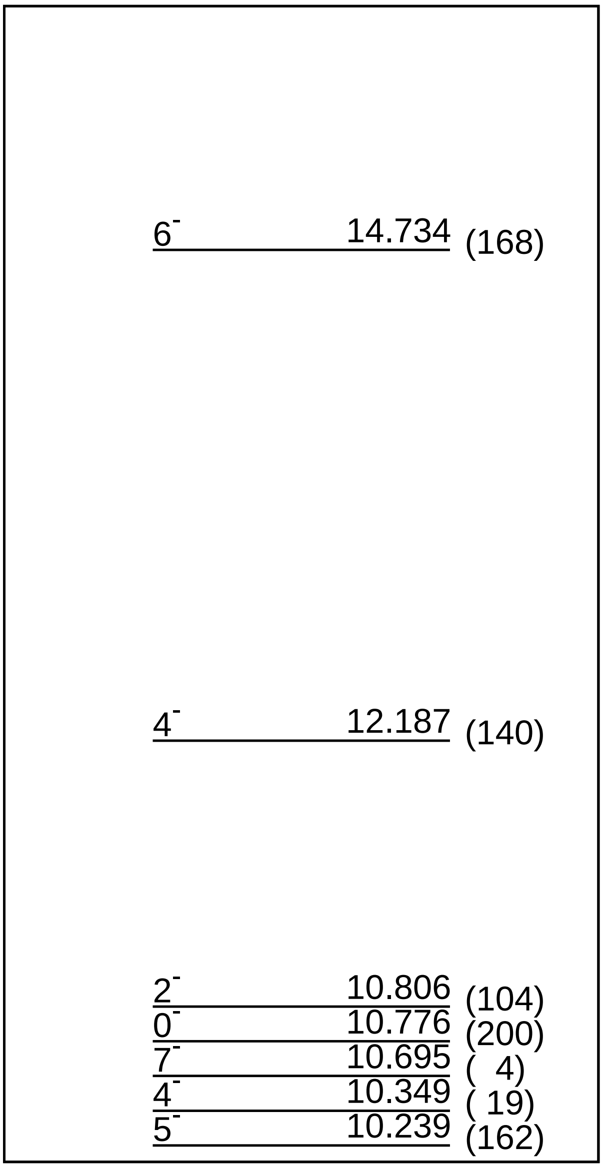

Figure 2. Calculated excited states in ^{18}Ne with a total width smaller than 200 keV and a branching ratio for decay to unbound states larger than 0.7. The spin and parity, and energy in MeV of the decaying level are given in the figure. The width of the resonances in KeV, are shown in parenthesis.

before reaching the final daughter nucleus ^{16}O in the ground state.

This is quite surprising, since simple barrier penetration considerations would favour a decay with the largest amount of energy being carried out by the first proton, thus to the ground state of ^{17}F that is bound, and consequently the second proton would not be emitted. A smaller percentage decays directly by simultaneous two proton emission. A theoretical analysis in terms of sequential decay, can lead to the identification of possible excited states, candidates for the emission of the second proton.

Since ^{18}Ne is a spherical nucleus, the half-life can be calculated according to scattering theory, from the knowledge of the proton state and the spectroscopic factor. The latter, can be determined from a standard shell model calculation with a realistic interaction. We have used the interaction of reference [18] which was fitted to the experimental excitation energies, and reproduces the experimental data for all sd nuclei.

The calculation shows that there are excited states of negative parity at quite high energies in ^{18}Ne, which are very narrow, and prefer to decay by one proton emission to the excited states than to the ground state of the daughter ^{17}F, thus becoming possible candidates for the emission of a second proton in a sequential two-proton decay process. Some were confirmed by the experimental studies of Raciti and collaborators[15]. The calculation of branching ratios for decay to unbound proton states in ^{17}F, shows meaningful values for negative parity states at quite high energy, and are presented in figure 2. This example shows the power of proton emission to identify the spectra of proton radioactive nuclei.

In the region of production of medium heavy isotopes, N=Z nuclei play an important role, since rp processes seem to follow the N=Z line up to the neighbourhood of the double shell closure N=Z=50 nucleus ^{100}Sn. The structure of these drip-line nuclei influences the rates at which the reactions can proceed, and the residual pairing proton neutron interaction can be quite influential.

Proton emission from odd-odd nuclei, can also be useful in this context, since 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 [19]. The theoretical interpretation of proton emission from odd-odd based on the adiabatic quasi-particle model, is also well established [12], and includes the proper treatment of residual pairing and neutron-proton interactions. It is possible to single out the angular momentum and parity of the ground state of these emitters and estimate the effect of the residual np interaction.

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, the nuclear deformation, end the existence of isomeric states. This information, might be quite relevant for nuclear astrophysics studies.

Acknowledgments

This work was supported by the Fundação para a Ciência e a Tecnologia (Portugal), Project: CERN/FP/123606/2011.

References

[1] Thoennessen M, Sherrill B M 2011 *Nature* **473** 25
[2] Arnould M, Goriely S 2003 *Phys. Rep.* **384** 184
[3] Mazzocchi C, *et al.* 2007 *Phys. Rev. Lett.* **98** 212501
[4] Sonzogni A 2002 *Nucl. Data Sheets* **95** 1
[5] Pfutzner M, et al. 2002 *Eur. Phys. J.* A **14** 279
[6] Giovinazzo J, *et al.* 2002 *Phys. Rev. Lett.* **89** 102501
[7] Blank B, Ploszajczak M 2008 *Rep. Prog. Phys.* **71** 046301
[8] Fiorin G, Maglione E and Ferreira L S 2003 *Phys. Rev.* C **67** 054302
[9] Arumugam P, Ferreira L S and Maglione E 2009 *Phys. Lett.* B **680** 443
[10] Ferreira L S, Maglione E and Ring P 2011 *Phys. Lett.* B **701** 508
[11] Arumugam P, Maglione E and Ferreira L S 2008 *Phys. Rev.* C **78** 041305
[12] Patial M, Arumugam P, Jain A K, Maglione E and Ferreira L S 2013 *Phys. Rev.* C **88** 054302
[13] Procter M G, *et al.* 2013 *Phys. Lett.* B **725** 7984
[14] Almaraz-Calderon S *et al.* 2012 *Phys. Rev.* C **86** 025801
[15] G. Raciti, *et al.* 2008 *Phys. Rev. Lett.* **100** 192503
[16] C. J. Lin, *et al.* 2011 *AIP Conf. Proc.* **98** 1409
[17] Brown B A, Barker F C , Millener D J 2002 *Phys. Rev.* C **65** 051309(R)
[18] M. Bouhelal *et al.* 2011 Nuc. Phys. **A 864** 113
[19] Ferreira L S and Maglione E 2001 *Phys. Rev. Lett.* **86** 1721