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Nuclear structure constraints on nucleosynthesis

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Summary. — Nuclear structure properties of proton rich nuclei at the limits of stability are an importance input for nuclear astrophysics models. The theoretical interpretation of the experimental decay data of these nuclei, makes possible the assignment of nuclear levels, and proton separation energies, crucial to understand how the rp process for the formation of the elements flows, and how it ends.

1. – Introduction

One of the open questions within Nuclear Physics research topics, both on the experimental and theoretical sides, regards the formation of the elements, and the interpretation of their abundances in the Universe. Recent developments in ion separation, gamma detection, and time measurements, allowed to deal with very small cross sections, measure very short half lives of the order of the nanosecond, and observe the spectrum of drip line nuclei. The extremes of stability were reached for many regions of the nuclear chart specially, on the proton rich side that is almost defined up to Z=83. This is quite relevant to the understanding of nucleosynthesis processes that evolve from reactions between elements very far from stability. The path followed by the rapid proton capture rp process that lead to the nucleosynthesis of medium heavy elements in explosive astrophysical scenarios, involves nuclei at the p drip line, and is constrained by its location.

On the neutron rich side of the nuclear chart, the limits were reached up to Oxygen isotopes, Z=8 [1], and was extended up to Z =10, with the recent discovery in the BigRIPS at Riken, of ^{31}F and ^{34}Ne isotopes [2]. Heavy nuclei with masses larger than A=70, are mainly formed in the slow (s) and rapid (r) neutron-capture nucleosynthesis processes in supernovae explosions. The s- process runs close to the valley of stability, so its is better known, in contrast with the r-process, that runs very far from it. The time scale for n capture is competing with the time scale for the nucleus to undergo beta decay, so, it is quite challenging in the lab to add another neutron to a nucleus far from stability. Therefore, a major part of the nuclear chart on the heavy nuclear side is quite unknown, so are the trajectories for the n-capture processes.

There are many open questions in our understanding of the evolution of the rp-process and of the nuclei involved in it. At the early stages of of nucleosynthesis of light elements, a possible breakout path from the hot CNO cycle to the rp process goes through the sequence of reactions ^{14}O(α,p) ^{17}F(p,γ)^{18}Ne, that proceed through resonances of ^{18}Ne above the alpha decay threshold. These states are not easily accessed experimentally [3].

Along the path of the rp process, 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 with beta decay over p capture. The process will slow down, and the production of heavier elements is inhibited. The path through these nuclei, depends on the knowledge of their half lives as well as the ones of their neighbouring nuclei. But the energy spectrum and existence of specific resonances of the nuclei involved in the process also plays an important role. The existence of isomeric states, for example, might change the location of waiting points.

The rp- process has also been predicted to end up as a loop around neutron-deficient Sn-Sb-Te isotopes in the neighbourhood of 100Sn, which is a region of alpha emitters located at the verge of the proton drip-line. [4] The knowledge of which nucleus is involved in the loop, depends on the knowledge of the proton separation energies (Sp) of these isotopes, an important input in the network calculations [5].

The examples described above, prove that the input for nuclear astrophysics models to understand the trajectory, time scale and ending point of the rp- process requires the knowledge of the nuclear structure properties of nuclei at the extremes of stability. Even the great progress achieved in high precision mass measurements of nuclei at the extremes of stability, can provide an answer to all these questions. These facts, make it a difficult problem, since these nuclei are extremely unstable to be used in direct experiments. One has to resort to indirect processes, that proton decay from dip line nuclei provides. From the theoretical study of this phenomena [6-8], the interpretation of proton decay observables gives information on the quantum numbers and shape of the decaying nucleus, imposing constraints on Sp and thus providing an answer to open questions involving waiting points and to the end up cycle of the rp-process. It is the purpose of this work to present these theoretical studies.

2. – Proton emission and the rp process

Proton radioactive nuclei lie beyond the proton drip nuclei, with the decaying proton in a single particle resonance. The observation of its decay in fusion evaporation reactions, allows to measure the escaping energy of the proton, equivalently, the Q value, and the half life. In the case of production by a multifragmention reactions, only a time limit for the half-life is obtained.

Theoretical models have been developed to interpret decay from a deformed nucleus [9, 10], based on different assumptions. The non-adiabatic-quasi-particle model [11], is based on a full quantum treatment of decay, with very few parameters, and only coming from a well established mean field interaction.

It has a proper treatment of the residual pairing and in case of decay from an odd-odd nucleus [12,13] also includes the neutron-proton residual interactions. The rotational spectra of the daughter nucleus is taken into account by the coupling of the quasi-particles with the spectra of the daughter nucleus. If this spectra does not exist, the Coriolis interaction will be diagonalized in the quasi-particle states base.

The model, been very successful in explaining many aspects of the structure of odd-even nuclei, with an odd number of protons [14], as well as odd-odd nuclei [13], including the breaking of axial symmetry. The spins and parities of the decaying states, and the nuclear shape parameters, could be assigned. In the case of odd-odd nuclei, it is possible to estimate the effect of the residual np interaction.

2˙1. *Resonances in* ^{18}Ne. – 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. Two proton radioactivity from ^{18}Ne was observed for the first time at the Laboratori Nazionali del Sud in Catania [15], and later in another experiment in Lanzhou [16]. The analysis of these experiment of Ref. [15], beside finding the simultaneous two proton emission from a 1^- state at 6.15 MeV, has also shown at higher excitation energy a strong branch, ≈69%, for sequential decay emission of one proton after the other, going through excited states of ^{17}F before reaching the final daughter nucleus ^{16}O in the ground state.

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 directly 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 ref. [17] which was fitted to the experimental excitation energies, and reproduces the experimental data for all sd nuclei.

The calculation [8] shows that there are excited states of negative parity at quite high energies, above 10 MeV, which are very narrow, and prefer to decay by one proton emission to the excited states instead of going 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 of these states were confirmed by the experimental results of ref. [15]. This example shows the power of proton emission to identify the spectra of proton radioactive nuclei.

2˙2. *The waiting point* ^{72}Kr. – Around Z=70, 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 position of possible bottlenecks.

To establish the most probable path through these nuclei, not only their half lives have to be well determined, but the knowledge of the proton separation energies, and half-lives of the neighbouring nuclei also needs 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.

In a multi-fragmentation experiment at RIBF Riken [6], the isotopes ^{72}Rb and ^{73}Rb were produced granting the measurement of the half-life for proton emission from the ground state of ^{72}Rb, and an upper limit for the half-life of ^{73}Rb which was not directly observed. The nucleus ^{73}Rb decays to the waiting point ^{72}Kr, and there is the open question about the possibility of being overtaken by two proton capture, and guaranty the flow of the rp-process. This depends on the proton separation energy in ^{73}Rb, which was not measured in the p decay experiment. The theoretical interpretation of decay, provided by the non-adiabatic particle model, could reproduce the experimental half-life,

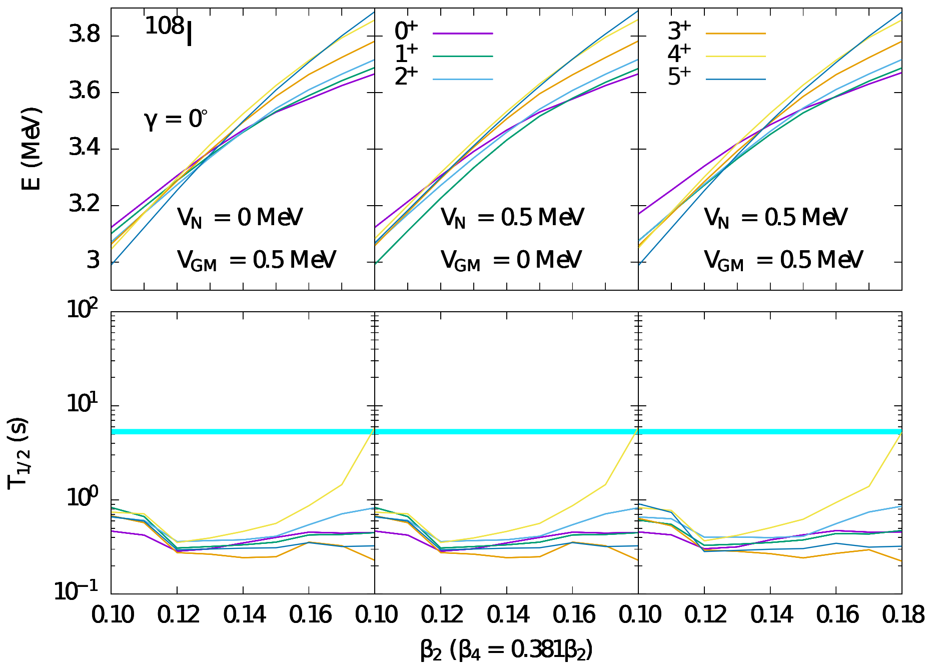

Fig. 1. – Rotational energies (upper panels) and half lives (lower panels) of ^{108}I, for decay from positive parity states, as a function of β deformation, and with triaxial deformation γ=0. The np interaction is taken as a constant force. Different values for the force are considered changing the GM splitting and the Newby shif. The horizontal bar indicates the experimental half-life.

if the nucleus as a deformation $\beta_2 \approx 0.37$, consistent with Möller-Nix prediction [18], the decaying state is the $3/2^-$ state, and the proton escaping energy is larger than 600 KeV. For details see ref. [6]. A proton separation energy S_p=-600 keV is consistent with S_p=-570(200) keV suggested in the recent evaluation of atomic masses [19,20]. 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 $3/2^-$.

With the present limit for the proton separation energy, the possible effect of bypassing ^{72}Kr on a one-zone and one- dimensional model of an x-ray burst [21], was not observed. There is no p stable ^{73}Rb for a two-proton capture to occur, therefore, ^{72}Kr is a good waiting point.

2·3. *The Sn-Sb-Te end cycle.* – The synthesis of heavy nuclei via the rp process is limited to nuclei with charges up to Z=54. One of the questions about the identification of the isotopes involved in the ending loop of the rp process, that goes through the Sn-Sb-Te cycle, is the participation of ^{104}Sb, from which p emission is not known. A weak proton emission branch of .5% was recently observed in the neighbour nucleus ^{108}I [5] at Argonne National Lab, which mainly decays by alpha particle emission. With the measured $Q_p(^{108I})$ from this reaction, and the previously known Q values for α decay of ^{108}I, and ^{107}Te, it was possible to indirectly extract by energy conservation, the Q value for p-emission from ^{104}Sb.

The use of this energy in a network calculations with a one-zone X-ray burst model [21], could not predict a significant branching to the Sn-Sb-Te cycle via the ^{104}Sb isotope

[5]. However, besides the measurement of Q_p, and the half life ^{108}I, there is no knowledge about its nuclear structure, but it could be obtained from a theoretical interpretation of these decay observables.

Since it is an odd-odd nucleus, 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 [12]. Therefore, there will be various possible candidate states for decay.

The comparison with the experimental data, will allow to select the core model, and it has shown that axial symmetry is broken. It was only possible to interpret the experimental rotational spectra of the daughter nucleus ^{107}Te assuming non-axial deformation γ of order of 30^o. The calculated half-lives corresponding to decay from a 0^+ and 1^+ states were in agreement with the experimental data at this deformation. For details, see ref. [7]. The effect of a np residual interaction taken as a constant force with standard parameters, led us to conclude that the 1^+ was the decaying state, and also helped to completely exclude the possibility that axial symmetry was not broken, as fig. 1 shows. In the figure, no decaying state is able to cross the experimental value of the half-life, at any value of β deformation, without γ deformation.

3. – Conclusions

From the examples discussed in this work, it can be concluded that the study of proton emission from drip-line nuclei can provide answers to the flow and end cycle of the rp-process, the sequence of proton captures and β decays responsible for the burning of hydrogen into heavier elements up to Z=54. The theoretical interpretation of the experimental decay data in terms of the non-adiabatic quasi-particle model, is able to predict the deformation, and existence of possible resonances of the emitter, the nuclear structure properties of the decaying state, and impose constraints on the separation energy. All this information is crucial for nuclear astrophysics models.

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