Beta decay along the N=Z line and its relevance in rp-process and X-Ray bursts

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Abstract. Nucleosynthesis in Type I X-ray bursts (XRB) proceeds eventually through the rp-process near the proton drip-line. Several N=Z nuclei act as waiting points in the reaction network chain. Astrophysical calculations of XRB light curves depend upon the theoretical modelling of the beta decays of interest, with the N=Z waiting points ^{64}Ge, ^{68}Se, ^{72}Kr, ^{76}Sr, and their second-neighbours N=Z+2 being key nuclei in this context. We have carried out different experimental campaigns at ISOLDE (CERN) to determine the B(GT) distributions, in the decay of several N=Z, N=Z+2 and their daughters, of particular relevance in rp-process calculations. To this aim the Total Absorption Spectroscopy technique is applied. Here we present results on the beta decay of ^{64}Ga and the status of the analysis of ^{64}Ge. Our results provide benchmarks for testing and constraining models under terrestrial conditions that can be used later for predictions in stellar environments.

1 Introduction

Nucleosynthesis in explosive hydrogen burning at high temperatures ($T > 10^8$ K) is characterized mainly by the rapid proton capture (rp-) process [1]. Discussions of the possible scenarios for such extreme conditions can be found in Refs. [2] and [3], where Type I X-ray bursts (XRBs) are suggested as possible sites for the rp-process. These explosions are produced in binary systems in which a neutron star accretes hydrogen-rich material from a low-mass companion star, typically a Main Sequence or a Red-Giant star. Thermonuclear ignition takes place in semi-degenerate conditions, when the temperature and density in the

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accreted envelope become high enough to allow for a breakout from the hot CNO cycle. Nucleosynthesis eventually proceeds near the proton drip-line via the rp-process [4]. Type I XRBs are characterized by $T_{peak} = 1 - 3$ GK and $\rho = 10^6 - 10^7$ g cm^{-3}. To date, 118 XRB sources exhibiting these characteristics have been discovered, the last one reported in June-2022 [5].

Discussions of the main features and observations of XRBs can be found in Refs. [4][6][7]. In these works, different models of Type I XRBs are presented, with a focus on the nuclear physics processes involved along the rp-process path, and the sensitivity of the luminosity curves to changes in particular reaction cross sections and/or weak-decay rates (see for instance Fig. 1). It turns out that the beta decay of the waiting points and second-neighbours ^{64,66}Ge, ^{68,70}Se, ^{72,74}Kr and ^{76,78}Sr are particularly relevant for the energy generation, reaction flow, and final composition of the ashes from the burst [4]. Some of these decays, namely Kr and Sr, have been studied by our collaboration in the past at ISOLDE [8-11]. Lately, we have concentrated our efforts in the lighter systems, more specifically Ge and Se isotopes and their decay daughters, pointed out as key decays in most of the XRB models described e.g., in [4].

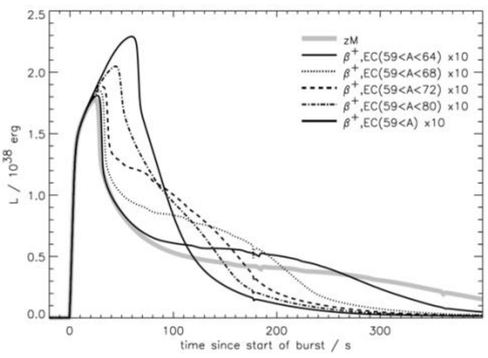

Fig. 1. Taken from [6]: sensitivity of the light curve of the first pulse in model zM to variations along the waiting points in the vicinity of A = 60, 64, and 68. The nominal light curve is shown along with the result when all weak rates above A = 59 are multiplied by 10. Also shown are the results of progressively adding in accelerations to flows in the mass ranges A = 60–63, 64–67, 68–71, and 72–79

Accurate measurements in terrestrial conditions of the aforementioned waiting points, daughters and neighbours are therefore essential to validate and constrain the theoretical models used for the computation of stellar decay rates because, as pointed out in [7], many decay rates computed in stellar conditions do not converge to their laboratory values for terrestrial conditions, thus putting in question the model used for these calculations. In this context, it was first pointed out by Sarriguren [12][13], pursued later by others [14][15], that the process of electron capture from the continuum (cEC), as well as the decay from thermally populated states in the WP nuclei and neighbours, actually play an important role in the weak-decay rates of nuclei close to the proton drip-line in XRB calculations. Quoting Ref. [12]: *"Although these decay properties (B(GT) distributions and half-lives) may be different at high ρ and T existing in rp-process scenarios, success in their description under terrestrial conditions is a requirement for a reliable calculation of the weak decay rates in more general conditions"*. In all the theoretical works mentioned in this paragraph the authors have used our experimental data taken with Lucrecia, the Total Absorption Spectrometer (TAS) at ISOLDE [8-11], for comparison and benchmark.

In the next section, the Total Absorption Spectroscopy technique will be explained and, in the following one, results on ^{64,66}Ga will be shown, along with some preliminary data reduction for the decay of ^{64}Ge.

2 Experimental technique

Even though one might think that the relevant physical quantity, as far as XRB model calculations is concerned, may be the half-life of the nucleus, this gives very limited information on the nuclear structure. In fact, different Gamow-Teller strength distributions (B(GT)) obtained with different models might lead to the same half-life. Therefore, in order to validate a theoretical model, capable of making predictions in a wide region of the nuclear chart and at stellar temperature and densities, one needs accurate experimental B(GT) distributions at terrestrial conditions, rather than β-decay half-lives [13]. Over the years it has been shown that the best tool to perform such an experimental study, in medium mass and heavy nuclei, is the so-called Total Absorption Spectroscopy (TAS) technique. Details on this technique can be found in [16].

The TAS technique is based on the use of gamma detectors of very high efficiency to absorb entire gamma cascades, rather than individual gamma rays, following the beta decay. The analysis of the data, to obtain a reliable B(GT) distribution, is based on the unfolding procedure described in [17]. One such detector is Lucrecia, at ISOLDE, described in [16]. It consists of a large NaI(Tl) cylindrical crystal, 38 cm diameter × 38 cm long, plus some ancillary detectors such as a HPGe telescope for X rays and gamma rays, and a plastic scintillator for betas. In spite of being the most sensitive way of measuring the missing beta strength, unseen in traditional high-resolution beta-decay experiments, the TAS technique provides data that require complex reduction and unfolding methods [17]. In particular, a proper TAS analysis requires an accurate estimation of all contaminants in the spectrum (room background, daughter activity, pileup contribution…).

With the aim of covering the the rp-process path down to its bottleneck ^{64}Ge, the experiment IS570 was carried out at ISOLDE, where we measured the decays of ^{64,65,66}Ge and their daughters ^{64,65,66}Ga.

3 Results

In the process of analysis of ^{64}Ge decay, we need to estimate the ^{64}Ga decay contribution and, with this aim, we measured clean ^{64}Ga samples during the IS570 run. Fortunately, ^{64}Ga, with $T_{1/2}$ = 2.6 min and Q_{EC} = 7.2 MeV, is interesting *per se*, and not only as a contamination in the decay spectrum of ^{64}Ge. In particular, ^{64}Ga decay is very relevant for isospin-mixing consideration since one can measure the beta population of the 0^+ ground state of the daughter nucleus ^{64}Zn that is, in principle, isospin forbidden Fermi $0^+ \rightarrow 0^+$, but populated as a consequence of isospin impurity of ^{64}Ga ground state [18]. The mixing of T=0 and T=1 in the ground state of ^{64}Ga is quantified by an admixture amplitude α that can be derived experimentally from the measured beta strength.

Fig. 2 shows the measured spectrum and resulting beta strength (integral) from our analysis of ^{64}Ga beta decay. In the left panel we can see, in black colour, the TAS spectrum as measured by the Lucrecia spectrometer at ISOLDE. This spectrum is overlaid to the Geant4 simulation of the same decay measured with the same detector, in red colour. As we can see, the fit is virtually perfect until 4.5 MeV excitation energy, where some discrepancies appear. The biggest difference lies at ~6 MeV, where the TAS data show a resonance that is not present in the simulation and therefore has not been reported or included in the Evaluated Nuclear Structure File ENSDF.

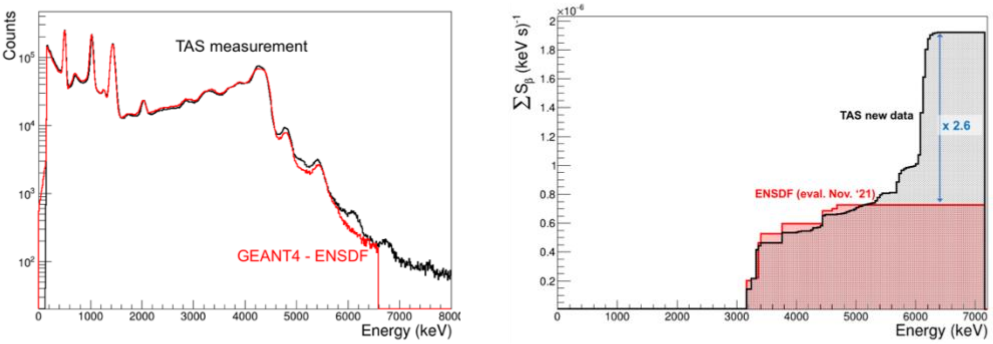

Fig. 2. Left: TAS spectrum of the beta decay of ^{64}Ga (black) compared to the Geant4 simulation of the same decay in the same detector using ENSDF data (red). Right: beta-strength distribution (integral) of the same decay resulting from the analysis of the TAS data (black) compared to the one from ENSDF (red).

The results of the analysis of the TAS spectrum of the left panel of Fig. 2 (black) are plotted in the right panel of the same figure, in black colour, in the form of the sum of the beta strength as a function of excitation energy in the daughter nucleus. In the same graph we see, in red colour, the same beta strength as derived from the evaluated data from previous works [18][19] (ENSDF - Evaluated November 2021). As we can see, the small differences between the ENSDF data and the new TAS data in the spectrum of Fig. 2 left, result in a factor of 2.6 more strength detected with the TAS measurement than in previous measurements. This difference results in a different isospin impurity derived from the beta strength and is, therefore, very relevant for isospin-mixing considerations. In this context, the preliminary admixture amplitude derived from our work $|\alpha| = 19.9\times10^{-3}$ is slightly smaller than the one from previous works $|\alpha| = 21.7\times10^{-3}$ [18].

The beta decay of ^{64}Ge, that is, according to [4], perhaps the most relevant in the region as far as rp-process calculations is concerned, is still under analysis. Fig. 3 shows the direct TAS spectrum of this decay, in black, compared to the Geant4 simulation of the same decay measured with the same detector, in red. Although no further analysis has been performed so far, already from the TAS spectrum one can see striking differences between the two spectra, and obvious new resonances appear from 2 MeV on. This decay is presently under analysis and we expect new results soon that will be published elsewhere.

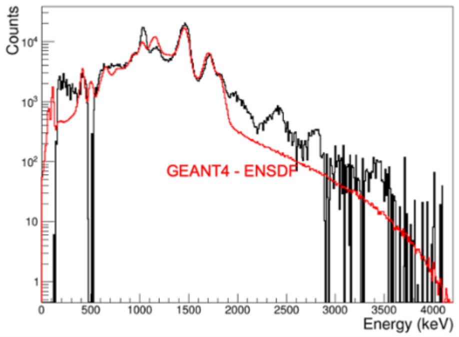

Fig. 3. TAS spectrum of the beta decay of ^{64}Ge (black) compared to the Geant4 simulation of the same decay in the same detector using ENSDF data (red).

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References

1. R.K. Wallace et al., Astrophys. J. Suppl. **45**, 389 (1981)
2. H. Schatz et al., Physics Reports **294**, 167 (1998)
3. H. Schatz et al., Nucl Phys A **777**, 601 (2006)
4. A. Parikh et al., Prog. Part. Nucl. Phys. **69**, 225 (2013)
5. P. Bult et al., Astrophys. J. Lett. **935**, L32 (2022)
6. S. Woosley et al., Astrophys. J. Suppl. **151**, 75 (2004)
7. J. Jose et al., Astrophys. J. Suppl. **189**, 204 (2010)
8. E. Poirier et al., Phys. Rev. C **69**, 034307 (2004)
9. E. Nacher et al., Phys. Rev. Lett. **92**, 232501 (2004)
10. A.B. Pérez et al., Phys. Rev. C **88**, 014324 (2013)
11. J.A. Briz et al., Phys. Rev. C **92**, 054326 (2015)
12. P. Sarriguren, Phys. Lett. B **680**, 438 (2009)
13. P. Sarriguren, Phys. Rev. C **83**, 025801 (2011)
14. Jameel-Un Nabi, Astrophys. Space Sci. **339**, 305 (2012)
15. A. Petrovici et al., Phys. Rev. C **100**, 015810 (2019)
16. B. Rubio et al., J. Phys. G **44**, 084004 (2017)
17. J. L. Taín et al., Nucl. Inst. and Methods A **571**, 728 (2007)
18. S. Raman et al., Nuclear Physics A **254**, 131 (1975)
19. L.G. Mann et al., Nucl. Phys. A **97**, 425 (1967)