EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Beta decay along the rp-process path for accurate stellar weak-decay rates: ^{68}Se and ^{70}Se

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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 ^{68}Se being a key nucleus in this context. Several such theoretical calculations have shown that, in these high-density and high-temperature scenarios, continuum electron capture and decay rates from excited states play an important role, in particular for nuclear species at and around the waiting-point nuclei. This proposal is aimed at the study of the beta decay of the waiting point nucleus ^{68}Se and its N=Z+2 second-neighbour ^{70}Se, with the main goal of determining the B(GT) distribution for these decays with the Total Absorption gamma-ray Spectroscopy method. The proposed study would provide a benchmark for testing and constraining models under terrestrial conditions that can be used later for predictions in stellar environments.

Requested shifts: 18 shifts, (split into 2 runs over 1 or 2 years)

Physics Case

Nucleosynthesis in explosive hydrogen burning at high temperatures ($T > 10^8$ K) is characterized mainly by the rapid proton capture (rp-) process [WAL81]. Discussions of the possible scenarios for such extreme conditions can be found in Refs. [SCH98] and [SCH06], 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 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 [PAR13]. Type I XRBs are characterized by $T_{peak} = 1 – 3$ GK and $\rho = 10^6 – 10^7$ g cm^{-3}. To date, 114 XRB sources exhibiting these characteristics have been discovered, the last one reported in March-2020 [BUI20].

Discussions of the main features and observations of XRBs can be found in Refs. [WOO04][JOS10][PAR13]. 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 [PAR13]. Some of these decays have been studied by our collaboration in the past at ISOLDE [POI04][NAC04][PER13][BRI15], however, there is very little knowledge of the decay pattern of ^{68}Se and ^{70}Se, that have been pointed out as key decays in most of the XRB models described for instance in [PAR13].

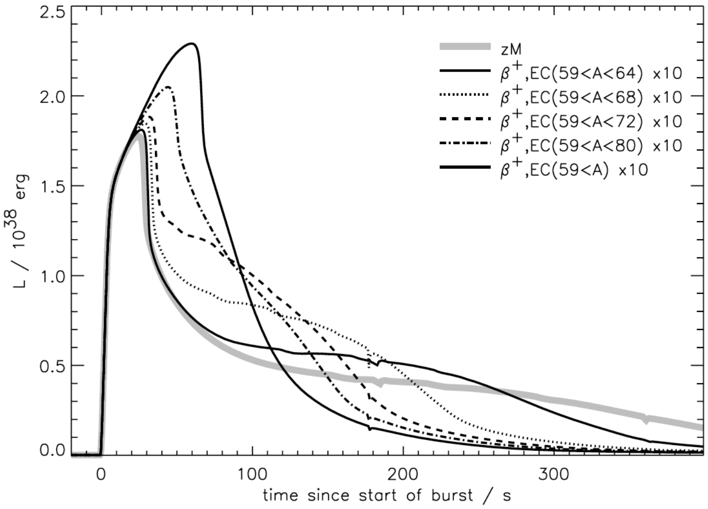

Fig. 1 *Taken from [WOO04]: Sensitivity of the light curve of the first pulse in model zM to variations along the waiting points in the vicinity of A = 60, 64, and 68. The nominal light curve is shown along with the result when all weak rates above A = 59 are multiplied by 10. Also shown are the results 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 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 [JOS10], 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 [SAR09][SAR11], pursued later by Nabi [NAB12], and recently reiterated by Petrovici [PET19], 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. Ref. [PET19], for instance, shows that the beta decay of ^{68}Se and ^{72}Kr have significant effects on the energy generation, reaction flow, and final composition of the ashes from the burst. We know from Ref. [SAR11] that the cEC-decay rates are higher than the β^+-decay rates by a factor of 8 for the WP nucleus ^{68}Se, and in the case of its even-even neighbour ^{70}Se this factor grows by as much as 150 (see Fig. 2 middle panels, black dots and blue dash-dot curves). Quoting Ref. [SAR09]: *"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 works mentioned in this paragraph the authors have used our experimental data taken with *Lucrecia*, the Total Absorption Spectrometer (TAS) at ISOLDE [POI04][NAC04][PER13][BRI15], to validate and constrain their calculations.**

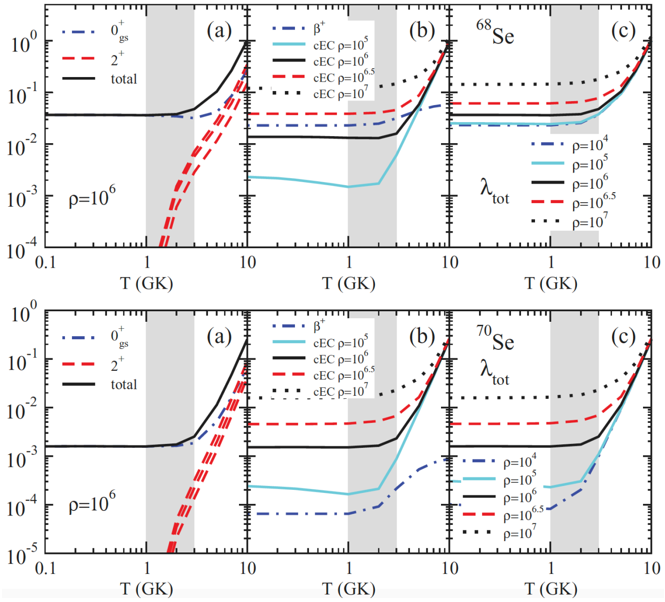

Fig. 2 *Decay rates in* s^{-1} *of* ^{68}*Se (upper panel) and* ^{70}*Se (lower panel) as a function of the temperature, taken from Ref. [SAR11].*

(a) Decomposition of the total rates into their contributions from the decays of the ground state and excited 2^+ *states.*

(b) Decomposition of the rates into their cEC and β^+ *components, evaluated at different densities, where ρ stands for* ρY_e *(mol* cm^{-3}*)*

(c) Total rates at various densities.

Previous Studies

Unfortunately, the β-decays of ^{68,70}Se are not well known. In particular, being the Q_{EC} value of the former 4705(2) keV [AME16], the highest known level populated in beta decay lies at 426 keV in ^{68}As [BAU94]. This lack of information on the rest of the Q_{EC} window is due to the low gamma efficiency of the experimental setups. This is why no B(GT) distribution is given in [BAU94]. The situation is not much better in ^{70}Se. Under these circumstances the Total Absorption Spectroscopy (TAS) measurement is the most appropriate approach to provide meaningful information in this region (see [RUB17] and references therein). This is the reason why we presented a proposal to the INTC in 2013 aimed at the study of the β-decays of ^{64,66}Ge and ^{68,70}Se and the determination of their respective B(GT) distributions [NAC13]. The proposal was approved for the measurement of the Se isotopes but not for Ge. However, during the course of the run in 2016, we could not see any Se beam but were able to proceed with measurements on Ge instead. At that time, we tried to extract Se as a molecule SeCO to avoid various sources of contamination, but unfortunately there was a much higher production of GeS molecules in the ion source and we could not measure the decay of ^{68}Se but ^{64}Ge instead. The analysis of the beta decay of ^{64}Ge is ongoing, and from the clean X-ray gated spectra we already see that our data contain a large fraction of the B(GT), that has not been observed in any previous experiment on this decay. The main goal of this new proposal is to measure the beta decay of ^{68}Se and ^{70}Se because of their relevance in the rp-process path, to serve as validation and constrain the decay rate calculations in the region (e.g. [SAR11][PET19]).

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, 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 [SAR11]. 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 technique. Details on this technique can be found in [RUB17]. It 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 [TAI07]. One such detector is Lucrecia, at ISOLDE, described in [RUB17]. Over the years, the use of this detector has provided the basis for several PhD theses and published articles [POI04][NAC04][PER12][BRI15][EST15] that have served as benchmarks for testing the aforementioned model calculations of [SAR11] and [PET19] among others.

One main ingredient for the TAS data analysis is the response function of the detector to the decay of interest. In other words: from the TAS data we will extract the beta intensity distribution and therefore the B(GT), the critical quantity for the astrophysical calculations, as long as we have a prior knowledge of the gamma de-excitation pattern of the daughter nucleus (level scheme and gamma branching ratios). Unfortunately, the only measurement of the beta-decay of ^{68}Se, that provides very limited information on the level scheme and gamma branching ratios of interest, dates back to 1994 [BAU94]. The most recent measurement of the same decay aimed at the determination of beta end-point energies does not include any information about the level scheme of the daughter [WOR04]. This is why we are now proposing to perform a second measurement of this decay at the ISOLDE Decay Station (IDS), where a set of segmented clover detectors can be combined with the conversion-electron spectrometer SPEDE [PAP18] to perform a full high-resolution study of the decays of interest.

Production

For the production and separation of ^{68,70}Se there are two different possibilities using a ZrO_2 fibre target. Firstly, from the measurements of $^{70}SeCO^+$ produced from ZrO_2-MK5 unit [HUR07] a production rate in the range of 100-200 ^{68}Se ions/μC is expected. We note that, at the ISOLDE-SC, the ^{68}SeCO yield was about 120 ions/μC [BAU94]. The extraction and separation of Se as a molecule, namely SeCO, will prevent a huge undesired contamination of ^{68}Ga. A second possibility, that would yield a much lower intensity, rises from the work of Chrysalidis et al. [CHR19], where the ISOLDE RILIS has been tested with a new laser scheme to ionise Se. In this second approach, we estimate a ^{68}Se yield of 20 at/s laser-ionised and extracted with the RILIS. Making a conservative assumption of a 70% beam transmission to our setup, we estimate 14 at/s implanted at the centre of the TAS or at the IDS chamber. In any case, we request an assessment of the Se beam production within the ISOLDE Target and Ion Source Development (TISD) programme. In what follows we will assume the worst-case scenario and use the more conservative yield of 20 at/s for the calculations.

For the TAS measurement, with this production-implantation rate, and taking into account that we will measure in symmetric cycles of 100 s (less than 1% losses in tape transport), we calculate 400000 decays per shift, which means 320000 counts in TAS-singles (total efficiency of TAS ~80%) and 128000 counts in TAS-beta coincidences per shift (efficiency of the beta detector ~40%). Based on those numbers, we have calculated that the beam time required is 6 shifts for ^{68}Se, aiming at 700000 counts in the beta-gated TAS spectrum. Since the production rate of the daughter is 2 orders of magnitude higher, we estimate 2 shifts for the change, re-adjustments in tape cycles and measurement of ^{68}As. For mass 70 the production rates are again roughly 2 orders of magnitude higher than those for mass 68, therefore 2 more shifts are required for ^{70}Se and the daughter ^{70}As.

For the IDS measurement, we have roughly 7.5% detection efficiency for conversion electrons below 400 keV, and, on average, 10% efficiency for gammas in the region of $E\gamma$~200 keV and 2.5% for $E\gamma$~2000 keV. In the most conservative scenario, we aim at 1000 counts in a 2 MeV peak in the HPGe singles energy spectrum (in γ-γ this means ~10-100 counts). This would require 6 shifts. In this case we do not need to measure the daughter, however we will also use 2 extra shifts for the decay of ^{70}Se. We do not need to perform the IDS and the TAS measurement one after the other. They can take place independently during different campaigns.

Summary of requested shifts:

8 shifts to measure ^{68}Se decay and its daughter decay with the TAS.
2 shifts to measure ^{70}Se decay and its daughter decay with the TAS.
6 shifts to measure ^{68}Se decay with the IDS combined gamma-conversion electron setup.
2 shifts to measure ^{70}Se decay with the IDS combined gamma-conversion electron setup.

A total of **18 shifts** are requested in this proposal.

References:

[AME16] W.J. Huang et al., Chinese Phys. C 41 (2017) 030002
[BAU94] P. Baumann et al., Phys. Rev. C 50 (1994) 1180
[BRI15] J.A. Briz et al., Phys. Rev. C 92 (2015) 054326
[BUI20] D.J.K. Buisson et al., reported to The Astronomer's Telegram (Apr-2020) (http://www.astronomerstelegram.org/?read=13563)
[CHR19] K. Chrysalidis et al., Eur. Phys. J. A (2019) 55: 173
[EST15] M. E. Estévez Aguado et al. Phys. Rev. C 92 (2015) 044321
[FIS08] J.L. Fisker, et al., Astrophys. J. Suppl., 174 (2008) 261
[HUR07] A.M. Hurst et al., Physical Review Letters 98 (2007) 072501
[JOS10] J. Jose et al., Astrophys. J. Suppl. 189 (2010) 204
[NAB12] Jameel-Un Nabi, Astrophys. Space Sci. 339 (2012) 305
[NAC04] E. Nácher et al., Phys. Rev. Lett. 92 (2004) 232501
[NAC13] E. Nácher et al., CERN-INTC-2013-009 / INTC-P-374
[PAP18] P. Papadakis et al., Eur. Phys. J. A (2018) 54: 42
[PAR08] A. Parikh et al., Astrophys. J. Suppl. 178 (2008) 110
[PAR13] A. Parikh et al., Prog. Part. Nucl. Phys. 69 (2013) 225.
[PEN09] L. Penescu et al., CERN-EN-Note-2009-001 STI
[PER13] A.B. Pérez et al., Phys. Rev. C 88 (2013) 014324
[POI04] E. Poirier et al., Phys. Rev. C 69 (2004) 034307
[RUB17] B. Rubio et al., J. Phys. G 44 (2017) 084004
[SAR09] P. Sarriguren, Phys. Lett. B 680 (2009) 438
[SAR11] P. Sarriguren, Phys. Rev. C 83 (2011) 025801
[SCH98] H. Schatz et al., Physics Reports 294 (1998) 167
[SCH06] H. Schatz et al., Nucl Phys A 777 (2006) 601
[TAI07] J. L. Taín et al., Nucl. Inst. and Methods A 571 (2007) 728
[WAL81] R.K. Wallace et al., Astrophys. J. Suppl. 45 (1981) 389
[WOO04] S. Woosley et al., Astrophys. J. Suppl. (2004) 75
[WOR04] A. Wöhr et al., Nucl. Phys. A 742 (2004) 349

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the Choose an item.	**Availability**	**Design and manufacturing**
TAS & IDS	☒ Existing	☐ To be used without any modification ☒ To be modified (The Tape Station should be updated)

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards	*[Part 1 of the experiment/equipment]*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure			
Vacuum	High Vacuum [10^{-6} mbar]		
Temperature	LN2 temperature [77 K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid			
Electrical and electromagnetic			
Electricity	6.0kV (HPGe det. HV supply)		
Static electricity			
Magnetic field			
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material			
Beam particle type	Ions : 68Se and 70Se		
Beam intensity	20 $s^{-1}$and 10^{5} s^{-1}, respectively		
Beam energy	60 keV		
Cooling liquids			
Gases			
Calibration sources:	☒		
• Open source	☐		
• Sealed source	☒ [ISO standard]		
• Isotope	^{152}Eu, ^{133}Ba, ^{22}Na, ^{241}Am, ^{60}Co		
• Activity	1 – 10 kBq		
Use of activated material:			
• Description	☒ ^{24}Na, 2 samples on tape		
• Dose rate on contact and in 10 cm distance	[dose][mSv]		
• Isotope	^{24}Na		
• Activity	50 kBq and 50 kBq		
Non-ionizing radiation			
Laser			
UV light			

Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

0.1 Hazard identification

3.2 Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): *(make a rough estimate of the total power consumption of the additional equipment used in the experiment)*
2.5 kW