EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Completing the puzzle around the ^{79}Se s-process branching with the ^{80}Se(n,γ) cross-section measurement

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V. Babiano Suarez[1], L. Caballero-Ontanaya[1], F. Calviño[2], A. Casanovas[2], G. Cescutti[3], J.W. den Hartogh[4], C. Domingo-Pardo[1], C. Guerrero[5], S. Heinitz[6], R. Hirschi[4,7], I. Ladarescu[1], C. Lederer-Woods[8], J. Lerendegui-Marco[5], A. St. J. Murphy[9], N. Nishimura[10], R. Reifarth[11], D. Schumann[6], J.L. Taín[1], A. Tarifeño-Saldivia[2] and the n_TOF Collaboration

[1] Instituto de Física Corpuscular (CSIC-Universitat de Valencia), Valencia, Spain
[2] Universitat Politècnica de Catalunya (UPC), Barcelona, Spain
[3] INAF, Observatorio Astronomico di Trieste, Trieste, Italy
[4] Astrophysics group, Lennard-Jones Laboratories, Keele University, Staffordshire, UK
[5] Universidad de Sevilla, Spain
[6] Paul Scherrer Institut, PSI Villigen, Switzerland
[7] Kavli Institute WPI, University of Tokyo, Japan
[8] University of Edinburgh, UK
[9] SUPA, School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK
[10] Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, Japan
[11] University of Frankfurt, Germany

Spokesperson(s): César Domingo-Pardo (Cesar.Domingo@ific.uv.es)
Luis Caballero Ontanaya (caballero@ific.uv.es)
Ariel Tarifeño-Saldivia (atarisal@gmail.com)

Technical coordinator: O. Aberle (oliver.aberle@cern.ch)

Abstract

We propose to measure the ^{80}Se(n,γ) cross section with high accuracy and high resolution at n_TOF EAR1, over the full energy range of astrophysical interest. These data are needed for a consistent interpretation of the temperature-sensitive s-process branching at ^{79}Se. The latter represents a key s-process branching point in the nucleosynthesis of heavy elements during core He-burning and shell C-burning in massive stars. The ^{80}Se cross section directly affects the stellar yield of the “cold” s-only branching product in this region, namely ^{82}Kr. There exist only one previous TOF measurement on ^{80}Se. However, the latter suffers of insufficient accuracy and completeness, owing to the 60cm flight-path used, the low energy cut-off at 3keV and a measuring set-up rather sensitive to scattered neutron backgrounds. All these aspects can be significantly improved with the present proposed experiment. This proposal represents a continuation of the Letter-of-intent CERN-INTC-2014-005.

Requested protons: [3x10^{18}] protons on target.
Experimental Area: EAR1.

1. Introduction and motivation

1.1. The s-process branching around ^{79}Se and the need for a new ^{80}Se(n,γ) measurement

The life-cycle of massive stars ($M>8M_{\odot}$) spans from H-burning (zero-age main-sequence), to He-burning and shell C-burning [Ben12]. The C-burning shell of the star is still active when the stellar core collapses thereby undergoing a supernova explosion. The latter two evolutionary stages, He- and C-burning, are characterized by a large release of neutrons via the ^{22}Ne(α,n) reaction, which induces nucleosynthesis of heavy elements up to A~90 on pre-existing Fe-seed nuclei [Fri16, Kap11]. Freshly synthesized long-lived radioactive nuclei ($T_{1/2}$>10 y) split this nucleosynthesis path, thus producing a local abundance isotopic pattern that can be used to probe the physical conditions of these different evolutionary stages.

One example is ^{79}Se($T_{1/2}$=3.27(8)x10^{5}y) (Fig.1-left). This nucleus has the nuclear peculiarity that it has a few quantum states at low excitation energy (Fig.1-right). These levels are thermally populated in the stellar environment and β-decay from these states is much faster than from the ground state, thus changing the effective half-life and the strength of the branching according to the thermal conditions of each stellar evolutionary stage. The final abundance pattern surrounding ^{79}Se and, in particular, the s-only nuclei ^{80,82}Kr[Ott88], are thus sensitive to the different thermal regimes of the two main evolutionary stages: the ~30 keV characteristic of He-burning and the ~90 keV regime in C-burning.

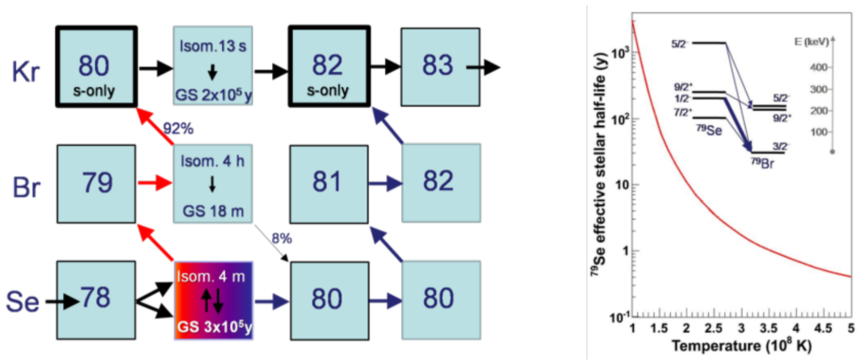

Figure 1(Left) The s-process path splits at ^{79}Se and this branching favours the nucleosynthesis of ^{80}Kr during the higher temperatures characteristic of shell C-burning. (Right) The effective half-life of ^{79}Se decreases with increasing temperature due to the β-decays from the ½- state in ^{79}Se populated in the stellar environment.

In order to analyze this s-process branching and extract information about the thermal conditions, one needs to know the neutron capture cross section of the ^{79}Se(n,γ) reaction, and the neutron capture rates of the neighboring nuclei as well. As discussed in the LoI[Dom14], the direct measurement of ^{79}Se(n,γ) is still out of experimental access, mainly due to limitations in both the existing measuring techniques and the possibility to produce a sufficiently pure and large sample of ^{79}Se. In the framework of the HYMNS ERC project[Dom16], this proposal intends to pave the way towards such a measurement by means of completing the nuclear data needs surrounding the ^{79}Se nucleus. Please, note that another proposal is being submitted also in this INTC-PAC, with the aim of developing new techniques that can be used for challenging measurements on small- and radioactive samples, such as ^{79}Se(n,γ).

An important step forward has been accomplished by the recent measurement at CERN n_TOF of ^{77,78}Se(n,γ) [Led17]. There is also a significant uncertainty contribution from the modeling of the weak rates involved in the decay (both β-, β+ and EC) of ^{80}Br at stellar temperatures, as discussed in [Nis17]. However, a consistent analysis of this branching will certainly benefit of an improved uncertainty of <5% for the neutron capture rates of all involved nuclei, and this calls for a measurement of the ^{80}Se(n,γ) cross section, as discussed below.

A post-processing calculation carried out with the NETZ tool for a representative 25M$_\odot$ single-zone trajectory [Weig95] shows that, while variations of the ^{79}Se(n,γ) cross section affect mainly the production of the β-decay branch (^{79}Br and ^{80}Kr), the nuclei synthesized via neutron-capture on ^{79}Se (^{81}Br, ^{82}Kr and ^{84}Kr) are still significantly affected by variations of the ^{80}Se(n,γ) cross section itself.

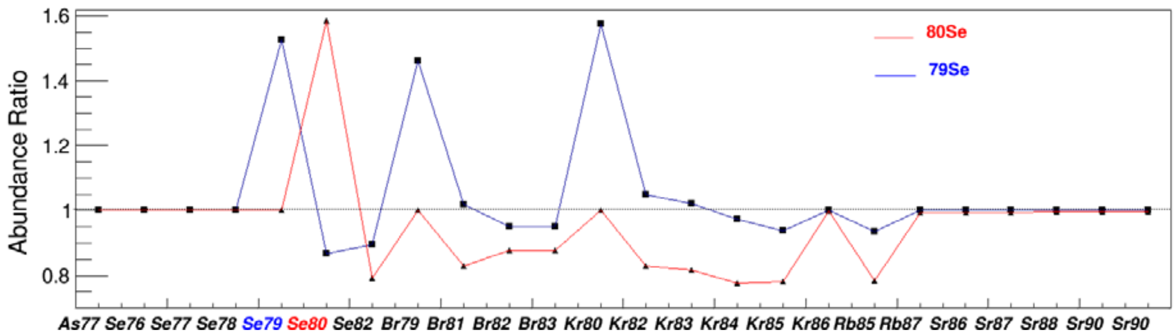

Figure 2. Single-zone post-processing calculation made with NETZ, showing the impact of a factor 0.5 in the (n,γ) cross section of both ^{79,80}Se.

For the sake of clarity, in this graphical sensitivity study the same cross-section (CS) variation factor of 0.5 was used for both ^{79}Se and ^{80}Se. While such a change may be representative of the present uncertainty on ^{79}Se, it is substantially larger than the estimated ~10% uncertainty at 30 keV for the CS of ^{80}Se given in KADONIS [Kadonis]. In this respect, it is worth to emphasize two aspects; Firstly, the uncertainty on the CS in the relevant energy region for shell C-burning, around 90 keV, is significantly larger than the 10% quoted at 30 keV for ^{80}Se. Secondly, neither the MACS, nor the 10% uncertainty quoted in KADONIS include the effect of the 3 keV low energy cut-off in the previous measurement [Wal86]. A calculation using the R-Matrix code SAMMY [Lar08] indicates that the resonances below 3 keV may amount to 30% and 7% of the MACS at 8 keV and 30 keV, respectively.

The sensitivity calculation shown above also illustrates that, while ^{79}Se affects mainly ^{79}Br and ^{80}Kr, the ^{80}Se cross section induces a smaller amplitude but far-reaching propagation effect over 9 heavier mass isotopes of Se, Br and Kr, hereby reaching the reference s-only 82Kr, and beyond. Therefore, a reliable and quantitative interpretation of the branching at 79Se will necessarily require of an enhanced accuracy (<5%) measurement of the ^{80}Se(n,γ) cross section in the full 1 keV-to-100 keV energy range, as commonly requested by stellar modellers [Nis17,Kap11].

Finally, a recent sensitivity study [Ces17] discusses also the relevance of the ^{80}Se(n,γ) cross section in low mass AGB stars (main s-process), where its current (KADONIS) uncertainty induces already an asymetric abundance variation of +29/-6% for ^{80}Se itself.

Regarding the status of the data, there exist only one previous TOF measurement of ^{80}Se[Walter86] (Fig.3), which suffers of two aspects. On one hand, it has a low-energy cut-off at 3 keV, which prevented the measurement of (one or more) large s-wave resonances in the keV-region. While these resonances could barely affect the nucleosynthesis during the hot conditions of shell-carbon burning, they can play a crucial role during core He-burning, where the temperatures of ~30 keV are reached. Apparently this effect is being neglected in present nucleosynthesis calculations. The second limiting factor of the previous experiment concerns the rather poor energy resolution due to the 60 cm short flight-path used.

These two aspects can be substantially improved by means of a new measurement at CERN n_TOF EAR1, where the full energy scale from thermal up to several hundreds of keV becomes available with an unparalleled TOF resolution thanks to the 185 m long flight path. A simulation of the expected quality of the data, as it would be measured at n_TOF is given below in Fig.5.

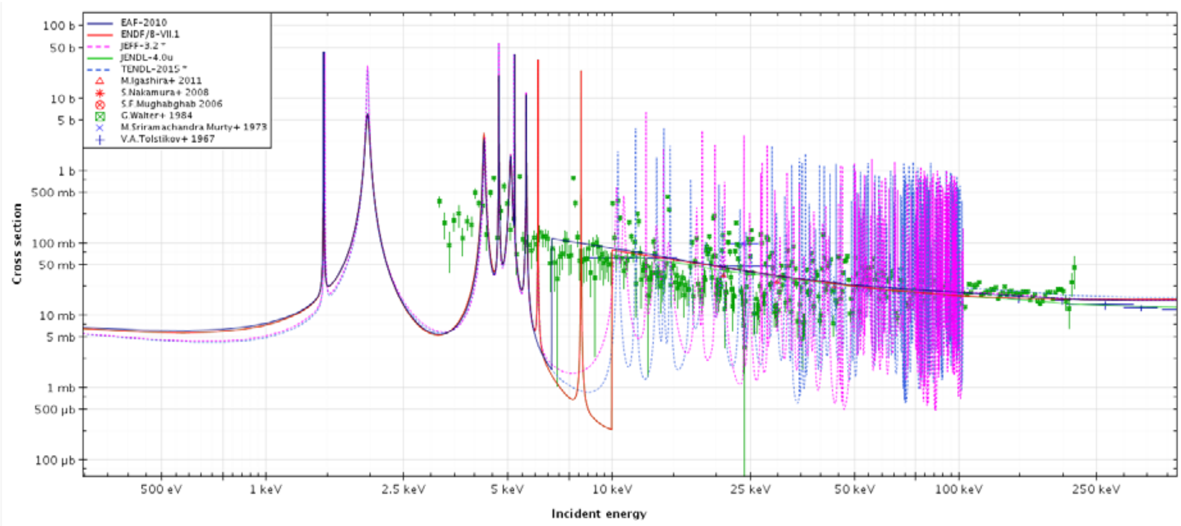

Figure 3Status of the data illustrated with strong discrepancies among different evaluations, mainly due to the limited resolution of the previous TOF measurement (green data points). See text for details.

2. Experimental apparatus and methodology

For the measurement ^{80}Se itself we plan to use an enriched sample of 4 g of ^{80}Se and the conventional set-up of four C_6D_6 detectors placed at backward angles and covering a large solid angle. The saturated resonance method[Mac76] will be applied by regularly measuring a ^{197}Au sample. Background will be evaluated from dedicated empty, C- and Pb-sample measurements. The latter runs will be relevant for the proper evaluation of the cross section in the high-energy domain.

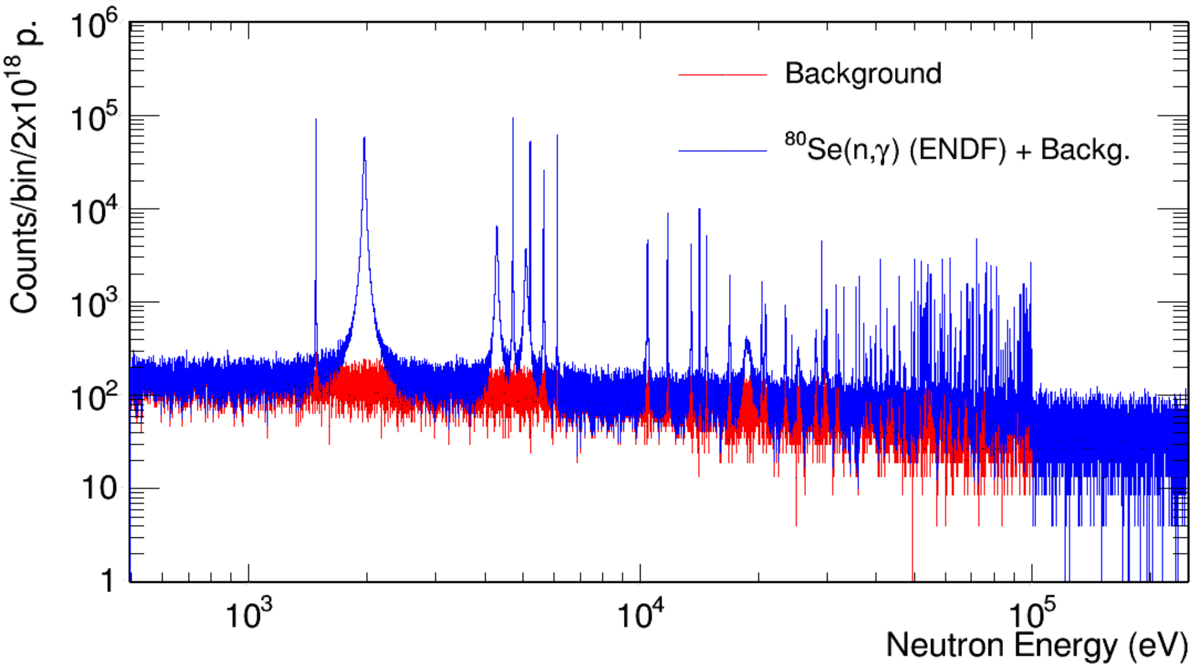

Figure 4. Simulation of the background expected in the measurement and the total statistics accumulated for a total of 2x10^{18} protons.

3. Requested beam time

The total amount of beam time is mainly determined by the 2.5x10^{18} p on ^{80}Se and the 5x10^{17}p for the background evaluation. Both of them are required for a reliable evaluation of the cross section in the 100 keV energy range, which is the important quantity of shell C-burning in MSs.

Summary of requested protons

The overall beam time request is summarized in Table 1. The usual gold, for normalization purposes, and background measurements are all included.

Sample	Objective(s)	Protons	Area	Set-up
^{80}Se	^{80}Se(n,γ) via C6D6	$2.5 \cdot 10^{18}$	EAR1	$4xC_6D_6$
Dummy	Background for ^{80}Se(n,γ)	$2.5 \cdot 10^{17}$	EAR1	$4xC_6D_6$
Au, Pb, C	Normalization ^{80}Se(n,γ), Beam-induced background in (n,γ)	$2.5 \cdot 10^{17}$	EAR1	$4xC_6D_6$
Total protons requested:		**$3x10^{18}$**		

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