

First $^{80}\text{Se}(n,\gamma)$ cross section measurement with high resolution in the full stellar energy range 1 eV - 100 keV and its astrophysical implications for the s -process

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Abstract. Most elements heavier than iron have been generated in the stellar media by means of neutron capture reactions, approximately half are produced by the slow neutron capture or *s*-process. Radiative neutron capture cross section measurements are of fundamental importance for the study of this mechanism. In this contribution we present a brief summary on the measurement and results for the $^{80}\text{Se}(n,\gamma)$ cross-section. The experiment was carried out at CERN n_TOF EAR1 via the time of flight (ToF) technique, using four C_6D_6 scintillation detectors with very fast response. More than a hundred new resonances have been analyzed for the first time with a high accuracy. The MACS obtained at $kT = 8$ keV is 36% smaller than the recommended value in KADONIS. Some of the astrophysical implications of this result are elucidated in this contribution.

1 Introduction

The *s*-process is one of the main nucleosynthesis mechanisms proposed to explain the abundance curve of elements [1]. For the nucleosynthesis of elements with mass $A > 90$, the

s-process is ascribed to low mass stars during their AGB evolutionary phase, in which neutrons are released by the reactions $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ and $^{13}\text{C}(\alpha,n)^{16}\text{O}$ corresponding to He-flash and ^{13}C -pocket, respectively [2]. For the mass region $60 < A < 90$ the weak *s*-process was introduced [1]. This additional component takes place in massive stars where neutrons are released by the reactions $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ and $^{12}\text{C}(^{12}\text{C},n)^{23}\text{Mg}$ during the core-He and shell-C burning stages [2]. For both main and weak *s*-process components the relatively low neutron flux allows unstable nuclei produced to β -decay before capturing another neutron. In some specific cases where the beta-decay half-life spans between weeks and several years, the unstable nucleus can capture another neutron before decaying, inducing a split in the *s*-process path. In these branching-point nuclei temperature and neutron density play an important role in shaping the final isotopic-abundance pattern. Because of the branching sensitivity to the varying physical conditions and evolutionary time-scales, stellar models [3–7] are required for a realistic assessment of the *s*-process production yields, based on the neutron capture cross sections and β -decay rates of all isotopes involved.

^{79}Se (3.27×10^5 y [8]) is one of the most relevant *s*-process branching [9] isotopes, for it allows to constrain the thermal conditions during the last evolutionary stage of massive-stars, before they explode as supernova. The thermal sensitivity of the nucleosynthesis around ^{79}Se arises from a few quantum levels at low excitation energy that are populated in the stellar media. The comparison between the abundances observed for the *s*-only isotopes of Kr [10], and those predicted by the stellar models, will give information about the thermal conditions of the stellar media. To this aim one needs to know both, the cross-section of the branching nucleus ^{79}Se , whose measurement is scheduled for 2022 [11], and also the cross sections of the neighbouring stable nuclei. In this context, we carried out the neutron capture cross section measurement of the ^{80}Se isotope using the ToF technique, at CERN n_TOF [12], under the framework of the ERC-funded project HYMNS [13]. Experimentally, there existed only one previous measurement on ^{80}Se using the ToF technique [14]. However, the latter had a poor neutron-energy resolution and a rather limited neutron energy range. These drawbacks have been remarkably improved with the present high resolution measurement, which covers the entire energy range of astrophysical interest between 1 eV and 100 keV.

2 Experimental setup and measuring technique

At CERN n_TOF [15] neutrons are produced via spallation reactions of a proton beam impinging on a lead block. 7×10^{12} protons reach the spallation target every proton-pulse, thereby generating ~ 300 neutrons per incident proton. The outgoing neutrons pass through a layer of borated water which moderates their energy leading to a white neutron flux covering the range from meV to GeV in each single shot. Charged particles are removed from the beam using a magnet, whereas the rest of particles are collimated into a beam by two different collimators along the beam line. Neutrons travel ~ 185 m to reach the experimental area EAR1, where the pulsed beam shows a Gaussian profile of 18 mm FWHM at the sample position [16]. In addition to neutrons, a flux of γ -rays generated by spallation- and neutron captures in the moderator, reaches the experimental hall. The prompt γ -rays is called γ -flash and saturates the response of all radiation detectors for few μs with a very steep rise-edge. This is utilized to determine the time reference for determining the ToF of each neutron bunch. Therefore, the kinetic energy in eV of a neutron with a measured ToF t_{ToF} (μs) is given by Eq. 1, in which L is the flight distance in m. The short bunch width of 6 ns RMS and the long flight distance ensure an excellent neutron-energy resolution.

$$E_n = \left(\frac{72.2977L}{t_{\text{ToF}}} \right)^2 \quad (1)$$

Table 1. Disk shaped samples of 20 mm diameter used during the $^{80}\text{Se}(n,\gamma)$ ToF experiment. Dummy is not included.

Sample	Pureness (%)	Mass (g)	Thickness (mm)
^{80}Se	99.87(10)	2.965(5)	3.50(1)
^{197}Au	99.99	0.600(5)	0.10(1)
^{nat}Pb	100	7.300(5)	2.10(1)

Fig. 1 shows a photograph of the experimental setup consisting in four C_6D_6 scintillation detectors [17] placed at 125° with respect to the beam line, and their faces pointing at the capture sample from ~ 10 cm distance. These detectors are built in carbon fiber to minimize contaminant neutron captures in structural materials, an effect known as intrinsic neutron sensitivity. Each detector contains approximately 1 l volume of C_6D_6 scintillation liquid, which is coupled to a traditional PMT to give a very fast response.

Their low efficiency allows one to apply the Pulse-Height Weighting Technique [18, 19].

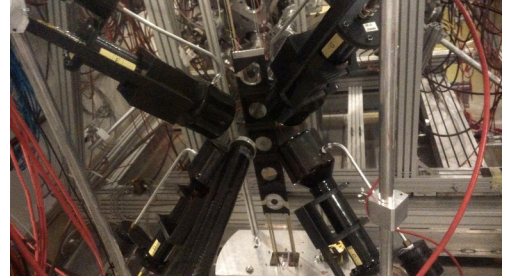
The samples used for this experiment are listed in Tab. 1. Apart from the selenium sample under study, gold was measured to normalize the obtained $^{80}\text{Se}(n,\gamma)$ yield by means of the Saturated Resonance Method (SRM) [20]. The ancillary lead sample was measured to estimate the background contribution corresponding to neutrons scattered by the sample and captured in the structural material of the experimental hall [21]. In addition, a replica of the ^{80}Se sample without the sample itself, called empty sample, was measured to estimate the background component unrelated to the sample and caused by neutrons captured in the surroundings.

3 Data analysis

The measured count-rate as a function of the ToF was transformed into a neutron capture yield by means of Eq. 2. N^w stands for the weighted number of counts already background subtracted, the neutron flux is indicated by N_n and the energy of the capture cascade corresponding is $E_C \approx S_n + E_n$.

$$Y(E_n) = \frac{N^w(E_n)}{N_n(E_n)E_C(E_n)} \quad (2)$$

Before calculating the capture yield, the performance of all C_6D_6 detectors along the experiment was studied in terms of gain and count-rate stability to filter-out possible accidental errors or systematic bias in the data taking. The detectors were calibrated using radioactive sources of ^{137}Cs , ^{88}Y and AmBe together with the $^{197}\text{Au}(n,\gamma)$ deposited energy spectra, ensuring a valid range between 662 keV and 6.512 MeV. Additionally, a series of Monte Carlo simulations of the entire experimental setup were performed to calculate the weighting function, which was applied following the methodology described in Ref. [19]. The latter includes yield-correction factors to account for the threshold-effects in the detectors, as well as γ -ray summing and conversion-electron effects. The neutron flux available during the experiment was determined from the evaluated version measured with high precision at n_TOF [22].

**Figure 1.** General view of experimental setup mounted in EAR1 for the measurement of the $^{80}\text{Se}(n,\gamma)$ cross section.

Disagreements between the determined and real neutron flux, or between simulated and true experimental setup were taken into account using the aforementioned SRM [20]. After subtracting all backgrounds present in the measurement [21], the capture yield was obtained using Eq. 2.

Once the yield was calculated, a resonance analysis was carried out using the SAMMY code [23]. This code is based on the R-matrix theory that gives a phenomenological description of the neutron induced reactions [24, 25]. SAMMY performs a Bayesian fit to the experimental data using an initial set of R-matrix resonance parameters and employing, by default, the recommended Reich-Moore approximation. Experimental effects such as Doppler broadening or neutron multiple scattering effects are taken into account in SAMMY by providing experimental data as temperature or sample thickness. Fig. 2 shows the final capture yield obtained in this work and fitted with SAMMY. In summary, 113 resonances have been analyzed, 98 of them for the first time and only 15 were previously known from transmission [26, 27]. There was no resonance data available from the previous ToF measurement [14]. The high resolution and high statistics of the measurement led us to propose a spin-parity change in the first resonance at 1.47 keV, and to individually analyze the multiple scattering component in the second resonance at 1.98 keV of neutron energy.

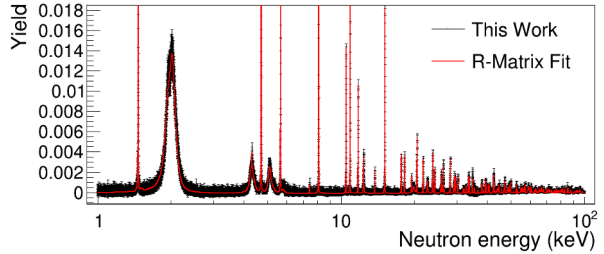


Figure 2. Measured $^{80}\text{Se}(n,\gamma)$ yield between 1 keV and 100 keV (red data-points) and R-matrix analysis fit (red curve).

4 MACS

During the *s*-process, neutrons in the stars are thermalized following the Maxwell distribution of velocities. Hence, the MACS is the input quantity required in stellar models to study this nucleosynthesis mechanism. At a temperature T , the MACS is given by Eq. 3.

$$\text{MACS} = \frac{\langle \sigma v \rangle}{v_T} = \frac{2}{(kT)^2 \sqrt{\pi}} \int_{E_i=0}^{E_f=\infty} \sigma_\gamma(E) E e^{-E/kT} dE. \quad (3)$$

The MACS for ^{80}Se was determined from the measured capture yield (Fig. 2) by means of the SAMMY code. Fig. 3 shows the MACS of $^{80}\text{Se}(n,\gamma)$ determined in this work and compared to that obtained from resonance parameters from the JEFF3.3 evaluated library [28]. Also the MACS from KADoNiS [29] and that calculated in the previous measurement [14] are displayed for comparison.

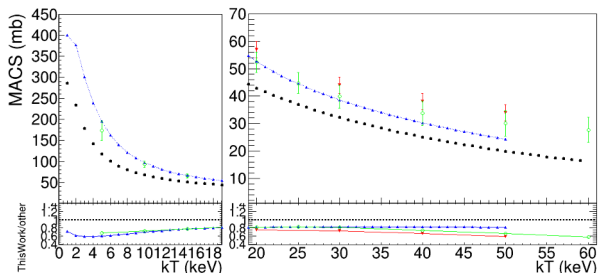


Figure 3. MACS of $^{80}\text{Se}(n,\gamma)$ determined in this work compared to evaluated libraries and previous measurement.

The ratio between this work and the rest of contributions is displayed in the bottom panel of the figure. On average, our MACS is between 20% and 40% lower than previous values.

Along the TP-AGB evolutionary stage, thermal energies of $kT \sim 8$ keV and $kT \sim 23$ keV are reached. In massive stars neutrons are produced at energies of $kT \sim 26$ keV and $kT \sim 90$ keV during core He-burning and shell C-burning, respectively [2]. Differences in MACS at these temperatures are more influential on the astrophysical aspects. Tab. 2 displays the different results at energies close to these points, in which the compared models have available data. At $kT = 10$ keV, the MACS obtained from the JEFF3.3 evaluated library is compatible with that available in KADoNiS, but both are 40% overestimated compared to the new result at this energy. Relative differences decrease at 30 keV, where the new MACS is smaller by 30%. Finally, following this trend, the new value for the MACS at 90 keV is 25% smaller than that obtained from JEFF3.3. However, the MACS in KADoNiS is overestimated by a factor of 2.5, whereas no value is available at this point from the previous measurement [14].

Table 2. Value of the MACS at three different temperatures. Only statistical uncertainties are included in these results.

	MACS (mb)		
	at 10 keV	at 30 keV	at 90 keV
JEFF 3.3	96.9	38.7	11.9
KADoNiS	93.6(6.8)	39.8(4.1)	23.7(4.3)
Walter et al.	–	44(3)	–
This Work	67.6(4)	32.2(3)	9.5(1)

5 Summary and outlook

A high resolution measurement of the $^{80}\text{Se}(n,\gamma)$ cross section has been carried out at CERN n_TOF covering for the first time a very broad neutron-energy range, from meV up to 100 keV. The MACS could be accurately determined for the relevant stellar temperatures, significantly improving previous statistical and systematic uncertainties. As next steps we intend to investigate the impact of the new results on weak s-process nucleosynthesis and massive stars [30]. This results will be required for a full interpretation of the ^{79}Se branching, whose measurement is scheduled at CERN n_TOF for 2022 [11].

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