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## $^{80}\text{Se}(n,\gamma)$ cross-section measurement at CERN n TOF

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## $^{80}\text{Se}(n,\gamma)$ cross-section measurement at CERN n\_TOF

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$^{80}\text{Se}(n,\gamma)$  cross-section measurement at CERN n\_TOF

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**Abstract.** Radiative neutron capture cross section measurements are of fundamental importance for the study of the slow neutron capture (*s*-) process of nucleosynthesis. This mechanism is responsible for the formation of most elements heavier than iron in the Universe. Particularly relevant are branching nuclei along the *s*-process path, which are sensitive to the physical conditions of the stellar environment. One such example is the branching at  $^{79}\text{Se}$  ( $3.27 \times 10^5$  y), which shows a thermally dependent  $\beta$ -decay rate. However, an astrophysically consistent interpretation requires also the knowledge of the closest neighbour isotopes involved. In particular, the  $^{80}\text{Se}(n,\gamma)$  cross section directly affects the stellar yield of the “cold” branch leading to the formation of the *s*-only  $^{82}\text{Kr}$ . Experimentally, there exists only one previous measurement on  $^{80}\text{Se}$  using the time of flight (TOF) technique. However, the latter suffers from some limitations that are described in this presentation. These drawbacks have been significantly improved in a recent measurement at CERN n\_TOF. This contribution presents a summary of the latter measurement and the status of the data analysis.

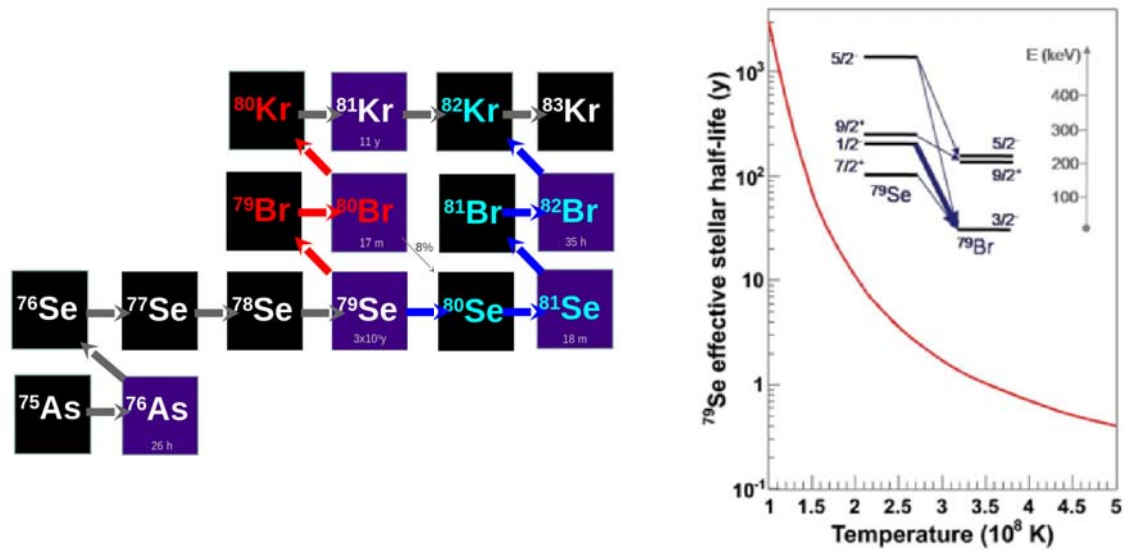
## 1. Astrophysical motivation and previous data

During the core He-burning and shell C-burning evolutionary stages of massive stars ( $M > 8M_{\odot}$ ), a large amount of neutrons are released via the  $^{22}\text{Ne}(\alpha, n)$  reaction [1]. This activates nucleosynthesis of heavy elements with masses up to  $A \sim 90$  on pre-existing Fe-seed nuclei. Long-lived radioactive nuclei ( $T_{1/2} > 10$  y) may produce a split in the nucleosynthesis path, thus producing a local isotopic abundance pattern that can be used to probe the physical conditions along different evolutionary stages, mainly during the  $\sim 30$  keV characteristic of He-burning and the  $\sim 90$  keV regime in C-burning [2]. In this contribution we focus on the *s*-process branching nucleus  $^{79}\text{Se}$  ( $T_{1/2} = 3.27(8) \times 10^5$  y) [3], which has the peculiarity that it has a few quantum states at low excitation energy that are thermally populated in the stellar environment.  $\beta$ -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 the stellar environment (see Fig. 1). In this way, the abundance ratio of the *s*-only nuclei  $^{80,82}\text{Kr}$ , in combination with the  $^{79}\text{Se}(n,\gamma)$  cross section can be used to extract information about the thermal conditions of the environment [4].

In order to analyze this *s*-process branching reliably, one needs to know the neutron capture cross section of the  $^{79}\text{Se}(n,\gamma)$  reaction, as well as the neutron capture rates of the closest neighboring nuclei (see Fig. 1). A direct measurement of  $^{79}\text{Se}(n,\gamma)$  has been proposed for the experimental campaign of CERN after the present long shutdown (LS2) [6]. Preceding that experiment, several of the closest neighbours have been measured at CERN n\_TOF, thereby covering also the main energy range of interest. In particular,  $^{77,78}\text{Se}(n,\gamma)$  were measured in other recent works [7]. This contribution presents the measurement and the status of the analysis for the  $^{80}\text{Se}(n,\gamma)$  data.

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**Figure 1.** Nuclear chart and  $s$ -process path around the  $^{79}\text{Se}$  branching (left). Effective stellar half-life of  $^{79}\text{Se}$  as a function of the temperature (right) [5].

Regarding previous data, there exists only one previous TOF measurement on  $^{80}\text{Se}$ , which helped to constrain the physical conditions of the weak  $s$ -process [4]. However, the latter measurement suffers of some limitations that are explained in the following. On one hand, cross section data was obtained only beyond neutron energies of  $\sim 3$  keV. This prevented the measurement of one large  $s$ -wave resonance 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 temperatures of  $\sim 30$  keV are reached. Apparently, this effect is being neglected in present nucleosynthesis calculations. A second limitation of the previous experiment concerns the low energy resolution, which is due to the 60 cm flight-path used [4]. With the new experiment at CERN n\_TOF these two aspects have been significantly improved. The new measurement was carried out at the EAR1 station, thereby covering a flight-path of 185 m. The long flight path in combination with the low duty-cycle (0.25 Hz) allows one to cover with high resolution the full neutron energy range from thermal up to several hundreds of keV. Although the neutron-energy differential capture cross section will be convoluted with a Maxwell-Boltzmann distribution, a high TOF resolution becomes important to assess different experimental effects, such as to reliably account for contaminant isotopes in the sample. Finally, the set-up used in the previous experiment (see Fig. 3 in ref. [4]) may be of concern in terms of neutron-sensitivity bias for the resonances with large elastic scattering width  $\Gamma_n$ . Neutrons scattered in the sample at the energy of those resonances can be easily captured in the surrounding structural materials, thereby artificially enhancing the cross section. At n\_TOF a big effort has been made in order to reduce as much as possible this type of background [8] [9]. An assessment of possible neutron-sensitivity deviations in our or previous experiments will be made in future stages of the data analysis.

## 2. Methodology

For the measurement of  $^{80}\text{Se}(n,\gamma)$  we used a selenium sample enriched to 99.87% in  $^{80}\text{Se}$ . Two different pellets with masses of 0.966(2) g and 2.920(2) g and a diameter of 20 mm were produced at the Paul Scherrer Institute (PSI). The reason to produce two samples of different thicknesses was to have a more reliable assessment of the multiple scattering effects in the case of resonances with large scattering width  $\Gamma_n$ . The total number of protons used to measure these samples was  $1.92 \times 10^{18}$ , most of them dedicated to the heavier sample. More details are given in Table 1. Additional samples were also measured such as gold, lead and an empty frame. Gold was measured to apply the saturated resonance method [10], while lead and an empty frame were used to determine the measurement background. Furthermore, the neutron flux was monitored with a  $^6\text{Li}$  foil intercepting the beam, and  $^3\text{H}$  products of the  $^6\text{Li}(n,\alpha)$  reaction were measured by using a silicon monitor placed off-beam.

For the TOF measurement we used the experimental area 1 (EAR1) of CERN n\_TOF. Here, the pulsed neutron beam produced in the spallation target travels in high vacuum to reach the sample 185 m downstream. The time of flight is measured with a resolution of 2 ns using 500 MHz fast digitizers. The energy of neutrons is determined using the non-relativistic kinetic energy expression. When neutrons impinge on the sample, they can be captured thereby building compound nuclei. The latter are initially in an excited state, which de-excite by emitting a prompt cascade of gamma rays. By detecting this radiation one can determine the probability of a neutron to be captured by the sample depending on its energy, i.e. its neutron capture cross section.

In this experiment low efficiency  $C_6D_6$  liquid scintillators were used to register the prompt capture gamma rays. Due to their low efficiency, at most one of the  $\gamma$ -rays from each cascade is recorded. For this reason, the Pulse Height Weighting Technique (PHWT) [11] has to be applied to the measured data. In this technique, a low detection efficiency and a proportionality between efficiency and energy of the detected gamma ray are required to avoid systematic bias in the final cross section due to the cascade multiplicity or decay path. More details can be found in [12]. The first condition is easy to achieve using low Z materials for the sensitive (small) volume of the detectors ( $C_6D_6$  liquid scintillators). The second condition is not trivial and a weighting function has to be calculated, validated and applied to the detector response in order to make the efficiency proportional to the energy of the gamma ray. For an accurate use of the PHWT one needs to take into account several experimental effects, related with the low energy noise-discriminating threshold in the acquisition, with the  $\gamma$ -ray summing probability and other similar effects [12].

## 3. Preliminary Results

The n\_TOF experimental weighted count rate as a function of the neutron energy is shown in Fig. 2 (red histogram) with an arbitrary scale. For comparison, the previous

**Table 1.** Number of protons dedicated for each sample measured during  $^{80}\text{Se}(n,\gamma)$  experiment.

Sample	Mass (g)	Number of protons
$^{80}\text{Se}$	2.920	$1.824 \times 10^{18}$
$^{80}\text{Se}$	0.996	$9.618 \times 10^{16}$
$^{197}\text{Au}$	0.644	$2.136 \times 10^{17}$
$^{nat}\text{Pb}$	7.281	$1.164 \times 10^{17}$
Empty	–	$5.091 \times 10^{17}$

cross section measurement [4] is also shown (blue dots). The aforementioned strong  $s$ -wave resonance below 3 keV can be observed, together with a narrower resonance at lower energy that can be unambiguously assigned to  $^{80}\text{Se}$ .

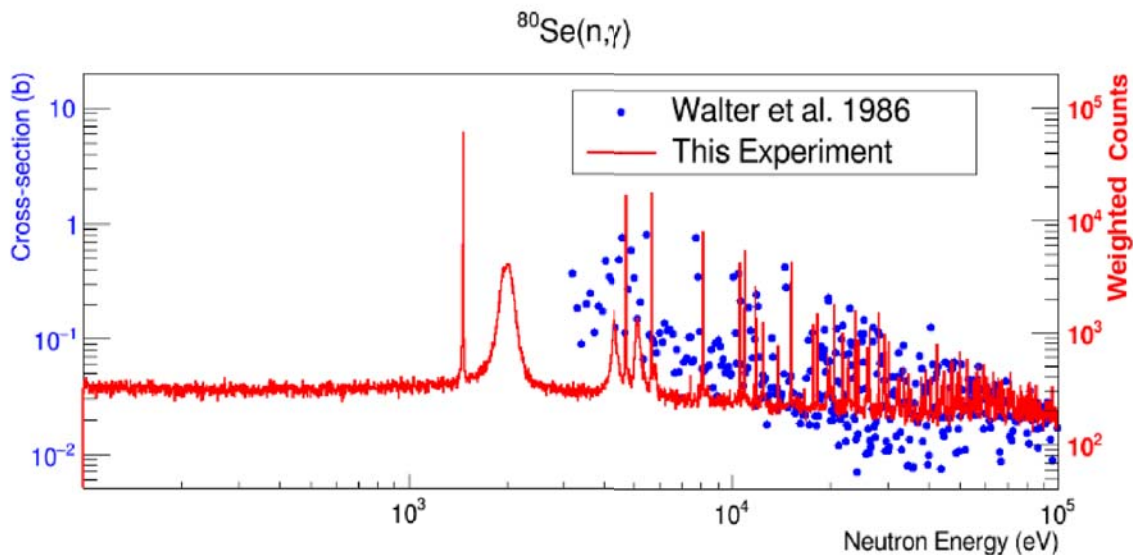
Previous to this result, a count rate consistency study was performed in order to detect possible discrepancies between count rates in the detectors. On it, ratios between count rates of  $C_6D_6$  detectors and the silicon monitor were calculated. These ratios have to remain constant along the experiment, and any variation in the number of counts registered by the silicon monitor must also occur in the  $C_6D_6$  detectors keeping the ratio between them constant. After this systematic study, a hundred percent of the total statistic was verified.

The weighted count-rate histogram shows an improvement of a factor of about 2 in signal-to-background ratio, when compared to the raw count-rate histogram. This is due to the “harder” nature of the capture gamma rays in selenium, when compared to the background radiation. In summary, over the full energy range of interest we have observed around 80 resonances from  $\sim\text{eV}$  up to  $\sim 100$  keV with sufficient statistics for a reliable R-matrix analysis. Next steps to complete the data analysis are summarized in the section below.

#### 4. Summary and outlook

With the new measurement at CERN n\_TOF one can claim that a significant improvement in terms of resolution and completeness has been achieved for the  $^{80}\text{Se}(n,\gamma)$  reaction with respect to previous data. The final results shall be relevant, together with other results in this mass region, towards a consistent interpretation of the branching at  $^{79}\text{Se}$ . The next steps to complete the analysis of  $^{80}\text{Se}(n,\gamma)$  are summarized in the following. Firstly, the weighting function needs to be validated on the basis of Monte-Carlo simulations of the capture cascade of  $^{80}\text{Se}+n$ , as reported in Ref. [12]. These simulations will serve also for the determination of the aforementioned threshold- and summing-correction factors. Secondly, the n\_TOF weighted count-rate histogram needs to be converted to capture yield by using the neutron-energy dependent neutron flux of EAR1. A similar analysis of the background related runs shall allow us to evaluate the contribution of different background sources during the experiment. The capture





**Figure 2.** Experimental neutron energy spectrum in red, compared to available data of Walter et al. experiment in blue dots.

yield will be analyzed with an R-matrix code, such as SAMMY [13], in order to extract the cross section and the resonance parameters. Given the large number of resonances observed in the resolved resonance region, a statistical analysis will be performed in order to determine the level density and strength in  $^{81}\text{Se}$ . This information can be of interest in order to use the statistical nuclear model to extrapolate the cross section at higher neutron energy (beyond  $\sim 100$  keV).

Finally, we plan to carry out an astrophysical interpretation of the measured data using computational tools, such as those developed by NuGrid collaboration [14].

## 5. Acknowledgement

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