EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Proposal to the ISOLDE and Neutron Time-of-Flight Committee

# Neutron capture cross section of $^{88}$Sr and $^{89}$Y

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## Abstract

We propose to measure the neutron capture cross sections of the two neutron magic isotopes: $^{88}$Sr and $^{89}$Y. This project aims at the substantial improvement of existing results for applications in nuclear astrophysics and emerging nuclear technologies. In particular, the superior quality of the data that can be obtained at n_TOF will allow a better characterization of s-process nucleosynthesis.

**Requested protons**: 3.5 x $10^{18}$ protons on target
**Experimental Area**: EAR1

## Introduction

The origin of the elemental abundances from iron to uranium can be almost completely assigned to neutron capture reactions by two main stellar scenarios, each being responsible for the production of about one half of the abundances in the mass region $A \geq 56$. During explosive nucleosynthesis (occurring in supernovae events and/or neutron star mergers) short-lived and very neutron-rich nuclei are produced via the rapid neutron capture process (r process) [1].

The remaining half of the heavy elements is related to the slow neutron capture process (the s process), which produces nuclei with mass $88 \leq A \leq 210$ during the advanced burning phases of stellar evolution [1]. Depending on the stellar mass, it operates in thermally pulsing low-mass Asymptotic Giant Branch (AGB) stars (main component) [2] or during core He and shell C burning in massive stars (weak component) [3].

Under s-process conditions, temperatures are $\approx (1\text{-}9)\times 10^8$ K and neutron densities can vary between $\approx 10^6$ and $10^{11}$ $\text{cm}^{-3}$. Because typical neutron capture times are much larger than average half lives of β-unstable nuclei, the reaction path of the s-process follows the valley of stability by a sequence of neutron captures and β-decays once an unstable isotope is encountered.

The Solar System abundances of Sr, Y and Zr are relatively high. These elements are mostly synthesized by the s process in AGB stars (their production in massive stars is limited to a few percent of the total solar abundance [4]). Their abundances hence define the "ls" (light-s) s-process index routinely used to compare theoretical models to observations. The existence of this first peak is due to $^{88}$Sr, $^{89}$Y, and $^{90}$Zr, all having a magic number of neutrons (N=50), which implies that their neutron-capture cross sections are lower than those of neighboring nuclei. As a result, they act as bottlenecks on the neutron-capture path, constraining the value of the total neutron flux necessary to proceed to the production of heavier elements up to the second s-process peak, corresponding to the next bottleneck at Ba, La, Ce, with neutron magic number of 82 (defining the heavy-s "hs" index).

The neutron cross section of $^{90}$Zr has been already measured by the n_TOF collaboration [5]. In this proposal we concentrate on the remaining two neutron magic nuclei of the first s-process abundance peak. As already anticipated, the neutron cross sections of $^{88}$Sr (the most abundant Sr isotope, 82% in the Sun) and $^{89}$Y (the only stable isotope of Y) do not only influence the abundance of neighboring isotopes, but the whole s process abundance distribution. The Sr and Y abundances in stars are relatively easy to derive from high-resolution spectra thanks to a large number of strong lines, which ensures that are always available, depending on the spectra coverage (hence its inclusion in all studies to determine "ls"). As a consequence, they have been used extensively to constrain stellar models [6] and even astrophysical scenarios, e.g., related to the origin of chemical anomalies in ancient globular clusters [7]. Fig. 1 shows the Y/La abundance ratios, used as representative of the ratio of the abundances produced at the first and second s-process peaks, which is a proxy for the s-process efficiency. Compared to model predictions of the s-process, represented by the lines [8], the Y/La ratio allows one to understand how the s-process has evolved in other galaxies. With respect to Y, Sr lines often suffer from saturation effects and, therefore, its abundance may be less reliable than the Y one. However, very precise Sr isotopic ratios can be determined in pre-solar grains [9]. Their anomalous isotopic compositions show variations too large to be explained only by known chemical and physical fractionation processes in the solar system and, thus, are signatures of nucleosynthesis occurred in past generations of stars. There are unassailable evidences that SiC grains originated in asymptotic giant branch (AGB) stars prior to formation of the solar system. As shown in Figure 1 right panel, Sr isotopic ratios also depend on the adopted neutron cross sections [10].

In summary, a combined study of $^{88}$Sr and $^{89}$Y neutron cross sections would put firm constraints on stellar models, which can be tested with both stellar spectroscopic observations and laboratory pre-solar grains isotopic measurements.

Furthermore, it is currently hotly debated if AGB stars can account for the total abundance of Sr, Y and Zr in the solar system [20-22]. A precise and accurate determination of the aforementioned neutron cross sections is a premise to further investigate all these topics.

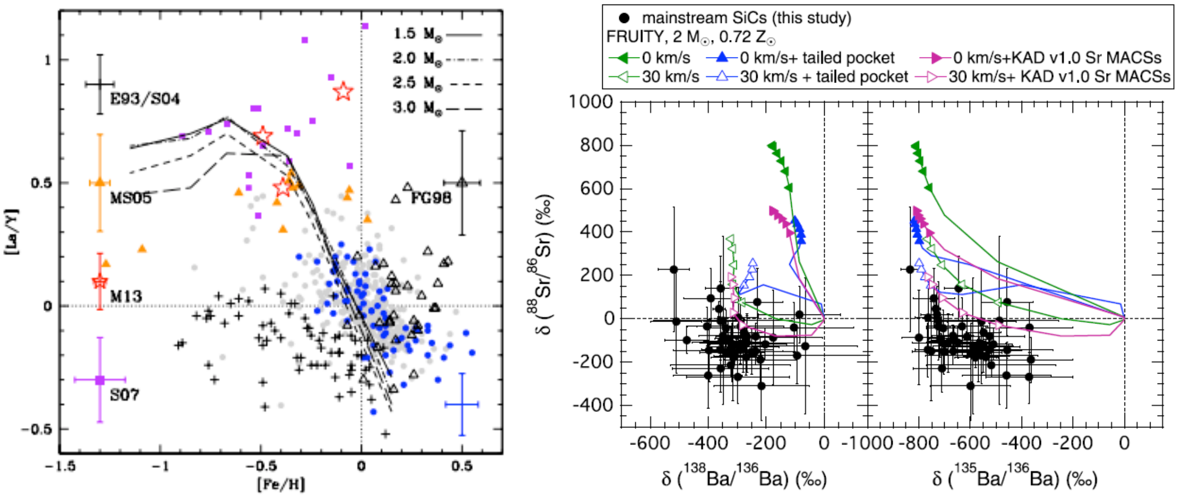

**Figure 1) Left panel: La/Y abundance ratios [11], where [La/Y] represent the logarithm of the ratio with respect to the solar value, as function of the metallicity of the star, represented by the Fe abundance [Fe/H],observed in stars both in our Galaxy (E93 [12], FG98 [13], S04 [14]) and the nearby dwarf galaxy Sagittarius(MS05[15], S07[16], M13[17]) . Right panel: Four-isotope plots of strontium vs. barium isotopic ratios deviations from solar. Test results of standard calculation computed with Bao et al. [18] and the KADoNiS v1.0 [19] strontium MACS values are compared with the grain data from [10].**

Apart from the impact on problems in Nuclear Astrophysics the neutron capture cross section of $^{89}$Y isotope is of interest in advanced nuclear technology. In fact the Yttrium hydride offers advantages as a moderator for high temperature thermal nuclear reactors. In contrast to other hydrides considered as moderators, this material retains its relatively high content of hydrogen at very high temperatures, between 850 °C to 1150 °C. In addition, the nuclear properties of yttrium hydride are favourable, and its thermal conductivity is excellent [23].

Another use of yttrium is as an inert matrix fuel (IMF). Different concepts have been developed during the last decade to transmute transuranic elements (TRU) using uranium-free inert matrix fuels in a once-through-cycle to reduce the amount of TRU in the nuclear waste. For today's LWRs yttrium stabilised zirconia (YSZ), as well as other oxides like alumina, spinel or ceria, have been proposed as inert matrix materials. By employing IMF, a larger fraction of plutonium can potentially be consumed in comparison with MOX fuels without breeding new plutonium [24]. Yttrium is also a candidate for the realization of super-magnets in fusion reactors [25].

Despite the need of high-quality neutron resonance parameters, as motivated above, the available data libraries show important discrepancies. The status of experimental data for

$^{89}$Y for the neutron induced capture cross section in the energy region between 10 keV and 1000 keV is illustrated in Figure 2. Resonance parameters are reported in Refs. [26-33,35,36], but large discrepancies can also be observed between various results. The status of the experimental data is also reflected in the quality the cross sections in the evaluated data libraries (see e.g. Figure 3 and Figure 4 for a comparison of the cross sections recommended in the different libraries, for $^{88}$Sr and $^{89}$Y respectively).

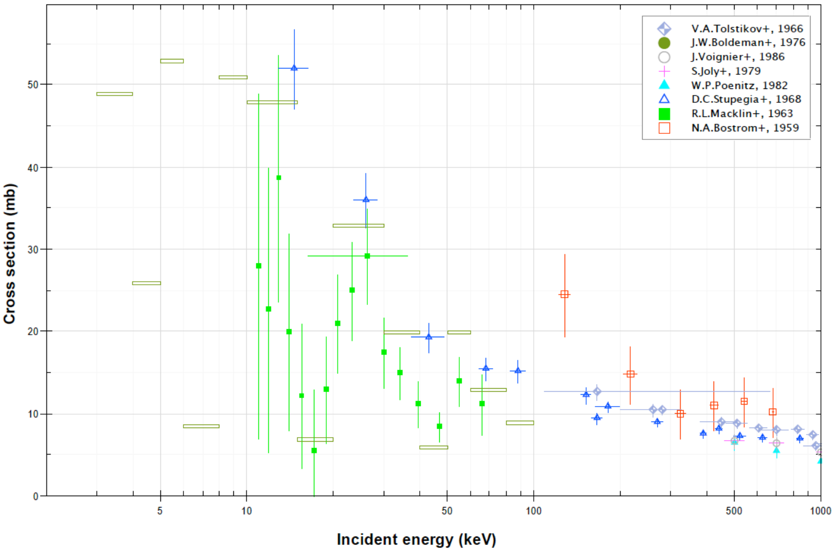

**Figure 2 Cross section data for the $^{89}$Y(n,γ) $^{90}$Y reaction available in the EXFOR data base**

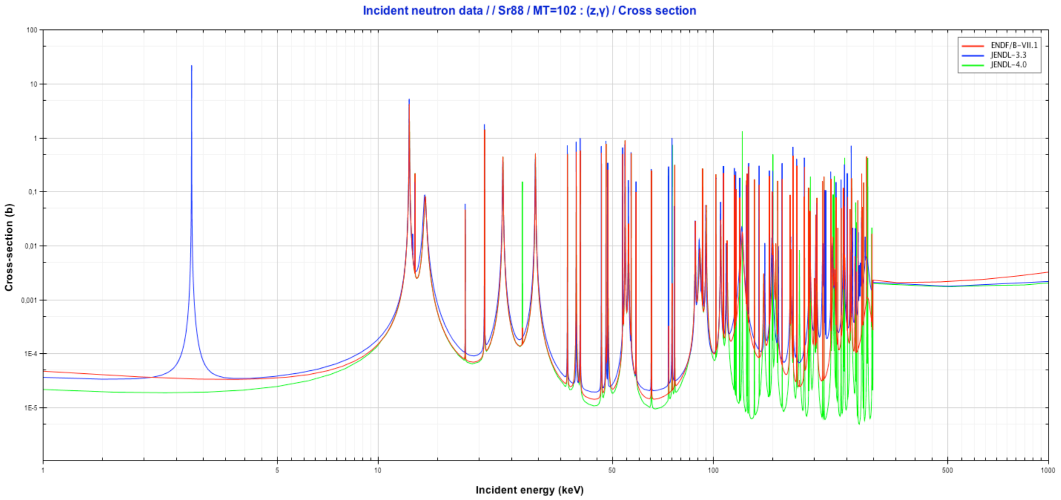

**Figure 3 Comparison of the $^{88}$Sr(n,γ) cross section recommended in different data libraries**

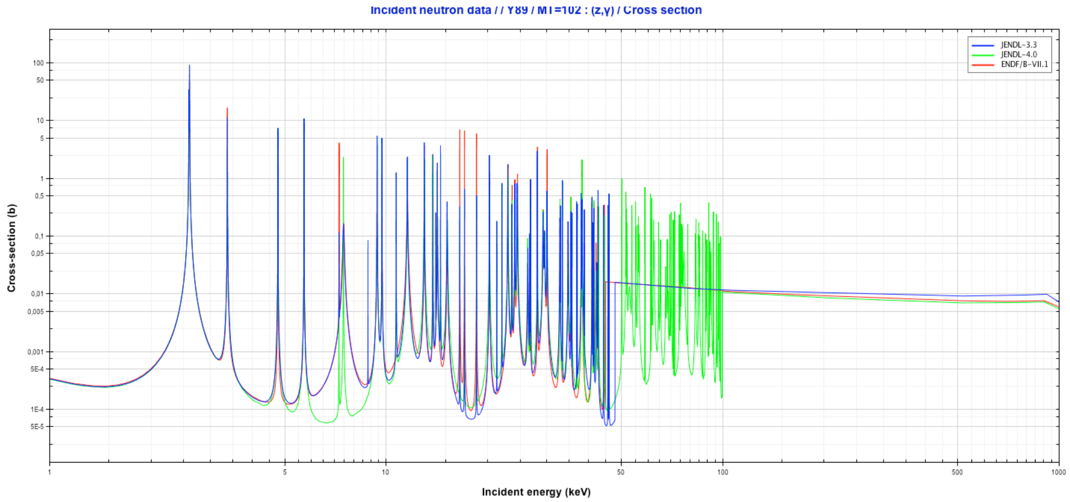

**Figure 4** Comparison of the $^{89}$Y(n,γ) cross section recommended in different data libraries

A similar situation is found for the Maxwellian Averaged Cross Section (MACS), the most important quantity of Astrophysical interest. As reported in Table 1 and Table 2 discrepancies exist among the MACS calculated on the basis of experimental data, evaluated libraries and theoretical predictions. In particular, for $^{88}$Sr, a recent measurement from Katabuchi seems to indicate that the MACS is at least 30% higher than previously measured and the one predicted on the basis of currently evaluated cross sections. A new, high-accuracy and high-resolution measurement on both isotopes, in a wide energy range, would therefore be highly desirable, in order to obtain a more reliable estimate of the MACS at various temperatures, and provide the basis for improvements in evaluated cross section.

**Table 1 Comparison among the experimental, library evaluated data and theoretical predictions MACSs at 30 keV for $^{89}$Y isotope**

| Reference | Year | Type | MACS at 30keV |
|---|---|---|---|
| Käppeler[34] | 1990 | Activation | 19±0.6 |
| Musgrove[35] | 1978 | Capture | 21±3 |
| Boldeman[36] | 1977 | Capture | 13.5±1.3 |
| ENDF-B/VII.1[37] | 2011 | Evaluated | 21.36 |
| JEFF3.1[38] | 2004 | Evaluated | 27.26 |
| JENDL4.0[39] | 2002 | Evaluated | 20.22 |
| Rauscher[40] | 2000 | Theoretical | 65 |
| Goriely[41] | 2005 | Theoretical | 16,6 |

**Table 2 Comparison among the experimental, library evaluated data and theoretical predictions MACSs at 30 keV for $^{88}$Sr isotope**

| Reference | Year | Type | MACS at 30keV |
|---|---|---|---|
| Katabuchi [42] | 2011 | Capture | 9.4±0.63 |
| Koehler[43] | 2000 | Capture | 6.01±0.17 |
| Käppeler [34] | 1990 | Activation | 6.13±0.18 |
| Musgrove [35] | 1978 | Capture | 6.2±0.5 |
| ENDF-B/VII.1[37] | 2011 | Evaluated | 5.22 |
| JEFF3.3[38] | 2004 | Evaluated | 6.35 |
| JENDL4.0[39] | 2002 | Evaluated | 5.33 |
| Rauscher[40] | 2000 | Theoretical | 13 |
| Goriely[41] | 2005 | Theoretical | 5,2 |

## The n_TOF measurement

We propose to measure the neutron capture cross sections of $^{89}$Y and $^{88}$Sr at the Experimental Area 1 of the n_TOF facility up to 1 MeV by means of $C_6D_6$ liquid scintillators, which are optimized with respect to neutron sensitivity. Relative to previous measurements, higher quality data can be produced at n_TOF thanks to the combination of the convenient features of the neutron beam, in particular the high resolution and wide energy range, with the high performances of the detection and acquisition systems.

The samples for the planned measurements will be delivered by Goodfellow [44] in form of metal disk with a purity of 99,9% for $^{89}$Y, and by ISOFLEX [45] in form of carbonate powder with an enrichment > 99.9% for the $^{88}$Sr . We propose to use relatively massive samples of a few grams, in order to minimize the proton beam request. The masses have been determined to avoid saturation of the main resonances and keep multiple scattering effects to a reasonable level. The diameter of both samples is 3 cm, to intercept almost entirely the neutron beam.

The request for the number of protons is based on the need to characterize the most important resonances, all in the keV region, as well as to measure with good statistical accuracy the Unresolved Resonance Region. The count rate was evaluated by means of the neutron capture cross sections listed in the ENDF library[37], taking into account the efficiency of the proposed setup. The count-rate estimate, for a resolution of 3000 bins per decade, is shown in Figures 5 and 6. The green line indicates the level of expected background, which has been estimated on the basis of previous experiments performed in EAR-1.

From the count rate estimate the total number of counts in a resonance at approximately 100 keV is of the order of a few hundred counts for both isotopes, resulting in a statistical accuracy of < 5% in the energetic range from thermal to 100 keV, for a number of protons of 1x10$^{18}$ and 1.5x10$^{18}$ for $^{89}$Y and $^{88}$Sr, respectively. An additional 1x10$^{18}$ protons is needed in the measurement for background determination and normalization purposes.

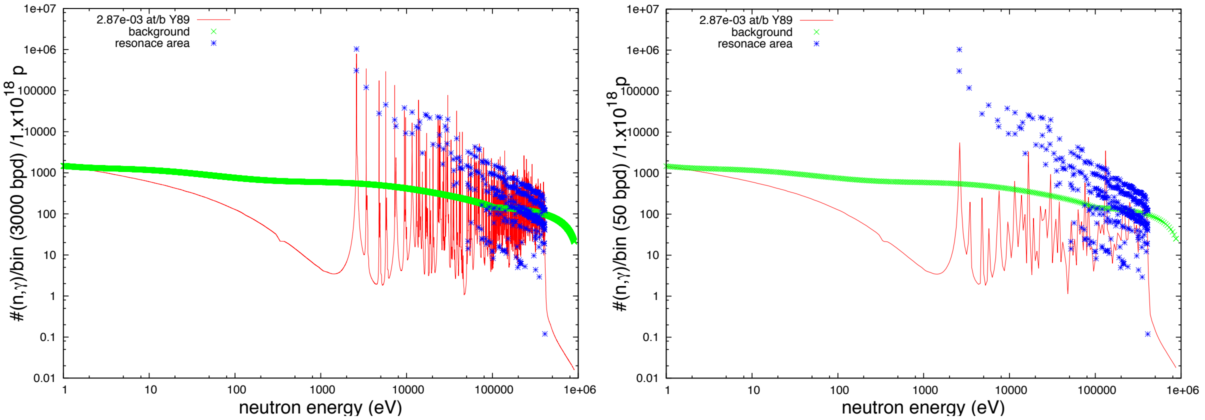

**Figure 5 Count rate estimates for $^{89}$Y for 3000 and 50 bins/decade (left and right upper panels, respectively), for the sample specification reported in Table 3.**

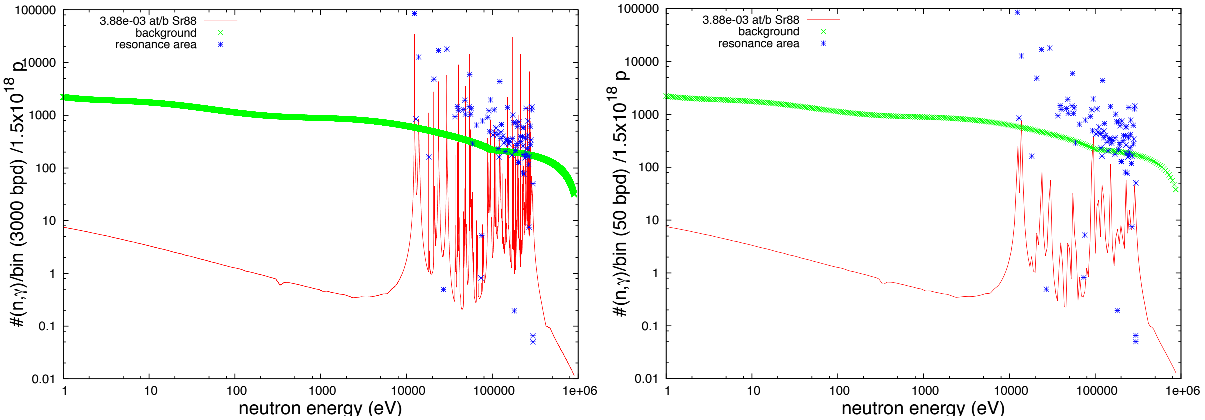

**Figure 6 Count rate estimates for $^{88}$Sr(Top) for 3000 and 50 bins/decade (left and right upper panels, respectively), for the sample specification reported in Table 3.**

## Summary of requested protons:

The requested number of protons for the different samples to be used in the measurement are listed in Table 3. A total of 3.5x10$^{18}$ protons is required for this proposal.

**Table 3 Sample and the requested number of protons for each sample.**

| Sample | Mass(g) | Purity | Thickness (at/b) | No. of protons(x$10^{18}$) |
|---|---|---|---|---|
| $^{88}$Sr | 4 | 99.9 | 3.88 x $10^{-3}$ | 1,5 |
| $^{89}$Y | 3 | 99.9 | 2.87 x $10^{-3}$ | 1.0 |
| Au | | | | 0.2 |
| Empty frame | | | | 0.4 |
| Filters | | | | 0.2 |
| Al(can) | | | | 0.2 |
| **Total** | | | | **3.5** |

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