EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Tackling the *s*-process stellar neutron density via the ^{147}Pm(n,γ) reaction

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Abstract

Branching points along the reaction path of the slow nucleosynthesis process are very special isotopes for which there is competition between neutron capture and β-decay. The accurate knowledge of the decay properties and capture cross sections in the vicinity of these branching points are of key importance for determining the stellar conditions, namely the neutron density and temperature during the main s-process component in low-mass AGB stars. However, accurate values of these quantities, in particular capture cross sections at the corresponding stellar temperatures, are difficult to measure; thus data are very scarce and, when existing, very limited.

For the particular and important case of the branching at A=147/148, the main branching point is ^{147}Pm; for which there was a very challenging and successful activation measurement in 2003 at the stellar neutron energy of kT=25 keV using just 28 ng of material. In the main s-process, however, 95% of the neutron exposure takes place during H-burning episodes in thermally pulsing AGB stars at temperatures of around 90 MK (kT=8 keV). A comprehensive understanding of the branching at ^{147}Pm therefore requires measuring the neutron capture cross section over a broad energy range.

With the inauguration of the new CERN neutron beam line n_TOF-EAR2 and the availability of a specially produced ^{147}Pm sample of 300 μg we propose to measure the associated $\sigma(n,\gamma)$ in the full energy range of interest for astrophysics, providing the first ever experimental MACS values over the full energy range between 5 and 100 keV.

Requested protons: $2\cdot10^{18}$ protons on target
Experimental Area: EAR-2

1. **Introduction, motivation and objectives**

Nucleosynthesis via the slow neutron capture (*s*) process in stars is responsible for the formation of about 50% of the elemental abundances between iron and bismuth. The phenomenological picture of the classical *s* process was formulated about 50 years ago in the seminal papers of Burbidge et al. [1] and of Cameron [2] in 1957, where the entire *s*-process panorama was already sketched in its essential parts. They explain how the elements heavier than iron are produced by a continuous chain of neutron capture reactions and β-decays that give rise to the heavy elements. The phenomenology of the *s* process implies that the solar abundance distribution is composed of two parts, a main component, which is responsible for the mass region from Y to Bi, and a weak component, which contributes to the region from Fe to Sr. The main and weak components can be assigned to low mass stars (between 1 and 3 solar masses) and to massive stars (more than 8 solar masses), respectively; see Käppeler et al. [3] for a recent and comprehensive review of the topic.

The *s* process path goes along the stability valley until a sufficiently long-lived isotope is reached, long-lived enough so that there is a competition between neutron capture and β-decay. This competition results in branchings of the reaction path, which proved particularly useful, since the resulting isotopic patterns carry direct information on the physical conditions during the *s* process, i.e., neutron density, temperature and pressure.

Due to the difficulty of producing enough material of the 21 *s*-process branching points outlined by Käppeler et al. [3], only two have been measured by time-of-flight (i.e. MACS at all energies): ^{63}Ni (Lederer et al. [4] at n_TOF and Weigand [5] at DANCE) and ^{151}Sm (Abbondanno et al. [6] at n_TOF and Wisshak et al. [7] at KIT).

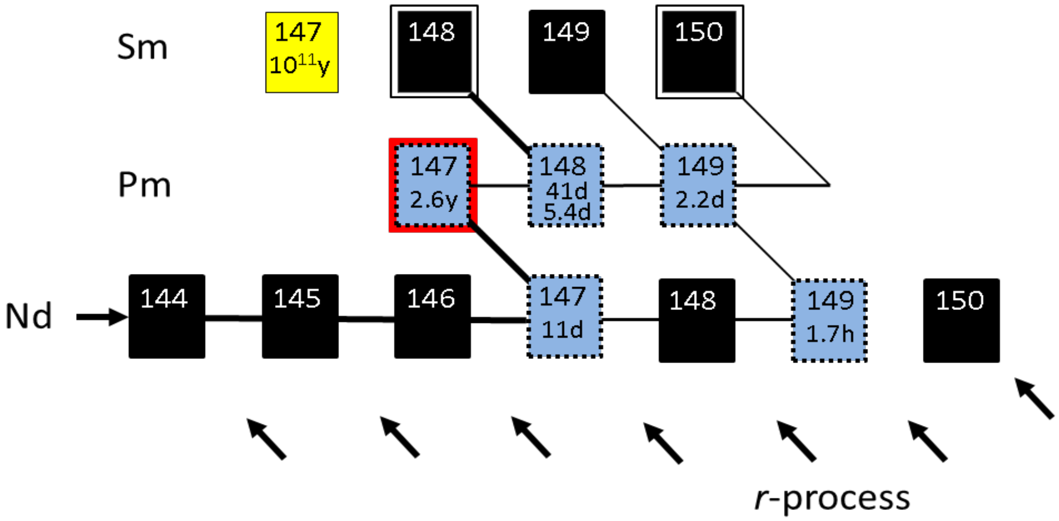

Figure 1. The *s*-process flow in the mass region A=144-150. Branching points are indicated by dotted blue boxes, and the one of interest in this work (^{147}Pm) is marked in red. The *s*-only isotopes ^{148}Sm and ^{150}Sm are indicated by double squares.

In this work, within the EC project *NeutAndalus* [8], we are particularly interested in the branching in the A=147-148 region, that is the Nd-Pm-Sm region. A detailed analysis of this branching will become important for constraining models of AGB star evolution and to put accurate constraints on recently proposed phenomena such as the interplay between metallicity and initial stellar mass, mixing processes or hot bottom burning effects [9]. In turn, these aspects are of relevance for understanding the role of the main *s*-process contribution in galactic chemical evolution models.

The *s*-process neutron capture flow in this region is sketched in Figure 1 [10], where one sees that ^{148}Sm and ^{150}Sm are *s*-only isotopes because they are shielded from the *r*-process by their Nd isobars. The ^{148}Sm to ^{150}Sm abundance ratio is very well known because they are rare-earth nuclei, which are not affected by chemical fractionation processes. Therefore this branching can provide very valuable information about the stellar conditions of this process if the capture cross section of the branching isotopes, mainly ^{147}Pm but also ^{147}Nd, are known. Furthermore, the measurement of the ^{147}Pm capture cross section will directly constrain the stellar reaction rate as used in the astrophysical models, since the contribution of neutron captures on thermally populated excited states for ^{147}Pm these are predicted to be very small, between 0% at kT=5 keV and 6% at kT=30 keV [11,12].

As of today there has only been one attempt to determine experimentally the ^{147}Pm capture cross section in the region relevant for astrophysics. This corresponds to the challenging, and successful, activation measurement by Reifarth et al. [13] at Forschungszentrum Karlsruhe in 2003, in which they irradiated 28 ng of ^{147}Pm with a Maxwellian neutron energy distribution resembling the stellar one at kT=25 keV. As illustrated in Figure 2, the value obtained in that work is on average 30% smaller than all previous calculations, which is not surprising considering that the existing calculations in the last decade are different from each other by more than a factor of two.

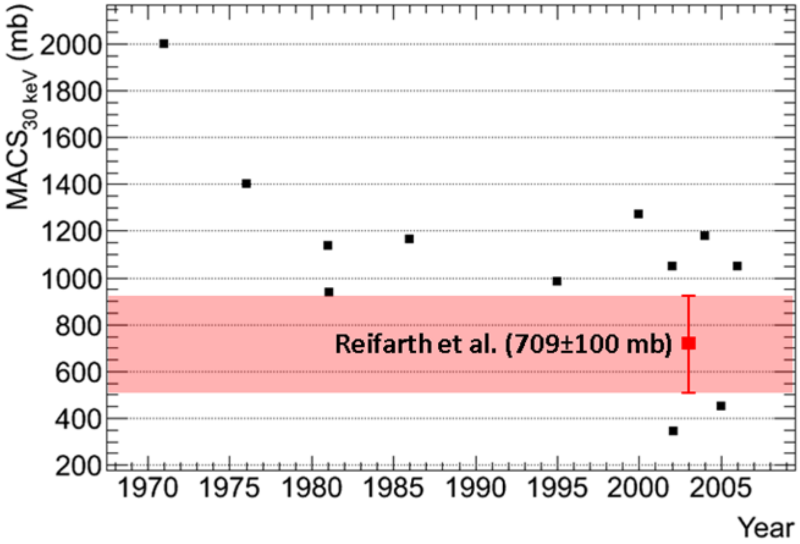

Figure 2. Summary of the calculated (black) and measured (red) MACS values at 30 keV as given by KADoNiS [14].

Although this result allowed for a first reliable understanding of this branching and helped to estimate the range of temperatures and neutron densities in the main s-process component, one has to consider that 95% of the neutron exposure in TP-AGB stars happens at much lower stellar temperatures, of about 90 MK (kT = 8 keV). Therefore, a measurement of the cross section in that neutron energy range is highly desirable.

Today, thanks to the availability of the new CERN neutron beam line n_TOF-EAR2, which will become operative in Summer 2014, it is possible to make the first time-of-flight measurement of this cross section in the full neutron energy range of interest.

2. **Sample preparation**

As in most challenging capture cross section experiments, the material availability and sample preparation are crucial and not trivial. In the case of ^{147}Pm it has been already outlined that the only experiment to date was made with only 28 ng of material. This amount was enough for an activation analysis, but not for a time-of-flight experiment. In order to produce a sample with sufficient mass we have established a collaboration between n_TOF, the Institut Laue Langevin ILL (Grenoble, France) and the Paul Scherrer Institute

PSI (Villigen Switzerland) in order to produce the isotope of interest and prepare the corresponding sample. Along Summer of 2013 two 5 mm diameter pellets with a total mass of 97 mg ^{146}Nd (isotopic purity 98.8%) have been irradiated with thermal neutrons for 56.7 days at the ILL high-flux reactor at a thermal neutron flux in excess of 10^{15} neutrons/s/cm^2.

This irradiation produced ~300 μg of ^{147}Pm via the ^{146}Nd(n,γ)^{147}Nd(β$^-$) reaction. This amount of ^{147}Pm is embedded in the Nd sample, and thus advanced chemical purification techniques will be used to separate Pm from the dominating Nd in the sample. This separation is being carried out by the RadWasteAnalytics Group at PSI using ion exchange chromatography, precipitation and other radiochemical techniques.

3. **The measurement**

The experiment will be carried out at the new n_TOF EAR-2 beam line [15], the new 20 meters flight path measuring station featuring an increased (x27) neutron beam intensity with respect to the existing n_TOF EAR-1 [16].

The γ-ray cascades with a total energy of around 6 MeV emitted after each capture reaction in ^{147}Pm will be detected using a set of four new low neutron sensitivity C_6D_6 detectors [17] and employing the Monte Carlo based Pulse Height Weighting Technique (PWHT) as described in [18] for the data analysis. Both the detectors and the analysis techniques have been widely used at n_TOF for this type of measurements.

The determination of the normalization and the different sources of background will follow the procedures and techniques employed at n_TOF in previous measurements. The product of the beam interception factor and detection efficiency will be provided by a measurement of a ^{197}Au sample of similar geometry as the one of ^{147}Pm (Saturated Resonance Method [19]), while the background will be characterized through sample-out and dummy-sample measurements. Unfortunately, since the background conditions in the new n_TOF-EAR-2 beam line have not been characterized yet, this proposal does not include any estimation on the background expected during the measurement. Therefore, the lessons learned during the commissioning of EAR-2 will be of upmost value for estimating beforehand the expected background and prepare the experiment and schedule beam time allocation for background measurements accordingly.

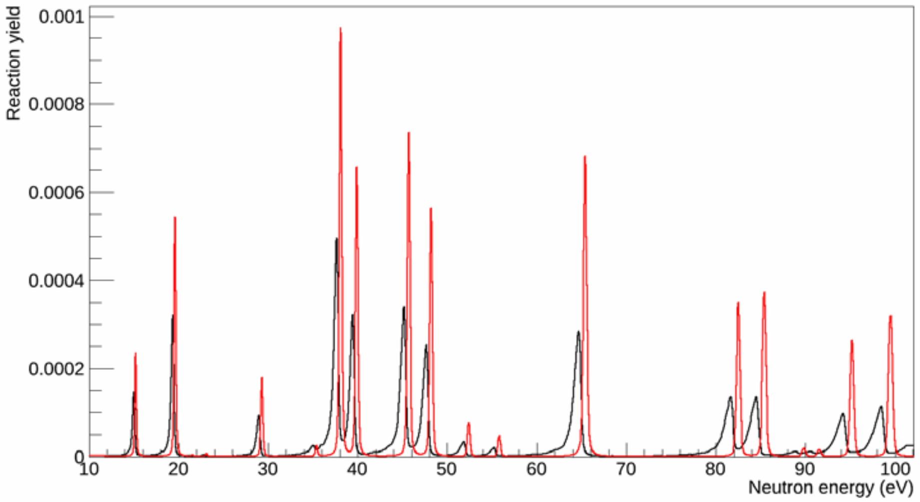

Figure 3. Calculated reaction yield for the ^{147}Pm sample at n_TOF EAR-2 with (black) and without (red) considering the broadening effect of the resolution function.

One question that arises is whether the reduced energy resolution of EAR-2 would allow identifying individual resonances in ^{147}Pm. The calculations with the values of the Resolution Function given by FLUKA simulations of EAR-2 show that we should be able to observe and analyse individual resonances (see Figure 3) at least up to the 100 eV high energy limit of the resolved resonance region adopted by evaluations.

4. Objectives and beam time request

The neutron capture cross section of ^{147}Pm has never been measured before over a broad neutron energy range. Therefore, the calculation of the beam time request relies on evaluated cross sections, which are based on the previous activation measurement at 25 keV and semi-empirical extrapolations, as well as on the systematics from neighboring isotones. In the evaluations the resolved resonance region (RRR) ranges up to 102 eV, considering the expected level spacing in ^{148}Pm, higher energy resonances should become observable in our measurement.

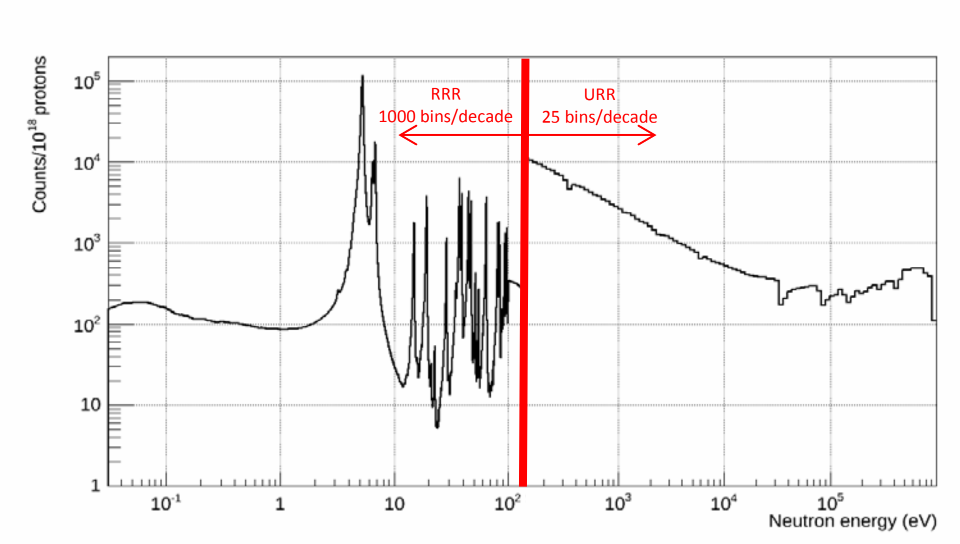

Figure 4. Expected number of counts as function of the neutron energy for a total of 10^{18} protons allocated to the ^{147}Pm sample. Note the different binning in the resolved (RRR) and unresolved (URR) resonance regions.

In order to estimate the proton request we have assumed that we need to record a minimum of 1000 counts at the resonances peaks in the RRR with a resolution of 1000 bins per neutron energy decade (enough to allow an accurate resonance shape analysis). Above 102 eV, the unresolved resonance region (URR) will be analysed with just 25 bins/decade, enough to fit the point wise cross sections using the Hauser-Feshbach formalism. In this energy region the goal is to reach a statistical uncertainty of at least 7%, so that it does not dominate over the systematic uncertainty. In order to reach these goals in the RRR and URR a total of 10^{18} protons must be allocated to the measurement of the ^{147}Pm sample, which should allow us to determine this neutron capture cross section for the first time over a very broad neutron energy range, as it is illustrated in Figure 4. At this point one should note that the calculation is based on the cross section from models, which can be up to a factor of 2 too low or too high.

Table 1. Summary of the beam time request.

Sample	**Objective**	**Protons**
^{147}Pm	Capture Cross section of ^{147}Pm	$1\text{x}10^{18}$
Empty	Overall beam-on background	$0.2\text{x}10^{18}$
Dummy	Sample backing related background	$0.6\text{x}10^{18}$
^{197}Au	Normalization	$0.2\text{x}10^{18}$
^{147}Pm (beam-off)	Sample activity background	-
Total		$2\text{x}10^{18}$

In addition to the beam time allocated to the ^{147}Pm sample, a sizable number of protons need to be allocated to the measurements for characterizing the background and determining the normalization value. The background from neutrons scattered at the sample itself is expected to produce a negligible contribution, since the cross section for scattering is smaller than for capture and our efficiency for detecting capture reactions is ~10^3 times larger than for scattered neutrons. Since there are no measurements available, the beam time request for these measurements is based on the experience from n_TOF EAR-1.

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