EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

First measurement of the s-process branching ^{79}Se(n,γ)

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Abstract

Selenium-79 is a branching point in the slow neutron capture process (s-process) with relevant implications in nucleosynthesis and in stellar models. The products of the s-process nucleosynthesis after ^{79}Se are the s-only isotopes ^{80,82}Kr, whose solar system abundances are accurately known. This information, in conjunction with the experimental cross section of ^{79}Se(n,γ) will allow one to extract reliable conditions for the temperature and neutron density, as well as the role of the *main* and *weak* s-process contributions to the

nucleosynthesis in the A=80 mass region. This letter of intent summarises the astrophysical relevance of the proposed measurement. From the experimental point of view we believe that such a challenging measurement, which relies on a really small amount of sample material (8 mg), will benefit remarkably from an alternative measuring technique which is being developed for such cases (see Ref.[1]). The method aims at neutron capture cross section measurements with an unprecedented level of sensitivity. In combination with the large neutron flux available at n_TOF EAR2 this method should enable the first (n,γ) measurement of ^{79}Se despite of the very limited amount of sample material available. The sample is being prepared at PSI (Switzerland) and ILL (France), and its production process and status are summarized in this LoI.

Introduction:

Neutron capture cross sections are a crucial ingredient for stellar models, which describe the production of elements heavier than iron. The slow neutron capture process (s-process) is responsible for about half of the solar system isotopic abundances of elements heavier than iron. This mechanism operates in AGB stars, where two alternate burning shells, one of H and an inner one of He, surround an inert degenerated CO-core. s-process elements are produced by neutron captures on seed nuclei in the He-rich intershell, between the two burning shells. The He intershell is periodically swept by convective instabilities induced by a He-burning runaway, where ^{12}C is synthesized. The main neutron source for AGB stars of mass $M<4M_{\odot}$ and $T=10^8$ K is the ^{13}C(α,n)^{16}O reaction (main s-process component) with a neutron density of $N_n<10^7$ cm^{-3}. Towards the end of the He-burning pulses, also the ^{22}Ne(α,n) reaction is partially activated [2]. Although it contributes only about 5% of the total neutron exposure, the higher neutron density of up to 10^{10} cm^{-3} strongly affects the final abundance pattern of the s-process branchings. Branchings in the reaction path occur at unstable isotopes by the competition between neutron capture and beta decay (Fig. 1).

In more massive stars, the s-process takes place during the pre-supernova evolution, i.e. during convective core He-burning and convective C-shell burning. While low mass stars are essentially producing the s abundances between Zr and Pb (main component), massive stars are responsible for most of the weak s component between Fe and Sr. In this case also the neutron source ^{22}Ne(α,n)^{25}Mg is activated at temperatures of $3.5\cdot10^8$ K and neutron densities larger than 10^{10} cm^{-3} can be reached.

Because a high neutron density favours the production of the neutron rich nuclides in s-process branchings, a different s-process pattern is expected depending on whether the first or the second neutron source reaction is more active. The knowledge of the neutron capture cross sections of the branching nuclei together with observed element abundances allows one to estimate the thermal conditions and the neutron density at the s-process site. Because branching nuclei are unstable, direct neutron capture measurements are generally very difficult at conventional neutron facilities.

The reaction to be considered in this LoI for n_TOF EAR-2 is ^{79}Se(n,γ). The knowledge of the neutron capture cross section of ^{79}Se will provide a crucial test for the understanding of s-process nucleosynthesis in massive stars [3]. The ^{79}Se branching is particularly relevant because it is located in the transition region between weak and the main s-process components. As shown in Fig. 1 this branching is characterized the s-only isotopes ^{80}Kr and ^{82}Kr, which are shielded from the rapid neutron capture process by their stable (or almost stable) isobars ^{80}Se and ^{82}Se ($t_{1/2}$ = 10^{20} y). The abundance ratio of ^{80}Kr and ^{82}Kr is well characterized in the solar material and by analyses of pre-solar grains [4], thus allowing to extract reliable conclusions about the stellar conditions by comparing the abundances predicted by stellar models on the basis of the ^{79}Se(n,γ) cross section with the observed abundance ratio. The branching at ^{79}Se is particularly well suited for determining the thermal conditions of the stellar environment (Fig.1), while neighbouring branchings, like the one at ^{85}Kr, provide complementary information on the neutron density.

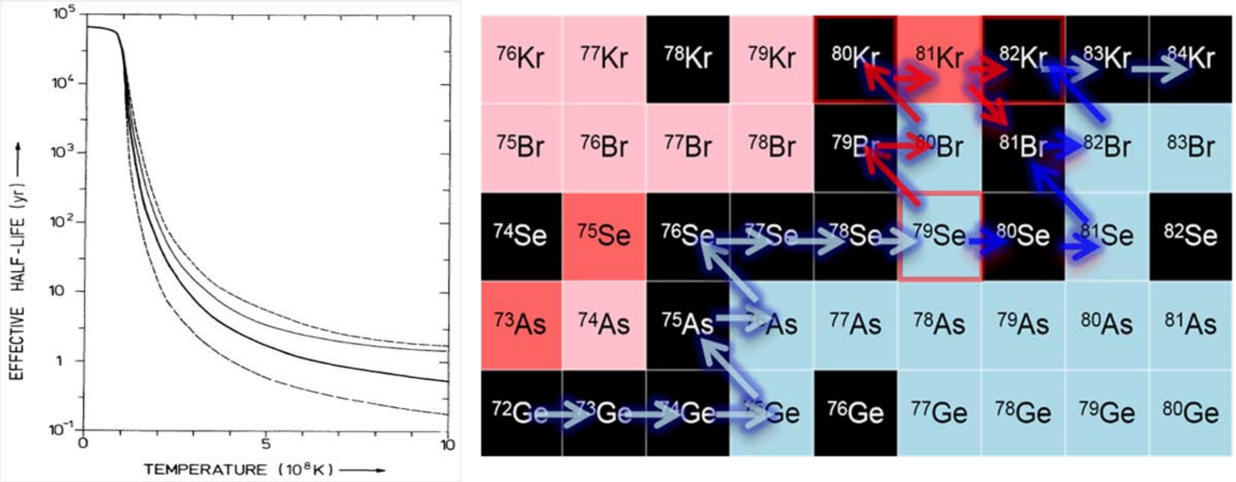

Figure 1. (Left) The beta-decay of ^{79}Se shows a pronounced rate dependence with the stellar temperature, which is particularly well suited for constraining thermal conditions in massive stars (Figure from Ref.[5]). (Right) The branching at 79Se yields the s-only ^{80}Kr and ^{82}Kr.

Once the ^{79}Se(n,γ) cross section has been measured, the temperature (and the effective half-life in the stellar environment) can be determined quite straight-forward by comparing the ratio of the ^{80}Kr and ^{82}Kr abundances calculated with stellar models (which include the experimental cross section as an essential input) versus the observed Kr-abundance ratio.

Experimental approach:

Since ^{80}Se is stable, the neutron activation method is not applicable in this case. Thus, the most convenient way to access the ^{79}Se cross section is to use a very intense neutron flux in combination with the time-of-flight method, and detect prompt gamma-rays emitted in the capture events. However, because ^{79}Se is unstable, only small amounts of this isotope can be obtained for an experiment (see section below). Given the small amount of ^{79}Se material that will be available (about 8 mg), the background radiation in the experimental area represents the main challenge for measuring this cross section, especially in the keV energy region of interest for astrophysics. This is illustrated in Fig.2, where the expected count rates for the isotope of interest (^{79}Se) and the primary sample (^{78}Se) are shown as a function of neutron energy. The nearly constant curve (black dots) shows the estimated background level (at EAR1), which indeed would hinder the observation of many relevant resonances in the keV region. This count-rate calculation is based on a theoretical estimation of the ^{79}Se (n,γ) cross section, which is affected by an uncertainty of a factor of two, or more. In order to reliably tackle this measurement it is crucial to improve the signal-to-background conditions.

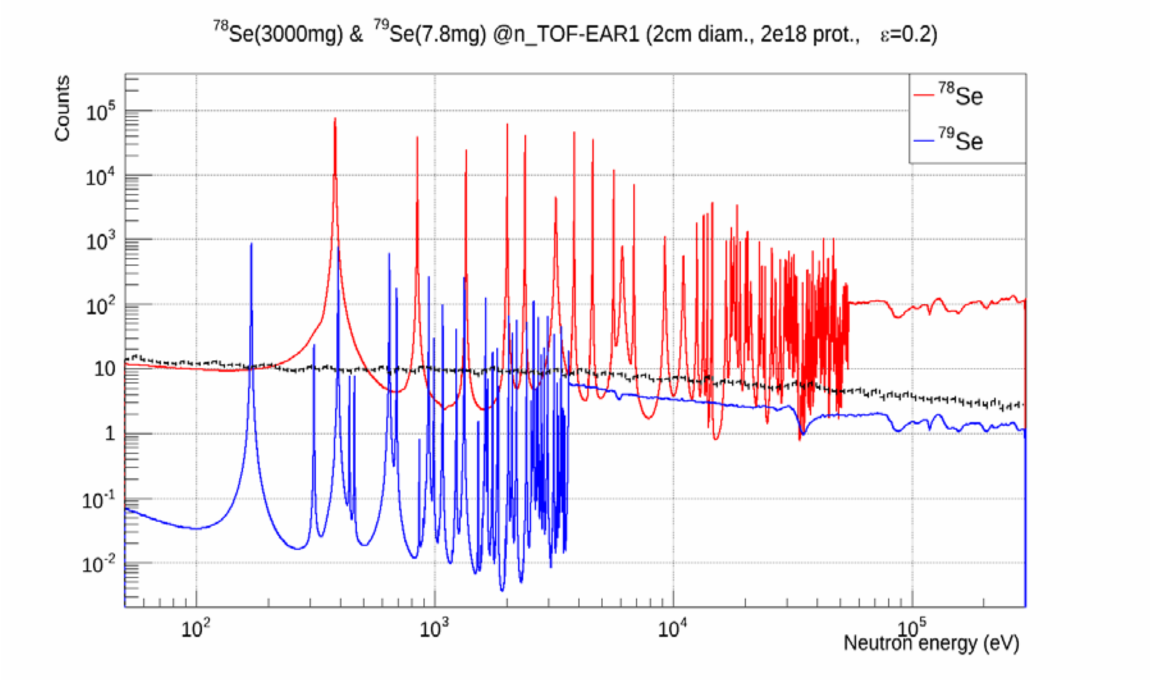

Figure 2. Expected count rate as a function of the neutron energy for the Se-sample using a set-up consisting of four C_6D_6 detectors at EAR1. The different colors indicate the count rate contributions from ^{79}Se (blue), from the primary ^{78}Se material in the sample (red) and from the background (black).

With this aim, an alternative detection method is being investigated, which is based on total energy detectors with imaging capability (i-TED) [1]. The latter approach is expected to provide the improvement in signal-to-background ratio necessary for accessing the intended cross section, despite of having only few mg of ^{79}Se available. Preliminary calculations [1] indicate that the i-TED method can provide an enhancement in detection sensitivity of about one order of magnitude compared to the conventional setup of C_6D_6 detectors (Fig.2). Such an improvement in signal-to-background ratio should enable the measurement of the ^{79}Se(n,γ) cross section. The main limitation of the i-TED system should be its low detection efficiency (about a factor of 5 less than the C_6D_6 set-up), but this will be compensated by the high flux in EAR2, which is expected to be a factor of 25 higher than at EAR1. For more details about this measuring technique the reader is referred to Ref.[1]. In the next section, the current status and future plans for the production of the sample will be summarized.

Production of the ^{79}Se sample:

A sample of ^{79}Se is being produced in collaboration between PSI (Switzerland) and ILL (France). Essentially, the production method is based on the irradiation of a ^{78}Se sample under the very intense thermal neutron fluence of the reactor at ILL. To this aim, first, the ^{78}Se sample needs to be produced with as little contaminants as possible. This is important, on one hand to avoid unstable products in the irradiated sample whose activity may exceed the dose rate limitations at ILL, and on the other hand to perturb as little as possible the planned (n,γ) cross section measurement at CERN n_TOF.

For the neutron irradiation at ILL, selenium shows the additional difficulty that its melting point is low (217 °C). For safety reasons during the irradiation at ILL, an alloy with another element which yields a higher melting temperature needs to be produced. After considering several possibilities, we have chosen a compound of Pb-Se. Lead is a convenient "companion" due to the very small cross section of ^{208}Pb (0.36 mb at 30 keV), much lower than the value expected for ^{79}Se (260 mb at 30 keV). Previous dedicated tests at PSI have demonstrated successfully the viability of pressing a stable sample (pellet) of Se-Pb using natural abundance isotopes.

For the final sample, about 3 g of metallic powder enriched to 99.34% in ^{78}Se will be mixed with highly enriched lead (99% ^{208}Pb) in order to obtain an alloy sample of Pb-Se. Once produced, this alloy will be first pulverized and then pressed into a stable pellet of ^{78}Se^{208}Pb with little contributions from other isotopes. The resulting alloy-pellet will be irradiated during 2014 under the intense flux of thermal neutrons at the ILL facility of Grenoble for about 1-2 cycle(s), depending on reactor availability. After one cycle of irradiation we will obtain $5.9\text{x}10^{19}$ atoms of ^{79}Se, which corresponds to only 7.8 mg.

Outlook

The final proposal for this experiment will address the following aspects. First, the final amount of ^{79}Se available for the experiment, the chemical composition of the sample and the main contaminants will be quantified. This piece of yet missing information is important in order to estimate reliably the amount of beam time required for the measurement. On the basis of this information, the expected count rates and peak-to-background levels will be evaluated. The latter will be addressed more reliably by means of detailed MC simulations which are being carried out for an alternative detection system [1].

References:

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