EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Neutron capture cross section of ^{25}Mg and its astrophysical implications

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Abstract: We propose to measure the neutron capture cross section of the stable ^{25}Mg isotope. This experiment aims at the improvement of existing results for nuclear astrophysics. The measurement will be carried out under similar conditions as for the Mg-experiment that was completed at n_TOF during 2003. A metal ^{25}Mg-enriched sample will be used in the proposed experiment instead of a MgO powder sample, which was used in the previous measurement and prevented us to minimize the uncertainty of the measured cross section. This experiment will be part of an ongoing study for a comprehensive discussion of the s-process abundances in massive stars.

Requested protons: 2×10^{18} protons on target

1 Introduction

The slow neutron-capture process (s-process) [1] in stars is responsible for the origin of about half of the elemental abundances beyond iron that we observe today. The so-called *main* component [2] originates from low mass asymptotic giant branch (AGB) stars in the range of 1 to 3 solar masses ($M_\odot$) and is responsible for the s component of the elements between Zr and the Pb/Bi region. The complementary *weak* component [3] is provided by massive stars with $M \geq 8M_\odot$ and fills the gap between the Fe seed and ^{89}Y.
By far neutron production in low mass stars is due to (α, n) reactions on ^{13}C and only about 5% of the neutron balance is contributed by ^{22}Ne$(\alpha, n)^{25}$Mg reactions [3]. In contrast to low mass AGB stars, neutron production in massive stars is dominated by the ^{22}Ne$(\alpha, n)^{25}$Mg reaction. In this regime the efficiency of the s-process for the production of elements heavier than iron is strongly dependent on the capture cross-section of ^{25}Mg isotope, since it acts as an important neutron poison.
Since the (α, n) reaction on ^{22}Ne is an important $s-$process neutron source, several attempts to measure the reaction cross-section are present in literature. Direct experiments failed to reach the low α energies of astrophysical relevance. Therefore a series of indirect measurements via α particle transfer reactions have been performed to overcome this limitation. Alternatively, the ^{25}Mg$(n, \gamma)^{26}$Mg reaction can be used to populate the same excited states. Being the ^{22}Ne$(\alpha, n)^{25}$Mg cross section still poorly known, important constraints can be extracted from the study of the states of the ^{25}Mg+n compound nucleus. In particular the resonance states of the ^{22}Ne$(\alpha, n)^{25}$Mg have natural spin and parity (0^+, 1^-, 2^+, ...) and correspond only to a subset of ^{26}Mg states, which are populated in the ^{25}Mg(n, γ)^{26}Mg reaction.

2 The ^{25}Mg(n,γ) measurement performed at n_TOF

The available experimental data for ^{25}Mg were essentially based on a single measurement performed at the electron linear accelerator in Oak Ridge (ORELA). In order to improve cross section data on Mg, a series of capture experiments were proposed [4] and performed [5] at n_TOF in 2003. Enriched Mg samples, provided by the IPPE Obninsk institute (RUSSIA) were used. Their chemical form was MgO and this powder was compressed in a can. The transmission data from ORELA were obtained using a natural Mg sample (79% of ^{24}Mg, 10% of ^{25}Mg and 11% of ^{26}Mg). This total cross section data set is very important for the capture cross section determination. Since thick Mg targets have to be used to measure the capture cross section, several corrections such as multiple scattering and self-shielding have to be applied. These corrections depend on elastic cross-section and total cross section, quantities which are deduced from a transmission experiment. The combined analysis of total cross section data from ORELA and capture cross section data from n_TOF resulted in an important update of the (n,γ) cross section. These cross sections have been convoluted with a Maxwellian neutron energy distribution to obtain the actual stellar cross section (MACS). Important information on $s-$process abundances have been obtained [5]. The main results are reported in Fig. 1 which shows the s-process abundance distributions calculated with the set of MACS values from the

KADoNiS data base [6] (blue squares) and with the MACS of the Mg isotopes obtained at n_TOF (red circles). The relative differences of the two distributions are emphasized by their ratio in the right panel. In the mass region of the weak s process between $A \approx 60$ and 90 one finds a significant enhancement of the abundance distribution, indicating a reduced poisoning effect. This reduction is mainly due to the lower MACS of ^{25}Mg. The

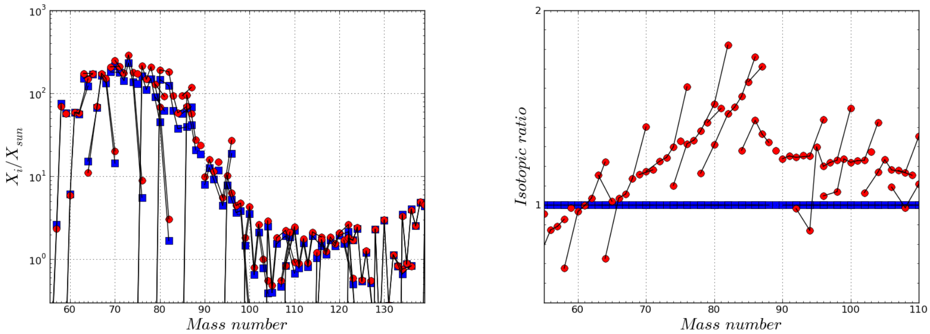

Figure 1: Left: Abundance distribution of the weak s process calculated with MACS values from the KADoNiS data base [6] (blue squares) and after replacing the MACS of the Mg isotopes by the present results (red circles). Right: The ratio of the two distributions indicates an average enhancement of 30% due to the reduced neutron poisoning effect.

average enhancement of about 30% underlines the importance of reliable cross section data for the light isotopes below the mass range of the Fe peak. As demonstrated by the results for the Mg isotopes, these elements can strongly influence the neutron balance of the s process with significant consequences for the overall abundance distribution as well as for the analysis of s-process branchings.

Constraints for the neutron source ^{22}Ne$(\alpha, n)^{25}$Mg were studied populating the same excited states using the ^{25}Mg$(n, \gamma)^{26}$Mg reaction as shown in Fig. 2. The reaction rates for the ^{22}Ne+α reaction at $s-$process temperatures are determined by the level structure of the compound nucleus ^{26}Mg above the α threshold ($Q = 10.615$ MeV) and near the neutron threshold ($S_n = 11.093$ MeV). The constraints are related to the assignment of the spin/parity of these states. From the combined analysis of capture and transmission data it was possible to assign the spin of some resonances, in particular there are strong evidence [5] for natural parity for the resonances at 19.86-keV ($E_x = 11.112$ MeV) and 72.66-keV ($E_x = 11.163$ MeV), and strong indications for non-natural parity for the resonances at 62.727-keV ($E_x = 11.154$ MeV) and 79.29-keV ($E_x = 11.169$ MeV). An example of spin assignment is given in Fig. 3 for the 19.86-keV resonance. The total angular momentum (or spin) $\vec{J}$ of the resonance results from the vector sum of **A)** the spin of the target nucleus ^{25}Mg ($\vec{I} = 5/2$); **B)** the spin of the projectile n ($\vec{i}$=1/2) and **C)** the angular momentum ℓ by the following relation: $\vec{J} = \vec{\ell} + \vec{I} + \vec{i}$. In this case, for a given angular momentum two channel spin $(\vec{I} + \vec{i})$ are allowed: $2 < |\vec{I} + \vec{i}| < 3$. From the asymmetry of the shape of the resonance (see Fig. 3) a $s-$ware resonance ($\ell = 0$) can be inferred. Therefore the spin of the 19.86-keV resonance can be either $\vec{J} = 2^+$ or $\vec{J} = 3^+$. The simultaneous resonance shape analysis of capture and transmission data excludes $\vec{J} = 3^+$, as can be seen in Fig. 3. Therefore being a natural spin/parity state of

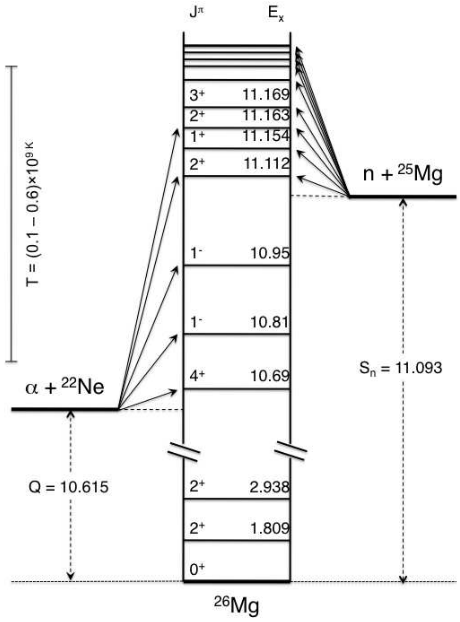

Figure 2: Level scheme (not to scale) of ^{26}Mg with the ^{22}Ne+α and ^{25}Mg+n entrance channels. The reaction $Q-$values and the neutron-separation energy S_n are in MeV. Spin/parity values of resonances are given together with the level energies. Note the negative Q-value for the ^{22}Ne$(\alpha, n)^{25}$Mg reaction.

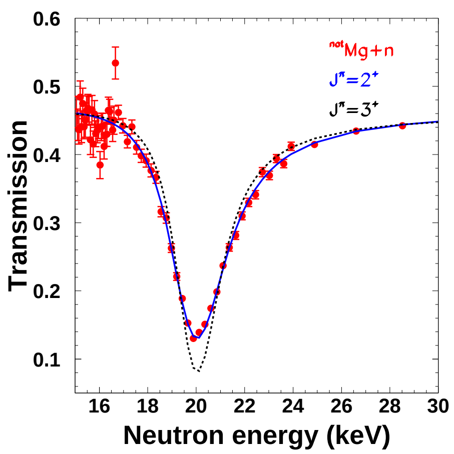

Figure 3: Transmission data for the 19.86-keV resonance in n+^{25}Mg reaction together with the result of the resonance shape analysis assuming different spins.

the ^{26}Mg compound nucleus, this level must participate in the ^{22}Ne$(\alpha, n)^{25}$Mg reaction.

3 Limiting factors of the previous measurements

Three aspects had a strong impact on the analysis of capture cross section of ^{25}Mg and on its parametrization in term of R-matrix.
A) A problem with the areal density of the enriched oxide sample used at n_TOF did not permit us to provide results with uncertainties better than 12%.
B) For most of the ^{25}Mg+n resonances in the energy region of interest ($E_n \lesssim 250$ keV) to $s-$process the spin and parity assignments remain uncertain because of the quality of the MgO capture sample used at n_TOF, and because the transmission data available is deduced from a $^{\rm nat}$Mg sample. Fig. 4 shows the transmission data from ORELA together with the result of the resonance shape analysis. The three almost saturated signals at

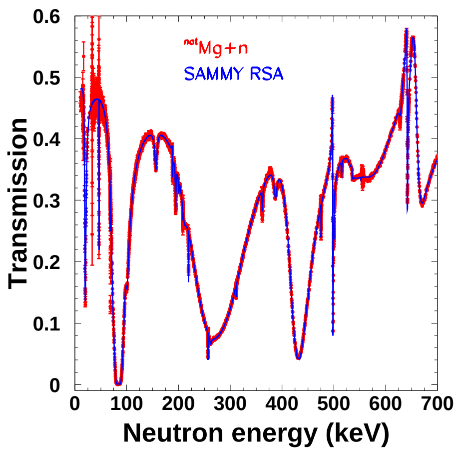

Figure 4: $^{\rm nat}$Mg+n transmission data (red symbols) and the SAMMY fit (blue line).

84 keV, 267 keV and 431 keV attributable to interaction of neutron with ^{24}Mg hide the resonances attributable to n+^{25}Mg in the same energy regions.
C) The capture measurement at n_TOF was performed during the so-called phase-I, using water as neutron moderator. Since the n_TOF facility has been upgraded in 2009, the new spallation target is equipped with two different circuits for cooling and moderation, thus offering more flexibility in the choice of the moderator. The use of borated water has reduced the background due to in-beam γ rays by a factor 10 in the energy region above 5 keV, which is the region of greatest interest for present case. Fig. 5 shows the comparison of the capture yield of $^{\rm nat}$Fe measured with a water moderator and with borated water as moderator.

4 The experimental program

We propose to measure the neutron capture cross section of ^{25}Mg taking profit of the upgraded tools available at the n_TOF facility. Moreover we will use a self-supporting (i. e. not compressed powder in a can) metal ^{25}Mg-enriched sample. This cross section will be determined up to about 300 keV by means of C_6D_6 liquid scintillators, which

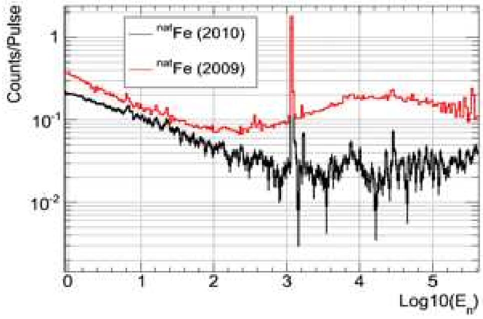

Figure 5: Comparison between the yields of $^{\mathrm{nat}}$Fe measured in 2009 (red), water was used as moderator, and in 2010 (black), borated water was used as moderator.

are optimized with respect to neutron sensitivity. An isotopically ^{25}Mg-enriched sample is provided by the Oak Ridge National Laboratory (USA). It is characterized by the following specifications:

Material:	Mg-25;
Chemical Form:	Mg metal disc (3-cm diameter);
Isotopic enrichment:	97.86%;
Quantity:	8.8 g;

Additional measurements could be performed at the neutron time-of-flight facility GELINA operated by the EC. A transmission measurement on the same sample will improve the analysis of the capture cross section eventually allowing for the spin assignment. Moreover dedicated measurements with HPGe detectors to detect single γ-ray transitions could be performed.

Summary of requested protons: The request for the number of protons is based on previous measurements with C_6D_6 scintillation detectors.Together with the ^{25}Mg samples, we plan to measure the yield for Au, C and Pb samples as well. Au is used for normalizing the yield and the carbon and lead samples are used to determine the background due to neutrons scattered by the sample. According to the previous capture measurements we request a total of 2×10^{18} protons for the present measurement.

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