EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Search for a resonance in ^{25}Mg(n,γ) cross section to constrain the ^{22}Ne(α,n)^{25}Mg neutron source reaction rate

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Abstract:

The ^{22}Ne(α,γ)^{26}Mg and ^{22}Ne(α,n)^{25}Mg nuclear reactions regulate the production of neutrons in Red Giant stars. In particular, this is true for the *weak s–process* in massive stars and for branchings points of the *main s–process* in asymptotic giant branch stars. The direct measurement of their cross sections in the energy region of interest is notably challenging. In the past, the n_TOF collaboration has performed several n+^{25}Mg experiments to constrain their reaction rates. After these measurements, it became clear that a weakly populated resonance in ^{25}Mg(n,γ)^{26}Mg at $E_n \approx 234$ keV – never observed so far – would have the largest impact on the ^{22}Ne+α reactions and therefore on neutron production in stars. Therefore, we propose to perform a neutron-capture measurement with a setup conceived and optimized for this resonance in the hundred-keV energy region at EAR1 and EAR2.

Requested protons: 4×10^{18} protons on target
Experimental Area: EAR1 and EAR2

1 Introduction

The slow neutron-capture process (*s–process*) is a fundamental mechanism in stellar nucleosynthesis [1], responsible for the production of roughly half of the elements heavier than iron. This process, primarily driven by neutron capture on seed nuclei, occurs in low-mass asymptotic giant branch (AGB) stars and massive stars. While the *s process* in low-mass AGB stars is predominantly fueled by the ^{13}C(α,n)^{16}O reaction, with an additional neutron production via the ^{22}Ne(α,n)^{25}Mg reaction during the thermal pulse phase in the hydrogen helium intershell region. In core helium burning in massive stars the ^{22}Ne(α,n)^{25}Mg neutron source is fueled by α capture reactions on the ^{14}N ashes of the preceding CNO burning phase. Therefore the ^{22}Ne(α,n)^{25}Mg reaction plays a crucial role in both low-mass and massive stars. In more detail, this reaction regulates the production of isotopes close to *s-process* branching points in AGB stars and determines the element distribution from Cu to Zr in massive stars.
The cross-section of the ^{22}Ne(α,n)^{25}Mg reaction, particularly at astrophysically relevant energies, remains uncertain [2, 3, 4]. Direct measurements at low energies are challenging due to the low cross section at low energies near the neutron threshold [5, 6]. To address this limitation, indirect methods have been employed. These include studies of the ^{25}Mg(n,γ)^{26}Mg neutron capture [7, 8], the ^{25}Mg(d,p)^{26}Mg neutron transfer reaction [9], and reactions such as ^{26}Mg(γ,n)^{25}Mg, ^{26}Mg(γ,γ')^{26}Mg and ^{22}Ne(^{6}Li,d)^{26}Mg, (see Refs.[2, 3] for a comprehensive discussion). By investigating the properties of the ^{26}Mg compound nucleus, valuable insights into the ^{22}Ne(α,n)^{25}Mg reaction can be gained. While previous studies have focused on determining the α strength of critical states, this study will specifically focus on the study of the weak single particle or neutron strength component complementing earlier measurements of the γ strength of the resonance states [10, 11].

2 Status of α+^{22}Ne nuclear data near $E_\alpha = 832$ keV

The resonance at about $E_\alpha = 832$ keV in ^{22}Ne(α,n) – corresponding to the compound state at $E_x = 11.32$ MeV in ^{26}Mg – is of particular significance for *s-process* nucleosynthesis. As comprehensively explained in Refs. [12, 2, 3], at temperatures of $kT = 30$ keV, the corresponding resonances contributes approximately 90% to the ^{22}Ne(α,γ)^{26}Mg reaction rate and 80% to the ^{22}Ne(α,n)^{25}Mg reaction rate. These astrophysical implications underscore the critical need for further investigation into the properties of this state. A new measurement of the resonance has been recently reported [4] and a broader study of the ^{22}Ne(α,n)^{25}Mg reaction over a wider energy range is currently underway at the INFN underground laboratory Gran Sasso [5, 6], which is expected to provide more accurate estimates for Γ_α.
On the other hand, the γ-ray width Γ_γ, the neutron width Γ_n, as well as the total width $\Gamma = \Gamma_\alpha + \Gamma_\gamma + \Gamma_n$ remain subject to considerable uncertainty. Measurements of the ^{22}Ne(α,γ)^{26}Mg reaction for the $E_\alpha = 832$-keV resonance are rather consistent (see Ref. [2] and reference therein) and so constraints on the strength of this resonance for the ^{22}Ne(α,n)^{25}Mg reaction can be made from better knowledge of the relative size of Γ_n and Γ_γ. So far, there are discrepancies in the experimental data from direct studies and indirect measurements of the resonance parameters. For instance, the indirect measurement in Ref. [13] reported a branching ratio $\Gamma_n/\Gamma_\gamma = 1.14 \pm 0.26$, while the measurement of Shahina and collaborators [4] mentioned above provides a significantly larger value of $\Gamma_n/\Gamma_\gamma = 2.85 \pm 0.71$. This inconsistency clearly calls for new measurements to determine the partial widths of this resonance.
In principle, Γ_n and Γ_γ could be accurately determined combining ^{25}Mg(n,γ)^{26}Mg and

^{25}Mg(n,tot) cross-section data [14]. However, this level has not been observed as a resonance in the n+^{25}Mg experiments performed by the n_TOF collaboration [7, 8]. More in detail, Fig. 1 illustrates the absence of a resonance at $E_n = 234$ keV – corresponding to the compound state at $E_x = 11.32$ MeV in ^{26}Mg – in the capture and transmission data obtained by the n_TOF collaboration [7, 8]. The experimental data is compared with the expected capture yield and transmission based on the resonance parameters from Ref. [15], assuming $\Gamma_\gamma = 1.5$ eV and different natural parity values for the resonance. In fact, the spin-parity assignment for this state has not been definitively determined, but it points to a 1^- natural parity state [3].

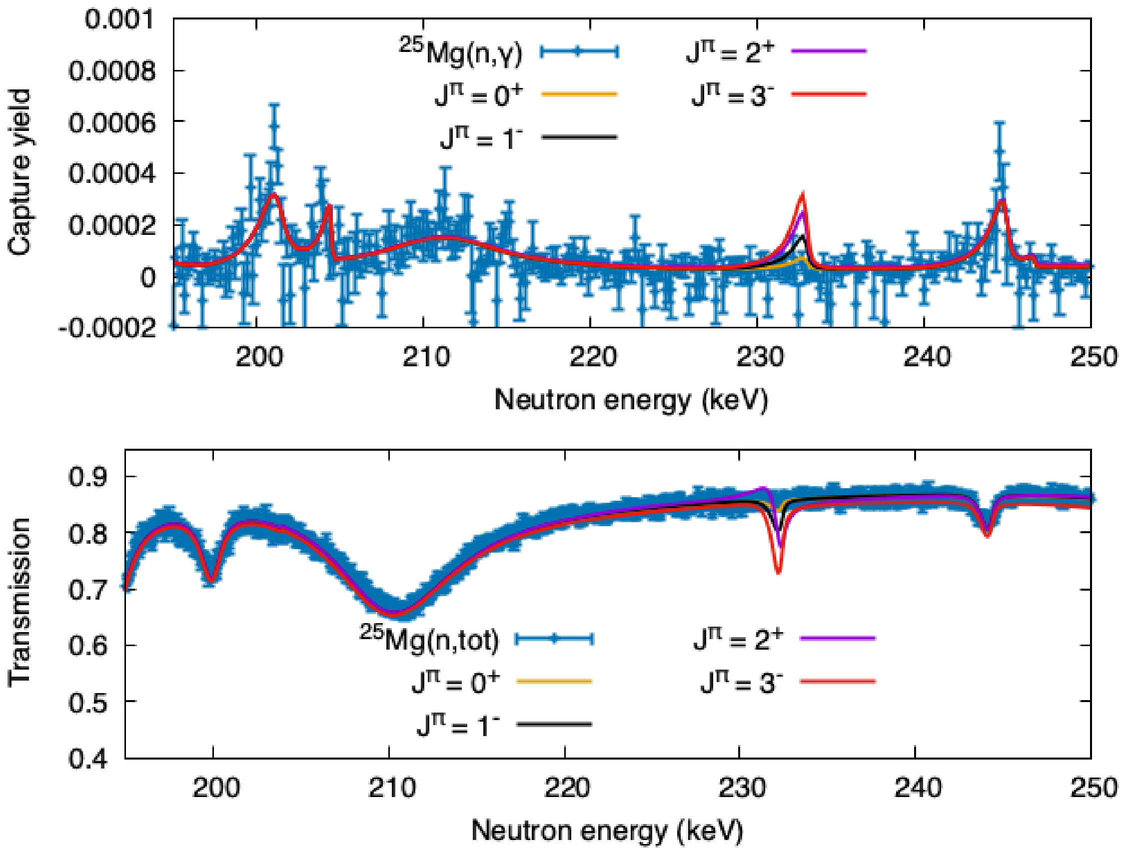

Figure 1: Capture and transmission data obtained in the n_TOF experiment [7, 8] and calculations of the expected values using the resonance parameters from Ref. [15]. A γ-ray width $\Gamma_\gamma = 1.5$ eV is used in the calculation.

The absence of such a neutron resonance at $E_n = 234$ keV in previous ^{25}Mg(n,γ)^{26}Mg and ^{25}Mg(n,tot) cross section measurements remains an open question. One possible explanation is that the resonance width $\Gamma = 250 \pm 170$ eV reported by Jaeger and collaborators [15] has been significantly overestimated due to experimental resolution limitations. This would also support the argument that the neutron partial width Γ_n should be comparable to the γ-ray partial width Γ_γ. This latter hypothesis being related to the role of α-cluster structure in ^{26}Mg compound states [3].

3 A neutron resonance at $E_n = 234$ keV?

The transmission data is sensitive to $g\Gamma_n$, where $g = \frac{2J+1}{(2I+1)(2i+1)}$ is the statistical spin factor and J, I and i are the spin of the resonance, the ^{25}Mg target nucleus and the impinging neutron, respectively. Moreover the shape of the resonance in transmission data is strongly influenced by the orbital angular momentum (ℓ) of the neutron-target system, as illustrated in Fig. 2. A visual inspection of the bottom panel of Fig. 1 compared to Fig. 2 suggests that either $\ell \neq 0$ and/or $\Gamma << 250$ eV, *i. e.*, the neutron width is significantly lower than reported in Ref. [15]. A more quantitative analysis, such as simultaneously fitting the transmission data and capture data with different resonance parameters (varying Γ_n, Γ_γ ℓ, and J^π), is necessary to further constrain the resonance properties.

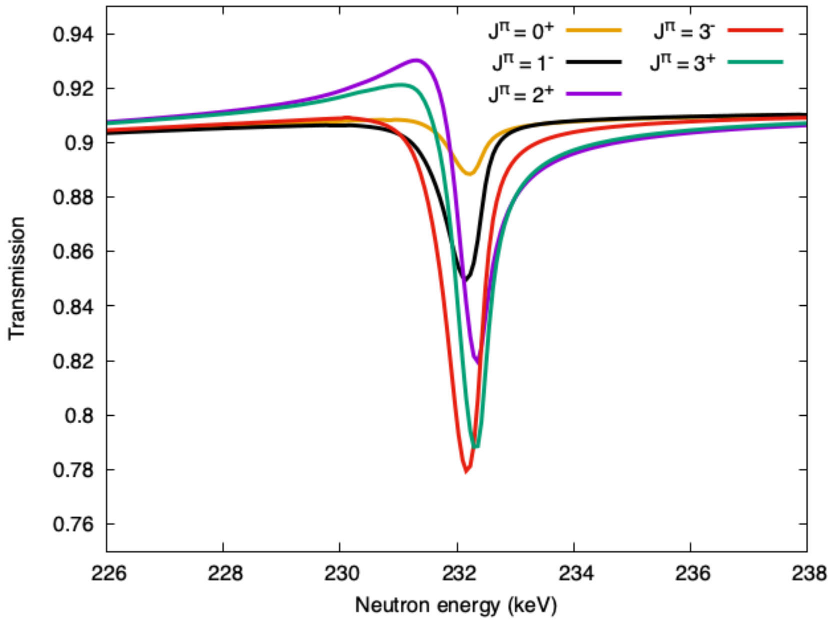

Figure 2: Calculated transmission using the resonance parameters from Ref. [15], while varying the spin parity assignment. For neutron s-wave resonances ($\ell = 0$): $J^\pi = 2^+$ and $J^\pi = 3^+$ the interference between resonant elastic scattering and hard-sphere elastic scattering results in an asymmetric shape.

While the transmission data provide strong evidence for a narrower resonance than previously reported, previous capture data from n_TOF suffer from severe limitations due to a combination of limited beam time (only 7×10^{17} protons were assigned to the capture measurement) and the use of an enriched ^{25}Mg sample optimized for the energy region below 200 keV [8]. This resulted in a significant lack of statistics, particularly in the energy region near $E_n = 234$ keV, leading to large uncertainties and hindering the precise determination of resonance parameters. Therefore, a dedicated capture measurement with improved statistics is highly recommended to investigate the properties of this weak resonance. This new measurement should utilize a thicker ^{25}Mg sample and allocate sufficient beam time to ensure adequate data collection in the energy region around $E_n = 234$ keV.

4 Proposed setup for a new capture experiment

We propose that a new capture measurement be performed in both EAR1 and EAR2 at the n_TOF facility to address the outstanding questions regarding the α+^{22}Ne resonance near $E_\alpha = 832$ keV, particularly the absence of a clear neutron resonance at $E_n = 234$ keV in previous ^{25}Mg(n,γ) experiments. While EAR1 offers superior energy resolution, crucial for precise resonance shape analysis, EAR2 is advantageous for achieving high statistical precision due to its higher neutron flux.
To optimize the measurement, several improvements are planned compared to the previous n+^{25}Mg experiment [14]:

- Increased detector array: an array of four C_6D_6 detectors will be employed, enhancing the detection efficiency compared to the previous setup with only two detectors.
- Thicker capture sample: a thicker ^{25}Mg sample with an areal density of 5.0×10^{-2} atoms/b (compared to 3.0×10^{-2} atoms/b previously) is expected to improve the signal-to-noise ratio, and increase the overall measurement sensitivity.
- Combined EAR1 and EAR2 measurements: the measurements will be performed in both EAR1 and EAR2, utilizing an array of 8 sTED detectors in EAR2. This combined approach will leverage the strengths of both experimental setups, providing high-resolution data from EAR1 and high-statistics data from EAR2, leading to a more comprehensive and robust dataset.

It is important to mention that the proposed measurement, in addition to the $E_n = 234$-keV resonance investigation, can partially cover the higher energy region corresponding to the excitation energy range measured by Jaeger [15]. This result is relevant for understanding the correspondence between the different resonances populated in α+^{22}Ne and n + ^{25}Mg.
Summary of requested protons: Based on the requirements of the proposed measurements in EAR1 and EAR2, and considering the experience gained from previous n+^{25}Mg and capture experiments, we request a total of 3.0×10^{18} protons for the measurement campaign in EAR1 and 1.0×10^{18} protons for the measurement campaign in EAR2. In both cases, 80% of beam time will be dedicated to ^{25}Mg(n,γ) and 20% to background measurements. More specifically, to ensure accurate data normalization and background subtraction, the measurements will include calibration samples of Au, C, and Pb. Au will be used for normalizing the neutron flux, while C and Pb samples will be used to determine the background due to neutrons scattered by the sample. On the other hand, the ^{25}Mg(n,γ) capture yield obtained with 2.4×10^{18} protons would reveal the presence of a weak neutron resonance at $E_n = 234$ keV, with partial widths on the order of 1 eV.
It is important to mention that, given the focus of this proposal (*i.e.* verifying the presence of the neutron resonance at $E_n = 234$ keV and possibly estimating its Γ_γ and Γ_n), the capture measurement in EAR1 could be performed in parallel with a transmission measurement campaign in the same experimental area.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

Please describe here below the main parts of your experimental set-up:

Part of the experiment	Design and manufacturing
C6D6, sTED	☒ To be used without any modification ☐ To be modified
Enriched ^{25}Mg sample	☒ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazard from flexible or transported equipment to the CERN site:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☐	
	Vacuum	☐	
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	
Electrical Safety	Electrical equipment and installations	☐	
	High Voltage equipment	☐	
Chemical Safety	CMR	☐	
	Toxic/Irritant	☐	
	Corrosive	☐	
	Oxidizing	☐	
	Flammable/Potentially explosive atmospheres	☐	
	Dangerous for the environment	☐	
Non-ionizing radiation Safety	Laser	☐	
	UV light	☐	
	Magnetic field	☐	
Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height	☐	
	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards		☐	