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**PROPOSAL**

# The importance of $^{22}$Ne($\alpha$,n)$^{25}$Mg as $s$-process neutron source and the $s$-process thermometer $^{151}$Sm

*The n_TOF Collaboration*

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# 1 Introduction

Neutron capture nucleosynthesis provides a sensitive tool for testing He burning scenarios in massive stars [1] as well as in low mass AGB stars [2]. During this phase of stellar evolution nuclei in the mass region between Fe and Bi are produced by the slow neutron capture process ($s$-process). Because of the relatively low neutron densities, neutron capture times are long compared to typical $\beta$-half-lives. This implies that the reaction path follows the stability valley and that the resulting abundances are essentially determined by the respective neutron capture cross sections. Hence, these data represent the most important nuclear physics input for $s$-process studies. In general, laboratory measurements are required in the energy range $0.1 < E_n < 300$ keV in order to obtain reliable averages over the stellar Maxwell-Boltzmann distribution for thermal energies between kT=5 keV and 30 keV. The extremely high neutron flux, the energy resolution and the excellent duty factor make the n_TOF facility at CERN a unique place for such measurements. This holds in particular if one deals with radioactive samples or with resonance-dominated cross sections. We plan to start our Nuclear Astrophysics programme with two experiments taking advantage of these specific features[3].

# 2 THE STELLAR (n,$\gamma$) CROSS SECTIONS OF THE STABLE Mg ISOTOPES

Reliable cross sections for the three stable Mg isotopes are important for the interpretation of the abundance ratios in interstellar grains that carry information on the $^{26}$Al production in red giants as well as for the relative importance of the $^{22}$Ne($\alpha$,n)$^{25}$Mg reaction as an $s$-process neutron source. Since the small cross sections of these light isotopes are difficult to measure the few available data suffer from severe systematic uncertainties. With the excellent resolution and the high flux of the CERN n_TOF facility the experimental techniques can be significantly improved resulting in a new and promising access to these persistent problems. The experience gained in this experiment will be of utmost importance for the long neglected mass region between C and Fe: Almost all of these elements were identified in interstellar grains and this source of information is mostly unexplored due to the lack of reliable neutron capture rates. This holds also for the role which these abundant isotopes play as neutron poisons for the $s$-process.

## 2.1 $s$-Process signatures in interstellar grains

Nucleosynthesis studies normally have to refer to the isotopic abundance distribution of solar material, which is best represented by the composition of primitive meteorites corresponding to that of the protosolar nebula [4, 5]. As far as the isotopic abundance patterns are concerned, there is perfect agreement between terrestrial and meteoritic data on average. However, fascinating anomalies have been discovered in meteoritic inclusions, which were identified as pristine material from various nucleosynthesis sites.

Beyond the representative solar mix, the isolation of such presolar grains has established a new field of "isotopic" astronomy. This exciting, new access to the chemical abundance memory of nature [6, 7, 8, 9] has attracted increasing interest from astrophysicists as well as from astronomers. These grains were identified to originate from circumstellar envelopes of mass-losing red giants and from supernova ejecta and have made their way through the interstellar medium without modification. Therefore, they contain "pure" $s$- and $r$-process material and, hence, represent important probes for these objects that allow to study the corresponding nucleosynthesis processes in the most direct way.

A variety of grains have meanwhile been found and isolated, e.g. micro-diamonds, $Si_3N_4$, and SiC-X from supernovae, SiC and corundum from AGB stars as well as graphite grains from both sources and from novae [9]. An illustrative example for the nuclear physics impact on these analyses are the isotopic anomalies for Ba and Nd, which were attributed to the *s*-process but could not be described quantitatively [10] until accurate neutron capture data became available [11, 12].

Since the anomalous isotope patterns can be measured very precisely, this information has to be complemented by accurate cross section data in order to achieve full interpretation in an astrophysical sense. This requirement represents quite a challenge since many of the interesting elements, e.g. O, Mg, Si, Ca, Ti, Cr, and Zr fall in mass regions where typical (n,$\gamma$) cross sections are small. So far, such data are scarce and exhibit rather large uncertainties, a situation that motivates the proposed experiment.

In particular, the *s*-process isotopic compositions carry very detailed information on the AGB phase of stellar evolution. In case of the Mg isotopes, there are two important questions:

i. The absence of strong $^{25}$Mg anomalies [13] provides evidence that the reaction $^{22}$Ne($\alpha$,n)$^{25}$Mg is a minor neutron source in the *s*-process. Its relative strength compared to the dominant $^{13}$C($\alpha$,n)$^{16}$O reaction can be derived from the enhancement of $^{25}$Mg in such grains.

ii. Many of these grains show large excesses of radiogenic $^{26}$Mg which are attributed to the in situ decay of radioactive $^{26}$Al ($t_{1/2}$=7 $10^5$ yr). The inferred $^{26}$Mg excesses range between $10^{-5}$ and 0.6 [14, 13]. These observations are directly linked to the question of how much of the galactic $^{26}$Al observed by satellite based $\gamma$-ray observations is produced by AGB stars.

Apart from this immediate astrophysical relevance the proposed experiment has a pilot function for a comprehensive study of the mass region between C and Fe which is important because these abundant isotopes act as neutron poisons for the *s*-process. In spite of their relatively small *s*-process components, these could be identified for almost all these elements in interstellar grains [9]. All these important aspects are almost unexplored due to the lack of reliable neutron capture rates.

### 2.2 The Mg cross sections

The small, resonance-dominated cross sections of the light nuclei between C and Fe are difficult to measure. The few available data suffer from severe systematic uncertainties due to unrecognized backgrounds in previous measurements, resulting cross section discrepancies of several 100%. With the excellent resolution and the high flux of the CERN n_TOF facility these persistent problems can be addressed in a new and promising way.

The available experimental data for $^{24}$Mg, $^{25}$Mg, and $^{26}$Mg are essentially based on a single measurement that was carried out at the electron linear accelerator in Oak Ridge [15]. Though fairly small uncertainties are claimed for the resulting cross sections, the setup used at that time was found rather sensitive to scattered neutrons. This problem led to discrepancies of factors two to four in case of the $^{208}$Pb and $^{209}$Bi cross sections, which are similarly dominated by relatively few resonances [16]. Recent activation studies on $^{26}$Mg [17, 18] have reported a three times smaller resonance contribution than in Ref. [15], thus confirming this severe problem of the existing data.

## 3 THE *s*-PROCESS THERMOMETER $^{151}$Sm

The stellar neutron capture rate of the unstable isotope $^{151}$Sm is required for an improved analysis of the $s$ abundances in the Sm-Eu-Gd region. This mass region exhibits a number of branchings which cause part of the reaction flow to bypass the $s$-only isotopes $^{152}$Gd and $^{154}$Gd. Hence, the abundances of these isotopes provide a possibility to constrain the strength of the branchings, which are - on the other hand - determined by the competition between $\beta$-decay and neutron capture. Since $^{151}$Sm is the only relevant branch point for $^{152}$Gd, a measurement of the neutron capture rate defines also its effective stellar $\beta$-decay rate. Because this rate depends on the stellar temperature, the $^{151}$Sm branching constitutes a thermometer for the $s$-process. The reliability of this thermometer can be substantially improved by the experimental determination of the (n,$\gamma$) cross section of $^{151}$Sm with a precision better than 25%.

### 3.1 Investigating the $s$-process temperature

Signatures of the $s$-process temperature can be found in branchings of the neutron capture chain of the $s$-process whenever the corresponding $\beta$-decay rate exhibits a pronounced temperature-dependence. The present situation [19] is characterized by uncertainties due to the yet missing experimental information on the neutron capture cross sections of the radioactive branch point nuclei. While the corresponding data for the relevant stable isotopes have been measured with accuracies of 1 to 2% [20, 21, 22], the cross sections of the radioactive branch point isotopes have so far only been obtained by comparably uncertain statistical model calculations. Regrettably, these uncertainties propagate into the evolving abundance pattern and veil the temperature effects.

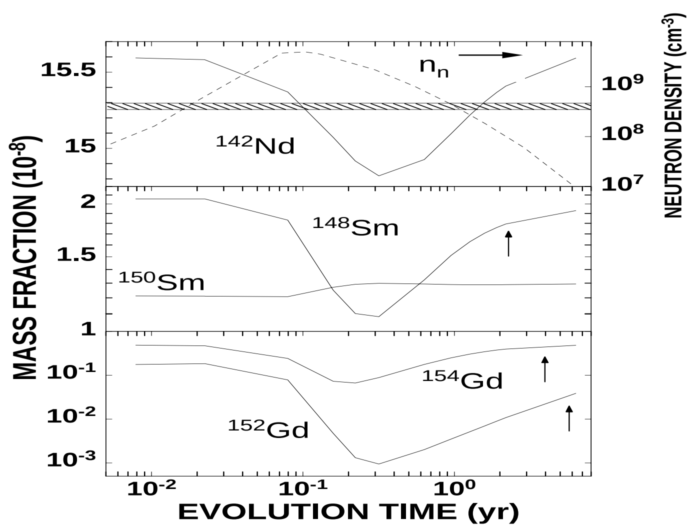


Figure 1: From top to bottom, the panels show the abundance evolution of the $s$-only isotopes $^{142}$Nd, $^{148,150}$Sm, and $^{152,154}$Gd during a helium shell flash. At maximum temperature and neutron density all isotopes are partially bypassed by the reaction flow due to related branchings. The corresponding depletion factors are quite different, thus representing a sensitive test for the stellar model. The dashed bar in the top panel indicates the neutron density obtained from the schematic, classical approach assuming constant neutron density and temperature [24].

In fact, the analysis of $s$-process branchings provides strong constraints for models of the yet uncertain stages of shell helium burning, from where the main $s$-process contributions between Zr and Bi originate [23]. This is illustrated in Fig. 1 which shows how the abundances in various branchings change as temperature and neutron density change during a typical He shell flash [24]. Note in particular the example of $^{152}$Gd, which is depleted by a factor 100 at maximum of temperature and neutron density. The proper description of the resulting $s$ abundances for a number of branchings clearly provides a very crucial test of any stellar model for the $s$-process site.

### 3.2 The $s$-process branching at $^{151}$Sm

The $s$-process reaction flow in the Sm–Eu–Gd region is illustrated in Fig. 2. This flow pattern exhibits several branchings due to the occurrence of sufficiently long-lived nuclei, where neutron capture can compete with $\beta$-decay. The branching at $^{151}$Sm is one of the most important examples. In this case the branching ratio is determined by the neutron flux (via the capture rate) and by the temperature of the stellar environment, since the $\beta$-decay half-life of $^{151}$Sm is significantly reduced from the laboratory value of 93 years to 3 years during the $s$-process [25]. Since the half-life of $^{151}$Sm against neutron capture is only about 0.13 years, most of the reaction flow continues via $^{152}$Sm. This implies, however, that any change of the $^{151}$Sm cross section affects the fraction towards $^{152}$Gd significantly.

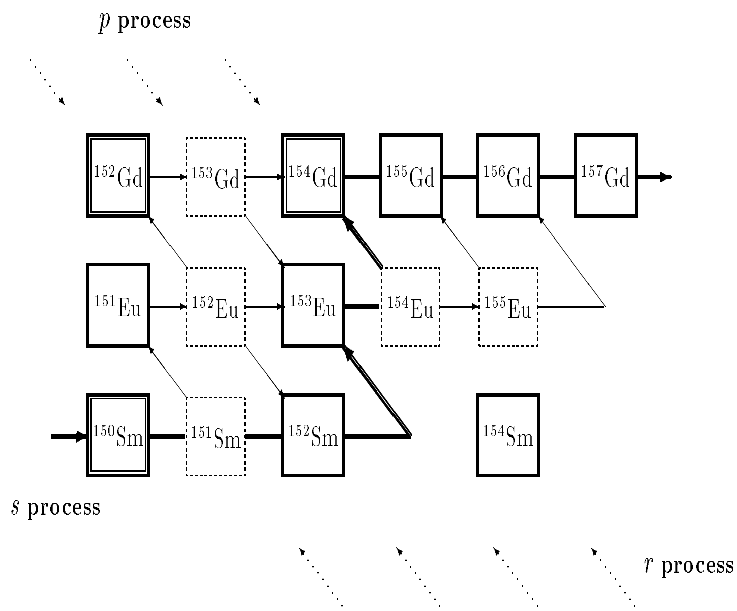


Figure 2: The $s$-process reaction flow in the Sm-Eu-Gd region with the important branching at $^{151}$Sm

The $s$-process region of Fig. 2 has been investigated recently [22] when the (n,$\gamma$) cross sections of the two $s$-only isotopes $^{152}$Gd and $^{154}$Gd were measured with good accuracy. These isotopes are crucial for defining the branching ratio, because they are shielded against the $\beta$-decay chains from the $r$ process by their stable samarium isobars. A major obstacle in this work was, however, that the neutron capture rate of $^{151}$Sm had to be determined by means of theoretical model calculations, which are known to carry uncertainties of about 50% [16].

## 4 The experimental programme

For a substantial improvement of these cross sections we, therefore, propose to measure at the CERN n_TOF facility the (n,$\gamma$) cross section of the isotopes $^{24}$Mg, $^{25}$Mg, and $^{26}$Mg and of the radioactive nucleus $^{151}$Sm, using an array of 4 $C_6D_6$ liquid scintillators (Fig. 3) read out by ADCs with a sampling rate of 1GHz. These measurements are planned to be performed in automn 2000 following the on-going Monte Carlo simulations and the test measurements of the actual background, after the completion of the inititial phase described in reference [26].

Isotopically enriched Mg samples of high purity for the planned measurements are provided by the IPPE Obninsk and CSNSM Orsay. They are characterized by the following specifications:

| | |
|---|---|
| Sample mass: | 200 mg and 1 g for each isotope; |
| Isotopic enrichment: | $\geq$98% or 99.9% for all isotopes |
| Chemical form: | metal foils; |
| Chemical purity: | $\geq$99.5%; |

The $^{151}$Sm sample for the planned measurement is provided by Oak Ridge National Laboratory in collaboration with FZK and Los Alamos National Laboratory. It is characterized by the following specifications:

| | |
|---|---|
| Sample mass: | 200 mg $^{151}$Sm; |
| Isotopic enrichment: | 90.05$\pm$0.03% $^{151}$Sm; main impurities: $^{150}$Sm (3.93%) and $^{152}$Sm (3.3%); |
| Chemical form: | $Sm_2O_3$ as powder, heated in oxygen at 1000 C to ensure stoichiometry and to remove water; |
| Chemical purity: | Eu/Sm ratio $\approx$ 2.0 $10^{-4}$; |
| Canning: | welded Ti can, wall thickness 0.2 mm, 10 mm diameter |

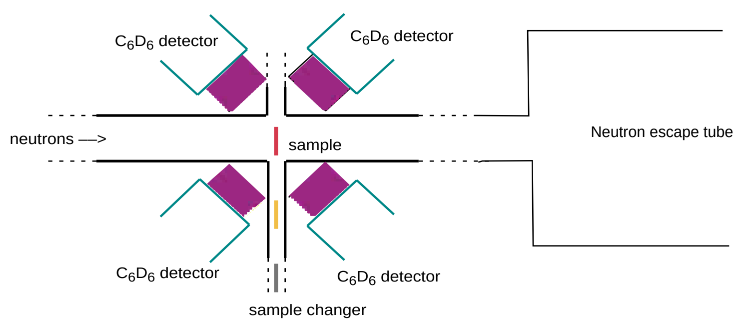


Figure 3: Schematic view of the experimental set-up

In order to achieve reliable measurements of (n,$\gamma$) cross sections the $\gamma$-backgrounds from the various sources have to be experimentally determined and the data appropriately corrected. The most feasible way to determine these background components is to perform succesive measurements of different samples mounted on a “sample changer” inside the evacuated beam tube. These samples are an empty container, identical to the one enclosing the $^{151}$Sm sample (to the substrate of the Mg samples), a reference sample of $^{197}Au$ and a scattering sample of Carbon or $^{208}Pb$, both enclosed by identical containers (identical substrates). The design of this “sample changer” is based on Monte Carlo simulations, minimising possible additional backgrounds from the interaction of scattered neutrons with its various parts.

For the Mg measurements we plan to use two different samples for each Mg isotope to match the count rates in the resonance peaks as well as the much smaller rates in between.

Based on the existing cross section data and assuming a realistic detection efficiency for capture events of 10%, total measuring times of about 2 and 4 days are estimated for the thick and thin samples, respectively. In addition, 2 to 3 days will be required for background runs to determine beam-related $\gamma$-counts and the effect of scattered neutrons. Therefore a total beam time of 21 days is requested for this experiment.

In the case of $^{151}$Sm the count rates in the relevant range from 1 to 100 keV are between 0.4 and 0.8 $\frac{events}{\Delta E \times pulse}$ with $\Delta$E/E=0.1. Based on the present knowledge of simulated fluence and backgrounds we estimate safely that the required total beam time for the $^{151}$Sm measurement will not exceed 10 days (Fig. 4).

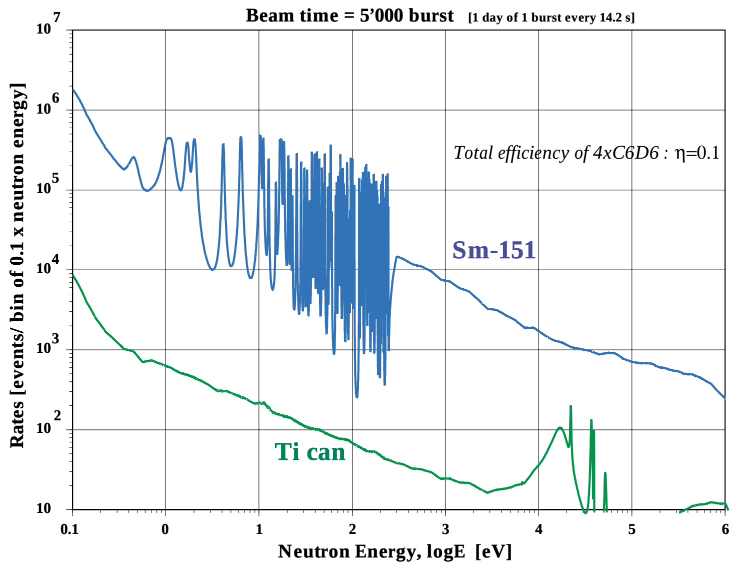


Figure 4: Simulated spectrum corresponding to one day of running assuming one burst per supercycle

From the existing expertise in the collaboration for measurements with $C_6D_6$ detectors [27, 28] the overall uncertainty of the resulting Mg cross sections is expected to be about 5%. Similarly the overall uncertainty of the resulting $^{151}$Sm cross section is expected to be better than 5%. The main contributions to this uncertainty come from the $C_6D_6$ efficiency for capture events (weighting function), from the flux measurement and from the sample activity in the case of $^{151}$Sm.

With the improved Mg cross sections reliable analyses of the above mentioned *s*-process problems can be performed for the first time. Moreover the results from $^{151}$Sm will allow considerably refined analyses of the *s*-process branchings at A=151/154 for probing the temperature and neutron density regime during He shell burning in low-mass AGB stars.

## 5 Beam time request

We intend to perform these measurements in automn 2000. These measurements beside their intrinsic scientific importance will reveal the potential of the n_TOF facility both for measurements of elements with low reaction cross sections and of radioactive materials, where the duty cycle plays a crucial role.

We ask for four weeks of beam time under the normal operation of one bunch per supercycle. The possibility of more than one bunch per supercycle will clearly benefit our programme and our experience with this new neutron source.

## References


[1] F. Käppeler *et al.*, Ap. J. **437**, 396 (1994).
[2] A. Jorissen, V. Smith, and D. Lambert, Astron. Astrophys. **261**, 164 (1992).
[3] The n_TOF Collaboration, "Proposal for a neutron time-of-flight facility", CERN/SPSC 99-08, SPSC/P310, March 1999.
[4] E. Anders and N. Grevesse, Geochim. Cosmochim. Acta **53**, 197 (1989).
[5] H. Palme and H. Beer, in *Landolt–Börnstein New Series, Group VI, Vol. VI/3a*, edited by O. Madelung (Springer, Berlin, 1993), p. 196.
[6] E. Anders and E. Zinner, Meteoritics **28**, 490 (1993).
[7] U. Ott, Nature **364**, 25 (1993).
[8] E. Zinner, Science **271**, 41 (1996).
[9] S. Amari and E. Zinner, Nucl. Phys. A **621**, 99c (1997).
[10] R. Gallino, C. Raiteri, and M. Busso, Ap. J. **410**, 400 (1993).
[11] K. Wisshak *et al.*, Phys. Rev. C **57**, 391 (1998).
[12] K. Guber, R. Spencer, P. Koehler, and R. Winters, Nucl. Phys. **A621**, 254c (1997).
[13] G. Huss, I. Hutcheon, and G. Wasserburg, Geochim. Cosmochim. Acta **61**, 5117 (1997).
[14] P. Hoppe *et al.*, Ap. J. **430**, 870 (1994).
[15] H. Weigmann, R. Macklin, and J. Harvey, Phys. Rev. C **14**, 1328 (1976).
[16] Z. Bao *et al.*, Atomic Data Nucl. Data Tables (2000), in print.
[17] P. Mohr, H. Beer, H. Oberhummer, and G. Staudt, Phys. Rev. C **58**, 932 (1998).
[18] P. Mohr *et al.*, Phys. Rev. C **60**, 017603 (1999).
[19] F. Käppeler, Prog. Nucl. Part. Phys. **43**, 419 (1999).
[20] F. Voss *et al.*, Phys. Rev. C **50**, 2582 (1994).
[21] P. Koehler *et al.*, Phys. Rev. C **54**, 1463 (1996).
[22] K. Wisshak *et al.*, Phys. Rev. C **52**, 2762 (1995).
[23] M. Busso, R. Gallino, and G. Wasserburg, Ann. Rev. Astron. Astrophys. **37**, 239 (1999).
[24] C. Arlandini *et al.*, Ap. J. **525**, 886 (1999).
[25] K. Takahashi and K. Yokoi, Atomic Data Nucl. Data Tables **36**, 375 (1987).
[26] The n_TOF Collaboration, "Determination of the neutron fluence, the beam characteristics and the backgrounds at the CERN-PS TOF Facility", CERN/INTC 2000-016, INTC/P123, February 2000.
[27] P. Mutti, F. Corvi, K. Athanassopoulos, and H. Beer, Nucl. Phys. **A621**, 262c (1997).
[28] C. Raepsaet *et al.*, in *Nuclear Data for Science and Technology*, edited by G. Reffo, A. Ventura, and C. Grandi (Societá Italiana di Fisica, Bologna, 1997), p. 1289.