EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Measurement of the neutron capture cross section of gadolinium even isotopes relevant to Nuclear Astrophysics

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Abstract:

We propose to measure the neutron capture cross-section of the stable isotopes ^{152}Gd, ^{154}Gd, ^{156}Gd, ^{158}Gd and ^{160}Gd. This experiment aims at the improvement of existing data of interest for nuclear astrophysics. The measurement will be carried out under similar conditions of previous measurements successfully completed at n_TOF with an optimized detection setup: a cutting-edge detector especially designed for accurate (n,γ) measurement will be exploited in combination with a series of isotopically enriched samples. Concerning the correction related to isotopic impurities, we count on taking advantage of the result of the measurement on the ^{155}Gd(n, γ) and ^{157}Gd(n, γ), subject of a different proposal.

Requested protons: 3.3×10^{18} **protons on target**
Experimental Area: n_TOF EAR-1 (185 m flight path)

1 Introduction and scientific motivation

Elements heavier than iron are produced by neutron-induced reactions and subsequent β decays. Two different processes can be distinguished: the rapid neutron-capture process (r process) and the slow neutron-capture process (s process) each being responsible for the production of about one half of the elemental abundances between iron and bismuth. The r process takes place in explosive scenarios like neutron star mergers and/or supernova explosions, which is also the typical site of p process, i. e. nucleosynthesis via proton capture. The s process takes place in the Red Giant phase of stars and depending on the initial mass of the star, slightly different regimes can be considered: the so called *weak* s-process in Massive stars and *main* s-process in low mass stars, also referred to as Asymptotic Giant Branch (AGB) stars [1].
The (n, γ) cross sections of gadolinium isotopes play an important role in the study of the details of the s-process nucleosynthesis. In particular, unlike most of the isotopes heavier than iron, ^{152}Gd and ^{154}Gd can be produced only via the s process because they are shielded against the β-decay chains from the r-process region by the stable samarium isobars, as shown in Figure 1.

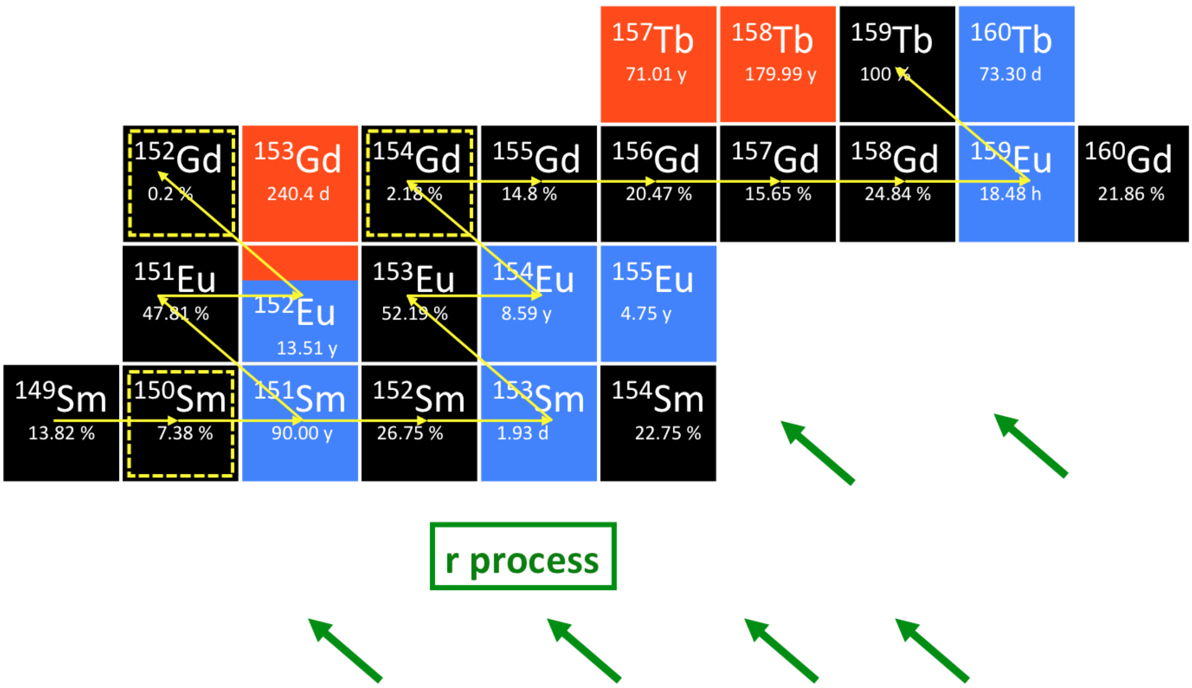

Figure 1: Simplified nucleosynthesis path of Sm, Eu, Gd and Tb during the s process. In black stable isotopes with natural occurring abundances are reported; β^- radioisotopes are in blue and β^+ in red, their terrestrial half-lives is shown. S-only isotopes are marked by double-framed quadrangles.

Those isotopes are of particular interest because their pure s-process origin allows to check the robustness of stellar models in galactic chemical evolution (GCE) models. In particular, hints on the shape and extension of the main s-process neutron source (the so-called ^{13}C pocket) can be derived. Recent GCE models yield abundances for ^{152}Gd and ^{154}Gd below that of the reference un-branched s-process isotope ^{150}Sm [2, 3]. Their theoretical abundance is very sensitive to the ^{152}Gd(n, γ) and ^{154}Gd(n, γ) cross sections (see e.g. ref. [3]). So far, the cause of the disagreement between GCE predictions and the solar distribution could not be identified

conclusively. Therefore, an accurate measurement of neutron capture cross-section can reduce the uncertainty attributable to nuclear physics input and eventually rule out one of the possible causes.
Moreover, the ^{152}Gd(n, γ) and ^{154}Gd(n, γ) cross section can affect the ^{151}Eu/(^{151}Eu+^{153}Eu) fraction, which has been measured in pre-solar SiC grains [4]. Also in this case, there is disagreement between theory and laboratory measurements and, therefore, a precise knowledge of all neutron capture cross sections in that region is mandatory.
Gadolinium isotopes are also attractive for the interpretation of astronomical observations regarding carbon-enhanced metal-poor (CEMP) stars. In those stars s-process and/or r-process enhancements have been detected. In that case more significative is the role of ^{158}Gd, since the abundance of ^{159}Tb, which is the only stable isotope of terbium, depends on the neutron capture on ^{158}Gd. Therefore the ratio of their observed abundances could help to determine the contribution from the s-process to the observed distribution. Also in this case, a key ingredient of the stellar calculation for the prediction of their abundances is the ^{158}Gd(n, γ) cross section.

2 Limiting factors of the previous measurements

Although several experiments can be found in literature (see for instance Experimental Nuclear Reaction Data database [5]), to date a systematic study of all isotopes has never been carried out in the energy region from thermal to about 1 MeV. As a consequence the experimental status of the gadolinium cross sections is still not completely clear. In particular, given the low natural abundance of the two s-only isotopes ^{152}Gd and ^{154}Gd, large uncertainties in their cross sections are related to the correction for isotopic impurities. Moreover in the case of ^{158}Gd the scarce information on the cross section is related to the poor knowledge of ^{156}Gd(n, γ) and ^{160}Gd(n, γ) cross sections. In addition, it is important to recall that for all isotopes the resolved resonance region has not been investigated with the same attention as for the unresolved resonance region, and evaluations are based on few measurements (*e.g.* Ref. [6] and Ref. [8]).
Different aspects had a sizable impact on past measurements, resulting in inconsistent results. For instance the MACS of ^{154}Gd calculated at 30 keV from results of ref. [7] and ref. [8] differs by more than 15%. In the case of ^{158}Gd the 5 reported stellar cross-sections at 30 keV span from 221 ± 20 mb to 423 ± 42 mb [9]. The origin of these discrepancies are related to: (i) the detector used in these experiments, which in some cases suffered from high neutron sensitivity; (ii) the experimental determination of the neutron flux, which might have been biased in some previous measurements; (iii) the lack of information on the cross section of impurities; and (iv) the enrichment of the samples and their quality in terms of canning and other material needed for the container (to avoid loss of material in case of oxide powder). It should also be noted that one of the most complete measurement performed so far [7] does not provide information on the resolved resonance region which can give a non negligible contribution to the MACS.

3 Proposed experimental setup

For the detection of the prompt γ rays resulting from the capture events, *i.e.* the electromagnetic cascade produced in the de-excitation of the compound nucleus formed in (n, γ) reactions, we propose to use the optimized C_6D_6 liquid scintillator detector, described in ref. [10]. They are characterized by a lower neutron sensitivity than the alternative capture detector available at n_TOF: the 4π BaF_2. In addition the C_6D_6 detector does not suffer from the so-called γ-flash (*i.e.* the prompt signal caused in the detector by spallation γ-rays and relativistic particles)

which blinds the detector for few microseconds. Therefore the proposed measurements can be safely carried out in the energy region of interest: from thermal to 1 MeV. This is an important aspect since the γ-flash in the 4π BaF_2 detector currently limits the energy range up to less than 100 keV.
In summary, the capture cross-section of the gadolinium stable isotopes will be measured with an array of 4 C_6D_6 scintillators at the n_TOF EAR-1 and exploiting the total energy system based on the so-called pulse height weighting technique. The only drawback is that the reduced energy resolution of the C_6D_6 detector does not permit to distinguish capture events by their different binding energies. Thus the measurement of most, if not all, stable gadolinium isotopes becomes fundamental for the accuracy of the final result.
As in many of the n_TOF experiments, the availability, preparation and characterization of suitable samples is rather important for the success of the measurement. In the present case we can profit from the accurate measurement of odd isotopes which is being proposed at n_TOF, to precisely estimate their influence as contaminants. Therefore in order to carry out an accurate measurement of the ^{152}Gd,^{154}Gd and ^{158}Gd capture cross-section, the 5 even isotopes must be investigated simultaneously. Highly enriched Gd_2O_3 powder from the National Isotope Development Center - USA can be used to prepare the sample. The relevant parameters of the gadolinium isotopes can be found in Table 1. Since the sample are available in form of powder, they need a canned container and instead of using Al (as in previous experiments) a very much lighter plastic material, named PEEK ($C_{20}H_{12}O_3$) will be used as container, thus reducing the impact of its background.

Table 1: Gadolinium isotopes

Isotope	Binding energy (MeV)	Natural abundance %	ORNL enrichment %
^{152}Gd	6.25	0.20	$32-51$
^{154}Gd	6.44	2.15	> 66 and 99.3
^{155}Gd	8.54	14.73	> 90
^{156}Gd	6.36	20.47	$93-99$
^{157}Gd	7.94	15.68	> 90
^{158}Gd	5.94	24.87	> 95
^{160}Gd	5.64	21.9	$95-98$

In addition to the 5 gadolinium samples ^{152,154,156,158,160}Gd, a gold sample, a graphite sample and a lead sample will be used for normalization purposes, and to study the background. All samples must have the same dimension, and will be prepared as discs of 1 cm radius. The ^{155,157}Gd samples are subject of a dedicated proposal, now being submitted to this Committee. Although the samples are typically provided by ORNL with certified characteristics, an independent characterization, in particular for the contamination, will be performed at PSI by the group participating in this proposal.

4 Beam time request

The gadolinium isotopes are characterized by a very high capture cross-section, as a consequence a favorable signal to background ratio is expected from the proposed measurement. In Figure 2 the expected counting rate for mono-isotopic gadolinium samples of 500 mg is shown. The calculation is based on the capture cross section retrieved from ENDF/B-VII [11] and considering a neutron irradiation corresponding to 5×10^{17} protons for each sample. In all cases the uncertainty due to counting statistic in the unresolved resonance region is better than 3% with 100 bin per energy decade.

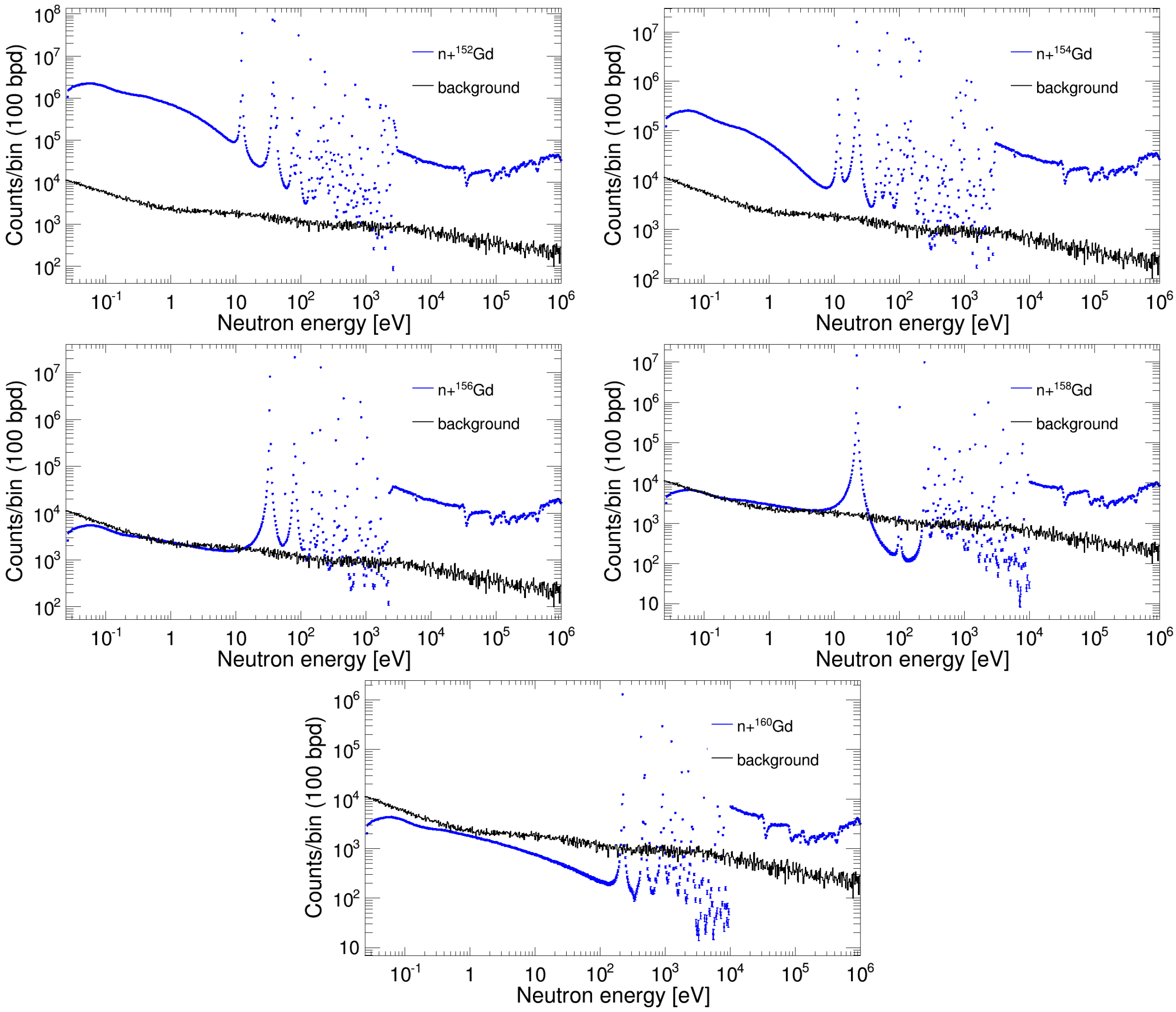

Figure 2: Expected counting rate for the (n, γ) reaction on even gadolinium isotopes using mono-isotopic samples of 500 mg. In each calculation the neutron irradiation corresponds to an intensity of 5×10^{17} protons. The black line represents the expected background level during measurement.

The quantity of gadolinium in the samples results from a compromise between the need of reducing the requested beam time and the optimization of expected count rate in the resonance region. Samples with a mass exceeding few hundreds of milligrams would result in a shorter measurement, but would produce in some resonances a saturation of the experimental observable, *i.e.* the capture yield, thus preventing one from extracting information on the capture cross-section. On the other hand, the beam time request is calculated so to achieve a final accuracy better than 5% in the unresolved resonance region. A conservative value of 20% for the detection efficiency is assumed in the calculation shown in Figure 2 and a correction factor is applied in

order to take into account the area of the samples, which is smaller than the dimension of the neutron beam, intercepting approximatively 65% of the beam intensity.
As in previous C_6D_6 measurements, the estimation of the different components of the background for the proposed measurement is based on ^{nat}Pb and ^{12}C measurement. This background study requires a total number of 0.4×10^{18} protons. In addition the normalization of capture data, the validation of the measurement at high energy and the cross-check of the flux stability is achieved by a cyclic measurement of a gold sample with 500 mg. This further study requires a neutron intensity corresponding to 0.4×10^{18} protons.
In summary the total proton request is 3.3×10^{18} protons on target. The final beam share can undergo small changes depending on the preliminary results of the measurement.

5 Conclusion

We propose to measure the capture cross section of even gadolinium isotopes because of their astrophysical relevance. Measurement results are present in literature, however large discrepancies are still present which call for a more systematic and accurate study. In this view, a series of measurements on enriched gadolinium samples is proposed at n_TOF EAR-1 making use of an array of C_6D_6 detectors. The objective is to determine stellar cross sections with overall uncertainty below 5% for thermal energies up to about $kT = 100$ keV. In total 3.3×10^{18} protons are requested to successfully complete the measurement.
Summary of requested protons: 3.3×10^{18} **protons on target** .

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