The $^{154}$Gd neutron capture cross section measured at the n_TOF facility and its astrophysical implications


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Abstract. The $(n, \gamma)$ cross sections of the gadolinium isotopes play an important role in the study of the stellar nucleosynthesis. In particular, among the isotopes heavier than Fe, $^{154}$Gd together with $^{152}$Gd have the peculiarity to be mainly produced by the slow capture process, the so-called s-process, since they are shielded against the $\beta$-decay chains from the r-process region by their stable samarium isotopes. Such a quasi pure s-process origin makes them crucial for testing the robustness of stellar models in galactic chemical evolution (GCE). According to recent models, the $^{154}$Gd and $^{152}$Gd abundances are expected to be 15-20% lower than the reference un-branched s-process $^{150}$Sm isotope. The close correlation between stellar abundances and neutron capture cross sections prompted for an accurate measurement of $^{154}$Gd cross section in order to reduce the uncertainty attributable to nuclear physics input and eventually rule out one of the possible causes of present discrepancies between observation and model predictions. To this end, the neutron capture cross section of $^{154}$Gd was measured in a wide neutron energy range (from thermal up to some keV) with high resolution in the first experimental area of the neutron time-of-flight facility n_TOF (EAR1) at CERN. In this contribution, after a brief description of the motivation and of the experimental setup used in the measurement, the preliminary results of the $^{154}$Gd neutron capture reaction as well as their astrophysical implications are presented.

1 Introduction

Neutron-induced reactions and $\beta$-decays are the main nuclear processes involved in the formation of elements heavier than iron. In particular, two main processes have been identified so far: the slow neutron-capture process (s-process) and the rapid one (r-process). The latter is responsible for the production of approximately half of the atomic nuclei heavier than iron and it is thought to take place in neutron stars mergers and Supernovae. The remaining half is synthesized via the s-process. Depending on the initial mass of the star, different regimes can be considered: the so called weak s-process component in Massive stars and the Main s-process component in the Asymptotic Giant Branch (AGB) phase of low-to-intermediate mass stars [1].

In this context, the $^6$Gd$(n, \gamma)^{11}$Gd cross sections play an important role in the detailed study of the s-process nucleosynthesis. In particular, the even isotopes $^{152,154}$Gd, unlike most of the isotopes heavier than iron, are mainly produced via the s-process because they are shielded against the $\beta$-decay chains from the r-process region by the stable samarium isotopes$^1$. In Figure 1 we show the s-process path in the Sm-Eu-Gd-Tb region.

Because of their quasi pure s-process nature, neutron capture reactions on even gadolinium isotopes ($^{152,154}$Gd) are essential ingredients to test the reliability of Galactic Chemical Evolution (CGE) models [2]. However, as shown in Figure 2, CGE calculations yield abundances for these isotopes up to 20% below the reference un-branched s-process isotope $^{150}$Sm ([3, 4]). A possible explanation for this disagreement was sought in the neutron-capture cross section of $^{152,154}$Gd which strongly affects the isotopic abundances.

To date, from an experimental point of view, the 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 present because of isotopic impurities corrections. This situation prompted the n_TOF Collaboration to perform a new measurement of the capture cross section for the $^{154}$Gd isotope from thermal to 1 MeV neutron energy at the CERN neutron time-of-flight facility, n_TOF. In this work, preliminary results and related astrophysical implications are reported.

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$^1$The possible contribution from the p-process is currently matter of debate.
play an important role in the detailed study of the s-debate. Shielded against the $\beta$ intermediate mass stars [1].

In Massive stars and the Main s-process component in different regimes can be considered: the so called weak s-process component. Neutron-induced reactions and $\beta$...
cently published in [10] for the $^{155}$Gd(n, γ) reaction have been used in order to extract the normalization factor (see Figure 4).

![Figure 4](image1.png)

**Figure 4.** The normalized $^{154}$Gd(n, γ) capture yield; structures at 2 and 2.5 eV neutron energy are due to the $^{155}$Gd presence ($\approx 17.5\%$) in the sample. A discrepancy between gold and $^{155}$Gd normalization methods is clearly visible.

The study of the background has been performed by means of dedicated measurements with the aim to evaluate the various components, i.e. the one produced by the neutron beam interaction in the experimental area (without the sample), and the one related to in-beam γ-rays. The first component has been evaluated with the empty-sample, while the in-beam γ-ray background has been obtained by combining data collected with the Pb and the empty-sample. As shown in Figure 5, the main background source arises from the empty-sample counts, that is the beam-related effect not linked to the presence of the sample.

![Figure 5](image2.png)

**Figure 5.** Weighted C6D6 time-of-flight spectrum of the $^{154}$Gd sample, together with background measurements. The empty-sample spectrum (Em) represents the main background source.

### 3.2 Resonance Shape Analysis

The Resolved Resonance Region (RRR) is analyzed with the bayesian R-Matrix code SAMMY, using the Reich-Moore approximation. Corrections for experimental conditions such as Doppler broadening, self-shielding and multiple scattering in the sample were taken into account by the code. As starting point, the ENDF/B-VII library resonance parameters were adopted for the fitting procedure. An example of the Resonance Shape Analysis (RSA) is shown in Figure 6, compared to evaluated yield.

![Figure 6](image3.png)

**Figure 6.** The RSA of the n_TOF data performed by SAMMY code compared to ENDF/B-VII evaluations.

A comparison between the capture kernel obtained by the preliminary fitting procedure on the n_TOF experimental data and the theoretical one calculated on the basis of the ENDF/B-VII evaluations (see Figure 7), show that on average the n_TOF data are $\approx 6-7\%$ higher than the evaluated data.

![Figure 7](image4.png)

**Figure 7.** The ratio between the capture kernel obtained by the fit of the n_TOF data and the one calculated with the ENDF/B-VII resonance parameters.

### 3.3 The Unresolved Resonance Region

The reaction rate and consequently the production and the isotopic abundance of $^{154}$Gd strongly depends on the
Maxwellian Averaged Cross Section (MACS). Approximately 70-80% of the MACS depends on the Unresolved Resonance Region (URR) and for this reason this represents a particularly important energy region. However, the experimental data available in the literature ([11, 12]) show discrepancies higher than 30% among themselves.

A comparison of the preliminary \textit{n\_TOF} experimental data and ENDF/B evaluation in the same energy region is shown in Figure 8. On average, the \textit{n\_TOF} data are in quite good agreement with the evaluated data in the URR, although sizable differences are present in some region.

The preliminary results obtained up to now have been used to calculate the \(^{154}\text{Gd}(n, \gamma)\) reaction. We computed a set of AGB models at close-to-solar metallicity with low-to-intermediate stellar masses (1.5 \(\leq M/M_\odot \leq 3.0\)). Based on the preliminary \textit{n\_TOF} data, a general increase of \(^{154}\text{Gd}\) (with respect to \(^{150}\text{Sm}\)) of about 5% is found. Such an increase is not sufficient to explain the current disagreement between stellar models and observations. We speculate that other neutron capture cross sections in the Sm-Eu-Gd have to be studied in detail as, for instance, the \(^{154}\text{Eu}\) neutron capture cross section, for which we do not dispose of an experimental MACS.

4 Conclusions

The results obtained so far in the Resolved Resonance Region and reported in this work have shown a \(^{154}\text{Gd}(n, \gamma)\) cross section substantially higher than the evaluated one in the ENDF/B library. Resonance Shape Analysis is still ongoing; new resonance structures up to 2 keV are present in the \textit{n\_TOF} data, which are not reported in any evaluated data library. In the Unresolved Resonance Region, \textit{n\_TOF} data are in a reasonable agreement with the evaluations, thus no big effect is expected on MACS value in this energy region.

Although the results here presented are preliminary and need further confirmation, it can presently be concluded that, based on these new data, no substantial changes in the synthesis of \(^{154}\text{Gd}\) have to be expected. As a consequence, the origin of the discrepancy between theory and observations has to be searched in other nuclear ingredients, as the neutron capture cross section on \(^{154}\text{Eu}\), whose decay largely influences the \(^{154}\text{Gd}\) abundance.

References