

Nuclear Astrophysics with Tagged Photons: NEPTUN @ S-DALINAC, Darmstadt

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Abstract. Tagged photons can be used to study astrophysically relevant cross sections with highest energy resolution. The tagging facility NEPTUN at the S-DALINAC, Darmstadt, Germany, is presented and it is demonstrated how NEPTUN can be used to study short-lived branching nuclei of s-process nucleosynthesis.

1. Motivation

The nucleosynthesis of the elements heavier than iron is today mainly explained by three processes: *s*, *r*, and *p* process. The *s* and the *r* process are based on neutron-capture reactions with adjacent β decays while the *p* process is governed by photodisintegration reactions such as (γ, n) , (γ, p) , or (γ, α) .

The study of the neutron capture cross section of the so-called branching nuclei of the *s* process is mandatory to understand the produced abundance patterns. However, direct measurements were only performed for long-lived branching nuclei so far (e.g. ^{151}Sm [1, 2] or ^{147}Pm [3]). For short-lived ones the measurement of the inverse (γ, n) reaction yields constraints for the theoretical prediction of the neutron capture cross section (e.g. [4, 5, 6]). This is realized using the activation technique with continuous-energy bremsstrahlung sources like e.g. the High Intensity Photon Setup (HIPS) at Darmstadt, Germany [7]. However, the energy resolution is quite poor because the cross section has to be deconvolved from the energy-integrated cross section I_σ

$$I_\sigma = N_t \cdot \int_{S_n}^{E_{\max}} \sigma(E) \cdot N_\gamma(E, E_{\max}) \cdot dE \quad (1)$$

with N_t being the number of target atoms, $\sigma(E)$ the (γ, n) cross section, and $N_\gamma(E, E_{\max})$ the photon flux, respectively.

To avoid this problem, quasi-monoenergetic photon beams from Laser Compton Backscattering facilities like e.g. HI γ S at Duke University [8] can be used. The energy range of the produced photon spectrum is much smaller compared to HIPS, however, the energy resolution at these facilities is still limited to values on the order of 100 keV.

To measure the energy dependence of the photodissociation cross section with better accuracy – especially in the astrophysically relevant region close above the threshold in the case of (γ, n) reactions – tagged photons can be used. The NEPTUN tagger setup [9, 10, 11] that is constructed at the S-DALINAC, Darmstadt, Germany, is suitable for high resolution studies of astrophysically relevant cross sections.

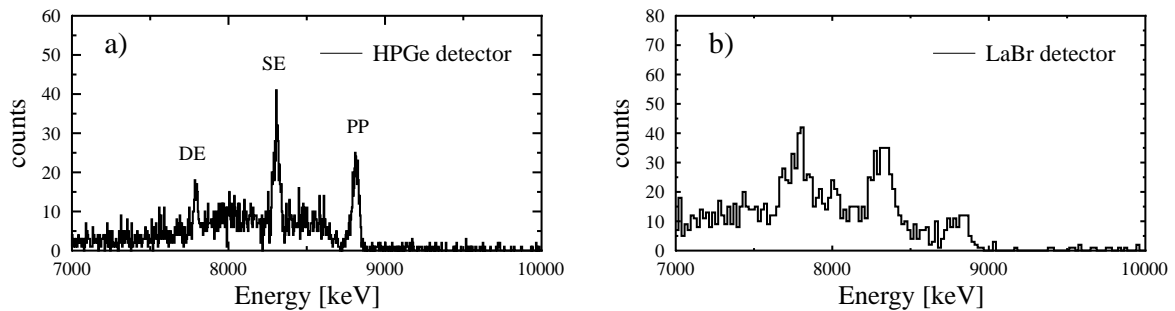


Figure 1. a) Spectrum of an in-beam HPGe detector at a tagged photon energy of about 8.8 MeV. The spectrum shows the typical detector response to monoenergetic photons, i.e. the photopeak (PP), single-escape (SE), and double-escape (DE) peaks, as well as a Compton continuum. b) Same spectrum for a LaBr₃ detector under identical experimental conditions. Both spectra were taken within about 2 hours of beamtime.

2. The NEPTUN photon tagging facility

The basic concept of photon tagging is to select photons of a given energy out of a continuous-energy bremsstrahlung spectrum. The Superconducting DArmstadt LINear ACcelerator S-DALINAC delivers a monoenergetic electron beam. To produce bremsstrahlung the beam strikes a thin radiator target. Typically, a gold target with a thickness of about 10 μm is used. Thus, it is guaranteed that 99% of the electrons produce at most one photon. This is crucial to guarantee the correlation between electron and photon energies described further down. Downstream the radiator target a large dipole magnet is located to analyze the *electrons*. Electrons that produced a photon are scattered into a cone such that 99% of them are located within an angle of 8°. The magnet's acceptance has been chosen accordingly.

The position of the electrons in the focal plane of the magnet is determined by a detector array that is built of 64 scintillating fibers attached to photomultipliers. The granularity of the array has been chosen to be 1 mm to meet the resolution power of the magnet. An upgrade to 128 fibers is in progress.

The energy of the scattered electrons deduced from the position in the focal plane has a nominal resolution of 25 keV (at an energy corresponding to 10 MeV tagged photons). Neglecting the recoil momentum, energy conservation yields

$$E_\gamma = E_0 - E_e \quad (2)$$

whereas E_γ is the photon energy, E_0 the energy of the primary electron beam, and E_e the energy of the scattered electron.

To be able to connect the photons to the corresponding electrons a coincidence setup is necessary. Data on the electron hits in the focal plane detector array are stored digitally in the ring buffer of a multihit-capable TDC. The photons or photon-induced reaction products trigger the readout of the ring buffer. Timing correlations between signals from these detectors and the focal plane fibers within up to 2 μs are possible which is favorable for experiments close to particle thresholds where reaction products need relatively long times to reach the detectors due to their low kinetic energy.

With the full focal plane setup the energy window to be measured in one run without a change of the magnetic field will be about $\Delta E_\gamma = 2 - 3$ MeV depending on the settings. NEPTUN has been designed to tag photons in the energy range from 6 – 20 MeV [9, 10, 11].

3. NEPTUN as a testing device for the characterization of photon detectors

NEPTUN has been shown to deliver a tagged photon beam of 35 keV energy resolution, already [11]. This is suited to explore the characteristics of detector materials and shapes. NEPTUN can be used to determine the energy resolution and single-escape probabilities up to 20 MeV. These properties are compared to results of simulations being the basis for ion beam experiments involving photon detection.

In a recent experiment the detector response of a LaBr₃ scintillator (1.5 inch diameter and length) with a photomultiplier has been studied. A first spectrum is shown in figure 1. For comparison, the detector response of a HPGe detector (100%) with an energy resolution exceeding the one of NEPTUN is shown.

4. The s-process branching nucleus ⁹⁵Zr

The s-process branching nucleus ⁹⁵Zr is located near the borderline between the weak and the main component of the s process [12]. Therefore, the prediction of the elemental abundance patterns corresponding to this branching is a crucial test for the validity of a full stellar model as described e.g. in [13].

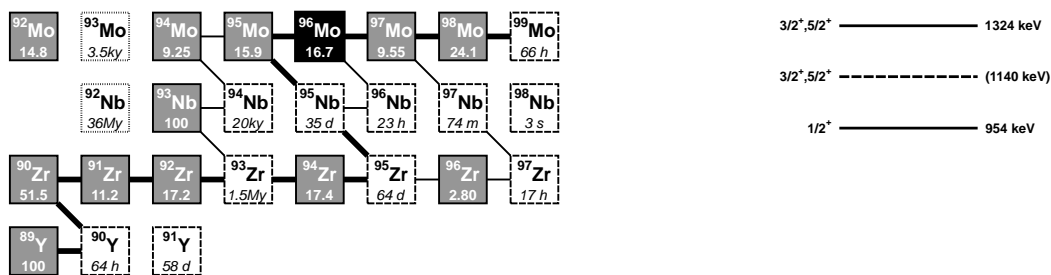


Figure 2. The s-process path around the branching nucleus ⁹⁵Zr. The main flow of the s-process is marked with thick lines, thinner lines indicate branches. Grey shaded boxes illustrate stable isotopes and their natural abundances. The s-only isotope ⁹⁶Mo is indicated by a black box. The white boxes display β -unstable nuclei and their ground-state half-lives (from [14]).

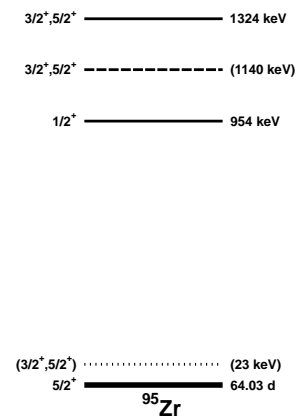


Figure 3. Complete level scheme of ⁹⁵Zr up to 1.5 MeV [16]. The level at 23 keV was only mentioned by [17] and could be excluded by [18].

Several problems concerning the prediction of the Zirconium abundance patterns measured in SiC grains are reported in [19]. The uncertainty in the predicted Maxwellian average cross section (MACS) of ⁹⁵Zr is mentioned as one of the possible error sources due to the wide range of predicted values. Another reason for the deviation between the measured and predicted abundance patterns might be the uncertainty in the half-life $T_{1/2}$ of ⁹⁵Zr at s-process temperatures. However, as confirmed by a recent measurement [18] the first excited level is at $E = 954$ keV and, thus, is not significantly populated at the mean temperature $kT = 30$ keV. Hence, the half-life of ⁹⁵Zr does not depend on temperature under s-process conditions and can be omitted as an error source because of its small uncertainty: $T_{1/2}(\text{}^{95}\text{Zr}) = (64.032 \pm 0.006)$ d [16].

The reaction ⁹⁵Zr(n, γ) is not accessible to a direct measurement. New high-intense neutron sources like e.g. FRANZ at Frankfurt, Germany, will enable measurements with smallest amounts of target material. However, the reaction product ⁹⁶Zr is stable and, thus, prohibits using

activation techniques. Therefore, either the neutrons or the γ cascades in ^{96}Zr have to be measured to determine the reaction yield. But this is also hampered due to the high intrinsic activity of a ^{95}Zr target. Although the cross section of the inverse reaction $^{96}\text{Zr}(\gamma, n)$ was already studied with bremsstrahlung [14] and Laser Compton Backscattered photons [15] an enhanced energy resolution is still desirable.

A study with NEPTUN would allow to distinguish between the population of the ground state and first excited state in ^{95}Zr . Thus, the energy dependence of both de-excitation channels can be developed separately. In addition the measurement of the angular distribution of the emitted neutrons as planned with the neutron detector array of NEPTUN [20] yields further information. A precise and detailed understanding of the cross section of $^{96}\text{Zr}(\gamma, n)$ is mandatory to extract reliable constraints on the neutron capture cross section of the s -process branching nucleus ^{95}Zr .

5. Outlook

The photon-tagging facility NEPTUN will enable high-resolution cross section measurements of importance in astrophysics like the investigation of neutron capture cross sections of short-lived s -process branching nuclei via the inverse reaction. Additionally, it is perfectly suited to characterize the response function of photon detectors as it can be treated like a monoenergetic photon source with energies between 2 MeV and 20 MeV. E.g. the CsI crystals to be used in the CALIFA array of the future R³B setup at GSI/FAIR will be investigated in near future.

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