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Constraining experimentally photon strength functions using real photons at the HIγS/TUNL facility

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Abstract. This contribution brings into focus two distinct sets of experiments carried out using real photons at the HIγS/TUNL facility - ^{78,80}Kr(γ,γ'), ^{94}Mo(γ,n) and ^{90}Zr(γ,n) cross section measurements. These measurements are relevant for constraining dipole photon strength function models used in large-scale calculations of stellar photonuclear reaction rates relevant for *p*-process nucleosynthesis. We report on the status of the very recent NRF measurements on ^{78,80}Kr, which will provide for the first time model-independent information on the low-energy part of the corresponding electric dipole photon strength functions, and discuss, with respect to our recently published photoneutron cross section measurements on ^{94}Mo and ^{90}Zr, the fact that measured neutrons that are correlated with excited states in the residual nucleus must be appropriately accounted for when determining the detection efficiency needed to extract the laboratory photoneutron cross sections.

1 Introduction

The astrophysical *p*-process is responsible for the nucleosynthesis beyond iron of about 35 proton-rich stable nuclei, termed as the *p*-nuclei [1]. In the solar system, the *p*-nuclei are one or two orders of magnitude less abundant than the *s*- or *r*-nuclei [2]. The astrophysical details of the *p*-process are still under discussion. So far, it has been impossible to reproduce solar abundances of all *p*-nuclei in a single process. Several different sites and independently operating processes seem to be required, but it is generally accepted that the main mechanism (also known as the *γ*-process) to produce *p*-nuclei involves photodisintegration reactions on pre-existing s/r-seed nuclei and *β*+ decays and that it occurs mainly in explosive O/Ne burning during supernova type II explosions at temperatures in the range of 2 – 3.5 GK. These seed nuclei are converted via (γ,n) reactions until in each isotopic chain a branching point nucleus is reached, which in turn can provide several pathways to produce a *p*-nucleus in the γ-process [1].

Modeling the *p*-process nucleosynthesis is a daunting task, requiring an extended network of about 20000 nuclear reactions linking about 2000 nuclei [1]. Obviously, it is not feasible to measure all the required cross sections since most of the nuclei in the network are radioactive. Thus, we will have to rely on theoretical calculations for the unknown reaction rates of interest, but not only that. Excited states are thermally populated in stellar plasma, whereas only reaction cross sections on the ground state of the target can be investigated in the laboratory (with a few exceptions, *i.e.*, ^{180m}Ta). Therefore, stellar plasma corrections for thermal effects are also required to determine stellar reaction rates and can only be provided by theory.

The higher the temperature of the stellar plasma, the more excited states contribute. Since the γ-process operates at 2-3.5 GK, the contribution of excited states is the most relevant for the photodisintegration reactions. The laboratory ground state contribution to the stellar rate for photodisintegration reactions of interest for the *p*-process is only a few tenth per mille [3, 4]. Therefore, photodisintegration cross section measurements can only be used to derive information on certain nuclear properties (such as photon strength functions (PSFs), nuclear level densities, nucleon-nucleus optical potentials) required for the calculation of the stellar rates and, thus, to test and validate the theory (statistical Hauser-Feshbach nuclear models).

In the following we discuss our recent efforts to study in the laboratory photonuclear reactions by means of two distinct experimental methods using real photon beams produced at the High Intensity γ-ray Source (HIγS) facility [5], in order to constrain PSF models.

2 Nuclear resonance fluorescence measurements on ^{78,80}Kr to constrain photon strength function models for *p*-process nucleosynthesis calculations

A theoretical study [6] discussed the location of the (γ,p)/(γ,n) and (γ,α)/(γ,n) line at γ-process temperatures, using updated reaction rates based on global Hauser-Feshbach calculations. The nucleus ^{80}Kr was identified as a key branching point in the *p*-process path, for which

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the (γ,p) and (γ,α) reaction rates were found within factors $f \leq 3$ and $f \leq 10$, respectively, of the (γ,n) rate, and within a factor of 3 of each other. These photonuclear reaction rates were calculated using the NON-SMOKER [7] statistical Hauser-Feshbach code, which used a semiclassical Lorentzian representation of the Giant Dipole Resonance (GDR) as a PSF model, the so-called Generalized Lorentzian model (GLO) and a shifted Fermi-gas model as nuclear level density model [8].

When the reaction rates are similar in magnitude, a small variation in any rate might either remove the branching or change its nature from (γ,p) to (γ,α) or vice versa. Hence, the branching established by the dominance of proton and/or α emission over neutron emission is crucial in determining the progenitors of the *p*-nuclei and depends on these photonuclear reaction rate ratios.

Figure 1 shows stellar reaction rates calculated with TALYS 1.96 code using the axially-symmetric-deformed Hartree-Fock-Bogoliubov (HFB) plus QRPA model based on the D1M Gogny interaction [9-12] and indicates, contrary to NON-SMOKER calculations, the dominance of the ^{80}Kr(γ,n) channel over the (γ,p) and (γ,α) channels, *i.e.* ~8 times larger than the (γ,p) for the temperature range of 3 GK, which is favourable for the nucleosynthesis of intermediate-mass *p*-nuclei. As expected, the dominance of the (γ,n) channel is even stronger in ^{79}Kr because of the lower neutron separation energy, implying that the production of the *p*-nucleus ^{78}Kr likely follows the ^{80}Kr(γ,n)^{79}Kr(γ,n)^{78}Kr path, contrary to the conclusions drawn in Ref. [6]. On the other hand, the destruction of the ^{78}Kr *p*-nucleus seems to be mainly influenced by the dominance of the (γ,p) channel.

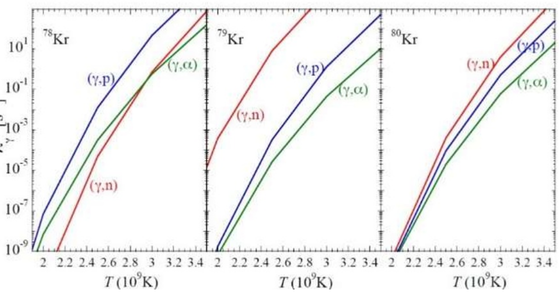

Figure 1. Stellar reaction rates calculated in TALYS with the microscopic D1M + QRPA PSF model**.**

To show the impact of the PSF models on the overproduction factors of *p*-nuclei, we compare in Figure 2 results obtained with the empirical GLO model to the semi-microscopic D1M + QRPA model for the case of Type Ia supernovae. The production of the ^{78}Kr *p*-nucleus via the path ^{80}Kr(γ,n)^{79}Kr(γ,n)^{78}Kr is increased by 54%, while the destruction of the ^{80}Kr is increased by a factor of 2.6 at 3 GK when using the D1M + QRPA model comparative to the GLO model.

The significant dependence of the rate ratios ^{80}Kr(γ,α)/(γ,n) and ^{80}Kr(γ,p)/(γ,n) on the PSF models, discussed above, provided the impetus to study experimentally the constraining of the dipole PSF models via ^{78,80}Kr(γ,γ') cross section measurements

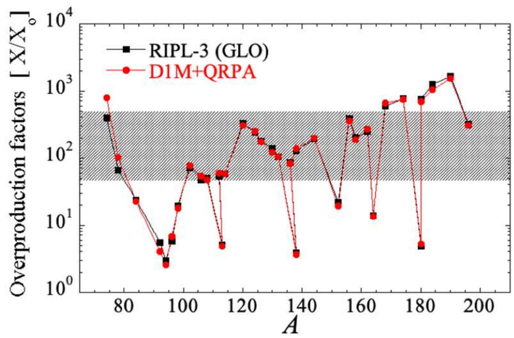

Figure 2. Overproduction factors of the *p*-nuclei in Type Ia supernovae [13] calculated with two different PSF models. See text for details.

Due to its high selectivity for dipole excitations (because of the low momentum transfer of real photons), real photon scattering via nuclear resonance fluorescence (NRF) using quasi-monoenergetic photon beams (as produced, for example, at the HIγS/TUNL facility [5]) is the method of choice to extract experimentally, with high accuracy and model independently [14], the dipole PSF in stable nuclei. Moreover, the quasi-monoenergetic and lineraly polarized photon beams of very high flux at HIγS makes this facility ideal for investigation of photoabsorption reaction cross section with *p*-nuclei as targets.

The NRF measurements on ^{78,80}Kr will provide for the first time information for the low-energy part of the electric dipole PSF in ^{78,80}Kr, as model-independent input into the *p*-process nucleosynthesis calculations. Recently, we successfully carried out such NRF measurements for photon beams of 6.40, 6.65, 6.95, 7.20, 7.28, 7.50, 7.80, 8.15, 8.45, 8.80, 8.92, 9.15, 9.55, 9.95, 10.35, 10.75, 11.20 MeV at the HIγS facility. Currently data analysis is in progress.

Our goal is to extract experimentally the *complete* dipole PSF, which implies studying both electric and magnetic PSFs. To put into perspective to what extent our data will constrain PSF models, in Figure 3 we show TALYS calculations for two different type of PSFs, considered to be "the two best options" in TALYS [15] – D1M + QRPA microscopic model and SMLO (simple modified Lorentzian) empirical model [16], where the

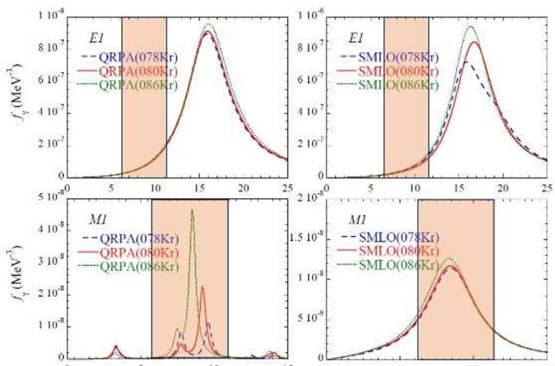

Figure 3. TALYS calculations for both electric and magnetic PSFs. See text for details.

highlighted regions correspond to the aforementioned experimental photon beam energies at which we conducted our measurements.

3 Photoneutron reaction cross section measurements on ^{94}Mo and ^{90}Zr relevant for the *p*-process nucleosynthesis

Recent studies [17, 18] of type Ia supernovae with two-dimensional models (deflagration and delayed detonation) demonstrated that both light and heavy *p*-nuclei, including the much-debated ^{92}Mo and ^{96,98}Ru, are produced with similar enhancement factors relative to solar abundances, provided an *s*-process enrichment of the progenitor is assumed. However, ^{94}Mo remained underproduced in these studies. Remarkably, ^{90}Zr, known as a genuine *s*-process nuclide, was significantly produced as well. In light of these intriguing findings, we were motivated to investigate the photoneutron reactions on ^{94}Mo and ^{90}Zr using real photon beams produced at the HIγS facility. We measured excitations functions from slightly above the respective neutron separation energies up to 13.5 MeV with the goal of extracting experimentally the PSFs to be used for calculation of photonuclear stellar reaction rates for the *p*-process nucleosynthesis.

Experimental details and our results regarding how sensitive the ^{94}Mo(γ,n) and ^{90}Zr(γ,n) stellar reaction rates are to the corresponding measured cross sections, especially in the vicinity of the neutron emission threshold, which is the energy region most relevant in astrophysics, can be found in our recent paper [19]. Here, we highlight an important experimental conclusion that we drew in Ref. [19] with respect to the neutron detection efficiency.

In our experiment the neutrons were detected using an assembly of 18 tubular proportional counters filled with ^{3}He gas at a pressure of ~6 atm and embedded in a cylindrical polyethylene body that served as a neuron moderator. For the energies studied in our work, the ^{94}Mo(γ,n) and ^{90}Zr(γ,n) reaction only proceed directly to the ground state of their respective residual nuclei at low beam energies. At higher energies, population of the ground state in the residual nuclei proceeds predominantly via the population of excited states which then γ decay to the ground state. Because the information on the neutron energy is lost by the thermalization of the neutrons in the moderator, determining the neutron detection efficiency for such a detector was a complex problem to tackle. The neutron detection efficiency depends on the neutron energy. Neutron energies in our work span a broad range from 20 keV up to ~4 MeV that correspond to detection efficiencies as high as ~55% and a slow as ~25%, respectively. These efficiencies were simulated in GEANT4 assuming isotropically distributed neutrons.

In the case of the ^{94}Mo(γ,n) reaction, Figure 4 shows that there is a good agreement between our cross-section results and the previous results by Utsunomiya *et al.* [20] and by Beil *et al.* [21] for photon beams below 10.8 MeV. However, above that beam energy, when neutrons are emitted predominantly from excited states in ^{93}Mo, there is a significant discrepancy between our results and previous results as high as ~30%. In Figure 4 we also show that our results become in reasonable agreement with the previous work if the neutron detection efficiency is calculated assuming that all detected neutrons are ground-state neutrons.

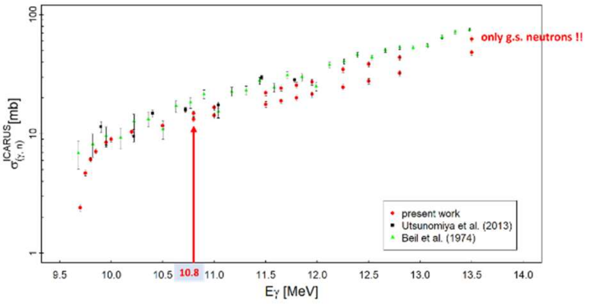

Figure 4. Excitation function for ^{94}Mo(γ,n) of our work compared with previous work. See text for details and Ref. [19].

To address this discrepancy between our work [19] and previous work [20, 21], new measurements using *flat-efficiency neutron detectors* (*e.g.* [22]) will be the best call of action.

4 Summary

In this contribution we report on the status of very recent NRF measurements on ^{78,80}Kr that aim to experimentally extract *model-independent* information on the corresponding low-energy dipole photon strength functions. Such information is vital for constraining theoretical PSF models, as the PSF constitutes one of the largest sources of uncertainty for calculations of stellar photodisintegration reaction rates relevant to the modeling of astrophysical *p*-process nucleosynthesis.

We also discuss, with respect to our recently published photoneutron cross section measurements on ^{94}Mo and ^{90}Zr [19], that measured neutrons that are correlated with excited states in the residual nucleus must be appropriately accounted for when determining the detection efficiency needed to extract the laboratory photoneutron cross sections – *if only ground state neutrons are considered, the detector efficiency will be underestimated and consequently the photoneutron reaction cross section will be overestimated.*

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References

1. M. Arnould, S. Goriely, The *p*-process of stellar nucleosynthesis: astrophysics and nuclear physics status, Phys. Rep. **384**, 1 (2003). https://doi.org/10.1016/S0370-1573(03)00242-4

2. M. Burbidge, G. Burbidge, W. A. Fowler, and F. Hoyle, Synthesis of the elements in stars, Rev. Mod. Phys. **29**, 547 (1957). https://doi.org/10.1103/RevModPhys.29.547
3. T. Rauscher, Sensitivity of astrophysical reaction rates to nuclear uncertainties, Astrophys. J. Suppl. **201**, 26 (2012). https://doi.org/10.1088/0067-0049/201/2/26
4. T. Rauscher, Photonuclear Reactions in Astrophysics, Nucl. Phys. News **28**, 12 (2018). https://doi.org/10.1080/10619127.2018.1463016
5. https://tunl.duke.edu/research/our-facilities
6. T. Rauscher, Branching in the γ process path revisited, Phys. Rev. C **73**, 015804 (2006). https://doi.org/10.1103/PhysRevC.73.015804
7. T. Rauscher and F.-K. Thielemann, Astrophysical reaction rates from statistical model calculations, At. Data Nucl. Data Tables **75**, 1 (2000). https://doi.org/10.1006/adnd.2000.0834
8. J. Kopecky, M. Uhl, Test of gamma-ray strength functions in nuclear reaction model calculations, Phys Rev. C **41**, 1941 (1990). https://doi.org/10.1103/PhysRevC.41.1941
9. M. Martini, S. Peru, S. Hillaire, S. Goriely, and F. Lechaftois, Large-scale deformed quasiparticle random-phase approximation calculations of the γ-ray strength function using the Gogny force, Phys. Rev. C **94**, 014304 (2016). https://doi.org/10.1103/PhysRevC.94.014304
10. S. Goriely, S. Hilaire, S. Peru, M. Martini, I. Deloncle, and F. Lechaftois, Gogny-Hartree-Fock-Bogolyubov plus quasiparticle random-phase approximation predictions of the $M1$ strength function and its impact on radiative neutron capture cross section, Phys. Rev. C **94**, 044306 (2016). https://doi.org/10.1103/PhysRevC.94.044306
11. S. Goriely, S. Hilaire, S. Peru, and K. Sieja, Gogny-HFB+QRPA dipole strength function and its application to radiative nucleon capture cross section, Phys. Rev. C **98**, 014327 (2018). https://doi.org/10.1103/PhysRevC.98.014327
12. S. Peru and H. Goutte, Role of deformation on giant resonances within the quasiparticle random-phase approximation and the Gogny force, Phys. Rev. C **77**, 044313 (2008). https://doi.org/10.1103/PhysRevC.77.044313
13. K. Nomoto, F.-K. Thielemann, K. Yokoi, Accreting white dwarf models for type I supernovae. III. Carbon deflagration supernovae, Astrophys. J. **286**, 644 (1984). https://doi.org/10.1086/162639
14. A. Zilges, D. L. Balabanski, J. Isaak, and N. Pietralla, Photonuclear reactions—From basic research to applications, Prog. Part. Nucl. Phys. **122**, 103903 (2022). https://doi.org/10.1016/j.ppnp.2021.103903
15. A. Koning, S. Hilaire, and S. Goriely, TALYS: modeling of nuclear reactions, Eur. Phys. J. A. **59**, 131 (2023). https://doi.org/10.1140/epja/s10050-023-01034-3
16. S. Goriely and V. Plujko, Simple empirical $E1$ and $M1$ strength functions for practical applications, Phys. Rev. C **99**, 014303 (2019). https://doi.org/10.1103/PhysRevC.99.014303
17. C. Travaglio, F. K. Röpke, R. Gallino, and W. Hillebrandt, Type Ia supernovae as sites of the p-process: two-dimensional models coupled to nucleosynthesis, Astrophys. J. **739**, 93 (2011). https://doi.org/10.1088/0004-637X/739/2/93
18. C. Travaglio, R. Gallino, T. Rauscher, F. K. Röpke, and W. Hillebrandt, Testing the role of Sne Ia for galactic chemical evolution of p-nuclei with two-dimensional models and with s-process seeds at different metallicities, Astrophys. J. **799**, 54 (2015). https://doi.org/10.1088/0004-637X/799/1/54
19. A. Banu, E. G. Meekins, J. A. Silano, H. J. Karwowski, and S. Goriely, Photoneutron cross section measurements on ^{94}Mo and ^{90}Zr relevant to the p-process nucleosynthesis, Phys. Rev. C **99**, 025802 (2019). https://doi.org/10.1103/PhysRevC.99.025802
20. H. Utsunomiya *et al*., Photoneutron cross sections for Mo isotopes: A step forward toward a unified understanding of (γ,n) and (n,γ) reactions, Phys. Rev. C **88**, 015805 (2013). https://doi.org/10.1103/PhysRevC.88.015805
21. H. Beil *et al.*, A study of the photoneutron contribution to the giant dipole resonance in double even Mo isotopes, Nucl. Phys. A **227**, 427 (1974). https://doi.org/10.1016/0375-9474(74)90769-6
22. A. Morozov, L. M. S. Margato, A. Blanco, and D. Galaviz, Concept of a fast neutron detector based on ^{10}B-RPCs, JINST. **17**, P02016 (2022). https://doi.org/10.1088/1748-0221/17/02/P02016