PROCEEDINGS OF SCIENCE

Probing astrophysical reaction-rate calculations in photoneutron experiments

PoS(NIC X)079

J. Hasper[*], **A. Zilges**
Institut für Kernphysik, Universität zu Köln, Germany
E-mail: `hasper@ikp.tu-darmstadt.de`

S. Müller, D. Savran, L. Schnorrenberger, K. Sonnabend

Institut für Kernphysik, Technische Universität Darmstadt, Germany

Advanced astrophysical reaction-network calculations for the nucleosynthesis of heavy elements within the *s*, *r*, and *p* processes involve ten thousands of reactions. Most of the reaction rates are adopted from calculations based on the Hauser-Feshbach theory. Experimental investigations of photoneutron reaction rates are well suited to test the reliability of these calculations and to constrain the nuclear-physics input relevant for statistical model codes. In this context, recent experimental results stemming from photoactivation experiments are discussed.

10th Symposium on Nuclei in the Cosmos
July 27 - August 1 2008
Mackinac Island, Michigan, USA

---

[*] Speaker.

1. Introduction

Most of the elements heavier than iron are produced by neutron capture processes in the so-called s and r processes [1, 2, 3]. However, a certain number of proton-rich isotopes between Se and Hg cannot be synthesized in either of these two processes and are often referred to as p nuclei [4, 5]. These nuclei are believed to originate from the so-called p process, in which most of the p abundances can be produced from s- and r-process seed nuclei by a combination of (γ, n), (γ, p) and (γ, α) reactions in explosive astrophysical scenarios like SN type II. Additional contributions to the p abundances presumably stem from further nucleosynthetic processes like the rp process, νp process, ν process, etc.. To pinpoint the contributions of the various processes to the nucleosynthesis of heavy elements an accurate knowledge of a huge number of reactions rates is required.

Large efforts have been made in the past decades to provide reliable experimental data for astrophysically relevant reactions. In particular, a comprehensive data base of highly-accurate neutron-capture cross sections on isotopes along the valley of stability has become available [6, 7]. These cross sections are of major importance for the s-process nucleosynthesis and have led to significant improvements on stellar models. Further improvements of these models are yet strongly hampered by cross-section uncertainties for several unstable isotopes along the s-process path having half-lives comparable to the timescale of a neutron capture during the s process. Measurements of the neutron-capture cross sections of these so-called *branching points* are very challenging due to a lack of a proper amount of target material and the high radioactivity of the sample itself. Although some pioneering experiments on several long-lived branching points using nanogram amounts of radioactive material have been performed in the last years (e. g., see Refs. [8, 9]), cross sections for shorter-lived branching points with half-lives less than several months cannot be measured directly at currently available experimental facilities. These cross sections have to be adopted from theoretical predictions which are subject to rather large uncertainties. A promising way to reduce these uncertainties is to measure the inverse reactions, i. e., the photoneutron reaction of the stable neighbouring nuclei [10]. As will be discussed in Sec. 3, these experiments allow to constrain some of the nuclear-physics input relevant for statistical model calculations of the inverse neutron-capture reaction.

Compared to the s process the experimental situation is much worse for the r and p processes. The explosive physical conditions governing these two processes rapidly move the reaction path away from the valley of stability towards unstable isotopes which can hardly be investigated in the laboratory. Therefore, the corresponding reaction rates have to be derived almost exclusively from calculations based on the Hauser-Feshbach theory. To improve the accuracy and robustness of these calculations as many experimental data as possible are mandatory to provide a stringent test for nuclear properties adopted for the various models. For this reason, photoneutron rates for photon energies in the astrophysically relevant energy region just above the neutron emission threshold have been investigated for isotopes covering a wide mass range in the last years. In Sec. 2 we report on experiments performed at the superconducting Darmstadt linear electron accelerator S-DALINAC.

2. Determination of astrophysically relevant photoneutron rates

The High-Intensity Photon Setup (HIPS) at the S-DALINAC serves as an excellent tool to investigate photodisintegration reactions just above the particle emission threshold. At this setup a monoenergetic beam of energy $E_0 < 10$ MeV is impinging on a thick copper radiator and is converted into highly-intense bremsstrahlung of maximum photon energy $E_{\mathrm{max}} = E_0$. This photon beam is used to irradiate the targets of interest at a photon flux of up to a few $10^7 \frac{\mathrm{photons}}{\mathrm{keV\,s\,cm^2}}$ for a duration of typically 24 hours. The photon flux is determined either by monitoring the photon-scattering reaction $^{11}\mathrm{B}(\gamma,\gamma')$ during the irradiation or is derived from the reaction yields of the well-known photoneutron reactions $^{187}\mathrm{Re}(\gamma,\mathrm{n})$ and $^{197}\mathrm{Au}(\gamma,\mathrm{n})$ (see Ref. [11] for details). The reaction yields, i. e., the number of induced photodisintegration reactions, for the targets of interest and for the two standards ^{187}Re and ^{197}Au are determined by measuring the γ transitions following the β decays of the produced unstable nuclei with HPGe detectors after the irradiation.

As described in Ref. [12], it is possible to approximate the spectral distribution of thermal Planck spectra for temperatures of a few GK using a superposition of bremsstrahlung spectra of various energies. Thus, ground-state reaction rates at typical p-process temperatures of $2-3$ GK can be directly derived from a certain number of irradiations performed at different energies E_{max} ranging from several hundreds of keV to 1-2 MeV above the neutron threshold. Using this method, experimental ground-state reaction rates for a large number of isotopes in the mass region $A > 185$ have been presented in several works, see, e. g., Ref. [13]. Recently, this data set has been extended by measurements on several isotopes in the rare-earth region [11]. The experimental data of photoneutron rates have been compared to calculations performed within the framework of two statistical model codes: the NON-SMOKER$^{\mathrm{WEB}}$ code by Rauscher [14] and the TALYS code by Koning *et al.* [15]. An overview of the results is given in Fig. 1. The calculations are in good agreement with the experiment within the experimental error bars showing mean deviations of only less than 20% to the experimental data. No systematic deviation between theory and experiment has been found as a function of neutron number. Even close to and at the neutron shell closures the calculations agree with the experimental data within a factor of two. This proves the accuracy of these statistical model codes. Moreover, since only global nuclear models have been adopted for

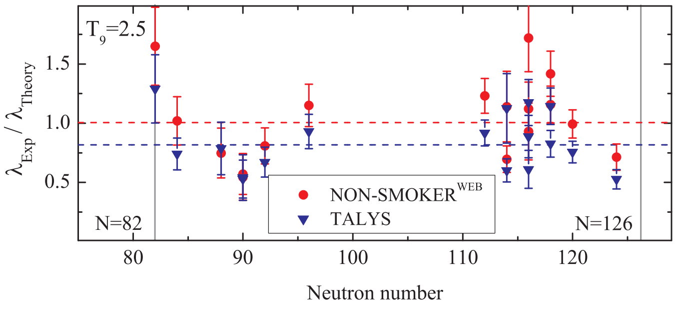

Figure 1: Comparison between experimentally determined stellar ground-state reaction rates λ_{Exp} and theoretical predictions $\lambda_{\mathrm{Theory}}$ using the two statistical model codes NON-SMOKER$^{\mathrm{WEB}}$ and TALYS, respectively. A temperature of 2.5 GK has been assumed. The data points refer to the isotopes ^{140}Ce, ^{142}Ce, ^{148}Nd, ^{150}Nd, ^{154}Sm, ^{154}Gd, ^{160}Gd, ^{187}Re, ^{191}Ir, ^{192}Pt, ^{192}Os, ^{193}Ir, ^{196}Hg, ^{197}Au, ^{198}Hg and ^{204}Hg. The dashed lines each indicate the mean ratio between theory and experiment.

both reaction codes (see default models described in Refs. [14, 15]), reliable reaction-rate predictions can be expected even for isotopes outside the valley of stability. Nevertheless, a systematic discrepancy between the two statistical model codes of about 25% has been determined which is discussed to some extent in the following section.

3. Discussion on nuclear properties of relevance for statistical model calculations

Whereas the Hauser-Feshbach theory is well established, discrepancies between the calculations using various codes mainly have to be ascribed to the adopted nuclear-physics input like optical-model potentials, nuclear level densities and γ-ray strength functions. The sensitivity of statistical model calculations to the different nuclear properties can be tested by varying the adopted values for γ transmission coefficients, particle transmission coefficients and nuclear level densities within a certain factor and studying the impact of this variation on the calculated cross sections. Exemplarily, Fig. 2 shows the results of such a sensitivity study for calculations of the reactions ^{148}Nd(γ, n) and ^{147}Nd(n, γ).

The calculation for the photoneutron reaction is found to be mainly sensitive to the γ transmission coefficent whereas other nuclear properties show only a negligible contribution. Consequently, predictions for photoneutron cross sections are highly dependent on the γ-ray strength function. Experimentally determined photoneutron rates, therefore, serve as a stringent test for various descriptions of this function. The discrepancy in the predicted photoneutron rates between the NON-SMOKER$^{\text{WEB}}$ code and the TALYS code outlined in the previous section, thus, most likely stems from the different models of the γ-ray strength function entering the reaction codes. Details about these models are given in Refs. [14, 15].

It becomes clear from Fig. 2 that an accurate knowledge of the γ-ray strength function also is of major importance for the calculation of neutron-capture cross sections. For those isotopes which cannot be studied directly via the neutron-capture reaction in the laboratory a promising approach is to derive a reliable description of the γ-ray strength function via the measurement of the inverse photoneutron reaction at energies very closely above the neutron threshold. As discussed in Sec. 1, such an approach is of particular interest for short-lived branching points in the *s* process.

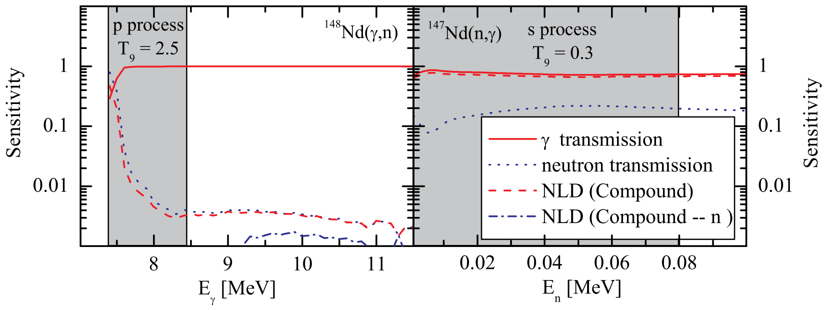

Figure 2: Sensitivity of predictions for stellar ground-state reaction rates to various nuclear input parameters which have been varied within a factor of 2. A sensitivity of 1 means that the predicted cross section changes by the same factor as the input parameter. The gray area indicates the astrophysically relevant energy region. These energy regions have been chosen to give a contribution of more than 95% to the total reaction rate at typical *p*- and *s*-process temperatures, respectively.

However, it has to be stressed that photoactivation experiments can only provide information of the γ-ray strength function for photon energies above the neutron threshold. Calculations of stellar photoneutron rates which also account for transitions stemming from thermally excited states as well as calculations of neutron-capture rates also strongly require an accurate description of the γ-ray strength function for photon energies below the threshold. This calls for complementary experiments in the future, e. g., photon-scattering experiments [16], which can also address this lower energy region.

4. Acknowledgments

We thank T. Rauscher for valuable discussions on statistical model calculations. This work was supported by the BMBF 06DA129 I and the DFG under contract SFB 634.

References

[1] E. Burbidge, G. Burbidge, W. Fowler and F. Hoyle, Rev. Mod. Phys. **29** (1957) 547

[2] F. Käppeler, Prog. Part. Nucl. Phys. **43** (1999) 419.

[3] J. J. Cowan; F.-K. Thielemann, J. W. Truran, Phys. Rep. **208** (1991) 267.

[4] D. L. Lambert, Astron. Astroph. Rev. **3** (1992) 201.

[5] M. Arnould, S. Goriely, Phys. Rep. **384** (2003) 1.

[6] Z. Y. Bao, H. Beer, F. Käppeler, F. Voss, K. Wisshak, T. Rauscher, At. Data Nucl. Data Tables **76** (2000) 70.

[7] I. Dillmann, M. Heil, F. Käppeler, R. Plag, T. Rauscher, and F.-K. Thielemann, AIP Conf. Proc. **819**, 123; online at http://www.kadonis.org

[8] R. Reifarth, C. Arlandini, M. Heil, F. Käppeler, P. V. Sedyshev, A. Mengoni, M. Herman, T. Rauscher, R. Gallino, Astrophys. J. **582** (2003) 1251.

[9] K. Wisshak, R. Gallino, F. Käppeler, M. Krticka, A. Mengoni , S. Raman, F. Voss, Phys. Rev. C **73** (2006) 015802.

[10] K. Sonnabend, P. Mohr, K. Vogt, A. Zilges, A. Mengoni, T. Rauscher, H. Beer, F. Käppeler, R. Gallino, Astrophys. J. **583** (2003) 506.

[11] J. Hasper, S. Müller, D. Savran, L. Schnorrenberger, K. Sonnabend, A. Zilges, Phys. Rev. C **77** (2008) 015803.

[12] P. Mohr, K. Vogt, M. Babilon, J. Enders, T. Hartmann, C. Hutter, T. Rauscher, S. Volz, A. Zilges, Phys. Lett. B **488** (2000) 127.

[13] K. Sonnabend, K. Vogt, D. Galaviz, S. Müller, A. Zilges, Phys. Rev. C **70** (2004) 035802.

[14] NON-SMOKER$^{\mathrm{WEB}}$, Version 4.6.0, http://nucastro.org/nonsmoker.html.

[15] A. Koning, S. Hilaire, M. C. Duijvestijn, Proceedings of the International Conference on Nuclear Data for Science and Technology - ND2004, AIP vol. 769, eds. R.C. Haight, M.B. Chadwick, T. Kawano, P. Talou, Sep. 26 - Oct. 1, 2004, Santa Fe, USA, p. 1154 (2005).

[16] S. Volz, N. Tsoneva, M. Babilon, M. Elvers, J. Hasper, R.-D. Herzberg, H. Lenske, K. Lindenberg, D. Savran, A. Zilges, Nucl. Phys. A **779** (2006) 1.