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Probing Hauser-Feshbach cross sections for the astrophysical *p* process*

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The reactions ^{170}Yb$(\gamma,n)^{169}$Yb, ^{169}Tm$(p,n)^{169}$Yb and ^{166}Er$(\alpha,n)^{169}$Yb have been measured with the activation method at energies close to the neutron threshold or to the Gamow window, respectively. Naturally composed target material was used and the induced activities were determined by γ spectroscopy with HPGe detectors in a low background environment. The reaction ^{170}Yb$(\gamma,n)^{169}$Yb was studied using bremsstrahlung radiation supported by the electron accelerator S-DALINAC at the Technische Universität Darmstadt. The charged particle induced reactions ^{169}Tm$(p,n)^{169}$Yb and ^{166}Er$(\alpha,n)^{169}$Yb were measured using the α-particle and proton beam provided by the FN Tandem Van de Graaff accelerator at the University of Notre Dame. Preliminary cross sections are presented and compared to theoretical predictions by the two Hauser-Feshbach codes TALYS and NON-SMOKER. The data can be used to optimize input parameters of the afore mentioned codes.

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1. Introduction

The nucleosynthesis of the heavy elements beyond the iron region mainly proceeds by means of neutron capture. Burbidge, Burbidge, Fowler, and Hoyle found in 1957 [1] that there have to be two different processes which are driven by this mechanism both contributing to the production of heavy elements to an equal amount. The first and best understood is the so-called *s* process [2] that proceeds via slow neutron capture reactions. The process is known to take place during Helium shell burning of AGB stars in such a way that β decay is faster than the capture of an additonal neutron when an unstable isotope is reached in most cases. Thus, the path of the *s* process runs along the valley of stability with branchings depending on the half-life and the neutron-capture cross section of the produced unstable isotope.

The second process based on this mechanism is the so-called *r* process taking place in extrem stellar sites like type II supernova explosions with high temperatures and high neutron densities. Neutron capture reactions occur within a time scale of one second and very neutron-rich isotopes along the neutron drip-line are produced. Finally when the neutron flux rapidly diminishes a sequence of β decays sets in building up many different stable isotopes above the iron region [2].

However, there are several stable isotopes on the proton-rich side of the valley of stability reaching ^{74}Se to ^{196}Hg which cannot be synthesised by means of neutron capture [3]. These so-called *p* nuclei are shielded against the production mechanism of *s* and *r* process and have to be produced in a distinct process which is called *p* process [4]. Taking place in explosive stellar environments like the O/Ne layer of massive stars just before and during the supernova explosion the process is mainly based on photodisintegration reactions like (γ,n), (γ,p) and (γ,α) of the seed distribution stemming from the neutron capture processes. This distribution is initially driven to the proton-rich side by a series of (γ,n) reactions. At some point, when the neutron separation energy is high (γ,p) and (γ,α) reactions start to compete. Branchings of the main reaction flux are generated driving the path to lower charge numbers. After a short time the process freezes out and β decays set in producing the *p* nuclei.

The astrophysical *p* process reaction network involves more than 1000 nuclei and 10,000 of reactions. For understanding and reproducing *p* nuclei abundances a huge amount of reaction rates under stellar conditions have to be known. The vast majority of these reactions is located off stability and, hence, is difficult to be accessed experimentally. In consequence, most reaction rates have to be calculated using codes based on the statistical Hauser-Feshbach (HF) model. These codes need nuclear physics input like masses and level densities of the involved nuclei and γ-strength functions as well as optical particle-nucleus potentials describing the formation and decay properties of the compound nucleus system. The qualitiy of these parameters determines the predictive power of the used HF codes. To test a special parameter (*e.g.* a global parametrization for α optical potentials) careful measurements of appropriate reactions are required. With these data the model can be probed but it can also be used to derive new more powerful parametrizations of global character.

In the last ten years extensive studies of (γ,n) reactions in the rare earth region were carried out at the superconducting electron accelerator S-DALINAC at Darmstadt via activation by bremsstrahlung [5, 6, 7, 8]. In general, a good agreement with HF predictions was found. Taking into account the restrictions of activation measurements these studies are nearly complete in the

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mass range from 140 to 210. Since experimental investigations of α- and proton-induced reactions in this mass region are rather scarce, the decision was made to extend the existing studies by measuring this kind of reactions at sub-Coulomb energies to provide further tests and a reliable data background for the HF input parameters.

For the above mentioned purpose, (α,n) and (p,n) reactions are perfectly suited to investigate the quality of optical α- and proton-nucleus potentials. This becomes obvious when looking at the dependence of the HF cross sections in Eq. 1.1:

$$\sigma_{\mathrm{HF}} = \sum_n (2J_n+1)\,\frac{\langle\Gamma^{\mathrm{form}}_{J_n}\rangle\langle\Gamma^{\mathrm{dec}}_{J_n}\rangle}{\langle\Gamma^{\mathrm{tot}}_{J_n}\rangle} \tag{1.1}$$

The HF model makes use of averaged widths $\langle\Gamma\rangle$ describing the propability of the formation and decay of the compound nucleus from and into a selected channel, respectivly. In the denominator of Eq. 1.1 the total decay width appears taking into account all open reaction channels. For charged particle induced reactions like (x,n) at sub-Coulomb energies it is clear that the width in the entrance channel $\langle\Gamma^{\mathrm{cp}}_{\mathrm{in}}\rangle$ is much smaller than the neutron width in the exit channel $\langle\Gamma^{\mathrm{n}}_{\mathrm{fi}}\rangle$. Furthermore, the total decay width $\langle\Gamma^{\mathrm{tot}}\rangle$ is mainly dominated by $\langle\Gamma^{\mathrm{n}}_{\mathrm{fi}}\rangle$ above the neutron separation energy and hence $\langle\Gamma^{\mathrm{n}}_{\mathrm{fi}}\rangle$ cancels with the denominator in Eq. 1.1. Since these averaged widths $\langle\Gamma\rangle$ are calculated using an optical particle-nucleus potential, measurements of (α,n) and (p,n) reactions are a perfect choice to test and improve the global parametrizations of these potentials (see also [9]).

In the above mentioned context the reactions $^{169}\mathrm{Tm}(p,n)^{169}\mathrm{Yb}$ and $^{166}\mathrm{Er}(\alpha,n)^{169}\mathrm{Yb}$ have been measured with the activation technique at the University of Notre Dame making use of the FN Tandem Van de Graaff accelerator. In addition, the photon-induced reaction $^{170}\mathrm{Yb}(\gamma,n)^{169}\mathrm{Yb}$ was measured at the Technische Universität Darmstadt using bremsstrahlung radiation produced by completely stopping the monoenergetic electron beam of the S-DALINAC. The preliminary results are presented including a comparison to the predictions of the HF codes NON-SMOKER [10] and TALYS [11]with standard settings.

2. Experimental details

All three reactions mentioned in the previous section were measured using the activation technique. The (γ,n) reaction on $^{170}\mathrm{Yb}$ was carried out at the High Intensity Photon Setup (HIPS) at the S-DALINAC in Darmstadt. The electron beam was used with energies from 8.9 MeV to 9.9MeV to produce continuous bremsstrahlung radiation in a thick radiator target. Seven naturally composed Yb_2O_3 targets were activated and the induced decay of the reaction products was detected with HPGe detectors under optimized background conditions. Beam current and energy stability were monitored by charge integration at the segmented radiator target.

At the University of Notre Dame the FN Tandem accelerator provided a proton beam with eight different energies ranging from 3.3 MeV to 7 MeV in the laboratory frame to study the reaction $^{169}\mathrm{Tm}(p,n)$. The metallic Thulium target foils were of natural composition with an average area density of 1.9 $\frac{\mathrm{mg}}{\mathrm{cm}^2}$ obtained from Oak Rich National Laboratories (ORNL). Activation durations from 1.9 h up to 60 h were necessary to produce a measurable reaction yield. To investigate the $^{166}\mathrm{Er}(\alpha,n)$ reaction the FN Tandem supported an α beam with seven different laboratory energies between 11.75 and 15 MeV at beam intensities up to 200 nA. Naturally composed target

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foils were obtained in metallic form from ORNL with an average area density of 0.8 $\frac{\text{mg}}{\text{cm}^2}$. For both reactions, several counting setups were available making use of HPGe detectors surrounded by massive lead and copper shielding. To monitor the target stability during activation the backscattered protons/α-particles were detected by a Si surface barrier detector positioned at 135° with respect to the incoming beam.

3. Analysis and discussion

In Fig. 1 the ratios of the energy integrated cross sections $\frac{I_{\text{HF}}}{I_{\text{exp}}}$ of the predictions and the measured reaction $^{170}\text{Yb}(\gamma,n)$ are shown. One can see that the prediction of the TALYS code (upper panel) deviate by a factor between 1.2 to 1.6 and exhibit a different energy dependence. The NON-SMOKER code (lower panel) predicts the correct energy dependence deviating only slightly in absolute value by a mean factor of 1.07.

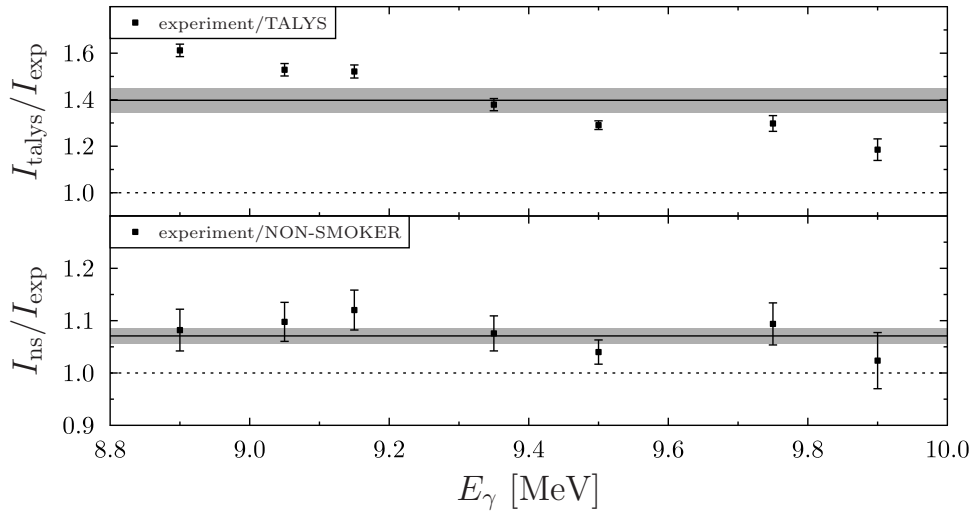

Figure 1: Integrated cross sections of the reaction $^{170}\text{Yb}(\gamma,n)$. In the upper panel a comparison to the cross section predicted by TALYS [11] (standard settings) is shown. In the lower panel, the result of a prediction using NON-SMOKER [10] is compared to the data.

For the reaction $^{169}\text{Tm}(p,n)$, a good agreement for the energy dependence was found by both codes (Fig. 2). While the TALYS code differs by a factor of 2, the NON-SMOKER code yields predictions that are in agreement within 2σ.

In Fig. 3, the cross section of $^{166}\text{Er}(\alpha,n)$ is shown. The TALYS prediction shows large deviations concerning the absolute value as well as the energy dependence. The energy dependence of the NON-SMOKER values are in quite good agreement with the data but overestimate the cross section by an average factor of 6.

Since all three reactions proceed through the same compound nucleus ^{170}Yb decaying into the neutron emission channel, it is clear that systematic uncertainties associated with information about the decay of the reaction product and the counting setup will affect all evaluated cross sections in the same way. Looking at the three cross sections at the same time, one can say that the large

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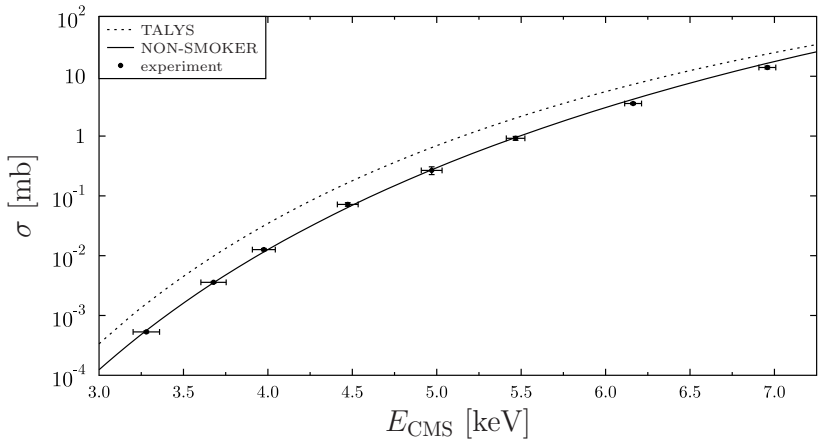

Figure 2: Cross sections of the reaction ^{166}Er(α,n) in comparison to the standard output of TALYS [11] and NON-SMOKER [10] are shown.

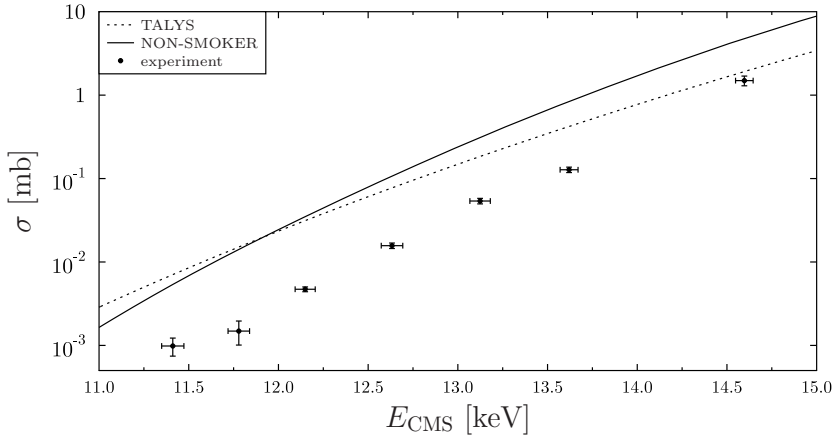

Figure 3: Cross sections of the reaction ^{169}Tm(p,n) in comparison to the standard output of TALYS [11] and NON-SMOKER [10] are shown.

deviations found for (α,n) are unlikely to come from unknown systematic effects. Otherwise, both cross sections of (γ,n) and (p,n) should show similar effects.

The results clearly underline that a further experimental investigation of charged-particle induced reactions on heavy nuclei is necessary to build up a reliable database. Especially for the case of reactions involving α particles the possibility of hugh deviations between measured and predicted cross sections is shown for another example. Thus, an improvement of the prediction of *p*-process abundances still relies on a better understanding of the nuclear physics input.

References

[1] Burbridge G., Burbridge M., Fowler W., Hoyle F., Reviews of Modern Physics. **29** (1957) 547

[2] Wallerstein G. *et al.*, Reviews of Modern Physics **69** (1997) 995

[3] Lambert D.L., Astronomy and Astrophysics Review **3** (1992) 201

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[4] Arnould M., Goriely S., Physics Reports **384** (2003) 1

[5] Vogt K. *et al.*, Physical Review C **63** (2001) 055802

[6] Sonnabend K. *et al.*, Physical Review C **70** (2004) 035802

[7] Hasper J. *et al.*, Physical Review C **77** (2008) 015803

[8] Müller S., PhD Thesis (2009), Technische Universität Darmstadt, unpublished

[9] Rauscher T., Nuclear Physics A **834** (2010) 635c

[10] Rauscher T., code NON-SMOKER^{WEB}, http://nucastro.org/websmoker.html

[11] Koning A.J., Hilaire S., Duijvestijn M.C., .TALYS-1.0., Proceedings of the International Conference on Nuclear Data for Science and Technology, April 22-27, 2007, Nice, France, editors O.Bersillon, F.Gunsing, E.Bauge, R.Jacqmin, and S.Leray, EDP Sciences, 2008, p. 211-214

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