The (n,α) Reaction Cross Section Calculations in Hauser-Feshbach Statistical Model

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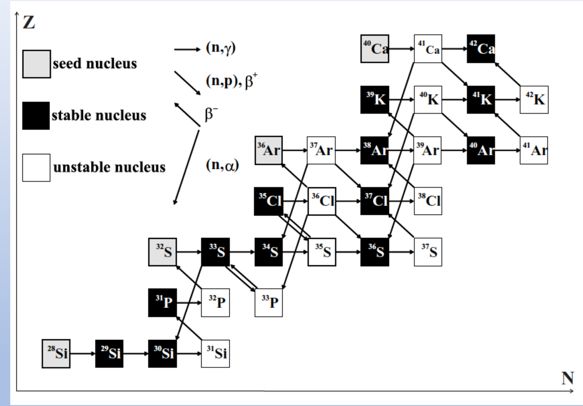
1 Abstract

The (n,α) reaction contributes in many processes of energy generation and nucleosynthesis in stellar environment. One of the aims of this work is to study (n,α) reaction cross sections for a set of nuclei involved in the weak s-process modeling. Theory framework is based on the statistical Hauser-Feshbach model within the TALYS code with nuclear masses and level densities based on Skyrme energy density functional, and global optical model potential. In addition to the analysis of the properties of calculated (n,α) cross sections, the Maxwellian averaged cross sections are described and analyzed for the range of temperatures in stellar environment. Model calculations determined astrophysically relevant energy windows in which (n,α) reactions occur in stars. Presented results on the effective energy windows for (n,α) reaction in weak s-process provide a guidance for the priority energy ranges in the future experimental studies. Another aim of this study is to explore the evolution of (n,α) reactions in Fe and Sn isotope chains in order to assess their properties with the increase of neutrons in target nucleus and compare with other relevant neutron induced reactions. The results show the evolution of the cross sections with pronounced maxima at low-mass isotopes, and rather strong decrease for neutron-rich nuclei consistent with the reduction of the reaction Q-value and increased contributions from other exit channels from compound nucleus. The analysis of the Maxwellian averaged cross sections at temperatures in stellar environment shows that while the (n,α) reactions contribute for the low-mass isotopes, in neutron induced reactions with nuclei with neutron excess, γ and neutron emission dominate.

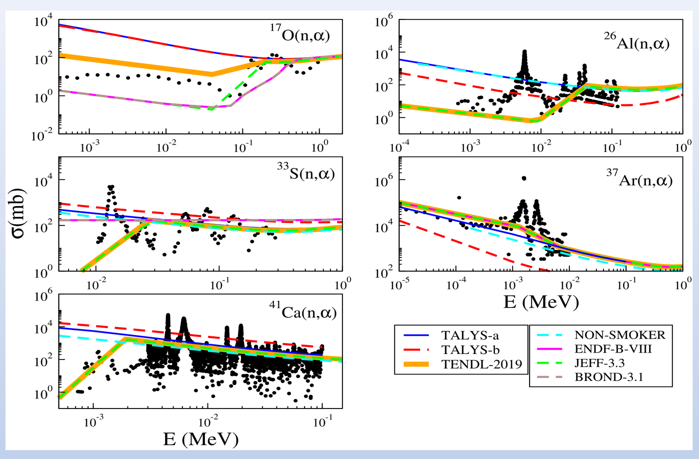
2 Introduction

Neutron induced reactions can result with emission of α particles. Since the properties of (n,α) reactions for many nuclei still remain beyond the reach of experimental studies, theoretical modelling is necessary to provide relevant cross sections for astrophysical applications. In this work, (n,α) reaction cross sections are investigated using the statistical Hauser-Feshbach model implemented in the nuclear reaction program TALYS [1,2]. In the first step (n,α) reactions are studied for nuclei used in weak s-process network calculations [3]: ^{17}O, ^{18}F, ^{22}Na, ^{26}Al, ^{33}S, ^{37}Ar, ^{39}Ar, ^{40}K, ^{41}Ca, ^{59}Ni, ^{65}Zn and ^{71}Ge. Maxwellian averaged cross sections (MACS) are calculated for the weak s-process nucleosynthesis and future experimental studies of (n,α) reactions. The evolution of (n,α) reaction cross sections are analyzed with increasing the neutron number in target nucleus for Fe and Sn isotope chains.

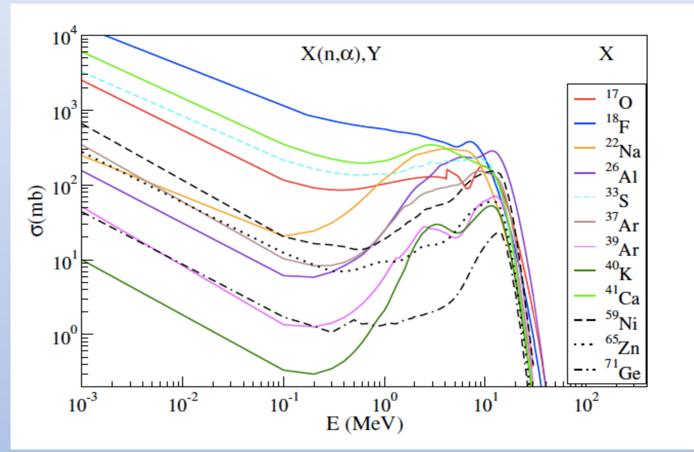


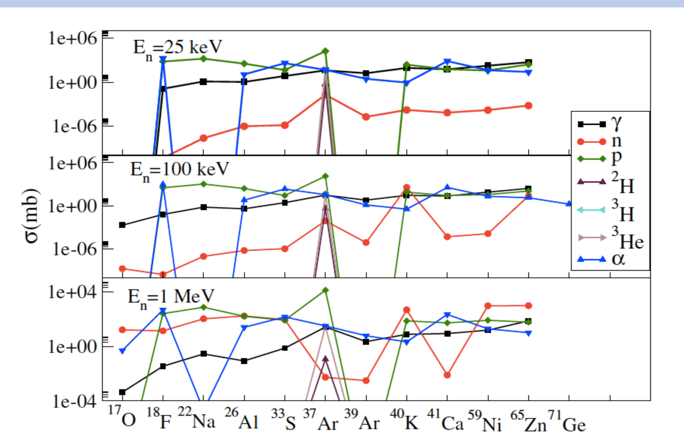
L. De Smet et al., PRC 75, 034617 (2007)

3 Cross Section



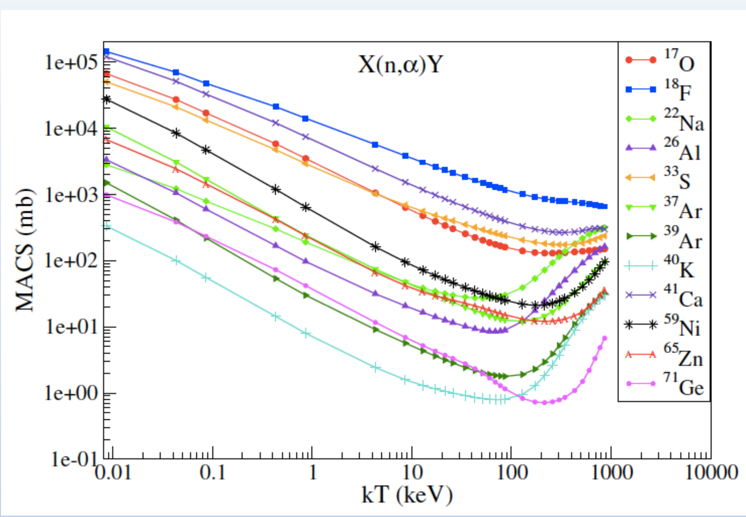
In the first step, calculated cross sections are compared with the set of available experimental data. The Hauser-Feshbach calculations are based on experimental masses with Fermi gas model for level density (Talys-a) and HFB-17 mass model with microscopic level density based on the Skyrme interaction (Talys-b).





The cross sections at low energies show the 1/v dependence that is a general feature in neutron induced reactions in this energy range. The shape of the cross sections corresponds to the general expectation for the compound nucleus reaction, i.e. the cross section increases to a maximum and then decreases because at higher energies new emission channels start opening. At low energies (E_n=25 keV), for some nuclei α exit channel can have considerable contribution.

4 Maxwellian Averaged Cross Sections (MACS)

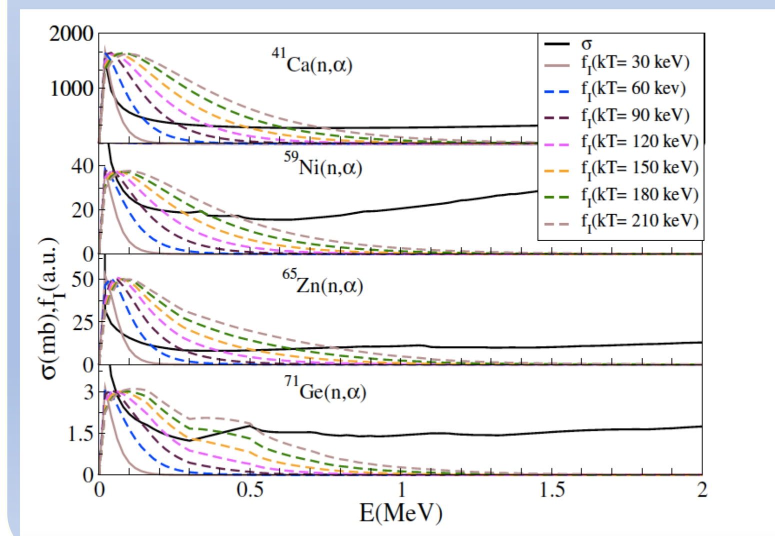


$$<\sigma>(kT) = \frac{2}{\sqrt{\pi}}(kT)^{-2}\int_0^{\infty}\sigma(E)Ee^{-\frac{E}{kT}}dE$$

Cross section averaged over the Maxwell-Boltzmann distribution

The MACS values for (n,α) reaction are calculated for selected set of nuclei and their dependence with temperature is investigated.

One of the objectives of this study is to determine what are the relevant energy ranges for the (n,α) reaction in stellar environment, that could contribute in modelling the nucleosynthesis. These relevant energy ranges, are determined through the overlap between the Maxwell Boltzmann distribution for neutrons and the low-energy tail of the reaction cross section,



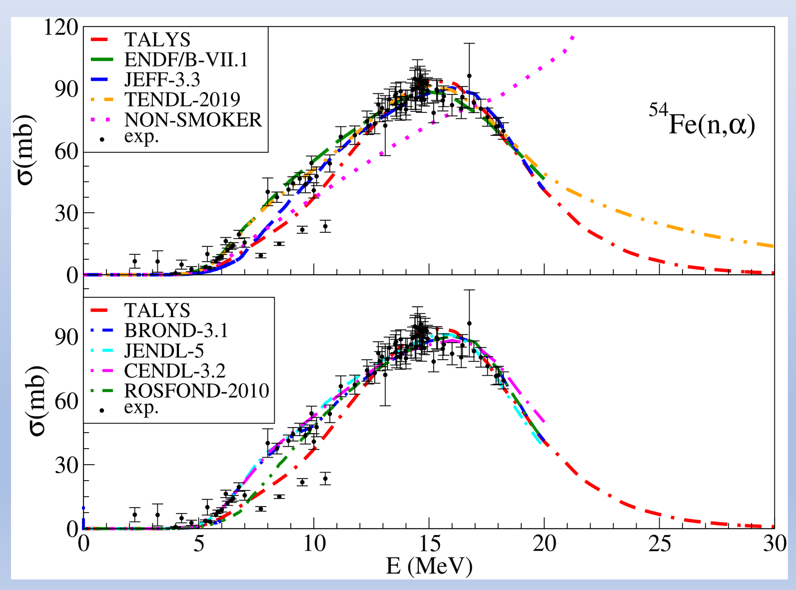
$$f_I(E) = \sigma(E)Ee^{-\frac{E}{kT}}$$

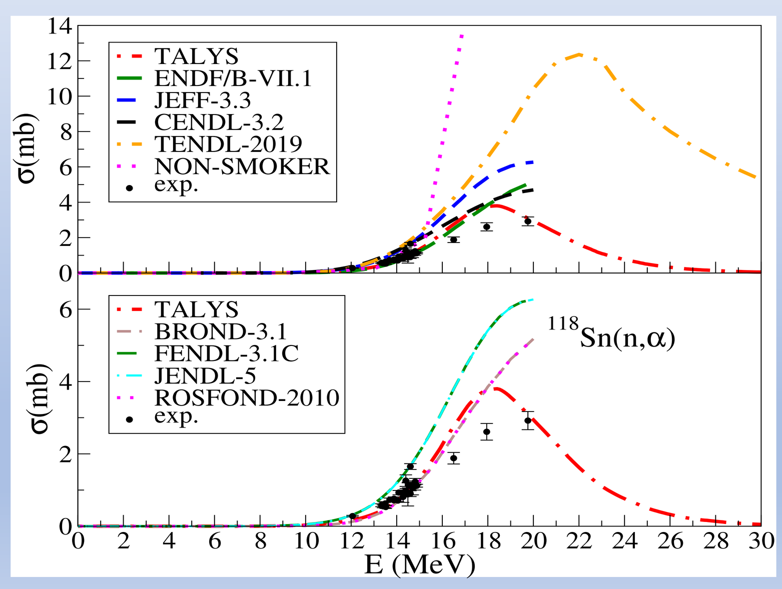
The reaction energy windows described by the function $f_I(E)$, are shown together with the corresponding (n,α) reaction cross sections. As expected, the reaction energy windows become wider with increasing temperature, but their exact location sensitively depends on the specific target nucleus under consideration.

To assess the accurate information on astrophysically relevant energy windows, calculations need to be performed for each nucleus of interest.

5 Benchmarking the calculations with experimental data

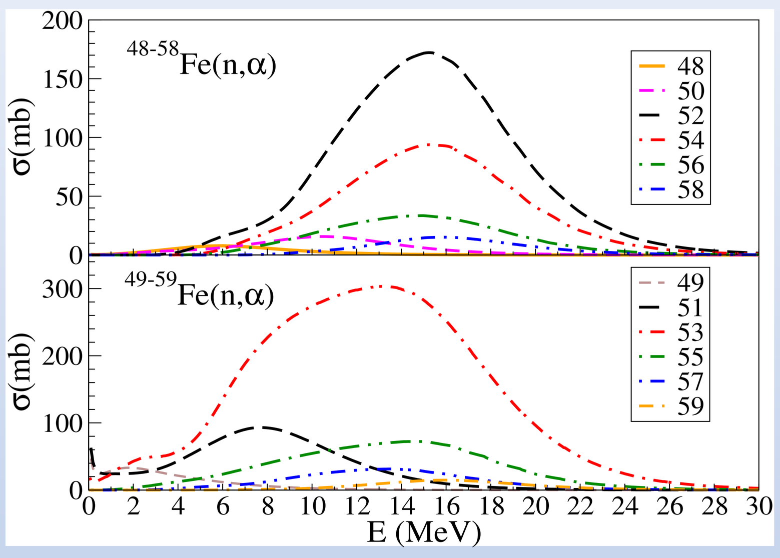
The evolution of (n,α) reaction cross sections is investigated along two representative isotope chains, Fe and Sn. The global optical model potential from Koning and Delaroche [4] is additionally adjusted (mass dependent parameters r_v and a_v in the volume central potential) by the experimental data separately for ^{54}Fe and ^{118}Sn for the study of the corresponding isotope chains. The experimental data of our calculation (TALYS) are compared with other models.

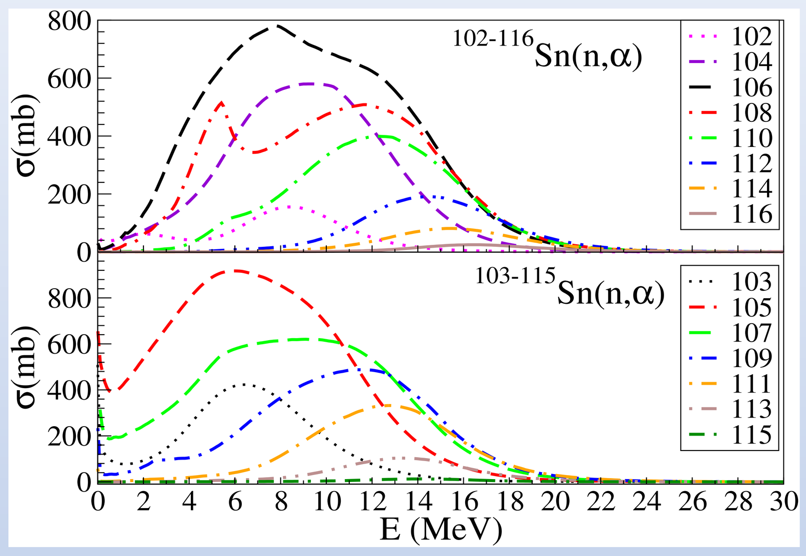




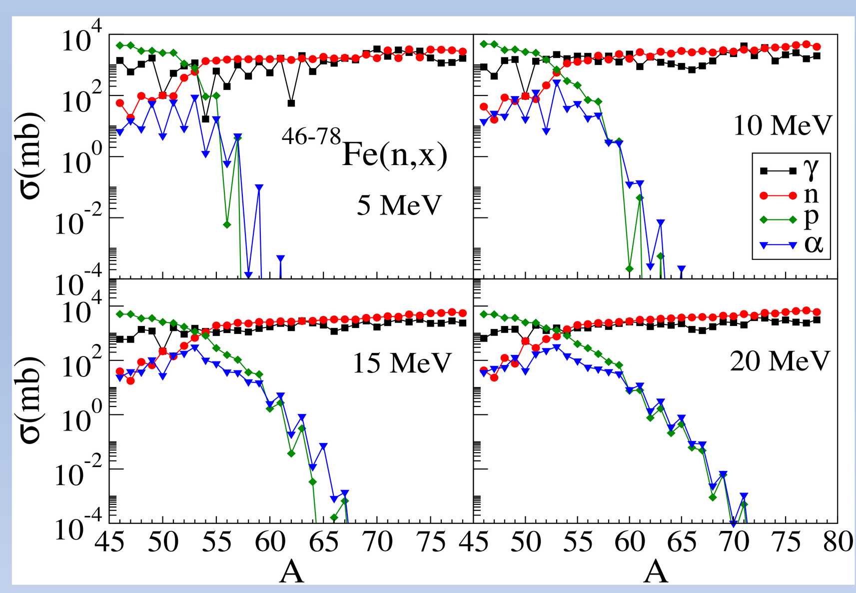
6 Isotopic Dependence of the Cross Section

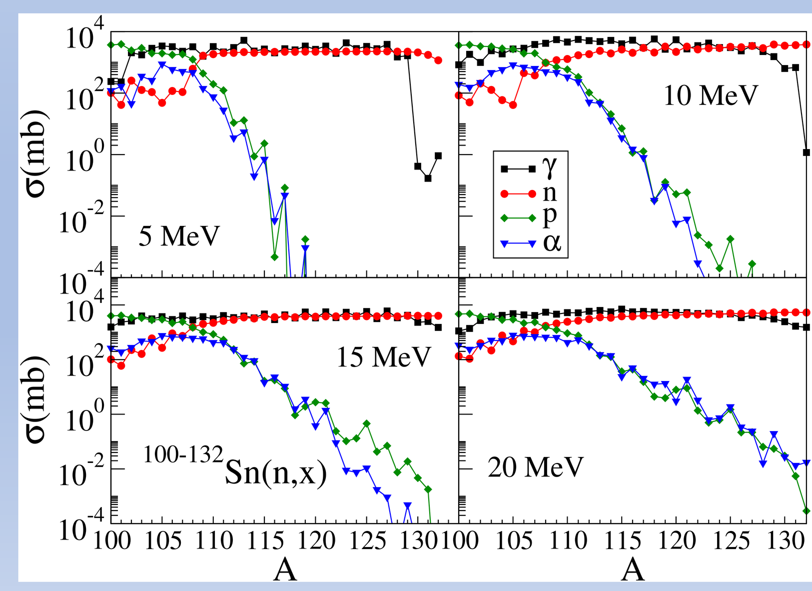
The theory framework benchmarked using the experimental data for ^{54}Fe and ^{118}Sn is employed in the study of the evolution of the (n,α) reaction cross sections for Fe and Sn isotope chains. The Fe and Sn isotopes with proton excess have rather small cross sections, and by increasing the neutron number the cross sections increase and with further increase of the neutron number, the cross sections become smaller.





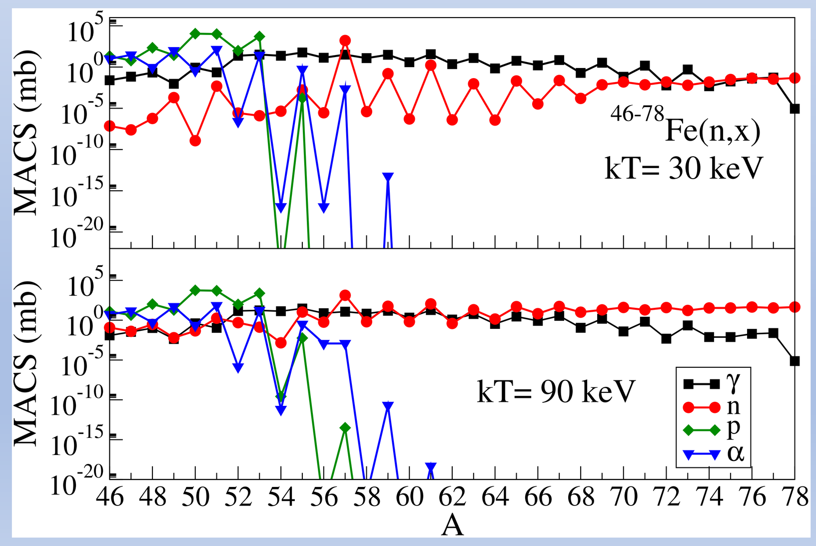
The evolution of (n,α) reaction cross sections is investigated in comparison with the cross sections for other relevant exit channels. One of the reasons for reducing the (n,α) reaction cross sections along the isotope chain are increasing contributions from other exit channels. In order to understand this dependence of the cross sections, it is interesting to inspect the corresponding reaction Q-values along the isotope chain. The Q-values systematically decrease with the number of neutrons, showing also odd-even staggering, thus, for more neutron rich isotopes more energy is required for the reaction.

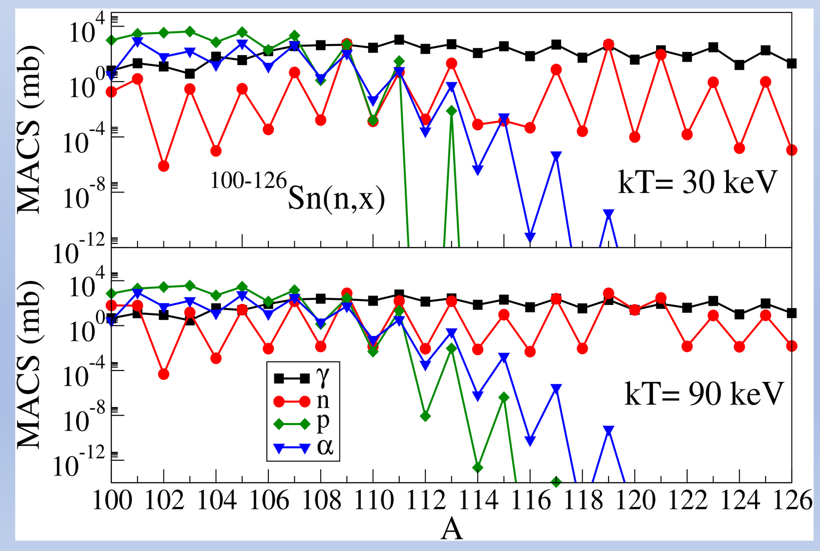




7 Isotopic Dependence of the MACS values

Only small modifications of the neutron capture reaction cross sections could have important implications on the path of nuclear processes contributing to the synthesis of chemical elements. The MACS values are investigated at two temperatures characteristic for stellar environment, kT = 30 keV (e.g., associated to the core He burning in massive stars), and kT = 90 keV (e.g., in supernova envelope where the r- process could occur). For comparison, in addition to the (n,α) reaction, also other exit channels from the neutron induced reactions are studied. For kT = 30 keV, for lighter Fe and Sn isotopes one can observe that α emission is as important as those with γ, n and p emission. The MACS values also rapidly decrease for the neutron-rich isotopes. One can also observe the sensitivity of the results on temperature, resulting in the reduction of the MACS values and modifications in their evolution along the isotope chains.





8 Conclusions

In this work we have investigated (n,α) reaction cross sections for the set of nuclei contributing to the s-process nucleosynthesis. Model calculations have been performed in the theory framework based on Hauser-Feshbach statistical model through its implementation in the nuclear reaction program TALYS. When possible, model calculations are kept consistent by using nuclear properties necessary for the reaction calculated in the framework of Skyrme energy density functional.

Model calculations in this work determined relevant energy windows for (n,α) reactions for the range of astrophysically represented temperatures, indicating a strong dependence of the exact location of the energy window on specific target nucleus under consideration. Quantitative predictions of astrophysically relevant energy windows for (n,α) reactions, that contribute in the s-process nucleosynthesis, provide a guidance for the future experimental studies of these reactions.

We have also investigated the evolution of (n,α) reaction cross sections for target nuclei within Fe and Sn isotope chains. Since the experimental data on (n,α) reaction cross sections are rather limited for Fe and Sn isotopes, and often restricted to narrow energy range, model calculations in this work provide a consistent and systematic insight into their isospin dependence and properties over the complete relevant energy range. The cross sections display maxima at low-mass isotopes, and with increase of neutron number they decrease, due to the corresponding reduction of the Q-value and additional contributions by emission of photons and neutrons. The MACS values show that while the (n,α) reactions contribute for the low-mass isotopes, in neutron induced reactions with nuclei with neutron excess, γ and neutron emission dominate. However, further studies are required to assess the role of (n,α) reactions in nucleosynthesis, in cases of nuclei with significant respective cross section.

References and acknowledgements

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PROVEDBA VRHUNSKIH ISTRAŽIVANJA U SKLOPU ZNANSTVENOG CENTRA IZVRSNOSTI ZA KVANTNE I KOMPLEKSNE SUSTAVE TE REPREZENTACIJE LIEJEVIH ALGEBRI

MINISTARSTVO REGIONALNOGA RAZVOJA I FONDOVA EUROPSKE UNIJE

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Operativni program KONKURENTNOST I KOHEZIJA

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TÜBİTAK