PROCEEDINGS OF SCIENCE

Sensitivity of r-nuclide distributions to the choice of nuclear mass model

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Theoretical estimates of the cross sections and rates of neutron capture reactions in the astrophysical r-process are obtained using the masses of unknown nuclei predicted in such approaches as FRDM, HFB and WS+RBF. We also used the mass values obtained by us in the phenomenological approach using local mass relations. Variations of predicted r-process yields, caused by nuclear models uncertainties, were studied.

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Astrophysical r-process is believed to be the main source of heavy elements in the Universe [1]. It is mostly studied with the help of computer simulations, as it takes place in extreme astrophysical conditions. Nuclear characteristics, that are taken as input parameters of these calculations, are usually experimentally unknown. Usage of theoretical mass models for the determination of masses of unstable neutron-rich nuclei, brings uncertainties to r-process simulations. This study aims to estimate these uncertainties, calculating r-process with different nuclear mass models. Previously, we carried out such studies using the example of neutron capture reactions on the neutron-rich terbium isotopes [2]. In this work we perform these estimates for all r-process neutron capture reactions and increase the number of considered mass models.

Simulation of the evolution of astrophysical nuclear reaction networks requires solution of ordinary differential equation systems, describing variations of isotope concentrations. Such systems are very large, with more than 150 thousand non-zero members, and are distinguished by large stiffness. In this work we use the SkyNet library [3] to calculate astrophysical nuclear network evolution. We use the canonical r-process model described, e.g., in [4]. In this approximation temperature and density are constant and large enough for intense neutron capture reactions, while the initial state consists of ^{56}Fe. Results of our r-process simulation with default REACLIB [5] astrophysical reaction rates are shown in the fig. 1 as final r-isotopes concentrations.

Nuclear reaction rates are the crucial parameters of the simulation. The reaction rate is defined as the reaction cross section folded with energy distribution of interacting particles and, therefore, strongly depends on nuclear parameters, such as nuclear masses. In this work we use TALYS program [6] to calculate reaction rates with pre-calculated tables of theoretical nuclear masses, obtained with three models : FRDM2012 [7], HFB-24 [8], WS+RBF [9]. We also used for calculations our estimates of the masses of unknown nuclei obtained in the phenomenological approach based on the local mass relation (LMR) associated with the neutron-proton interaction:

$$\Delta_{np}(N, Z) = B(N, Z) + B(N - 1, Z - 1) - B(N, Z - 1) - B(N - 1, Z), \qquad (1)$$

where $B(N, Z)$ is a binding energy of (N, Z) nucleus. Δ_{np} as a function of the mass number A is smooth enough to be approximated with a power law [10, 11], using experimentally obtained

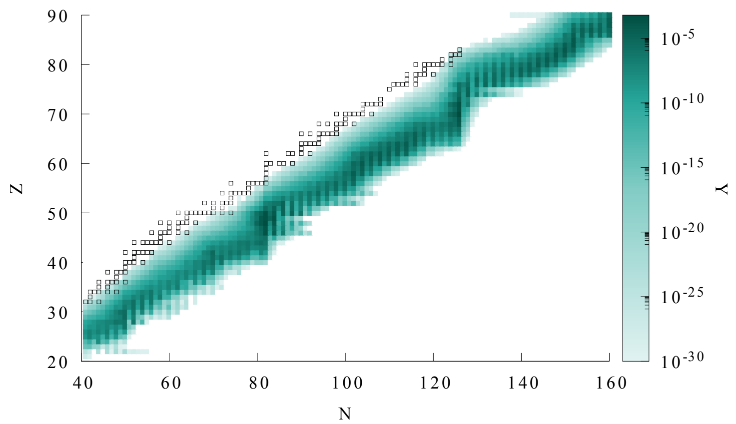

Figure 1: Resulting concentrations of 1 sec r-process simulation at $T9 = 1.2$ GK and density of 10^8 g/cm^3. Stable isotopes are marked with black squares. Standard astrophysical reaction rates from [5] were used.

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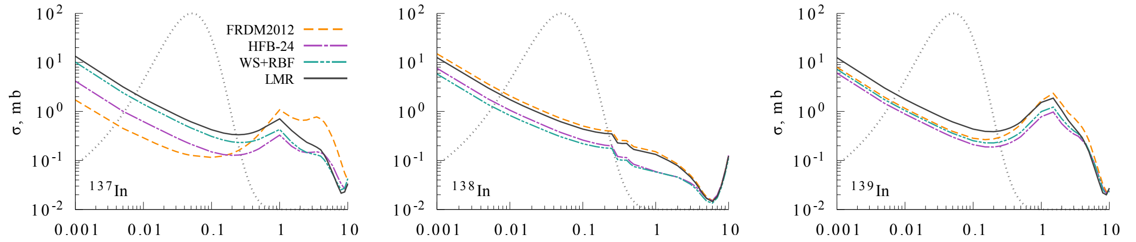

Figure 2: Theoretical cross sections of (n, γ) on the neutron-rich indium isotopesi with $A = 137 \div 140$, calculated with four different nuclear mass models. Grey dotted line represents neutron energy distribution at 1.2 GK.

binding energies. With such approximation mass of any isotope can be predicted, if binding energies of its three neighbours are known. Despite the simplicity of the approach, it gives fairly accurate predictions. The r.m.s. errors of predicted mass values with respect to the experimental data from AME2020 [12] results is $\sigma = 372$ keV, which is comparable with WS+RBF result $\sigma = 287$ keV and is much smaller than FRDM2012 ($\sigma = 881$ keV) and HFB-24 ($\sigma = 736$ keV) values.

Using the described nuclear mass models, we obtained cross sections and reaction rates of neutron capture reactions participating in r-process. Fig. 2 shows theoretical (n, γ) cross sections for neutron-rich indium isotopes. It is seen that variations of cross-sections are significant and an effect of uncertainties of the Q-values calculated with different mass models is evident. Moreover, their qualitative behavior might vary considerably, as the FRDM2012 plot for ^{137}In shows.

Theoretical reaction rates of neutron capture, calculated by us with four different nuclear mass models, were compiled in four astrophysical reaction rate databases in the REACLIB format. We used them as input parameters of our r-process model to observe the impact of mass model variation on the resulting r-nuclides distributions. Results of these simulations are presented on the fig. 3. As it can be observed, r-process yields show variations of up to 2 orders of magnitude. Qualitative

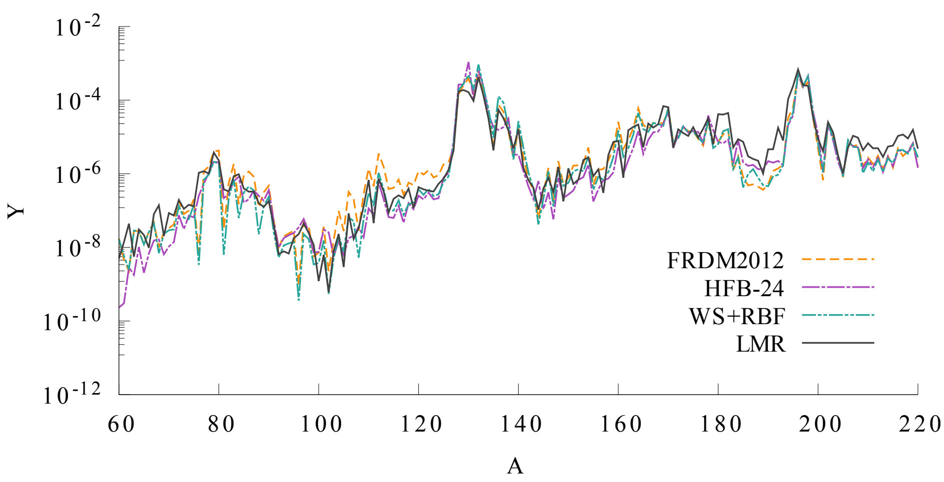

Figure 3: The yields of r-process simulated with four sets of (n, γ) rates, calculated with different nuclear mass models.

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differences are also noticeable, especially in the region of $A = 60 \div 110$, where both collective models FRDM2012 and HFB-24 show intense oscillations, not observed for other models. Use of LMR also lead to significant increase of yields in regions $A \geq 80$ and $170 \leq A \leq 190$. All models predict two peaks for the magic numbers of neutrons 82 and 126.

The results of our research illustrate strong dependence of the r-process simulation on the accuracy of predicted nuclear masses. While there are still uncertainties in our understanding of the r-process astrophysical scenarios, a significant progress in exotic nuclei models is crucial for r-process study.

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