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

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ABSTRACT

The astrophysical **r-process** of nucleosynthesis is one of the main sources of production of stable and neutron-rich isotopes beyond the iron peak in the Universe. It is believed to occur in extreme astrophysical scenarios, such as supernova explosions or neutron star and black hole collisions.

Theoretical r-process yields are strongly dependent on the choice of the **nuclear mass model** used for simulation of nuclear reactions. In the present study sets of astrophysical reaction rates were generated using different nuclear mass models. **Cross sections** and **rates of neutron capture reactions** were calculated using the TALYS nuclear reaction package. **Mass distributions of the nucleosynthesis products** were obtained and the sensitivity of calculation to the choice of the nuclear mass model was analyzed.

1. RELEVANCE

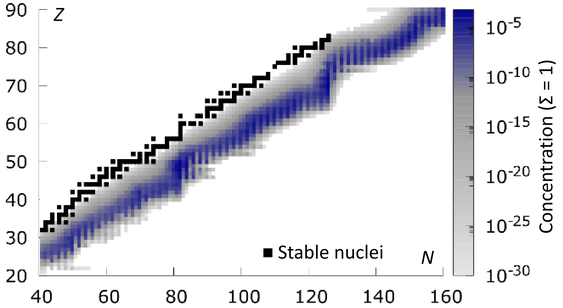
Computer simulations are the only feasible way of exploration of astrophysical nucleosynthesis of heavy elements. Computational models of r-process depend on a very large amount of input data from the fields of astrophysics and nuclear physics. One of the most important parameters that impacts calculation of the neutron capture rates is the masses of participating nuclei, especially in the little-studied exotic isotope regions of the nuclide chart. Most of such masses were obtained not experimentally, but from theoretical models. For some isotopes different models predict significantly different values, which brings uncertainties to r-process calculations.

2. SIMPLIFIED r-PROCESS MODEL

Concentrations of isotopes y_i in homogeneous medium is described by a set of ODEs:

$$\frac{dy_i}{dt} = \sum_{k\in K_i}\left(g_k\lambda_k\prod_{l\in L_k} y_l\right)$$

where λ_k are the rates of nuclear reactions where the isotope i is produced (when $g_k = +1$) or consumed (when $g_k = -1$).



↑ ***Fig. 1.*** *Simulation of a 1-sec r-process using reaction rates from REACLIB [1]. Total yields of reactions involving each isotope are shown.*

Model and initial conditions:

Simulations of the r-process yields are performed using the canonical model [2]: at the beginning of the r-process the medium consists of ^{56}Fe at the temperature and density of, respectively, $T = 1.2\cdot10^9$ GK and $\rho = 10^8$ g/cm^3. In the initial state of the system there are 1000 neutrons per iron nucleus. This simplified model does not depend on a specific astrophysical scenario. The ODEs are solved using the Skynet library [3].

Nuclear masses affect the results of simulation through the neutron capture rates λ_k. The rate is defined as the reaction cross section folded with the energy distribution of neutrons at the given temperature T:

$$\lambda(T) = \sqrt{\frac{8}{\pi m}}\frac{N_A}{(kT)^{3/2}G(T)}\int_0^\infty\sum_\mu\frac{(2I^\mu+1)}{(2I^0+1)}\sigma^\mu(E)E\cdot\exp\left(-\frac{E-E_x^\mu}{kT}\right)dT$$

Differences of masses of reacting nuclei determine the excitation energies at different stages of the reaction making its cross-section very sensitive to the mass model. For example, in statistical models of nuclear reactions excitation energies enter the Fermi-gas nuclear level densities. Uncertainties of $10^2 - 10^3$ keV can change their values by up to several orders of magnitude.

Scheme of calculations:

Preparation of nuclear mass table → **Calculation of cross sections and rates (TALYS)** → **Replacement of REACLIB rates** → **Calculation of r-process yields (Skynet)**

3. NUCLEAR MASS MODELS

Neutron capture cross sections and rates were calculated using TALYS [4] for ≈7000 nuclei with 4 mass tables:

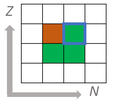
1) Finite-Range Droplet Model FRDM (2016) [5] (macro-microscopic);
2) Hartree-Fock + Skyrme potential HFB-24 model [6] (microscopic);
3) Weizsäcker-Skyrme model WS+RBF [7] (macro-microscopic);
4) local mass relations model [8] (phenomenological).

Method of local mass relation: The residual *np*-interaction $\Delta_{np}(Z,N)$ represents an *np*-correlation and shows smooth dependence on mass number A and is defined as:

$$\Delta_{np}(Z,N) = [B(Z,N) - B(Z,N-1)] - [B(Z-1,N) - B(Z-1,N-1)].$$

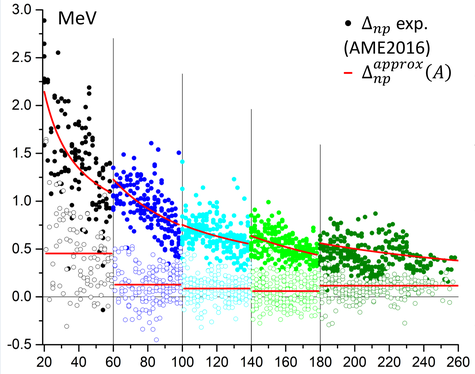
Binding energy evaluation is performed step-by-step (estimates obtained at the previous stage are used along with experimental data). One of four possible formulas:

$$B_{eval}(Z,N-1) = B(Z,N) - B(Z-1,N) + B(Z-1,N-1) - \Delta_{np}^{approx}(Z+N)$$

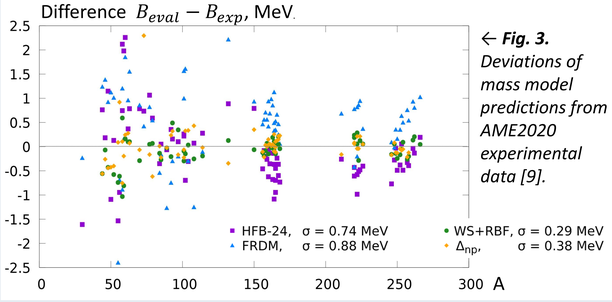


Different coefficients of approximation are used for different mass regions, separately for odd and even isotopes. Nuclei with $N = Z$, $Z \pm 1$ are excluded. Approximation formula: $\Delta_{np}^{approx}(A) = C_1 + C_2\cdot A^\gamma$.

Approximation coefficients C_1, C_2, γ, as well as a detailed description of the method and analysis of the results, are presented in [8].

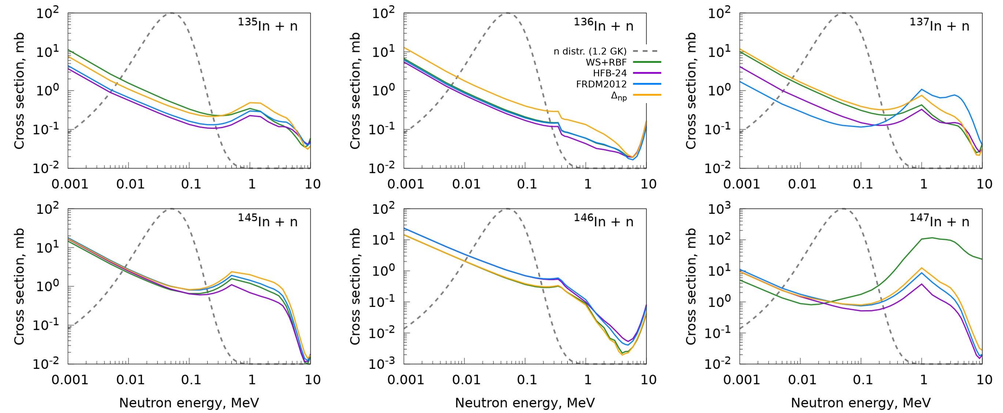


← ***Fig. 2.*** *Δ_{np} experimental points and approximation. Filled markers for values with even A, empty markers for odd A. The coefficient γ for odd A is 0. Experimental data from AME2016 [10].*



← ***Fig. 3.*** *Deviations of mass model predictions from AME2020 experimental data [9].*

4. CROSS SECTIONS and ABUNDANCES



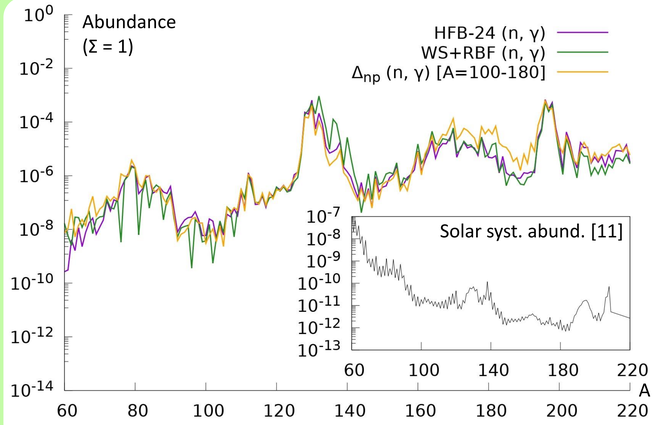
↑ ***Fig. 4.*** *Neutron capture on n-rich indium isotopes cross sections, calculated with TALYS package using four nuclear mass tables.*

Fig. 4 shows cross sections of neutron capture reaction calculated using TALYS with the considered mass models for six neutron-rich indium isotopes involved in r-process. Comparison with the reaction threshold values (see table) shows a complex correlation. For different mass models neutron capture cross sections on 135-147 In can differ up to an order of magnitude, and the agreement between different models is somewhat better for even isotopes, having odd number of neutrons. At the same time, no comparable odd-even dependence of thresholds and binding energies is seen.

Table 1. *Neutron capture thresholds for indium isotopes, MeV.*

	FRDM	HFB-24	WS+RBF	Δ_{np}
In-135	1.5013	1.5253	2.1947	1.5881
In-136	2.9513	3.1523	3.0987	3.1626
In-137	0.6613	1.2783	1.7529	1.5085
In-145	0.9813	1.1553	0.9471	0.8805
In-146	2.2213	2.4783	1.6641	1.8262
In-147	0.9113	1.0163	0.4616	0.8040

Simulated r-process yields are shown in fig. 5. Differences in theoretical values of binding energies lead to disagreement of predicted abundances of up to 3 orders of magnitude, especially in the A = 170 – 190 interval, where the mass predictions of Δ_{np} model also show noticeable difference with other models. The A ≈ 130 peak is relatively broadened in the WS+RBF calculation.



↑ ***Fig. 5.*** *r-nuclei abundances, generated in a 1 sec r-process simulation at the temperature of 1.2 GK.*

References:

[1] Cyburt R.H et al., ApJ. *2010*. 189. 240
[2] Arnould M. et al., Phys. Rep. *2007*. 450. 97
[3] Lippuner J. et al., ApJS. *2017*. 1. 233
[4] Koning A.J. et al., Nucl. D. Sheets. *2019*. 1. 155
[5] Moller P. et al., ADNDT. *1995*. 59. 185
[6] Goriely S. et al., Phys. Rev. Lett. *2017*. 102. 152503
[7] Na-Na Ma et al., 2019. Chinese Phys. C. *2019*. 43. 044105
[8] Vladimirova E.V. et al., Conf. Proc. AYSS-2020 (in print)
[9] Meng Wang et al. Chinese Phys. C. *2021*. 45. 030003
[10] Meng Wang et al., Chin. Phys. C. *2017*. 41. 030003
[11] K. Lodders. ApJ. *2003*. 591. 1220.