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Fission recycling in the r-process and formation of the second peak with A $\sim$ 130

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We discuss the influence of mass predictions and mass distribution of fission products on the formation of heavy elements on the final stages of the r-process in a very high neutron density environment (e.g. neutron star mergers), when the recycling of the r-process due to fission has occurred. Different evolution models as well as observations give the evidence of the existence at least two different astrophysical scenario for the r-process. All the models can be divided by duration of neutron exposition into two groups, in which the r-process nucleosynthesis is responsible for the formation of different nuclei. Scenario, in which the long-time solution is realized can be main for the formation of the most heavy nuclei. In such a scenario the important role belongs to fission, which is responsible in part to the recycling r-process into the region of nuclei with A= 120-140. But the utilization of new mass predictions and consistent reaction rates in the r-process calculations leads to the strong disagreement with observations, especially for nuclei in the vicinity of second peak at the abundance curve. We showed that the agreement between calculations and observations can be achieved due to prompt fission neutrons, considered as a part of the model of mass distribution of fission fragments.

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1. r-process in transuranium region and mass predictions.

The fission recycling is expected to be of significance [1] when the r-process duration becomes long enough to transform the major part of seeds into the transuranium nuclei and to give back the fission fragments into the r-process.

As a result of long duration of the r-process (long-time solution [1]) fission recycling occurs and fission products became new seeds with masses in the vicinity of the second peak on the r-element abundance curve and quasi equilibrium in formation of abundances between second peak and fission region can be reached. In this case the mass distribution of fission products (along with the consistent nuclear data such as the mass excess, fission barriers and reaction rates) is important for the production of nuclei with A$\sim$130.

As a model realizing the long-time solution we used one of the model calculations of neutron star merger [2] with the average initial value of neutron excess, defined by Y_e=0.1. In the r-process processing for this model the number of species due to fission recycling was approximately doubled.

In our r-process calculations, along with the neutron rates [5, 4] we use new set of fission rates [3]. The fission barrier predictions, used in calculations of the fission rates [3], were based on the new improvement of Extended Thomas-Fermi model with Strutinsky integral (ETFSI) [8], or Thomas-Fermi model [6], and mass predictions in accordance with [7, 9]. These data unfortunately made worse the agreement between observations of nuclear abundances and calculations, especially for mass region $120 < A < 140$ and strong shift of the calculated second peak on the abundance curve from position around A$\sim$130 in the region of bigger masses occurs (Fig.1) in compare with previous calculations [11], where the agreement with observations was good enough. The explanation is rather obvious - in comparison to the previously used mass formulae [13, 14], based on Hilf et al. mass predictions [13] and FRDM rates [12] the utilization of discussed consistent mass and fission barrier predictions (ETFSI or Thomas-Fermi) shifts the neutron drip line in the direction of heavier masses. For example, the mass prediction of [13] defines the atomic mass of the heaviest Cf isotope A=279, while the other mass model discussed above (ETFSI) predicts the existence of Cf isotopes heavier than A=300.

Problem is that for very high neutron density environments, when the r-process passes along (or near) the neutron drip-line, even the mass of light fission fragment when new mass predictions [6, 8] is applied can be greater than 130. Previously introduced mass distribution of fission fragments in the model of binary fission [10] was sufficiently good for getting the agreement between calculations and observation of heavy element abundances when FRDM mass predictions were used. In case when new mass predictions is applied, the neutron drip-line (and the r-process path also) turns out to be shifted to the region of more heavier isotopes.

The previous calculations of the r-process used a very simple models of binary fission, when only two fragments were taken into account in model of symmetric [5] or asymmetric [1] fission and prompt fission neutrons were not taken into account. As a result, the r-process in actinoide region goes on nuclei with atomic masses 280-300 instead of 250-260 when HM barrier and mass predictions were used [15].

When the calculations of the r-process with new rates but with old model of mass distribution of fission products have been done, the average masses of the or fission fragments increase, mostly exceed 130 and the position of the second peak on the calculated abundance curve does not reproduce the observed one. One of the possible explanation of the shift - incomplete description of mass distribution of fission fragments. Adopted in our previous works [11, 10, 3] model of fission products mass distribution, included in part the symmetric fission into to equal fission fragments for all nuclei with atomic masses $A > 260$, was not contradict the experimental data, thou did not take into account the prompt fission neutrons. But for up-to-date nucleosynthesis calculations with new nuclear rates, mass excesses and fission barriers predictions the introduction of prompt fission neutrons into the model of fission products mass predictions is urgent and should remove away "the excess of mass" and restore the agreement between calculations and observations.

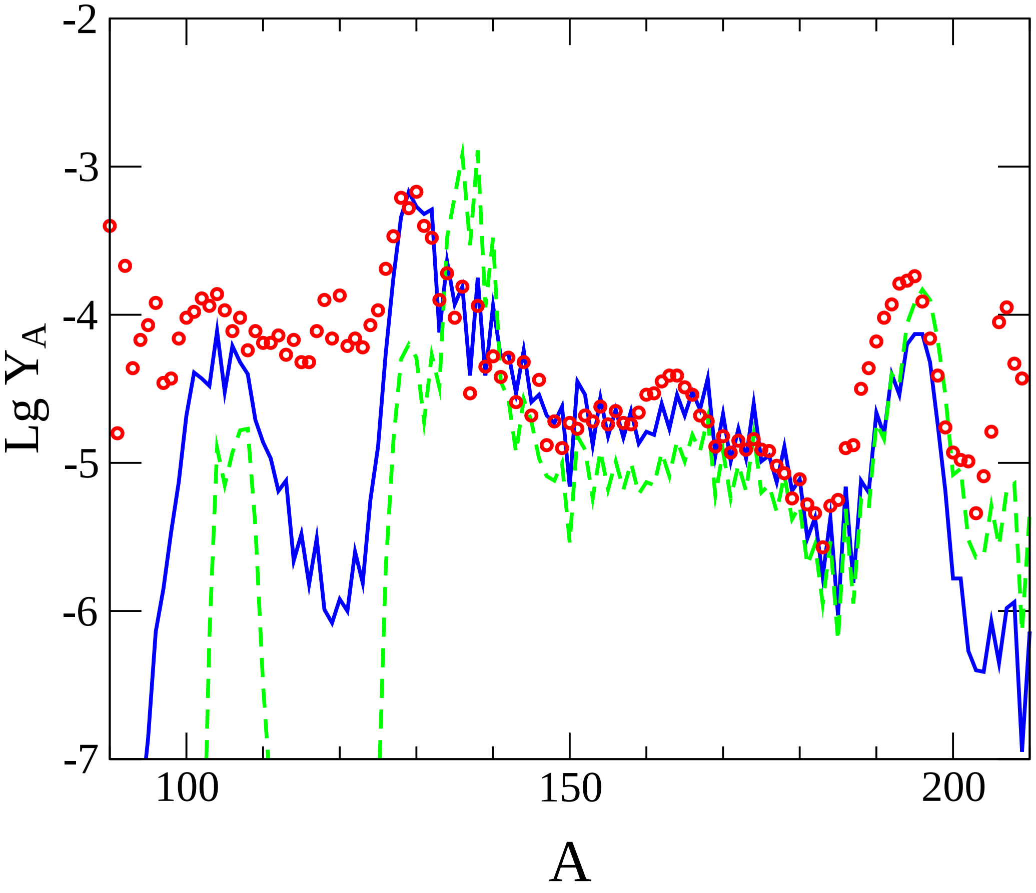

Figure 1: Calculated r-process abundances, used FRDM-data (line) and ETFSI mass-predictions (dashed line); circles - ss-abundance. Simple mass distribution model without prompt neutrons is used.

2. Mass distribution of fission fragments and calculations.

Previously [10] it was shown that combination of symmetric and asymmetric fission applied to the model of binary fission gave better agreement with observations especially with utilization mass distribution of Itkis et al. [18] for asymmetric fission instead of the expansion mass distribution for U235 for all nuclei [1]. Only two fission products were considered neglecting prompt fission neutrons with "averaged" values of fission product masses, defined as $A_1 = 130, Z_1 = 52 - (Z_f -$

$80) * 2/20$ and $A_2 = A_f - A_1, Z_2 = Z_f - Z_1$ in case when atomic number of mother nucleus $A_f < 260$ and symmetric fission otherwise. But for the r-process modelling with rates on the base of new mass predictions this model turns out too reductive.

According to the nuclear systematics [19, 20, 21] the multiplicity of prompt neutrons increases with increasing of both atomic number and mass number. The simple model of binary fission, when only fission fragments were considered we enriched by the emission of prompt neutrons.

In our present calculations we also added prompt fission neutrons into the mass model distribution and increased the number of fission products up to 40 daughter nuclei, with weight functions of isotope yields based on nuclear systematics. Thus we considered $(Z_f, A_f) \rightarrow \sum_{i,j} p_{ij} * [(Z_i, A_i) + (Z_j, A_j) + \nu_{ij} * n]$, where $\sum_{i,j} p_{ij} = 1$ and $Z_f = Z_i + Z_j, A_f = A_i + A_j + \nu_{ij}$ for any i, j. Neutron multiplicity per fission ν_{ij} is the linear function of A_f and $A_f - Z_f$. It is equal neutron multiplicity for experimentally known nuclei $\nu_p \approx 2 - 4$ and is extrapolated into neutron rich region up to values $\nu \approx 20$ near neutron drip-line. The extreme number of free neutrons is in agreement with published results [16] of neutron multiplicities, based on semi-empirical Monte-Carlo calculations [17].

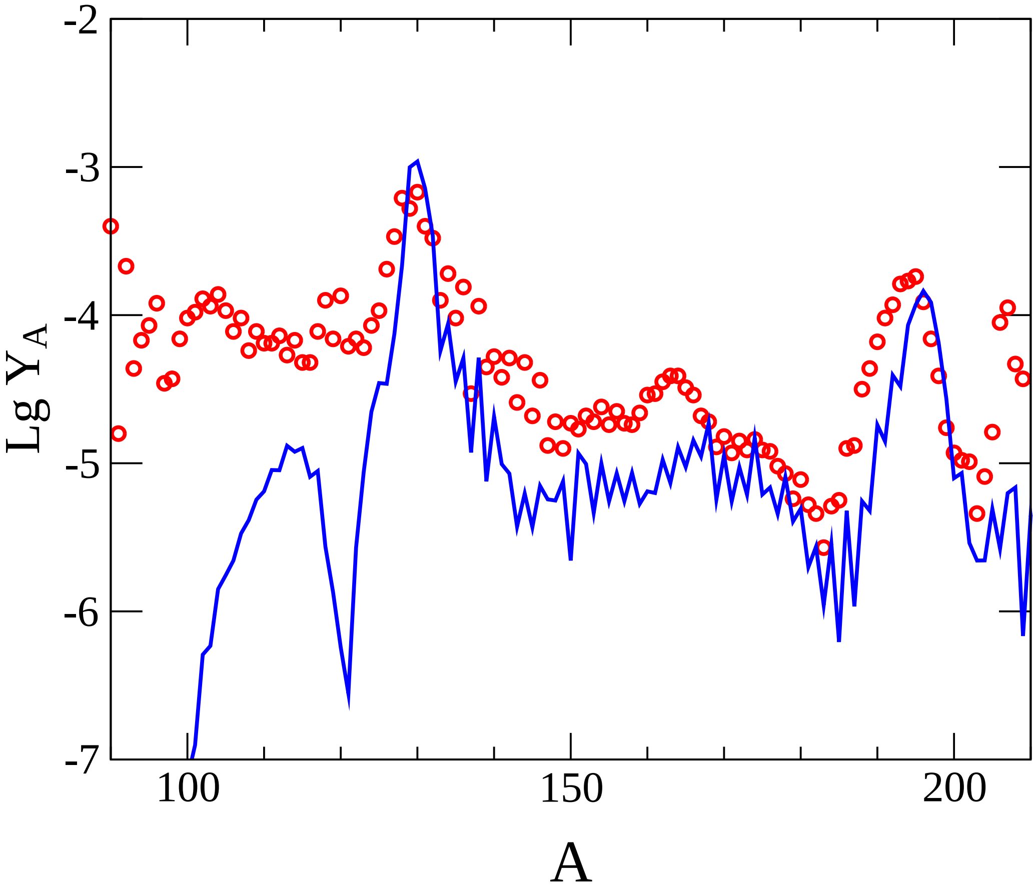

Figure 2: r-process abundances: circles - ss-abundance; line - present calculations with mass distribution model included prompt and delayed neutrons. ETFSI mass and rates predictions are used.

The details of fission of very neutron rich nuclei are not known, because such nuclei can not be investigated experimentally and theory predictions have a very short range. It is difficult to say what kind of emission - prompt or delayed neutrons will be important during fission of such an exotic nuclei. But no doubts the neutrons should be emitted - mass predictions show that fission fragments after the fission of very neutron rich nuclei in number of cases are unbound and only evaporation of neutrons or other light particles can lead to the bound nuclear configurations. For simplicity we consider all neutrons are prompt, because this proposition does not influence significantly upon the r-process yields.

Described above model of mass distribution of fission fragments with taking into account prompt fission neutrons was included in our calculations and received r-element abundances agree well with the observations (Fig.2). Of course the extrapolation accuracy of calculated neutron multiplicity in the region of very neutron rich nuclei may be not very high, but it is the problem of all nuclear data for experimentally unknown nuclei. Only the development of theory and future experiments can clarify the problem.

3. Conclusions

In numerical calculations of the r-process it was shown that utilization of self-consistent nuclear data (mass predictions and reaction rates on the base of ETFSI or Thomas-Fermi models) and simple model of binary fission leads to the disagreement between observations and calculated abundances.

When the fission model was enriched by taking into account the neutron multiplicity, the masses of fission fragments decreased and agreement between observations and calculations was restored. For the majority cases at least one of the fragments became lighter than 130 and recycling of the r-process occurs into the region before the second peak, that restored the agreement with observations for the nuclear yields in the vicinity of $A \sim 130$.

Consideration of detailed mass distribution with taking into account up to 20 different species for every fission product leads to smoothing effect of yields for nuclei around 130 and below. The utilized model of mass distribution is confirmed by detailed calculations of fission product mass distribution for different nuclei, at least for atomic mass numbers $A \geq 260$ [16]. We consider the further understanding of mass distribution of fission fragments will lead to the more accurate fission model. In asymptotic case this model should approach the mass distribution of experimentally known nuclei.

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