PROCEEDINGS OF SCIENCE

Obstacles to understanding the r-process, the nuclear requirements, and the still missing convincing sites

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The origin of half of the heavy elements remains a very challenging problem from both the astrophysics and nuclear physics perspectives. The r-process requires extreme neutron-rich conditions and involves very neutron-rich nuclei which have not yet been produced in the laboratory. We discuss here the state of the art and open issues in both of these extreme aspects. Progress for the two favored astrophysical sites, neutrino-driven winds and neutron-star mergers, is discussed, combined with the impact of the nuclear physics uncertainties on the observed abundances.

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1. Introduction

The r-process has been investigated for more than 50 years facing nuclear physics and astrophysics challenges. Now we are entering a new era with the opening of a new experimental frontier at FAIR, FRIB, and RIBF. At the same time, large-scale astronomical surveys and modern telescopes are providing novel insights, throughout our universe, into the origin of the elements. Along these unique experimental and observational achievements, great theoretical progress on nuclear structure and on modeling extreme astrophysical environments is being attained successfully supported by recent super-computing advances.

What do we know about the r-process? The first place to look for the fingerprint of this process is our solar system. The solar abundances contain a combination of various nucleosynthesis processes that were occurring before our sun formed. Subtracting from the total solar abundances the known contribution of other processes (e.g., s-process, p-process), the residual abundances left are known as the solar r-process component. However, these abundances do not necessary correspond to the end product of the rapid neutron capture process, but they may be a combination of different processes. Indeed observations [1] and galactic chemical evolution models [2] point to at least two processes contributing to the solar r-process. The solar r-process abundances present three peaks at $A \approx 80$, 130, 195 associated with neutron magic numbers $N = 50$, 82, 126, respectively. This indicates that the r-process path is far from the valley of β-stability (Fig. 1). In order to reach these extreme neutron-rich nuclei, very high neutron densities need to be attained. Therefore, the solar system abundances are telling us that half of the heavy elements are formed in an explosive astrophysical environment with high neutron densities.

Very old stars in the galactic halo provide more insights on the r-process. These ancient stars formed very early and in an interstellar medium contaminated by only few previous nucleosynthesis events. The abundances of these ultra-metal poor (UMP) stars show two clear underlying trends: 1) For elements between barium and lead ($56 < Z < 82$) the relative abundances are the same in UMP stars and in the solar system indicating that these elements are always produced in the same way by a robust r-process. 2) The scatter for elements between strontium and silver ($38 < Z < 47$) indicates an additional contribution for the production of those lighter heavy elements. This contribution may be associated with a weak r-process (see Ref. [1] and references therein) and with charged-particle reactions [3]. Moreover, new observations of two UMP stars [4] agree with the solar system r-process over the three peaks. This raises an important question: Are the three r-process peaks produced always simultaneously?

Another piece of information comes from galactic chemical evolution which builds the bridge between the oldest observed stars and our solar system. Observations of the evolution of Eu (typical r-process element) show large scatter for low metallicities in contrast to alpha-elements that are produced in core-collapse supernovae. Therefore, the production of Mg and Fe is not coupled to the r-process production. This may indicate that r-process elements are synthesized in rare events.

Although we are gaining lot of insights into the r-process with the impressed advances in observations, astrophysical models, chemical evolution constraints, and experiments with exotic nuclei, two challenging questions remain: Where does the r-process occur? What are the properties of the exotic nuclei involved in this process?

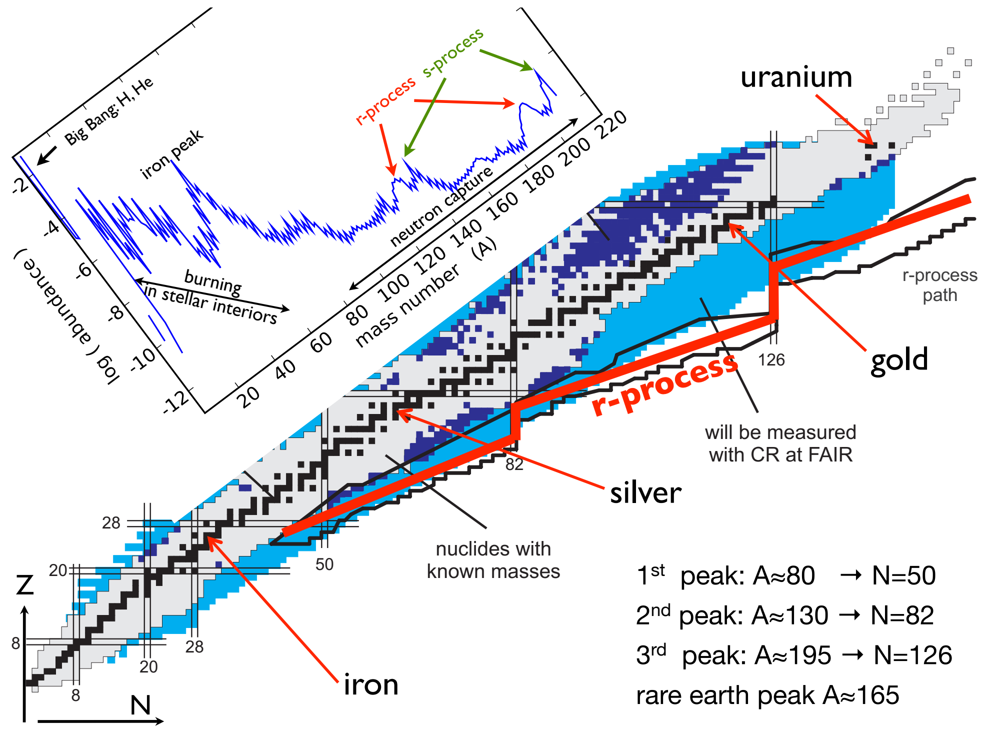

Figure 1: Nuclear chart and solar system abundanceces. In the nuclear chart a schematic r-process path is shown in red. The black squares are stable nuclei. The grey region corresponds to nuclei with known masses and the light-blue region will be meassured at FAIR.

2. Where does the r-process occur?

The high neutron densities required for the r-process point to the most neutron-rich objects in the universe: neutron stars. Two favourite candidates naturally arise: core-collapse supernovae that mark the explosive end of massive stars and the formation of neutron stars, and the merger of two neutron stars. Accretion disks around supermassive neutron stars or black holes are also an exciting but poorly explored possibility (see G. C. McLaughlin contribution: PoS(NIC XII)060).

In the core-collapse supernova different regions and phases of the explosion have been suggested as possible r-process sites. The best studied r-process candidate is the neutrino-driven wind which is discussed later. The explosion of fast rotating stars where the magnetic field is amplified up to 5×10^{15} G lead to magnetorotationally driven supernovae. New 3D MHD simulations ([5], F.-K. Thielemann contribution: PoS(NIC XII)061) show that matter is ejected in neutron-rich jets where the r-process can produce elements up to uranium. These events are rare and probably more frequent at low metallicities when the number of fast rotating stars was higher. Therefore, another event is required to explain the production of heavy elements at higher metallicities.

Two additional possibilities to explain the r-process in core-collapse supernovae are: 1) fast expanding shocked surface layers ([6], M. Eichler contribution: PoS(NIC XII)103) and 2) neutrino-induced r-process in the He shell [7].

2.1 Neutrino-driven winds

After a successful supernova explosion a proto-neutron star forms and cools emitting neutrinos. These neutrinos deposit energy in the outer layers of the neutron star which are ejected in what is known as a *neutrino-driven wind*. In this wind $10^{-5} - 10^{-4} M_{\odot}$ are accelerated even up to supersonic velocities and get relative high entropy.

Close to the neutron star, the temperature is very high and matter is dissociated in neutron and protons. As this matter expands, temperature and density drop and alpha particles form. At high temperatures ($T \approx 8$ GK) the composition is given by the nuclear statistical equilibrium (NSE). After NSE freeze-out a sequence of charged-particle reactions (mainly alpha captures) synthesize seed nuclei. The subsequent evolution depends on the neutron richness or the wind. If there are many neutrons available for every seed nucleus, the r-process can produce heavy elements. In neutron-rich conditions with few neutrons, a weak r-process may form elements up to $N = 50$ ($A \approx 90$). Recent studies (see e.g., [8]) have shown that the wind can be even proton-rich and then the νp-process becomes important ([9], C. Fröhlich contribution: PoS(NIC XII)066).

In order to have a successful r-process in neutrino-driven winds, i.e. a high neutron-to-seed ratio, three conditions are required: 1) fast expansion that inhibits the α-process and thus the formation of seed nuclei, 2) high entropy which is equivalent to high photon-to-baryon ratio: the photons destroy the seed nuclei, 3) neutron rich conditions or low electron fraction, $Y_e < 0.5$. The necessary conditions are well understood and studied (e.g., [10, 11]), however they are not realized in recent simulations (e.g., [12, 13, 8]). Typical values in the simulations are: $S_{\rm wind} = 50 - 120 \mathrm{k_B}/\mathrm{nuc}$, expansion time scales of few milliseconds, and $Y_e = 0.4 - 0.6$ (for an update on Y_e see G. Martínez-Pinedo contribution: PoS(NIC XII)054). Additional ingredients may change these numbers. For a recent review of neutrino-driven winds see Ref. [14].

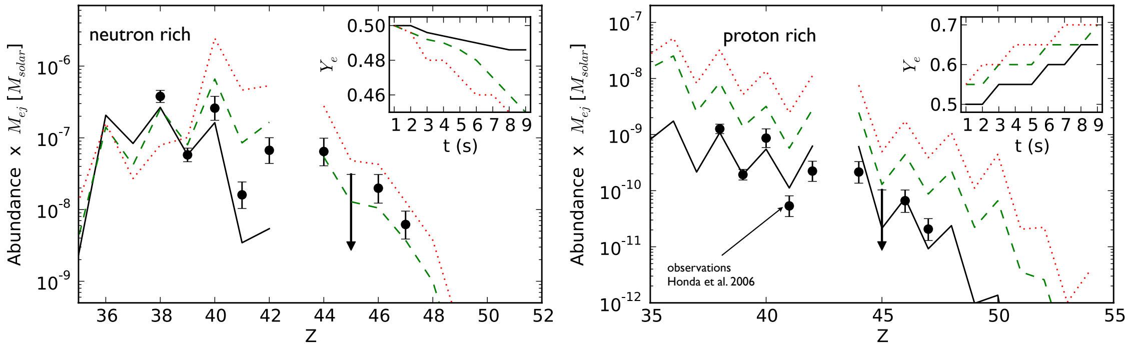

Figure 2: Elemental abundances for a superposition of mass zones with different electron fractions which are shown in the inset as a function of time after core collapse. The observed abundances are shown by dots and rescaled to fit the solid line abundances. The left panel corresponds to a weak r-process and the right one to the νp-process.

Summarizing, the current status is that hydrodynamical simulations do not reach the high entropy needed for an r-process and additional investigations are required to determine the neutron richness of the wind. However, the production of lighter heavy elements (from Sr to Ag) has been identified with charged-particle reactions, weak r-process, νp-process, or lighter element primary process. All these processes can occur in neutrino-driven winds and lead to elements up to Silver in every supernova [15] as suggested by Qian and Wasserburg [3]. Figure 2 shows the abundances for the weak r-process (left panel) and νp-process (right panel) compared to observations and based on neutrino-driven wind simulations [15].

2.2 Neutron star mergers

The merger of two neutron stars or a neutron star and a black hole provide the neutron-rich conditions for a successful r-process [16]. The question that emerges with this r-process candidate is: do neutron-star mergers occur early enough to explain UMP star abundances? This was pointed out by Argast et al. [17], but more investigations are required to draw further conclusions.

Neutron star mergers present also an exciting possibility to directly observe the r-process. As suggested in e.g., Ref. [18] the decay of the radioactive r-process nuclei will lead to a kilo-nova (see D. Kasen contribution: PoS(NIC XII)063). This electromagnetic counterpart can be used together with future gravitational wave detection to better understand these extreme astrophysical events (see C. Ott contribution: PoS(NIC XII)055).

We have performed an extended nucleosynthesis study of the r-process based on neutron star merger simulations [19][1]. We systematically explore the nucleosynthesis in the dynamic ejecta of compact binary mergers with 21 simulations of the merger of two neutron stars with masses in the range from 1.0 to 2.0 $M_\odot$ and 2 simulations of the merger of a neutron star and a black hole. In all cases the r-process is extremely robust with practically identical abundance patterns, see left panel in Fig. 3 This is mainly the result of the ejecta being extremely neutron rich ($Y_e < 0.04$) and undergoing fission cycling. The composition at the beginning of the r-process consists of very neutron-rich seed nuclei and $\approx 90\%$ of the mass of neutrons. The distribution of the seed nuclei reaches the drip line and it is very similar for all trajectories and simulations. The r-process starts and matter moves towards heavier nuclei until it reaches the fission region. The right panel in Fig. 3 shows the evolution of the average proton number, which can be used as nuclear fission indicator. At the maximum of $\langle Z \rangle$ matter has reached the region where fission becomes important. The daughter nuclei resulting from fission capture neutrons move first towards the drip line via neutron captures and then to higher Z where fission acts again. In that way several fission cycles occur and lead to oscillations in $\langle Z \rangle$ and to a robust abundance pattern.

The abundances obtained in our extended study are very robust against variations of the astrophysical conditions. However, they do not agree with the solar system abundances. These discrepancies may be cured or reduced by a better nuclear physics input in our reaction network. The uncertainties on extreme neutron-rich nuclei are a big challenge for the r-process and the origin of heavy elements and need to be studied in parallel to the search for the astrophysical site.

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[1] T. Rauscher question: *What is the difference between the previous Freiburghaus & Rosswog 1999 results for r-process in neutron star mergers and these new results? (The old seems to fit the solar abundances better overall.)* The present simulations of S. Rosswog present significant microphysics and numerical improvements. For example, current simulations provide a good estimate of the electron fraction since they include neutrino emission. In the old simulations this was taken as a parameter and varied to fit the solar system abundances. The differences between our new results and solar systems abundances may be due to nuclear physics input of the nucleosynthesis calculations.

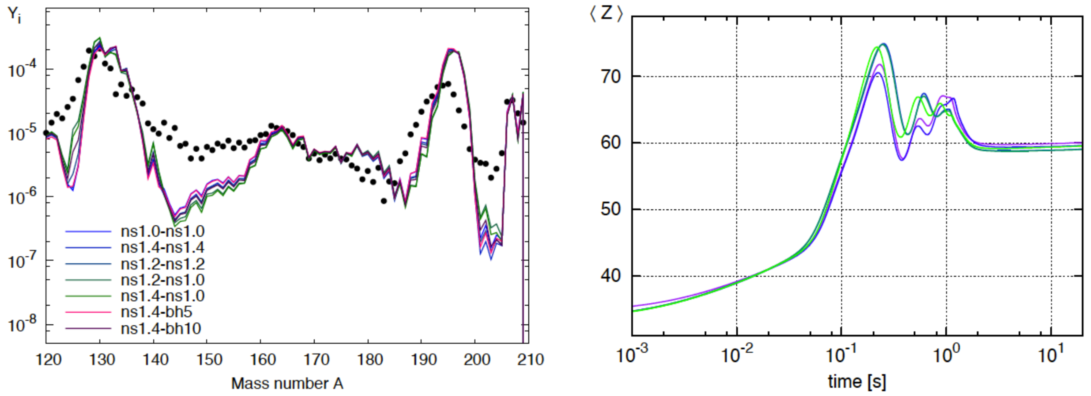

Figure 3: Nucleosynthesis resulting from neutron star mergers. The left panel shows the robust abundance pattern for a variety of merger simulations with different masses of the neutron star (“ns”) and the black hole (“bh”). In the caption, the numbers after “ns” and “bh” correspond to the masses of the compact object in $M_\odot$. The right panel shows the evolution of the average proton number for five trajectories of the simulation with ns1.4-ns1.4 (i.e., merger of two neutron stars both with mas $1.4 M_\odot$). In all cases $\langle Z \rangle$ drops due to fission and one can observe at least three fission cycles.

3. R-process and extreme neutron-rich nuclei

The r-process path involves nuclei far from stability for which no experimental data are available and theoretical extrapolations are still very uncertain. Nuclear masses, half lives, and reactions of exotic nuclei affect the calculated abundances that we want to compare to observations.

In recent years there was great progress in the field of nuclear masses from the experimental (see K. Blaum contribution: PoS(NIC XII)141) and theoretical perspectives (e.g., [20]). Nuclear masses are a key input for r-process calculations as they determine the energy thresholds for all relevant reactions: neutron capture, photo-dissociation, and beta decay. Recently, we have shown that an improvement of theoretical nuclear masses is achived by detailed microscopic treatment of correlations [21]. One can use the neutron separation energy to understand how the abundances depend on nuclear masses. Figure 4 shows half of the two neutron separation energy ($S_{2n}/2$) for nuclear masses of Delaroche et al. [22] with and without correlations. There are characteristic behaviours of S_{2n} which results in features of the abundances. First, the abrupt drop of S_{2n} around $A \approx 130$ and $A \approx 195$ corresponds to the magic numbers $N = 82$ and $N = 126$, respectively. For these nuclei with closed shells, neutron-capture cross sections are very small and the photodissociation rate is high for typical r-process temperatures. Therefore, the r-process path stops at these nuclei and waits for β-decay. It is here that matter accumulates and the abundance peaks form, as they are observed in the solar system (see Fig. 5). The second characteristic feature is the smoothness of the S_{2n} just before the magic numbers. Without correlations, the evolution of S_{2n} with A shows a pronounced dip just before the $N = 126$ magic number, associated with the transition from deformed to spherical nuclei. Nuclear correlation affects both features resulting in smaller peaks and less pronounced troughs in the final abundances as shown in Fig. 5. Although the masses of Delaroche et al. are not yet perfectly in agreement with experimental values, our study indicates the importance of including more microphysics in nuclear-masses calculations.

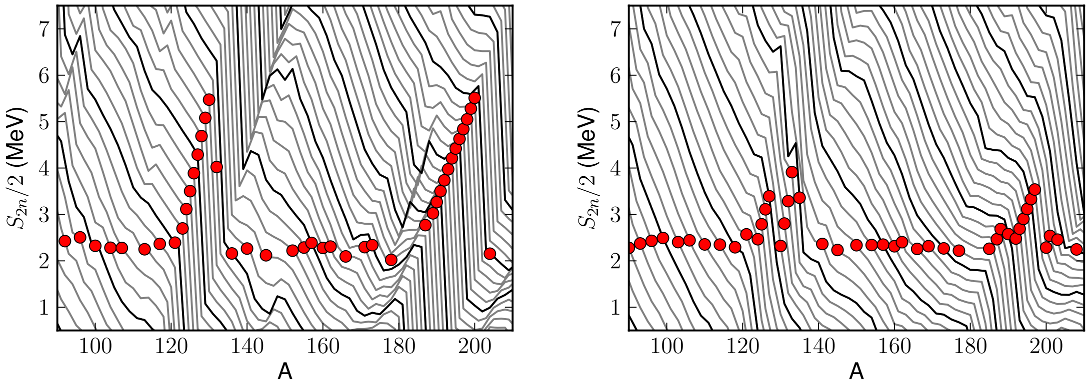

Figure 4: Half the two-neutron separation energy $S_{2n}/2$ for constant proton number as a function of mass number A. The lines represent isotopic chains from $Z = 30$ to $Z = 80$. The red dots mark the r-process path for a high entropy wind trajectory at r-process freeze-out (red line in Fig. 1). The left panel corresponds to the nuclear masses of Delaroche et al. without nuclear correlations. In the right panel nuclear correlations are included.

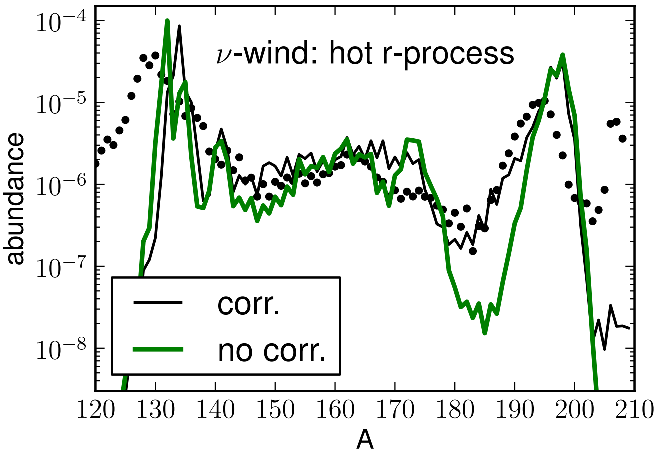

Figure 5: Abundances with and without nuclear correlations for a high entropy wind trajectory. The black dots are solar system r-process abundances.

Nuclear masses have a big impact on the strength and position of r-process peaks. The later is strongly affected by late neutron captures during the decay to stability [20, 23] (see M. Mumpower contribution: PoS(NIC XII)129). This is always the case for the 3rd r-process peak ($A \approx 195$), however when fission is significant (e.g., neutron star mergers) the second peak is determined by the fission yield distribution. Figure 6 shows the nuclear chart with the stable nuclei marked in black and the distribution of abundances indicated with colors. This snapshot corresponds to a time of 1 s after starting the r-process and to the temperature and density given on the top of the figure. The inset in the top left corner shows temperature (in GK) vs. density (in $\mathrm{g\,cm^{-3}}$) evolution with the red point corresponding to the moment for which the abundances are displayed. The abundances vs. mass number are also shown at this same moment in the right bottom corner inset. The arrow indicates schematically the fission that brings matter from heavy nuclei to the region around $N = 90$ and $Z = 45$. This leads to an increase of abundances in this region and towards the drip line since the daughter nuclei keep capturing neutrons[2]. The exact yield distribution has a huge impact on the final abundances in the region of the second peak, as shown in Fig. **??**. Here the final abundances are calculated based on different fission yield distributions[3] and the effect is clearly visible around $A = 140$. We can conclude that fission is key in very neutron-rich environments like neutron star mergers, therefore one needs better determinations of fission barriers and yield distributions.

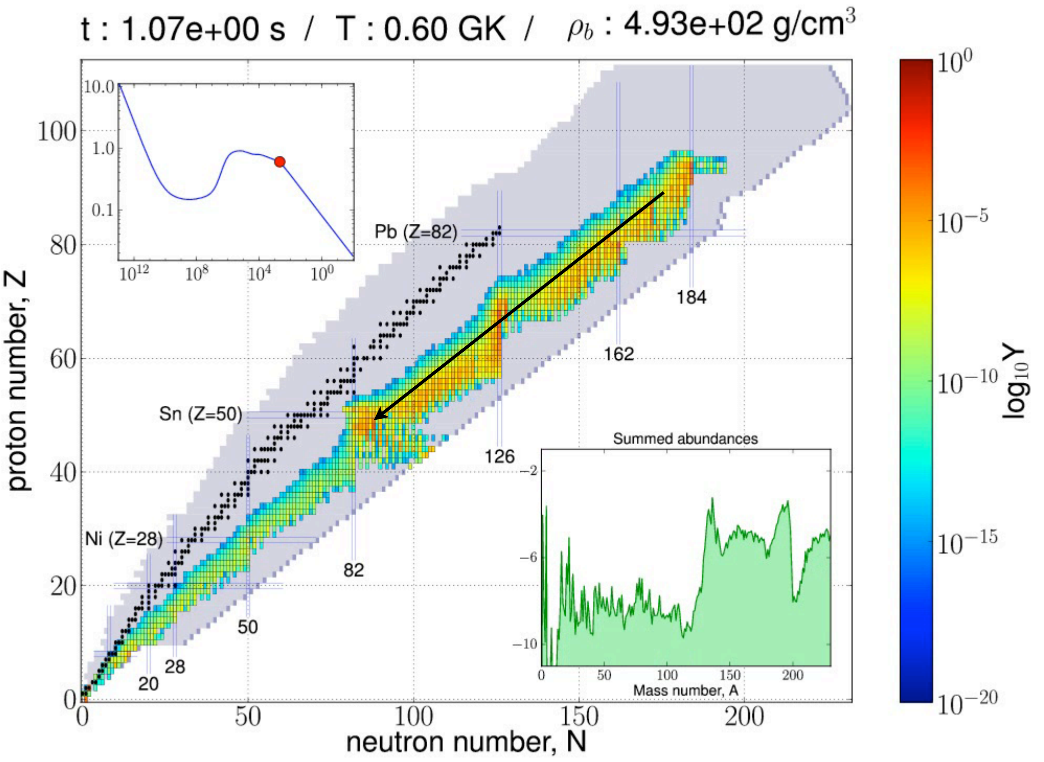

Figure 6: The effect of fission is shown by the abundance distribution during the r-process.

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[2] I. Dillmann question: *Double peak in NSM movie: is it due to fission barriers or beta-delayed neutron emission?* The structure seen in the movie is also visible in the snapshot of Fig. 6. These are due to the distribution of fission yields and to the further neutron captures on them.

[3] T. Kajino question: *Do you include fission process where fissile distribution is double peaked? Whose model is most reliable?* We have used the models indicated in the figure (see [19] for more details). Both models assumed a double peak distribution.

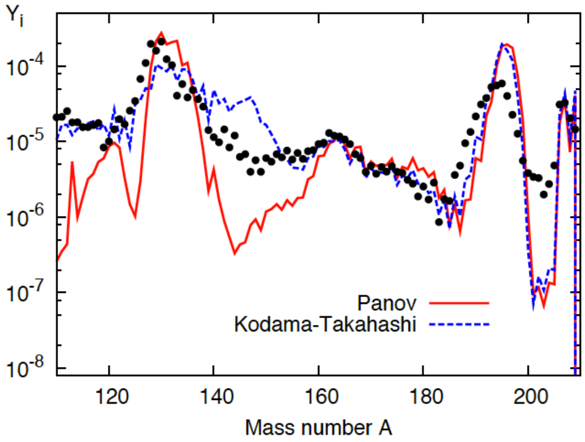

Figure 7: Final abundances based on two different fission yield distributions.

4. Conclusions

The origin of heavy r-process elements remains a challenging and exciting problem from the astrophysics and nuclear physics perspectives. The neutrino-driven wind was thought to be the appropriate site, but current simulations show that it is not possible to reach the extreme conditions that the r-process requires. However, neutrino-driven winds are an exciting possibility to explain the origin of elements between Sr and Ag. In neutron-rich winds, these elements are synthesized by the α-process followed by a weak r-process. While in proton-rich condition the νp-process can also produce elements up to silver.

In order to explain the origin of heavy r-process elements, exciting possibilities are being investigated: neutron star mergers, jet-like supernova explosions, He shell when radiated by neutrinos of the explosion, and accretion disks. We have shown that neutron star mergers lead to a robust r-process due to the extreme neutron-rich conditions and fission cycling.

The search for the astrophysical site of the r-process has to be carried out in parallel to the study of the extreme neutron-rich nuclei involved. Most of the nuclei participating in the r-process have not yet been produced in the laboratory. Therefore, the nucleosynthesis studies depend on theoretical models. Further improvements of these models guided by new experiments are key to understand the r-process. We have shown that nuclear correlations can improve the calculated nuclear masses and have a big impact on the abundances.

How many r-processes exist in the universe? Where do they occur and how often? What are the key nuclei and reactions involved? Although there are not yet clear answers to these questions, the latest advances in theory, experiments, observations and chemical evolution are showing us new facets of the origin of heavy elements. We are getting closer to answer the big and interdisciplinary question: What is the origin of heavy elements like gold and uranium?

Acknowledgments

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