Challenge on the Astrophysical R-process Calculation with Nuclear Mass Models *

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Abstract

Our understanding of the rapid neutron capture nucleosynthesis process in universe depends on the reliability of nuclear mass predictions. Initiated by the newly developed mass table in the relativistic mean field theory (RMF), in this paper the influence of mass models on the \( r \)-process calculations is investigated assuming the same astrophysical conditions. The different model predictions on the so far unreachable nuclei lead to significant deviations in the calculated \( r \)-process abundances.

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The rapid neutron capture (r-) process is introduced more than 50 years ago to explain the solar abundances not creating from the slow-neutron capture (s-) process and the proton-capture (p-) process [1]. It is responsible for the synthesis of about half of the nuclei beyond the iron group. The recent observations of extremely metal-poor ([Fe/H] ≈ -3) r-process enriched ([Ba/Eu] < 0) stars, show a consistent elemental abundances from Ba to the third r-process peak with the scaled solar system r-process abundance distribution. This consistency may indicate that the r-process abundance patterns are most possibly produced only by a single or at most a few r-process events for the heavier elements with Z ≥ 56, i.e., there may be only one or a few r-process sites in the early Galaxy.

However, the exact astrophysical site where the r-process proceeds has not been unambiguously identified, despite decades of work. This research is complicated by the required knowledge of both the astrophysical environments and the nuclear properties of very neutron-rich nuclei. Previous phenomenological studies indicate that the r-process occurs at temperatures around T ∼ 10^9 K and at extreme neutron fluxes with neutron number densities n_n > 10^{20} cm^{-3} [3, 4, 5]. Moreover, the r-process should be a dynamical process with changing conditions and paths [4].

On the other hand, the determined astrophysical condition for the r-process site relies on the extrapolation of theoretical nuclear models for the “terra incognita”. Among the required nuclear properties, the key one is the nuclear mass, from which one can directly determine the one-neutron separation energy, shell gap and also the beta-decay energy. As discussed in Ref. [5], though various nuclear mass models agree quite well with the known data, they disagree among each other towards the very neutron-rich side, where the r-process runs along. As a result, the required astrophysical condition for the r-process nucleosynthesis can vary for different model predictions [5].

In order to investigate the impact of nuclear mass models on the r-process nucleosynthesis, one should distinguish the astrophysical uncertainty from the nuclear physics uncertainty. In this letter, adopting the newly constructed mass table [6] in the relativistic mean field (RMF) theory, and assuming the same astrophysical conditions, the impact of different mass models on the r-process calculation will be investigated. Other mass models used include the finite-range droplet model (FRDM) [7], extended Thomas-Fermi plus Strutinsky integral with quenched shell (ETFSI-Q) [8] and the recent Hartree-Fock-Bogolyubov (HFB-13) model [9].

The RMF approach has made lots of successes in describing the nuclear properties far away from the β-stability line as reviewed, for example in Ref. [10]. The first systematic calculation of the nuclear ground state properties including nuclear masses, radii and deformations has been done recently for all the nuclei lying between the proton drip line and the neutron drip line [6]. A good agreement with the available data is found. The detailed analysis shows that the predictions of nuclear masses in the RMF are generally underesti-
mated with respect to the experimental data. However, considering the factor that with less than 10 parameters obtained from fitting several doubly magic nuclei, the RMF Lagrangian achieves almost the same prediction power ($\sim 0.65$ MeV) for one neutron separation energy $S_n$ \cite{11} as those highly parameterized mass models \cite{7, 8, 9}, thus it is very interesting to see to what extent the solar $r$-abundances can be reproduced using this new table.

We adopt a site-independent $r$-process calculation as in Ref. \cite{5}, where a configuration of 16 $r$-process components is chosen as a reasonable approximation to the real $r$-process site. The seed-nuclei iron are irradiated by neutron sources of high and continuous neutron densities $n_n$ ranging from $10^{20}$ to $10^{28}$ cm$^{-3}$ over a timescale $\tau$ at a high temperature ($T \sim 10^9$ K). The neutron captures proceed in $(n, \gamma)\leftrightarrow(\gamma, n)$ equilibrium, and the abundance flow from one isotopic chain to the next is governed by $\beta$-decays. Roughly, the $r$-process runs along the contour lines between 2 and 5 MeV of one neutron separation energies as illustrated in Fig. 1. Similar to the classical $s$-process \cite{12}, these different $r$-process components are assumed to satisfy a simply exponential formula, i.e., $\omega(n_n) = n_n^a, \tau(n_n) = b \times n_n^c$, where $\omega(n_n)$ and $\tau(n_n)$ are the corresponding weighting factor and neutron irradiation time for the component with a neutron density $n_n$. The parameters $a, b$ and $c$ are determined from the least-square fit to the solar $r$-process abundances.

The best simulation using the new RMF mass table is presented in Fig. 1. In this simulation, the $\beta$-decay properties are taken from the recent calculation \cite{13}. Furthermore, the available experimental results \cite{11, 14} have been included. The corresponding $r$-process path is indicated by the dark grey squares. The $r$-process abundance distribution, in general, can be well reproduced. However, the predicted large shell towards the neutron drip line in the RMF model leads to a large gap before the second and third abundance peaks. Previous investigations \cite{4, 15} showed that a quenched shell could avoid the jump in the $r$-process path and thus result in a better simulation to the observation. Nevertheless, it is still unclear whether there is a shell quenching effect or to what extent it is towards the neutron drip line, since the present experimental results are still in debate. One example is the shell gap at the critical waiting point $^{130}$Cd. It is firstly suggested to be a quenched shell in Ref. \cite{16}. However, a recent experiment result \cite{17}, interpreted by the state-of-the-art nuclear shell-model calculations, shows no evidence of shell quenching.

In order to disentangle the nuclear physics uncertainty from the astrophysical environment uncertainty, we have done the $r$-process calculations using respectively FRDM \cite{7}, ETFSI-Q \cite{8} and HFB-13 \cite{9} mass inputs while keeping the same $\beta$-decay properties. All the calculations have used the same astrophysical condition, i.e., the best case obtained using the RMF masses. Along with the observation \cite{12}, the abundance distributions around the third peak are compared with the RMF result in Fig. 2. It shows that the abundances around the neutron shells $N = 126$ strongly depends on the mass models applied. Before the
abundance peak, the RMF simulation shows a broad dip around $A = 170$, while the ETFSI-Q and HFB-13 simulations have a dip towards a large mass number ($\sim 180$). Differences also exist after the abundance peak.

The different deficiencies in reproducing the solar r-process abundances can be mainly traced back to two aspects. First, different nuclear mass models predict quite different shell evolution towards the neutron drip line. The shell gap energy at $N = 126$ in the RMF model is about 2 MeV larger than that in other models. A stronger shell structure will result in more nuclear matter accumulated in nuclides with a neutron magic number and less in nuclides around, which is reflected by dips on both sides of the abundance peak in the calculated r-process abundance. Second, different models assign different locations of the shape transition before the shell closures. The predicted r-process paths pass through the shape-transition ranges before going to the magic numbers $N = 82$ and 126. The first oblate nuclides for $Z = 60-63$ are in the mass number of 172-177 for the RMF predictions, while in the HFB-13 model the corresponding mass numbers are 178-179. One neutron separation energies for these nuclides at the shape-transition point will deviate from the approximately linear dependence of the mass number as predicted by a classical liquid droplet mass model, and eventually affect the r-process path. Together, both aspects result in a direct jump in the r-process path from $^{169}$Pr to $^{185}$Pr (15 mass units) in the RMF simulation (see Fig. 3). Different from the RMF simulation, abundances calculated in the HFB-13 simulation are also accumulated in the nuclides with the mass number 170-177, therefore a better reproduction of the solar r-process abundances at $A \sim 170$, however a worse reproduction at $A \sim 180$. The gap around the $N = 126$ shell also exist in other simulations though varying in magnitude and mass number. In the same astrophysical environment, the r-process path in the RMF simulation runs about 1-2 mass units towards the neutron drip line than those of other simulations.

In the present investigation, it is shown that the nature of the r-process is complicated due to the interplay between the nuclear physics and the astrophysical environment. Since it is still not accessible to measure most of the nuclei masses along the r-process path in the near future, further theoretical development aiming at the description of the know and unknown masses simultaneously is badly needed. If the astrophysical conditions for the r-process are identified precisely, this may serve as a constraint for the nuclear mass models. Equivalently, if nuclear masses are known in a good precision, it can be used to constraint the potential site for the r-process as well.

In the present letter, we have shown that the r-process calculation is quit sensitive to the nuclear mass inputs. Precise mass measurement of neutron-rich nuclides with an accuracy less than 100 keV are needed to decisively determine the shell evolution at $N = 82$ and 126 towards the neutron drip line, as well as the locations of the shape transition before
these shell closures. These experimental results will offer a primary constraint to the existing mass models and a strong motivation for further exploration of theoretical mass models, and furthermore, a better understanding the nature of the r-process nucleosynthesis. Meanwhile, as there is no clear evidence to accept or reject any mass model mentioned above, it is necessary to take different mass models into account in the r-process study.

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FIG. 1: Features of the r-process calculated using the new RMF mass table. Black squares denote β-stable nuclei, and magic proton and neutron numbers are indicated by pairs of parallel lines. The region in the main graph shows the calculated average one neutron separation energy ($S_{2n}/2$). The solid line denotes the border of nuclides with known masses in the neutron-rich side. The dark grey squares show the r-process path when using the RMF mass predictions and the FRDM half-lives. The observed and calculated solar r-process abundance curves are plotted versus the mass number $A$ in the inset, whose x-axis is curved slightly to follow the r-process path.
FIG. 2: Comparison of observed solar $r$-process abundances (filled circles) with theoretical abundance after $\beta$-decays calculated using RMF, FRDM, ETFSI-Q and HFB-13 mass models. The calculated abundances have been scaled to the solar $r$-process abundance at $A = 130$.

FIG. 3: The corresponding $r$-process pathes of Fig. 2 for the RMF and HFB-13 mass models. Shown are those isotopes with more than 10% population of each isotopic chain. For comparison the stable nuclei are labeled by black squares.