Systematic and Statistical Uncertainties in Simulated *r*-Process Abundances due to Uncertain Nuclear Masses

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Unknown nuclear masses are a major source of nuclear physics uncertainty for *r*-process nucleosynthesis calculations. Here we examine the systematic and statistical uncertainties that arise in *r*-process abundance predictions due to uncertainties in the masses of nuclear species on the neutron-rich side of stability. There is a long history of examining systematic uncertainties by the application of a variety of different mass models to *r*-process calculations. Here we expand upon such efforts by examining six DFT mass models, where we capture the full impact of each mass model by updating the other nuclear properties—including neutron capture rates, β-decay lifetimes, and β-delayed neutron emission probabilities—that depend on the masses. Unlike systematic effects, statistical uncertainties in the *r*-process pattern have just begun to be explored. Here we apply a global Monte Carlo approach, starting from the latest FRDM masses and considering random mass variations within the FRDM rms error. We find in each approach that uncertain nuclear masses produce dramatic uncertainties in calculated *r*-process yields, which can be reduced in upcoming experimental campaigns.

KEYWORDS: Binding energies and masses, *r*-process

1. Introduction

It has long been understood that nuclear masses are of key importance for *r*-process nucleosynthesis [1]. For an *r* process that proceeds in equilibrium between neutron captures and photodissociations, masses determine the relative abundances along each isotopic chain. Masses are also crucial inputs in the calculations of all other nuclear physics properties important for the *r* process, including β-decay properties and neutron capture rates; see recent reviews [2,3] and references therein.

In principle, if nuclear properties were well known across the nuclear chart, comparisons between the results of astrophysical simulations and observed abundance patterns would be able to constrain the yet-unknown *r*-process astrophysical site. However, there are two main limitations to this approach. On the astrophysics side, there are still large uncertainties in the hydrodynamics and neutrino physics of candidate events. On the nuclear physics side, very little experimental information is available for the thousands of nuclei that participate in the *r* process. Different theoretical models applied to determine the remaining data can disagree by large factors [3]. Here we examine an aspect of the latter limitation and attempt to quantify uncertainties in *r*-process abundance patterns that result from uncertainties in the masses of nuclei out to the neutron drip line.

2. DFT Masses

The typical approach to estimating the uncertainties in the *r*-process pattern due to nuclear mass uncertainties is to compare a series of *r*-process simulations run with distinct sets of nuclear data.

Here we consider a set of mass tables generated within the same theoretical framework—density functional theory—with six different Skyrme forces applied to *r*-process calculations. The resulting ranges in abundance patterns give a sense of the impact of systematic uncertainties in nuclear masses on the *r* process.
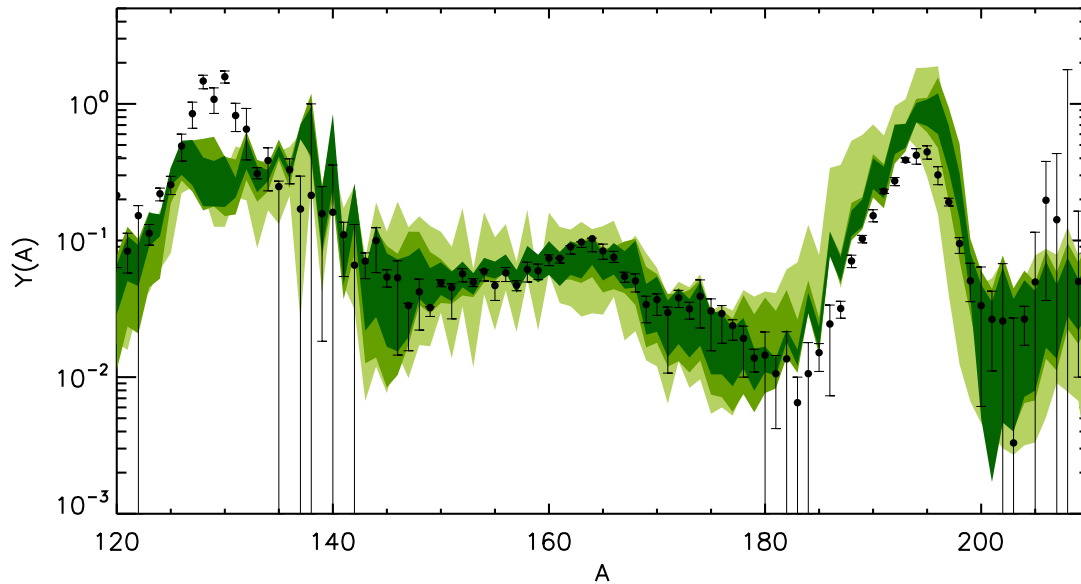

Fig. 1.   Resulting abundance pattern ranges obtained from six DFT mass formulae for an example neutron star merger trajectory. The darkest shaded region shows the resulting ranges when only neutron separation energies are changed, the middle shaded region shows the results when additionally all neutron capture rates are recalculated consistently with each mass formula, and the lightest shaded region shows the results when the β-decay properties are updated as well. Points are solar residuals from [2].

In Fig. 1, we show the ranges of abundance patterns obtained from the application of six DFT mass tables from [4] to an *r*-process calculation with a neutron star merger trajectory from [5]. Capturing the full influence of the different mass tables requires updating all other sets of theoretical nuclear data self consistently, including neutron capture rates and β-decay properties. The darkest shaded region shows the range in patterns that results when only the neutron separation energies are updated to be consistent with the chosen mass table. This would be expected to capture the majority of the influence of nuclear masses on a hot *r* process that proceeds in (n, γ)-(γ, n) equilibrium; for the very neutron-rich merger trajectory considered here, neutron capture continues well past the point where the temperatures drop low enough for photodissociation to become negligible, and so we expect much of the influence of the masses will be through the capture rates and β-decay properties. The middle shaded region shows the additional influence of the neutron capture rate updates, similar to [6]. Here we calculate the neutron capture rates self-consistently with each mass table with version 3.3.3 of the Los Alamos Hauser-Feshbach code CoH [7]. The lightest shaded region includes updates to the β-decay properties as well. The influence of the masses on the β-decay lifetimes is largely through the phase space, which goes roughly as Q_β^5. We take the nuclear matrix elements from [8] and recalculate the phase space factors with the appropriate DFT Q_β values. The probabilities for β-delayed neutron emission are calculated with CoH as in [9]. Thus, the lightest shaded band provides a full estimate of the uncertainty in the *r*-process pattern for a merger-type trajectory due to systematic

uncertainties in nuclear masses within a given theoretical framework.

3. Uncorrelated Mass Monte Carlo

Another approach to estimating the uncertainties in the *r*-process pattern due to uncertain masses considers the influence of random, uncorrelated errors. These can be explored via Monte Carlo variations in nuclear masses. Preliminary versions of such studies [13] have focused on hot *r*-process scenarios, where the primary influence of the masses is through the neutron separation energies as they appear in the photodissociation rate calculations. Here we report on a preliminary mass Monte Carlo study of a cold merger tidal tail trajectory.
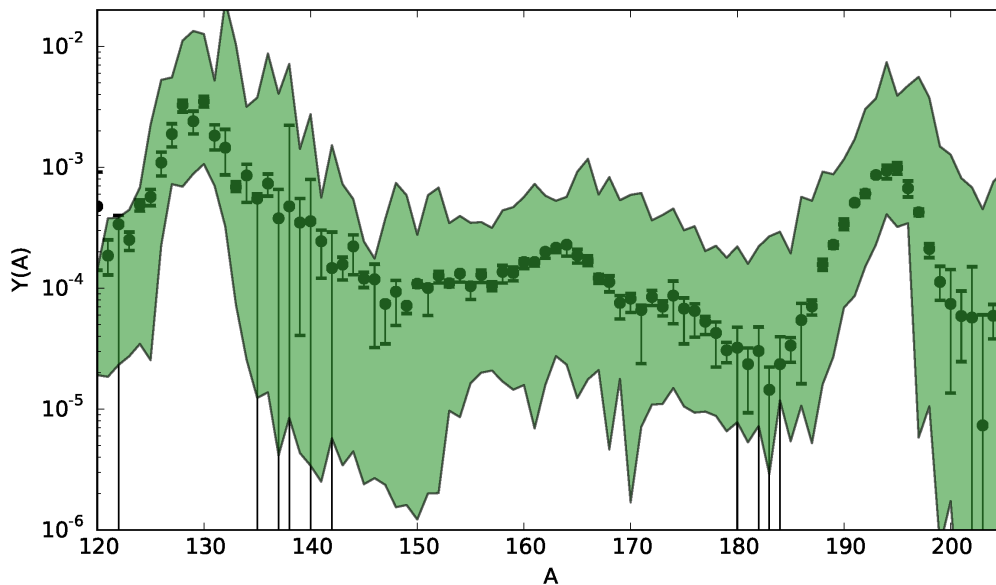

Fig. 2. Resulting abundance pattern variations from 1000 Monte Carlo steps for a neutron star merger trajectory. For each step, all theoretical masses are varied by random factors pulled from a Gaussian distribution with width 0.5 MeV, and all neutron capture rates and β-decay properties are updated to be consistent with the varied masses.

The study begins with a baseline *r*-process simulation. Here we use a neutron star merger trajectory from [5] as in Sec. 2. The baseline simulation is run with nuclear data calculated to be consistent with the 2012 version of the Finite-Range Droplet Model (FRDM). For each Monte Carlo step, uncorrelated individual mass variations are drawn from a Gaussian distribution with width 0.5 MeV, a value approximately equal to the rms deviation between FRDM masses and available experimental values. Neutron capture rates and β-decay properties are updated for each set of varied masses, as described in Sec. 2. Preliminary results from this study appear in Fig. 2, which shows abundance pattern variations resulting from 1000 such steps.

The resulting uncertainty bands in the final abundance patterns are similar in width to those reported for a hot *r* process, e.g. Fig. 10 in [3]. They are significantly broader, however, than those estimated by applying a range in mass models as in Fig. 1. This is despite the fact that the neutron separation energy variations that result from the uncorrelated mass Monte Carlo are roughly comparable to the range in neutron separation energy variations among the six DFT mass models considered
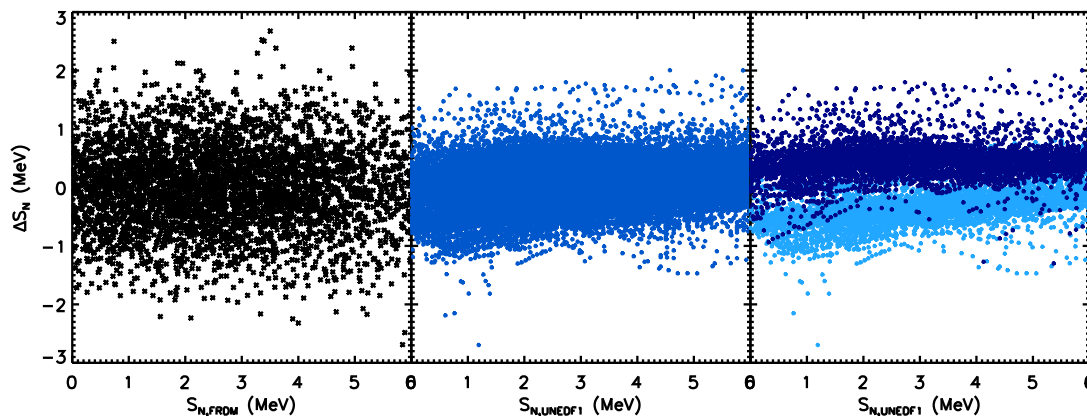
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Fig. 3. Separation energy variations resulting from a single Monte Carlo step (left), comparisons between UNEDF1 [10] masses and the five other DFT mass tables considered in the text (center), and comparisons between UNEDF1 and SkM* [11] (right, blue) or SV-min [12] (right, dark).

in Sec. 2, as shown in the first two panels of Fig. 3. The difference is presumably due to the correlations present in the mass model comparisons that are by definition not considered in the Monte Carlo studies. Also, in general the neutron separation energy variations between any two DFT mass models tend to be tighter than a Gaussian distribution of width 0.5 MeV will produce; this is illustrated in the third panel of Fig. 3.

Here we have considered two complementary methods to obtain error bars on r-process abundance patterns due to uncertain nuclear masses: an investigation of systematic uncertainties explored with a variety of DFT mass models and a treatment of random, uncorrelated errors using Monte Carlo mass variations. Work is currently underway on a third approach, in which well-quantified uncertainties in a particular mass model [10] are propagated to r-process simulations.

The results presented here illustrate the importance of future mass measurements. In addition, given the wide uncertainty in theoretical calculations for nuclei off stability, it is particularly important to conduct additional theory calculations that elucidate the patterns in nuclear properties that give rise to various abundance pattern features.

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