Implementing and evaluating modern nuclear models in the study of r-process nucleosynthesis

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Introduction

Simulations of the rapid neutron capture process, or *r* process, of nucleosynthesis rely heavily on theoretical models of neutron-rich nuclei. Variations across the many different available nuclear models introduce a significant source of uncertainty into *r*-process calculations, and a careful understanding of the nature and extent of this uncertainty is a critical step towards fully understanding the *r* process.

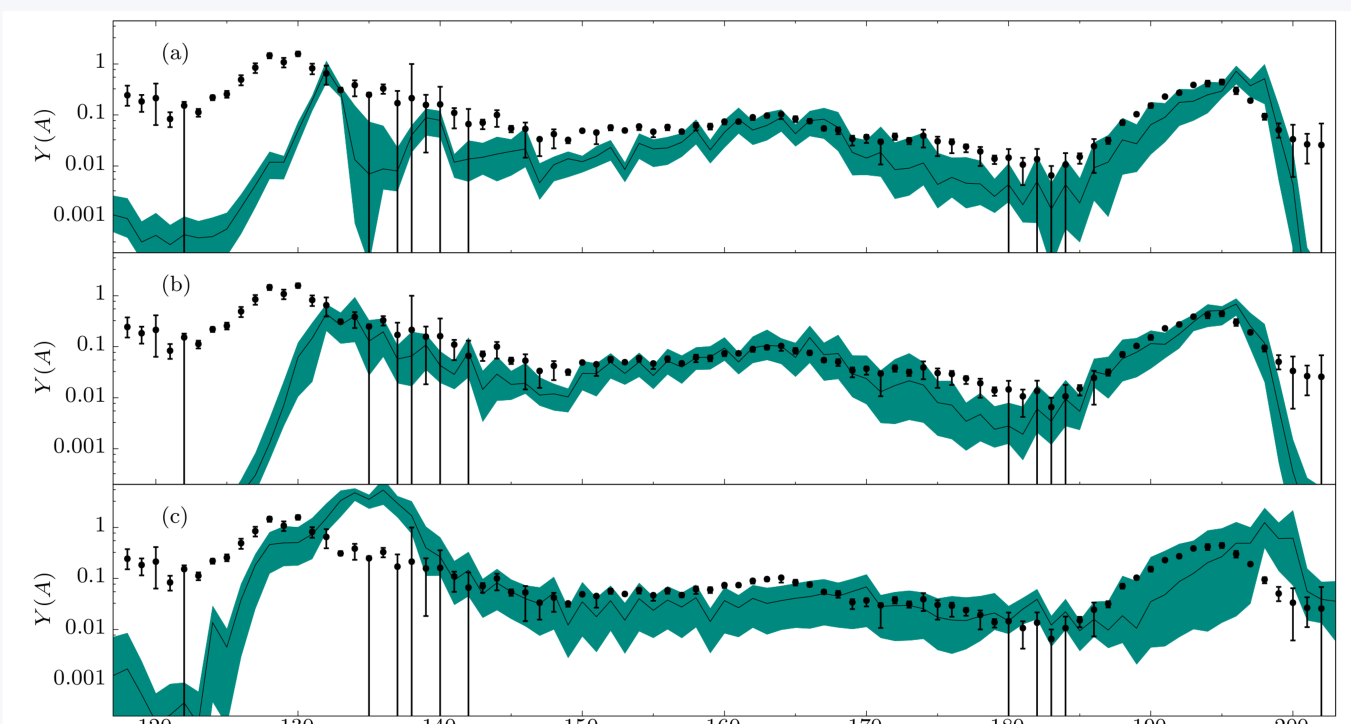

Figure 1

In this work, we investigate the statistical uncertainty of one particular nuclear model, UNEDF1 [1], and the associated uncertainty that propagates to *r*-process calculations. We build on past work that has carefully quantified the statistical uncertainty of the UNEDF1 parameters [2], and we sample 50 points within the 90% confidence region of the parameter space. We calculate complete mass tables for each, along with a self-consistent set of *r*-process inputs.

We focus on three distinct types of astrophysical conditions where the *r* process may occur: (a) a supernova-like high-entropy wind, (b) a low-entropy neutron star merger wind, and (c) fission-recycling outflow of a neutron star merger. The range of abundance patterns for each of these conditions, obtained by performing *r*-process simulations for each of our 50 datasets described above, is shown in Figure 1.

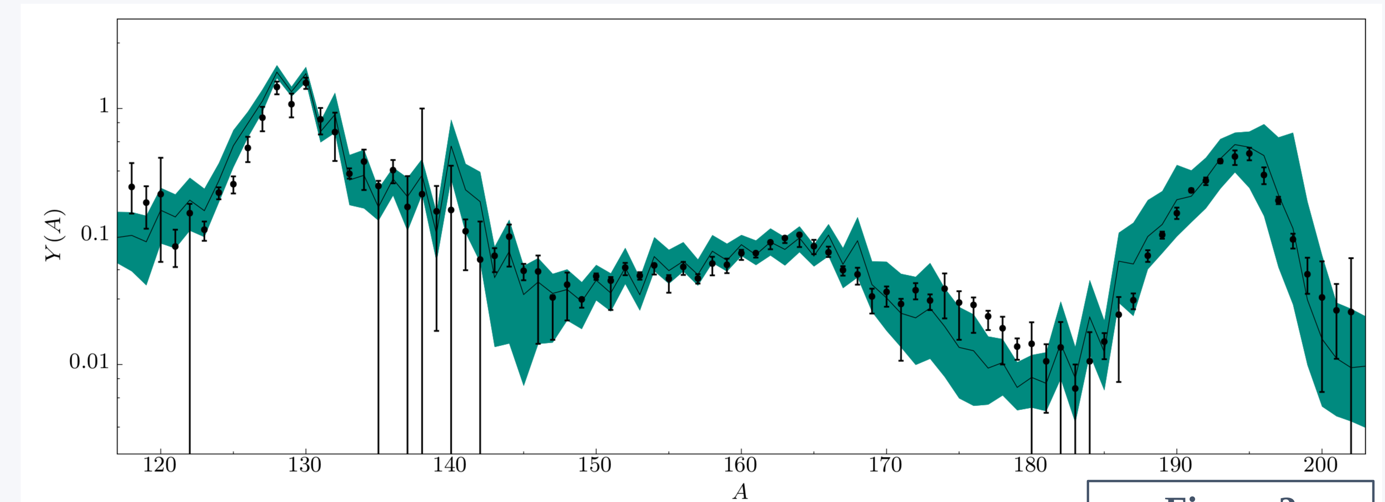

Figure 2

In an astrophysical *r*-process event, the overall composition of ejecta is formed in a range of individual conditions, with distributions in entropy, electron fraction, and final velocity expected. We sum together the contributions of ten representative conditions that arise in a hydrodynamical simulation of disk ejecta for a neutron star merger [3] and perform the same analysis as described for Figure 1. The overall range in abundances for this 'complete' event is shown in Figure 2.

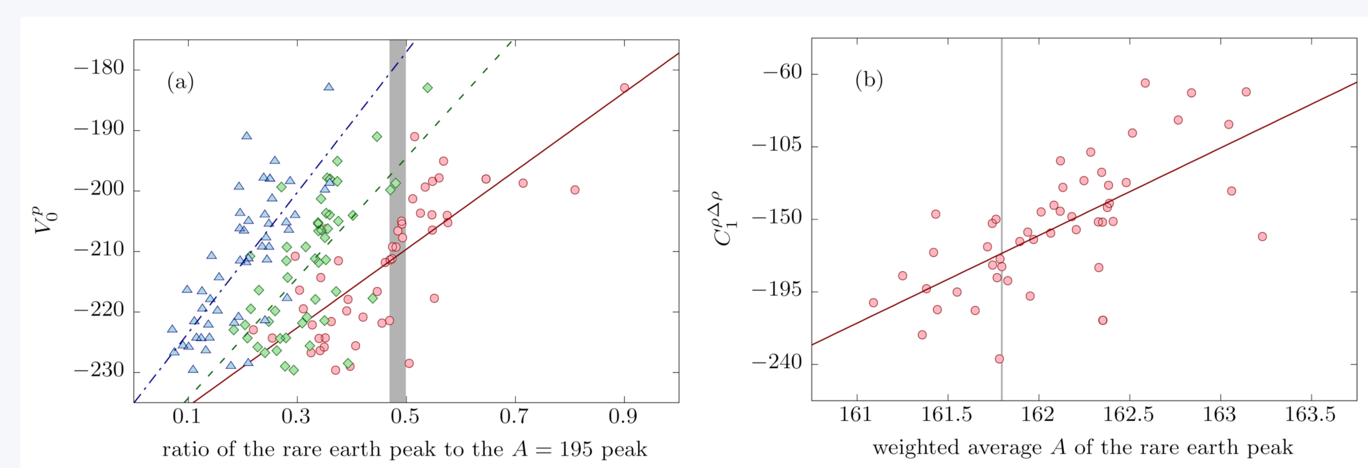

Figure 3

By carefully defining metrics on *r*-process abundance patterns, we are able to identify correlations between certain poorly-constrained UNEDF1 parameters and specific features of the corresponding *r*-process patterns.

In panel (a) of Figure 3, we show that the proton pairing strength is correlated with the ratio of material in the rare-earth region to that in the A=195 peak, with distinct correlations for each of the conditions we consider in Figure 1. Should this parameter become better-constrained in the future, this abundance pattern metric may be useful in diagnosing the conditions that contribute to observed *r*-process abundances.

Conversely, we identify another metric, the average mass number of material in the rare earth region, that is correlated with the isovector surface coupling constant. This correlation is shown for the low-entropy wind example in panel (b) of Figure 3. As uncertainties associated with the nuclear and astrophysics of the *r* process improve over time, this correlation may provide an important additional constraint on this term in the UNEDF1 parameterization.

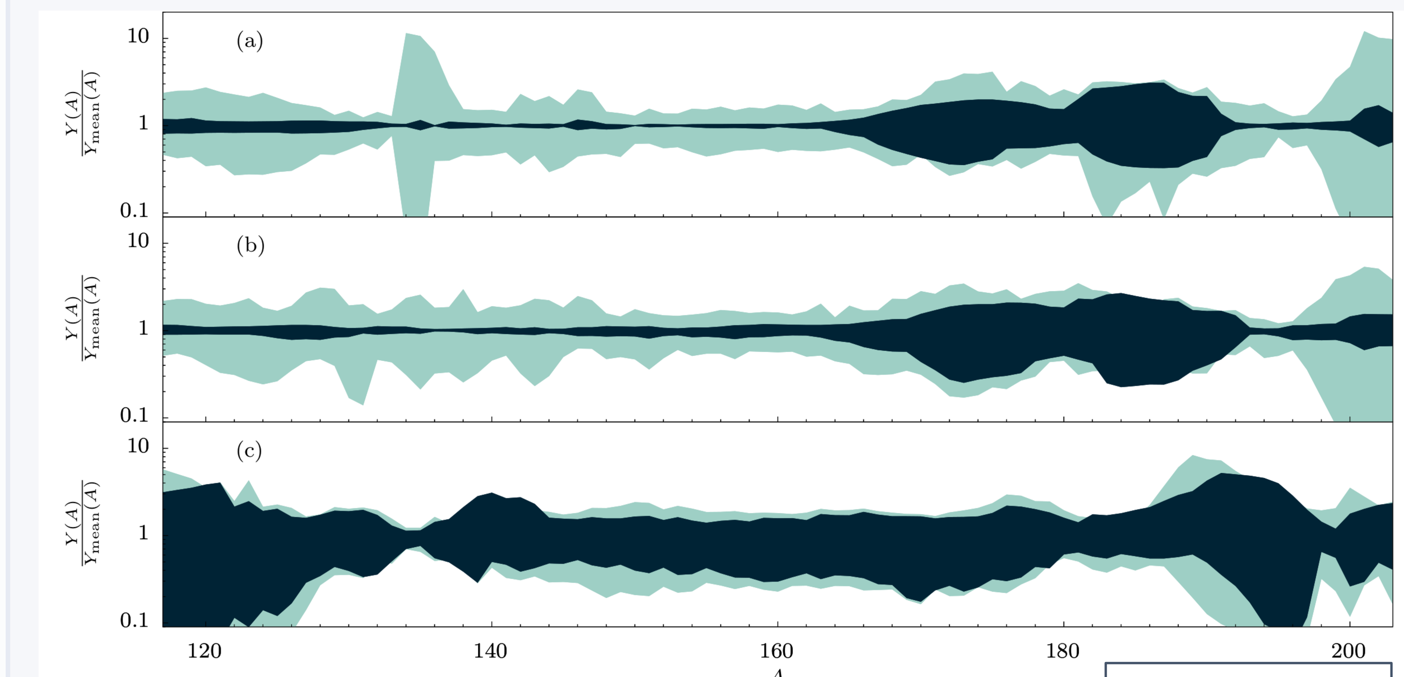

Figure 4

Finally, we anticipate how future experiments at the Facility for Rare Isotope Beams (FRIB) will be able to reduce the statistical uncertainty of UNEDF1 model predictions. Among our 50 UNEDF1 mass tables, predicted nuclear masses quickly diverge beyond the limits of currently available experimental data. With future experiments at FRIB, the onset of this divergence should be pushed back towards more neutron-rich nuclei.

We create an additional set of fifty 'post-FRIB' mass tables whose variations reflect these anticipated experiments; using these new tables, we repeat the analysis described for Figure 1. In Figure 4, we present a comparison of the two analyses, plotting the overall width of the patterns for the high-entropy wind (a), low-entropy wind (b), and fission-recycling (c) conditions. In each panel, the original fifty UNEDF1 datasets are represented by the light-shaded region and the 'post-FRIB' datasets by the dark-shaded region. For both of the wind conditions, the overall uncertainty is expected to greatly improve for A<~165 in response to future FRIB experiments, while for the fission recycling condition (c), further improvements to nuclear models will likely be needed.

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