UNCORRELATED NUCLEAR MASS UNCERTAINTIES AND r-PROCESS ABUNDANCE PREDICTIONS*

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Nuclear masses have long been recognized as key nuclear physics inputs for calculations of rapid neutron capture, or r-process, nucleosynthesis. Here, we investigate how uncorrelated uncertainties in nuclear masses translate into uncertainties in the final abundance pattern produced in r-process simulations. These uncertainties can obscure details of the abundance pattern that, in principle, could be used to diagnose the r-process astrophysical site. We additionally examine the impact of reductions of mass uncertainties that will come with new experiments.

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1. Introduction

Simulations of rapid neutron capture, or r-process, nucleosynthesis require realistic models of candidate astrophysical environments as well as reliable nuclear data for all nuclear species out to the neutron drip line [1, 2]. On the nuclear physics side, masses are of fundamental importance. For an r-process characterized by (n,γ)–(γ,n) equilibrium, masses determine the relative abundances of nuclei along each isotopic chain. Masses are also crucial inputs in the calculations of all other relevant quantities, such as β-decay rates, β-delayed neutron emission probabilities, neutron capture rates, and fission properties.

The vast majority of the masses required for r-process simulations have not (yet) been measured. Simulations therefore rely on theoretical models, ranging from parameterized fits extrapolated from stability [3, 4] to fully

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microscopic approaches [5]. The most commonly used models for astrophysical applications show r.m.s. deviations of 0.33–0.70 MeV with measured masses. However, these different approaches produce predictions toward the neutron drip line that can deviate by many MeV (see, *e.g.*, figures 5 and 6 of Ref. [2]). These uncertainties impact the precision with which the r-process can be modeled.

One way to quantify how mass model uncertainties influence r-process predictions is through Monte Carlo variations of individual masses [2, 6]. For each Monte Carlo step, all theoretical masses are modified randomly within an estimate of the mass uncertainty and an r-process simulation with the varied masses is run. After repeating thousands of such steps, we analyze the resulting ensemble of abundance patterns. We find large variances result, such that many key abundance pattern details are completely obscured (figure 10 of Ref. [2]).

We expect that the situation will improve markedly in the coming years, through mass measurement campaigns at current and planned radioactive isotope facilities. Here, we examine the potential impact of the corresponding reductions in mass uncertainties on r-process abundance pattern predictions.

2. Monte Carlo mass variations

We begin with a Monte Carlo mass variation study similar to Ref. [6]. Our baseline nuclear masses are taken to be the experimental and extrapolated masses from the 2012 Atomic Mass Evaluation [7], where available, and from the latest version of the Finite-Range Droplet Model (FRDM2012) [8] elsewhere. In the initial study, we randomly vary all of the extrapolated and theoretical mass values for each Monte Carlo step. The mass variations are chosen from a normal distribution with width equal to 0.5 MeV, a value similar to the r.m.s. deviation between FRDM2012 and AME2012 masses. We then recalculate the neutron separation energies and run an r-process network calculation. We repeat these steps — randomly varying masses and repeating the r-process simulation — 10,000 times for each complete study.

For the studies of this work, we choose a hot wind trajectory, parameterized as in [9] with entropy $s/k = 100$, timescale 80 ms, and initial electron fraction $Y_e = 0.26$, that produces a classic (n,γ)–(γ,n) equilibrium r-process. In this type of r-process, the primary influence of the masses is through the photodissociation rates $\lambda_\gamma(Z,N)$, which are set by detailed balance

$$\lambda_\gamma(Z,N) \propto T^{3/2} \exp\left[-\frac{S_n(Z,N)}{kT}\right] \langle\sigma v\rangle_{(Z,N-1)}\,, \qquad (1)$$

where T is the temperature, $\langle\sigma v\rangle_{(Z,N-1)}$ is the neutron capture rate of the neighboring nucleus, k is Boltzmann's constant, and $S_n(Z,N)$ is the neutron separation energy. Mass variations alter the neutron separation energies and, as shown above, the photodissociation rates; in an (n,γ)–(γ,n) equilibrium r-process, photodissociation rate changes can shift the equilibrium abundances along individual isotopic chains and thus reshape the final abundance pattern [10, 11]. Each set of varied masses in our Monte Carlo study will, therefore, produce a distinct final abundance pattern.

An example set of mass variations for one Monte Carlo step is shown in figure 1, compared to the mass differences between FRDM2012 and the AME2012. It is clear that there are nuclear structure trends present in the FRDM2012–AME2012 comparison that cannot be captured by random variations. Thus, our uncorrelated mass variations may result in an overestimate of the eventual impact on the r-process abundance pattern. On the other hand, we have no good estimate of theoretical model uncertainties away from the measured values, so our mass variations may be conservative.

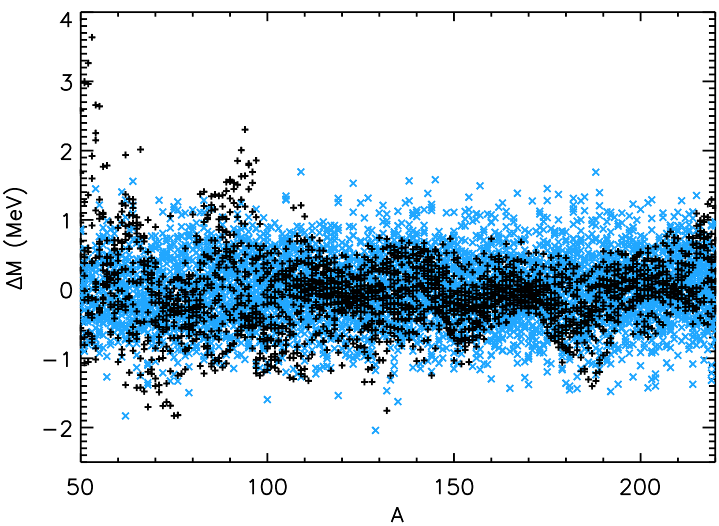

Fig. 1. Variations of nuclear masses for a single Monte Carlo step (gray/blue crosses), compared to the deviations between FRDM2012 and AME2012 (black crosses).

In any event, our aim here is to highlight the improvements that can be realized by new experimental data. To this end, we run three separate Monte Carlo studies, considering increasingly smaller sets of nuclei in our variations. Study A is as described above, where all theoretical and extrapolated masses are included in the variations. In study B, we additionally assume all of the AME2012 extrapolated masses are known and thus are not included in our mass variations. Finally, in study C, we optimistically estimate all masses relevant for the r-process within the reach of the upcoming Facility for Rare Isotope Beams for $Z < 65$ [12] are known and therefore are not varied. These regions are illustrated in figure 2.

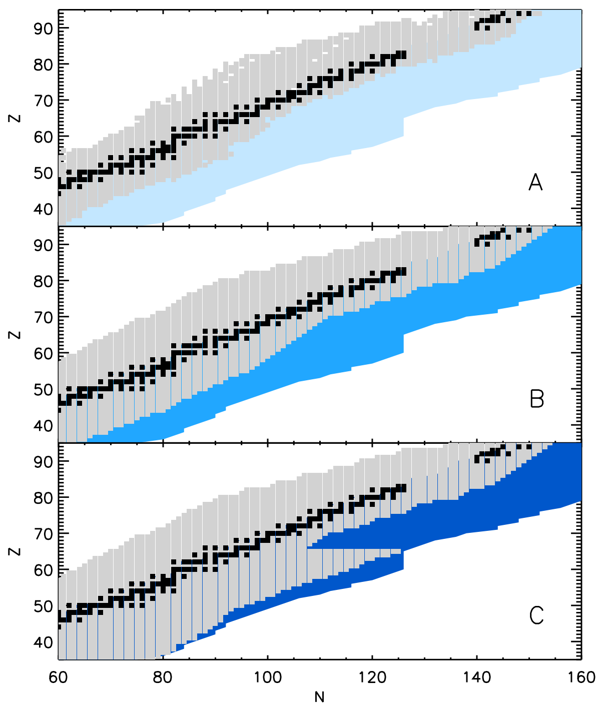

Fig. 2. Nuclear species included in the mass variations for each of the three Monte Carlo studies described in the text. The first study, A, varies extrapolated masses from the AME2012 and the theoretical masses from FRDM2012 (top panel, light gray/light blue shaded region); the second, B, only varies the theoretical masses (middle panel, gray/blue shaded region). The third, C, further excludes all nuclear species within the expected FRIB reach for $Z < 65$ [12] (varied masses shaded in dark gray/dark blue, bottom panel). The masses of species indicated by gray squares are taken to be fixed, and the black squares indicate stable species.

3. Results

At the conclusion of each study, we postprocess the output of the r-process network to generate the final isotopic and elemental abundance patterns. For each A (or Z), we find the mean and standard deviation of the abundance $Y(A)$ ($Y(Z)$). We then plot the region defined by $Y_{\rm mean} + \sigma$ and $Y_{\rm mean} - \sigma$, as shown in figures 3 and 4.

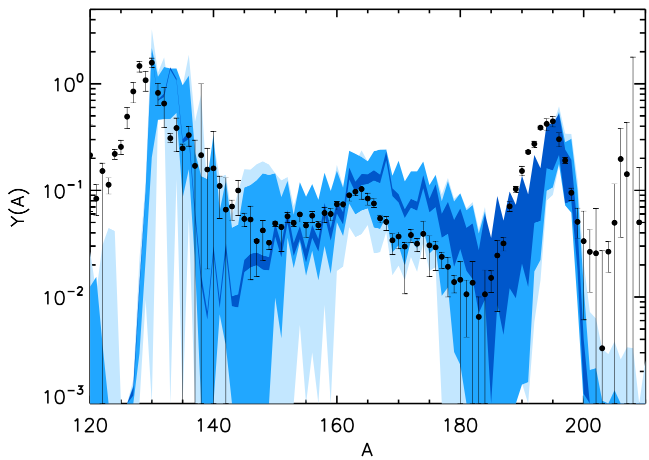

Fig. 3. Variances in final abundance patterns $Y(A)$ *vs.* A for Monte Carlo studies A (light gray/light blue shaded region), B (gray/blue shaded region), and C (dark gray/dark blue shaded region), as described in the text. The scaled solar abundances from Ref. [1] (circles) are included for comparison.

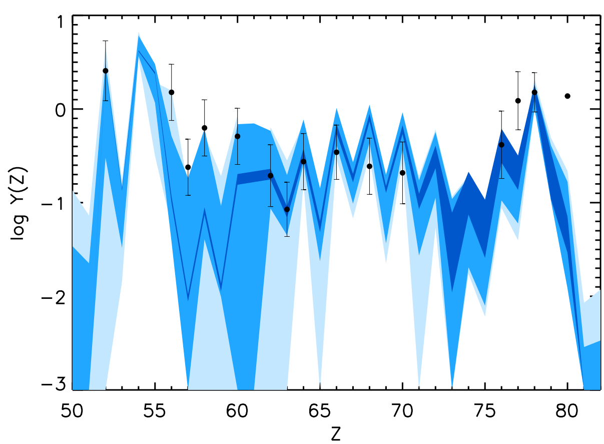

Fig. 4. Variances in final elemental abundance patterns $Y(A)$ *vs.* Z for Monte Carlo studies A (light gray/light blue shaded region), B (gray/blue shaded region), and C (dark gray/dark blue shaded region), compared to scaled abundances from r-process-enhanced metal-poor halo star HD160617 [13].

The isotopic abundance pattern variations for the three Monte Carlo studies are compared in figure 3. Study A is roughly consistent with previous work [6], showing abundance variations of an order of magnitude or more result from uncorrelated mass variations drawn from present-day mass uncertainties. Only the general features of the abundance pattern are discernible in this case; details such as the precise positions and heights of each of the peaks are washed out by the large variances. The situation improves somewhat if it is assumed that the extrapolated masses are known, as in study B. Variances throughout the pattern are reduced, quite sharply in some regions ($A \sim 130$, $150 < A < 160$). These gains are realistic to achieve in the near term. In the long term, we can look forward to the promise of next-generation facilities. These hold the potential to practically eliminate mass as a source of uncertainty for whole regions of the r-process pattern, as demonstrated in the results of study C.

Figure 4 shows the variances in final elemental abundance patterns for the three studies. Note that for certain regions of the pattern the variances are significantly smaller when the final abundances are averaged over element number rather than mass number. Even with current mass uncertainties, the abundances of platinum and the rare earths show variances within the error bars of spectroscopic abundance determinations for r-process enhanced metal-poor stars. The largest variances in study A are for the $56 < Z < 63$ region — a region where FRIB can have a tremendous impact.

The Monte Carlo studies described here considered variations in masses propagated to photodissociation rates only. This captures the primary influence of masses for a hot (n,γ)–(γ,n) equilibrium r-process. However, many candidate sites are cold or quickly fall out of (n,γ)–(γ,n) equilibrium, and the greatest impact of the masses in these scenarios is through their influence on neutron capture rates and β-decay properties [11]. Studies in progress include the propagation of mass variations to all affected nuclear data and, additionally, consider both correlated and uncorrelated mass variations. While more work is needed to carefully quantify the impact of nuclear data uncertainties on r-process simulations, it is clear from this preliminary study that present mass uncertainties are still too large for precision predictions and significant improvements can be obtained from increasing experimental reach.

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