Variances in r-process predictions from uncertain nuclear rates

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Abstract. Rapid neutron capture or 'r-process' nucleosynthesis is a critical process for creating approximately half of heavy elements above iron in the Universe. Simulations of the r-process require theoretical calculations of neutron capture and β-decay rates for thousands of short-lived nuclei for which no experimental data exists. We explore the impact of uncertainties in theoretical nuclear rates by performing global monte carlo simulations. We show that randomly varying neutron capture and β-decay rates within current theoretical model uncertainties results in large error bars for r-process predictions. We conclude that the reduction of rate uncertainties either by new measurements or by improved nuclear models will allow for more robust r-process predictions.

1. Introduction

The Facility for Anti-proton and Ion Research (FAIR) currently under construction at GSI will offer an array of insights into the frontiers of physics from heavy ion collisions to the production of rare isotopes [1]. The focus of the NUSTAR collaboration is to probe the physics of exotic nuclei with extreme neutron or proton excess [2]. Planned NUSTAR measurements will occur after the beam passes through the super-FRS (Fragment Recoil Separator) and are of particular interest to the astrophysics community as they provide insight into low energy nuclear structure, one of the biggest uncertainties that go into astrophysical models [3].

The astrophysical rapid neutron capture process or 'r-process' of nucleosynthesis is likely accountable for half of the neutron-rich nuclei found in nature [4]. Research in this area is motivated by one of the most challenging problems in theoretical physics: What is the site or sites where the r process may take place? Since most of the nuclei that participate in the r process remain unmeasured, theoretical calculations of nuclear masses and rates must be used to predict the final composition. With limited experimental data to constrain these models, predictions of the properties of short-lived nuclei can range drastically as one approaches the limits of nuclear existence.

To understand how these uncertainties impact predictions of final abundances we previously performed a global monte carlo investigation using a variation in unmeasured nuclear masses [5]. In this contribution we extend the methodology developed in our previous work to gauge the importance of uncertain neutron capture rates and β-decay rates on the final composition of the r process. We combine the set of final abundances obtained from these monte carlo studies to produce an estimation of error bars for these nuclear properties.

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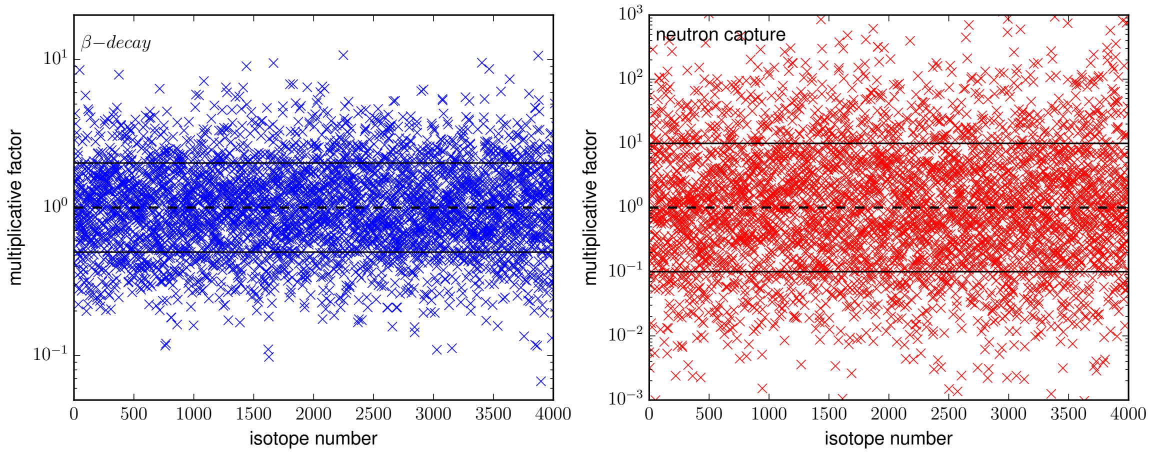

Figure 1. Multiplicative factors representing the uncertainty in β-decay rates (left panel) and neutron capture rates (right panel) sampled from the respective log-normal distributions for the first 4000 nuclei that enter into the reaction network. The dotted lines represent the mean of the underlying normal distributions, $\mu = 0$. The solid lines represent the current approximate uncertainties for β-decays ($\Delta \sim 2$) and neutron captures ($\Delta \sim 10$). The standard deviation for the underlying normal distributions is taken to be $\sigma = \ln(\Delta)$.

2. Calculations

For our astrophysical r-process conditions we use a parameterized model from Ref. [6] and note that this trajectory has also been used in our previous work [7]. This trajectory represents a 'hot' wind with entropy of 200 k_B, electron fraction of $Y_e = 0.3$ and timescale of 80 ms which produces a main r-process ($A \gtrsim 130$ and $Z \gtrsim 56$) component without fission recycling. The nuclear flow in this trajectory is initially controlled by a long equilibrium phase (lasting just over a second) between neutron capture and photo-dissociation channels, the so called $(n, \gamma) \rightleftarrows (\gamma, n)$ equilibrium. The equilibrium continues until the supply of free neutrons is exhausted and the r-process path, or set of most abundant isotopes moves back towards stability. Once this equilibrium breaks down, the last phase of the r process known as 'freeze-out' begins, and individual neutron capture rates may contribute to the predicted final abundances [8, 9]. The impact of β-decay rates is more consistent however, since these rates influence not only the timescale for heavy element production but also contribute to the relative abundances of isotopic chains for the entire r-process phase [10].

We calculate evolution of the r-process with a reduced reaction network used most recently in Ref. [5]. This network only contains reaction channels most relevant to the r-process which include neutron capture, photo-dissociation, β-decay and β-delayed neutron emission. We disable fission due to our choice of astrophysical conditions. These two simplifications greatly reduces our computational time allowing for more monte carlo steps to be achieved without altering our conclusions for a hot wind outflow.

As the basis for our theoretical nuclear models we use the Finite Range Droplet Model (FRDM1995) [11], Duflo Zuker (DZ) [12] and Hartree-Fock-Bogoliubov version 17 (HFB-17) [13]. Our neutron capture rates are calculated with a recently developed statistical model code, Capture Induced Gamma-ray Reactions (CIGAR) [14]. This model is based on the Hauser Feshbach approach which implicitly assumes that the level density is sufficiently high so that averaged values of the compound system can be computed. For our weak interaction data we use the publicly available dataset from Ref. [15] which includes β-decay rates and neutron emission

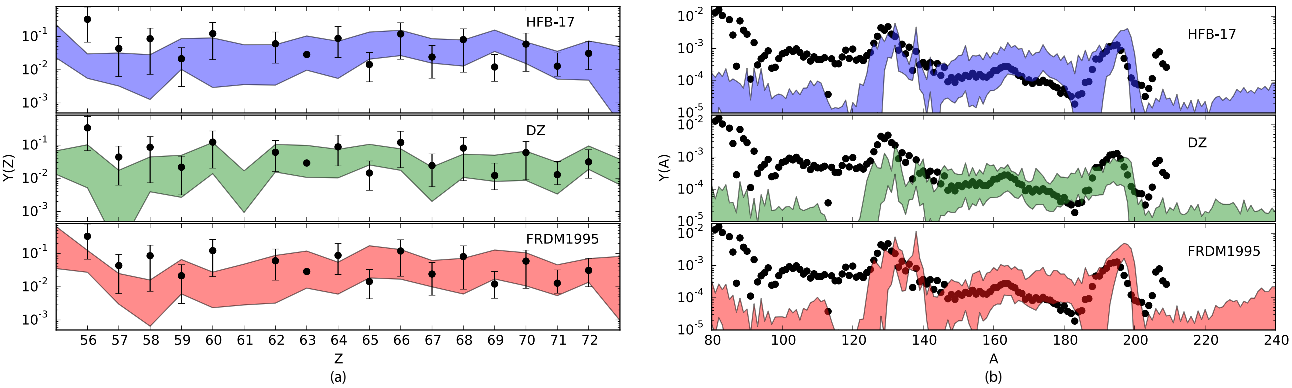

Figure 2. Variance in (a) elemental abundances and (b) isotopic abundances from current theoretical uncertainties in β-decay rates for three nuclear models (HFB-17, DZ, and FRDM1995). Elemental abundances are compared to the average of five r-process enriched metal poor stars and isotopic abundances are compared to the solar r-process residuals, both observations denoted by black dots.

probabilities. This model takes into account Gamow-Teller transitions and additionally includes a First-Forbidden component which is important for the computation of half-lives of neutron-rich nuclei near closed shells [16, 17]. We note that where available we use half-lives from the NNDC compilation [18] and that these measured values remain unvaried in our monte carlo simulations.

To estimate error bars on r-process abundances from uncertain nuclear rates we perform monte carlo variations of β-decays rates and neutron capture rates separately. We first fix our hot wind astrophysical trajectory and nuclear model. Then for a given monte carlo step, each rate that enters into the reaction network is varied by sampling multiplicative factors from a log-normal probability distribution:

$$p(x) = \frac{1}{x\sqrt{2\pi}\sigma} \exp\left[-\frac{(\mu - ln(x))^2}{2\sigma^2}\right] \tag{1}$$

where μ is the mean, and σ is the standard deviation of the underlying normal distribution and x is a random variable. To approximate current theoretical uncertainties in β-decay rates we modify each half-life in the network by sampling factors with underlying normal distribution values: $\mu = 0$ and $\sigma = \ln(2)$. The choice of $\sigma = \ln(2)$ for β-decay rates is motivated by Fig. 4 in Ref. [15]. To approximate current theoretical uncertainties in neutron capture rates we increase σ to $\ln(10)$, which is motivated by Fig. 8 in Ref. [19]. In Fig. 1 we show a representative sample distribution of rate factors for both β-decays (left panel) and neutron capture rates (right panel) for the first 4000 nuclei that enter into the reaction network. We note that with choice of $\mu = 0$, rate variations above and below theoretical values are sampled with equal weight.

Our final abundance patterns are compared to the averaged elemental abundances from five metal poor stars: CS22892-052 [20], CS31082-001 [21], HD115444 [22], HD221170 [23], and BD+17°3248 [24]. We also compare final compositions to the isotopic abundances of the solar r-process residuals [25].

3. Results

In this preliminary investigation each monte carlo study contains approximately 3000 abundance patterns. This abundance count is low relative to the size of the reaction network and

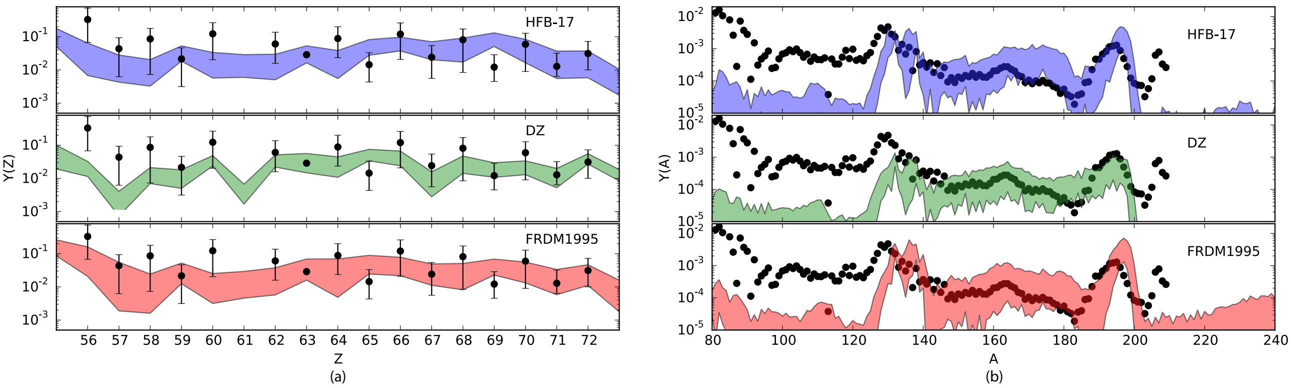

Figure 3. Variance in (a) elemental abundances and (b) isotopic abundances from current theoretical uncertainties in neutron capture rates for three nuclear models (HFB-17, DZ, and FRDM1995). Observational data (black dots) are the same as in Fig. 2.

consequently we plan to increase the number of monte carlo steps in a future analysis. A given monte carlo study contains only abundance patterns generated with a particular nuclear model and choice of rate variation, either neutron capture or β-decay. In the latter case, β-delayed neutron emission branching ratios are held fixed with values from Ref. [15]. Therefore, the impact of uncertain neutron capture rates and β-decay rates are analyzed independently. We estimate the current variability in r-process predictions by computing the standard deviation of a particular ensemble of isotopic and elemental abundances respectively.

We show the results of our β-decay monte carlo studies in Fig. 2 for both elemental, $Y(Z)$, and isotopic abundance predictions, $Y(A)$. These monte carlo studies were performed with the three aforementioned nuclear mass models, however all β-decay rate variations were based off the dataset from Ref. [15]. When plotting the elemental abundances we scale each study to the averaged halo star value of Europium ($Z = 63$) and note that the isotopic abundances are scaled to the rare earth region as outlined in Ref. [9]. The shaded color band in each panel of this figure represents the variance of the abundances from the monte carlo study performed with current theoretical uncertainties ($\sigma = \ln(2)$) for β-decay rates. We see that for the main r-process component ($A \gtrsim 130$ and $Z \gtrsim 56$) astrophysical observations (black dots) mostly lie within the error bars from our monte carlo study. The results of this study show that our ability to predict features in r-process abundances are washed out by the current uncertainties in theoretical weak decay properties.

In Fig. 3 we show the results of our neutron capture monte carlo studies with the same scaling and shading as in the previous figure. Again we find that for a main r-process component the observational constraints lie within the theoretical error bars. At first glance the results may come as a surprise since the chosen trajectory has a long duration $(n, \gamma) \rightleftarrows (\gamma, n)$ equilibrium, during which modifications to neutron capture rates are expected to play a minimal role. However, this result shows clearly that the final neutron captures during the last or 'freeze-out' stage of the r-process (once equilibrium has ended) are critical in determining final abundances, which reaffirms the conclusions drawn in our previous work [8, 9, 26]. If other astrophysical conditions are used, for example a 'cold' wind outflow, then we expect the dependence on neutron capture rates to increase resulting in a potentially larger variability in predicted abundances. This is because the r-process path in a cold outflow is controlled by a balance between β-decays and neutron captures.

4. Conclusions

We have used a monte carlo approach to estimate the variability of r-process predictions from uncertain nuclear β-decay and neutron capture rates in the context of a hot wind r-process. The current uncertainties in the thousands of nuclear rates that enter into network calculations were approximated by sampling multiplicative factors from a log-normal distribution which boosted or diminished individual rates. At each step in our monte carlo study the dataset of randomized rates was used as input into r-process network calculation to produce an abundance pattern. To estimate the error bars on r-process predictions from these nuclear model uncertainties we took the variance of the ensemble of abundances.

We have shown that the variance of abundance predictions with current theoretical calculations of β-decays and neutron capture rates span an order of magnitude (or more) for most of the main r-process component ($A \gtrsim 130$ and $Z \gtrsim 56$). It is therefore the uncertainties in nuclear models that limits the ability to resolve features found in elemental or isotopic abundance data. All astrophysical simulations of the r process use theoretical nuclear models and thus are subject to a similar resolving power. Ergo, in order to improve r-process predictions a concerted effort is required to achieve measurements on exotic nuclei. The role of FAIR and other facilities found worldwide play in this endeavor is two fold: (1) the inclusion of measured data directly into astrophysical simulations and (2) the reduction of uncertainties by providing more experimental data with which to constrain theoretical nuclear models. In addition to pursuing these difficult measurements, our group plans to continue to increase the efficacy of the methodology developed here by combining monte carlo studies of nuclear masses and rates. This extension will allow for the analysis of nuclear correlations and may reveal a new path towards understanding the reliability of nuclear models towards the neutron dripline.

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