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Nuclear Structure and Setting Constraints on the r-process?

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Abstract. One of the open questions in all of physics today has to do with the site of the r-process. There are uncertainties associated with the astrophysics, the observations, and the physics of nuclei far from stability. This paper uses existing nuclear physics models and their implied properties for nuclei far from stability to determine the nuclei that have the greatest impact on a given astrophysical scenario. The properties considered are nuclear masses, beta-decay rates, and neutron capture rates individually as well as in a correlated way to identify the most important nuclei in a given r-process trajectory. The ultimate goal is to set some constraints on potential sites of the r-process based on the nuclear properties.

1. Introduction
The NRC report "Connecting Quarks to the Cosmos" identified eleven of the most challenging open questions in all of Physics, Astrophysics, Astronomy, and Cosmology for the 21st Century. One of these questions is the identification of the site for the synthesis of the heavy elements via the r-process. Nuclei are made in stars from the primordial building blocks that resulted from the big bang and observations of early stars show abundances for the elements up to Fe. Beyond Fe, charged particle reactions are no longer effective and the heavier elements have to be made in processes that involve slow (s-process) and rapid (r-process) neutron capture reactions. The s-process and its path lie close to stability where the nuclear physics is well understood and the associated astrophysical sites have been identified. The r-process is thought to occur far from stability where the nuclear physics is unknown or challenging to measure and no astrophysical sites have yet been identified. While we have limited knowledge of the properties of specific nuclei far from stability, the nuclear processes that make up the r-process are well known: successive neutron captures and subsequent $\beta$-decays. The nuclear properties most relevant to the r-process include nuclear masses, $\beta$-decay rates, n-capture rates, and $\beta$-delayed neutron emission probabilities.

Experimental access to the very rich nuclei far from stability is a worldwide quest as evidenced by the developments of radioactive ion beam facilities across the globe. New facilities are being developed in the USA (CARIBU at ANL, NSCL and FRIB at MSU), in Canada (ISAC at TRIUMF), in Europe (ISOLDE at CERN), in France (SPIRAL II at GANIL), in Finland (Jyvaskyla), in Germany (FAIR at GSI Darmstadt), in Italy (Legnaro-SPES collaboration), in Japan (RIKEN), and in China (BRIF.CARIF in CIAE Beijing) to study the properties of exotic nuclei far from stability thought to be involved in the r-process. A specific r-process path may involve over three thousand nuclei and a large number of these remain a challenge to
The question is “which nuclei are the most important or most impactful to the r-process?” and “which ones should be given priority for measurements at the new facilities as they come online?”.

The approach we have chosen is one of simulation taking advantage of nuclear models for the properties of the most neutron rich nuclei, and comparing with the observed abundances of the r-process elements. The determination of nuclei whose changes in the relevant nuclear properties have the largest impact on the resulting abundances when compared to the observed r-process elemental abundances.

In the sensitivity studies described below, we have compared nuclear mass models in a fixed astrophysical scenario and then investigated the impact of a fixed nuclear model with variations in the r-process scenarios. Candidates for the site of the r-process are many, we have chosen two of the most likely scenarios which include two-neutron star mergers and supernova and determined the most important or most impactful nuclei using sensitivity studies. The elemental abundances resulting from the conditions in the cosmos are the results of complex processes that depend on the uncertainties in nuclear physics as well as the specifics of an astrophysical scenario.

Our longer term goal is to disentangle the nuclear uncertainties from the astrophysical ones and to attempt to set some constraints on potential astrophysical scenarios for the r-process.

2. Sensitivity Studies

The r-process proceeds via a sequence of neutron captures, photo-dissociations and β decays. Simulations of the r-process therefore require tabulations of β-decay lifetimes, neutron capture rates and neutron separation energies; photodissociation rates are determined from the capture rates and separation energies by detailed balance [?]:

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

In this equation, \( T \) is the temperature, \( \langle \sigma v \rangle_{(Z, A-1)} \) is the thermally-averaged value of the neutron capture cross section for the neighboring nucleus with one less neutron, and \( S_n(Z, A) \) is the neutron separation energy—the difference in binding between the nuclei \( (Z, A) \) and \( (Z, A - 1) \).

We have examined the impact of individual nuclear properties such as masses, β-decay rates, neutron capture rates, and β-delayed neutron emission probabilities on the r-process.

For example, in the sensitivity studies exploring the impact of nuclear masses on the r-process, we initially chose a specific astrophysical trajectory and examined examined the individual neutron separation energies [?] and eventually ±1 MeV in binding energy [?] within a given mass model, as they appear in Eqn. ??, in an attempt to determine the nuclei that have the greatest impact on the overall r-process abundances. All the calculations were done for the same initial astrophysical conditions. This comparison can be quantified by summing the differences in the final mass fractions:

\[
F_\pm = 100 \sum_A |X_{\text{baseline}}(A) - X_\pm \Delta S_n(A)|,
\]

where \( X(A) = AY(A) \) is the mass fraction of nuclei with mass number \( A \) (such that \( \sum_A X(A) = 1 \)), and the sum of \( A \) ranges over the entire abundance curve. The values of \( F = (F_+ + F_-)/2 \) are calculated for 3010 nuclei from \(^{56}\text{Fe}\) to \(^{294}\text{Fm}\). Nuclei that have the greatest impact on the r-process are those neutron rich nuclei near the closed shells at \( Z=28 \) and \( 50 \), and \( N=50, 82, \) and \( 126 \). Neutron separation energies include differences in mass of two nuclei. We followed with a complementary study with variations in the binding energy of an individual nucleus by ±1 MeV[?]. The results of the binding energy sensitivity study for the three nuclear masses are presented in Fig. 1. This figure shows the same bulk features as the separation energy
Figure 1. Sensitivity measures $F$ for each nucleus ($Z, N$) in the network, for three binding energy sensitivity studies using FRDM[?] (top panel), DZ[?] (middle panel), and HFB-21[?] (bottom panel) masses. All three studies use binding energy variations of $±1\text{MeV}$ and astrophysical conditions as used in Brett et al.[?], similar to the ‘H’ trajectory from Qian[?]. Stable nuclei are represented by solid black boxes. Overlaid in gray is the region of nuclear masses that have been reported as measured in AME2012[?] and the solid black line represents the predicted limits of accessibility for the production rates from FRIB[?]. It is clear from the concentration of $F$ intensities that FRIB will allow the measurements of a significant portion of the most impactful nuclei.
sensitivity studies shown in Fig. 3 of Brett et al. [7]. That is, the largest concentration of nuclei with great impact on the $r$-process as determined from the binding energy sensitivity studies and the separation energy sensitivity studies are clustered around the closed shells. The largest sensitivity measures $F$ are produced by variations in the masses of nuclei along and near the $r$-process path, particularly at the closed shells but the effect is somewhat more smeared out over the shell closures for the binding energy sensitivity studies. There are some minor differences between three mass models shown in Fig.1 for the binding energy sensitivity studies. However, there is a significant overlap in the nuclei that rise to the surface. Similarly, we examined the impact of individual $\beta$-decay rates [7] and $\beta$-delayed neutron emission probabilities [7] across the chart of nuclides in the context of a main $r$ process which produces nuclear flow out to the third ($A = 195$) abundance peak. All of these studies have provided insight into how the $r$-process proceeds, particularly at late times in the process once $(n, \gamma)$-$(\gamma, n)$ equilibrium has failed, and have pointed out the masses, decay rates, or capture rates with the greatest leverage on the final abundance pattern.

These studies, however, have looked at each piece of nuclear data in isolation. More recently [7], we have looked at the impact of these nuclear properties in a correlated way. That is we have made changes in mass value of an individual nucleus and then propagated the changes that such a variation causes on the relevant quantities of nearby nuclei. A change in one mass results in 12 changes for nuclei nearby. An example of the impact on the $r$-process abundances for
Figure 3. Nuclei from this study that significantly impact final r-process abundances in the \(N = 82\) region with an uncertainty of \(\pm 500\) keV. The black line shows the extent of measured masses from the AME 2012. Nuclei with masses measured within 100 keV are denoted by a dotted border and those greater denoted by solid border. Accessibility limits shown for CARIBU (dark gray) and FRIB (light gray).

Each of the nuclear properties (masses, n-capture rates, \(\beta\)-decay rates, and \(\beta\)-delayed neutron emission probabilities) for the case of \(^{140}\)Sn, is shown in Fig. ???. In panel (a) and (b) we added 500 keV to the mass of \(^{140}\)Sn (\(Z = 50\)) and propagated changes to all 12 nuclear physics properties of nearby nuclei.

Simulations shown in the Fig. ?? break down the impact of a this single mass change to the various processes. For example, the change in final abundances seen in panel (a) is dominated by the shift in separation energies. A smaller change comes from the \(\beta\)-decay rates as can be seen from the blue line in panel (c) of Fig. ???. A mass increase of 500 keV to \(^{140}\)Sn lowers the half-life of this nucleus by 30%, however this is not the dominant effect. Instead, the prevailing effect comes from the change in neutron emission probabilities. These quantities are extremely dependent on the two separation energies, as the Q-values control the distribution of \(\beta\)-strength that goes into each channel. In this situation, the increase of the \(\beta\)-decay rate of \(^{140}\)Sn coupled with the changes to \(P_{jn}\) values ensures a speedup of the nuclear flow in this region. panels(c) and (d). Breaking down by the color used in Fig. ?? we propagated changes to neutron capture rates (red), \(\beta\)-decay rates and associated \(P_{jn}\) values (blue) and one-neutron separation energies (green). The green simulation is the same type of calculation used in [?], except here we use different \(\beta\)-decay rates and r-process conditions. The effects of individual variations in 170 nuclear masses on r-process abundances are summarized in Fig. ???. Here we have taken the maximum F-value between the case where 500 keV was added to or subtracted from the FRDM mass. Qualitatively, the distribution of important nuclei agrees with previous work from [?] and lies within experimental reach of CARIBU and FRIB.

Mass uncertainties of \(\pm 0.5\) MeV can produce large local changes, on the order of 100% difference, and smaller global changes, on the order of 20-40% difference, to r-process abundances. In terms of our metric, a value of \(F \sim 30\) for a mass variation in a single nucleus
can yield over an order of magnitude local change in the $r$-process abundance predictions. The correlated studies were done with mass uncertainties as low as ±0.1 MeV, which are smaller than the RMS values of all the existing mass models. Yet the results suggest that nuclear masses in this region need to be known more accurately than 100 keV.

3. Conclusions
The broader goal of this work is to use nuclear properties to disentangle the complexities of the heavy element nucleosynthesis and potentially to gain some insight on how the $r$-process proceeds. We have done this by studying via simulations, the impact of all the relevant nuclear properties individually (including masses, beta decay rates, neutron capture rates, and $\beta$-delayed neutron emission probabilities) on the $r$-process. We have further examined the correlated effects of a change in mass of 500 keV and the propagated effect on twelve associated properties that one mass change impacts. As a result, we have shown the nuclei that are the most impactful to the $r$-process elemental abundances in a number of astrophysical scenarios. Even mass changes of ±100 keV have a significant impact on the $r$-process. This leads us to the conclusion that most of the available mass models with rms values of more than 500 keV on average do not have the precision needed to resolve between different astrophysical scenarios in a significant way.

Our results lead us to identify the most important nuclei to measure, to put direct constraints on the precision needed for measurements of nuclear properties and theoretical models, and perhaps in the longterm constrain $r$-process models.

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4. References