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Neutron Capture Rates and the Rare Earth Peak

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The r-process is an important component of heavy element nucleosynthesis. We study the sensitivity of the r-process abundance pattern to neutron capture rates along the rare earth peak ($A \sim 150$ to $A \sim 180$). We determine the type of conditions which produce a rare earth peak consistent with the solar r-process data. We identify important neutron capture rates among the rare earth isotopes and show how these rates influence specific sections of the abundance pattern.

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1. Introduction

The rapid neutron capture or r-process is one of two primary methods by which heavy element formation occurs. It is responsible for approximately half the abundance of nuclides above $A \sim 100$ [1]. The fast timescale of rapid neutron capture promotes competition between capture rates and beta rates allowing the r-process path to move far from stability. The understanding of this interplay between neutron capture, β-decay along with other nuclear reactions is crucial for unlocking the secrets of heavy element production. Previous studies of neutron capture rates have been performed by [2, 3] for isotopes in the $A = 130$ region of the r-process abundance pattern. Global capture rate modifications have also been performed [7]. However, a detailed study of neutron capture rates in the rare earth peak has not been performed. Because of it's location, the rare earth peak (REP) offer a great diagnostic for producing a consistent r-process pattern making it a unique tool for probing the r-process. In this contribution, we identify important neutron capture rates among the rare earth isotopes and show how these rates influence specific sections of the abundance pattern under two types of r-processes, hot (classical) and cold.[1] For each environment we isolate conditions which consistently produce the rare earth region in agreement with the solar data.

2. Modeling the R-process: Producing A Consistent Rare Earth Peak

The site or sites in which the r-process occurs still remains an open problem. There are several possible candidates which include supernovae [4], gamma ray bursts [5] and compact object mergers [6]. Along with nuclear physics inputs [8 – 10] our simulations use winds characterized by outflow timescale (τ), entropy (S), and electron fraction (Y_e) which could occur in any of these environments. Neutron capture rates are studied under two different types of winds: a classical, hot wind parameterized by [11] and a cold wind introduced by Wanajo [12] and parameteration from [13]. To systematically study neutron capture rates we first determined the set of wind conditions, (s,Y_e,τ) which best produced a rare earth peak matching the solar data. This is done by finding the smallest values of equation 2.1. The results are shown in Fig. 1.

$$R_{rep} = \sum_{A=150}^{A=180} \frac{|Y_A^{(S,\tau,Y_e)} - Y_A^{solar}|}{Y_A^{solar}} \tag{2.1}$$

3. Neutron Capture Studies

Our capture rate studies consist of a baseline simulation where the conditions and nuclear data input are fixed. Further simulations are performed using the same input with only an individual capture rate change by a factor, K. We evalute the effects of an individual capture rate, (N,Z) by considering the change induced on the final abundance pattern. This is quantified in equation 3.1,

$$F_K(N,Z) = 100 \sum_A \frac{|Y_A^K(N,Z) - Y_A^{baseline}|}{Y_A^{baseline}} \tag{3.1}$$

In Fig. 2 we show the results of two separate neutron capture rate change studies for a hot and cold environment.

[1] Global capture rate studies will be performed elsewhere.

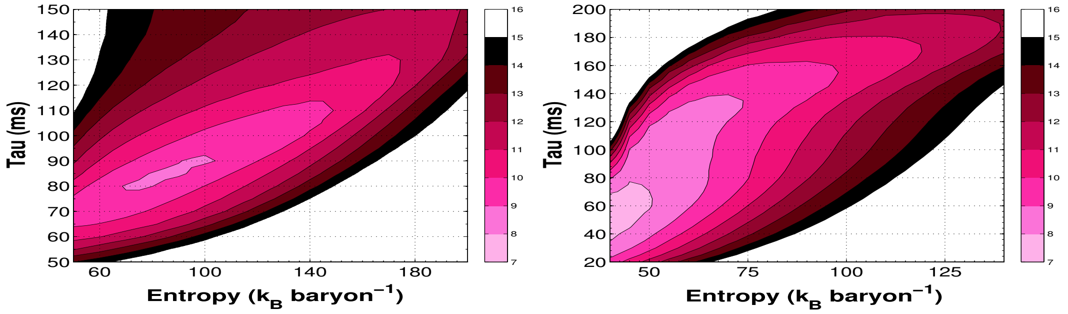

Figure 1: This figure highlights the regions where simulations produce rare earth peaks that best agree with the rare earth peak of the solar data, ($N_{\odot,r}$) using a hot (left panel) and cold (right panel) r-process. To produce strong r-processes with consistent abundance patterns out to the third peak ($A \sim 195$) we use $Y_e = .25$ which is consistent with compact object mergers [14]. The lighter pink colors represents simulations which match the solar data the best; smaller values of R_{rep}. In the white region unsatisfactory rare earth peaks are produced ($R_{rep} \gtrsim 15$).

4. Neutron Capture in the Rare Earth Sector

A change in neutron capture rate can lead to either a neutron capture effect where more material is shifted to the right, (Z,A)→(Z,A+1) and beyond in the N-Z plane relative to the abundance distribution of the unchanged capture rate or to a photo-dissociation effect where material shifts from the right to the left, (Z,A+1)←(Z,A) and beyond relative to the unchanged capture rate abundance distribution [3]. A large difference in nuclear flow between the baseline and capture rate simulation is the hallmark of a neutron catpure or photo-dissociation effect.

To highlight the effects of significantly influential neutron capture rates from our neutron capture studies (Fig. 2) we show in Fig. 3, a comparison of abundance curves between five elements from each wind and the solar abundances and baseline simulations.

Individual neutron capture rates can have significant influence on the flow of material through a specific region [2, 3]. This can occur only when the particular isotope is out of equilibrium with surrounding nuclei. In the hot r-process temperature are sufficiently high to support $(n,\gamma) \rightleftarrows (\gamma,n)$ equilibrium for long times. This can be seen in Fig. 2 by noting very little capture effects (the white region) in the bottom right portion of the top panel. In cold r-process $(n,\gamma) \rightleftarrows (\gamma,n)$ equilibrium is short lived, and so neutron capture effects manifest themselves earlier; see bottom right portion of the bottom panel in Fig. 2.[1]

Further constraints must be satisfied in order for a change in neutron capture rate to produce a significant neutron capture effect. For example large nuclear flow through the neutron capture reaction channel in the baseline simulation is required and the corresponding photo-dissociation flow should be small. Another significant constraint is the limitation of flow saturation. Flow saturation occurs when the sum of all in-flowing material matches the out-flowing material through the neutron capture channel. In the cold r-process the neutron capture flows of odd-N nuclei are closer to saturation than even-N nuclei; see the bottom right portion of the bottom panel of Fig. 2. A detailed discussion of this effect along with the other constraints will be provided in [15].

[1] In both cases the path pushes out towards the neutron dripline beyond the range of the figure.

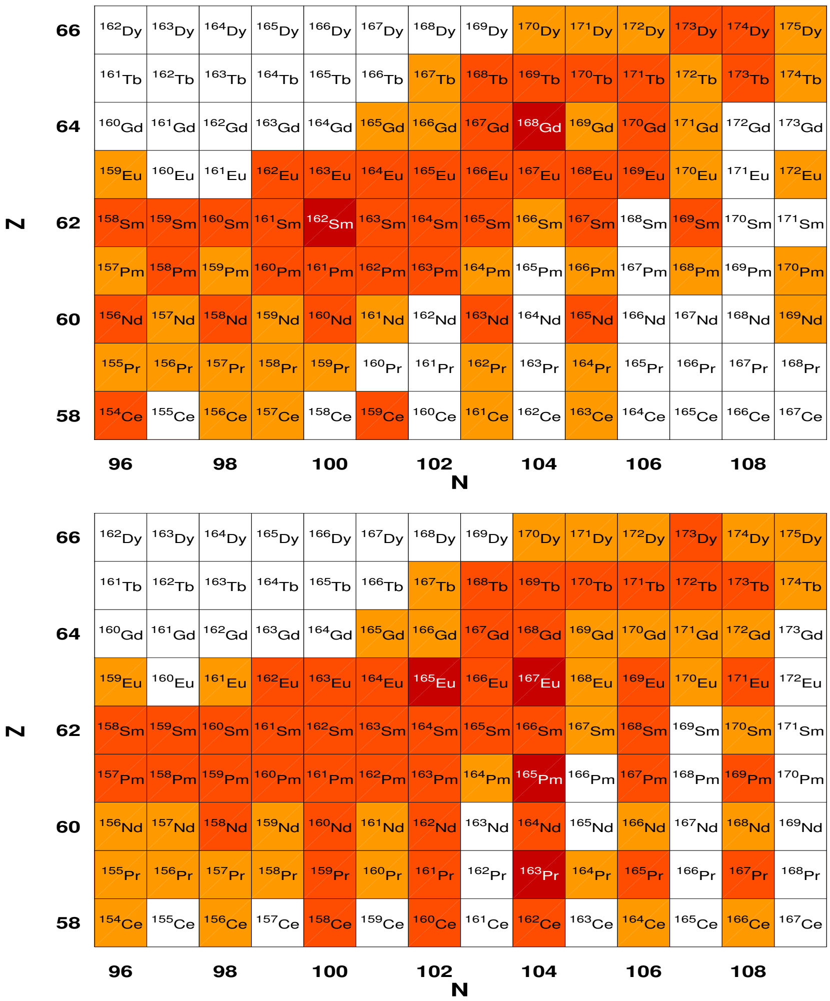

Figure 2: Highlighted are the neutron capture rates which significantly influence the abundance pattern for a hot (top panel) and cold (bottom panel) r-process. The conditions for the hot and cold environments were chosen from the minimization of R_{rep} using Fig. 1. In both cases the capture rates were changed by a factor of $K = 50$. However, individual neutron capture rates can vary by many orders of magnitude between theoretical models; see Fig. 1 in [2]. Each color represents a factor of two change in F with white representing little to no change.

5. Conclusions

Neutron capture rates in the rare earth region of the abundance pattern strongly influence the local features of this sector. These effects are local compared to the global modifications seen with capture rate changes in more abundant regions; for instance the $A = 130$ peak [2, 3]. The neutron capture effect is an out of equilibrium process occuring during freeze-out. While different environments e.g. hot and cold, highlight different regimes of nuclear physics, neutron capture rates are always found to be influential. Neutron capture rates in the rare earth peak play an important role in the r-process and must be well understood to accurately predict abundance patterns.

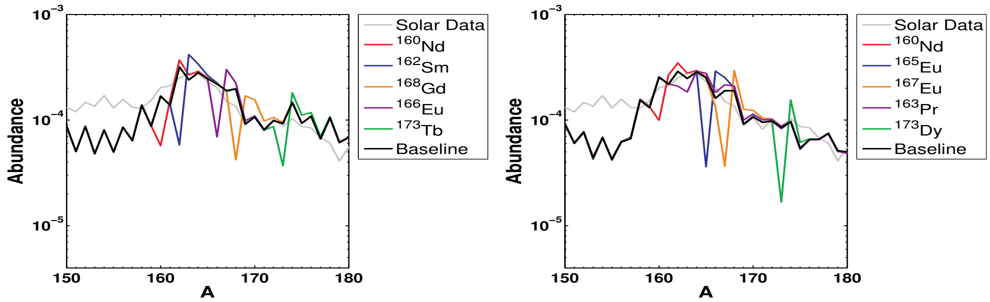

Figure 3: Shows the effect of individual neutron capture rates on the rare earth abundances. The baseline curve, $Y_{baseline}$ is shown in black and the solar data is shown in gray. For the two winds we highlight five elements whose neutron capture rates were changed individually by a factor of $K = 50$.

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