PROCEEDINGS OF SCIENCE

The Rare Earth Peak: A New r-Process Diagnostic

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The potential of an astrophysical environment for making r-process elements has been typically characterized by the neutron-to-seed ratio. We consider the rare earth peak as a new and independent tool for understanding the astrophysical conditions favorable for the main r-process. In the context of a high entropy r-process we discuss rare earth peak formation. We use features of a successful rare earth region to explore the types of astrophysical conditions that produce abundance patterns that best match data. This analysis allows for tighter constraints on the astrophysical conditions even after uncertainties in nuclear physics such as separation energies and neutron captures are taken into account. The efficacy of this tool depends on the input nuclear physics and so we point out important rates in the region which have the most influence on the final abundance pattern.

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1. Introduction

The rapid neutron capture process or 'r-process' was proposed by [1] as one method for production of the heavier elements above Iron. While many details of the r-process have been discovered, the site(s) of the r-process still remains uncertain. Proposed candidate sites include supernovae [2] and neutron star mergers [3]. However, both of these sites have their own pitfalls, see e.g. [4, 5]. Previous studies have used the neutron-to-seed ratio, R, as a metric to judge the potential of an astrophysical environment for making r-process elements. A sufficiently large neutron-to-seed ratio ($R \gtrsim 100$) at the start of the r-process phase is a key requirement to produce a main r-process out to the third peak ($A = 195$). In this contribution, we consider the rare earth peak as a new and independent tool for understanding the astrophysical conditions favorable for the main r-process. The rare earth peak forms away from closed shells and during freeze-out [6], the last stage of element formation, so it is a natural diagnostic of r-process conditions [7]. We use several features of a successful rare earth region to explore the types of astrophysical conditions that produce abundance patterns that best match data. This procedure depends critically on knowledge of the input nuclear physics, so we explore the sensitivity of final abundances to neutron capture rates in the region.

2. Calculations

We study the rare earth region in the context of a high entropy ($S > 100$) r-process and with an initial electron fraction of $Y_e = .40$. We use a range of wind conditions parameterizated by [6] to diagnose favorable r-process conditions and study the sensitivity of neutron capture rates. Two extreme conditions are of note: A "hot" r-process, which includes a period of $(n,\gamma) \rightleftarrows (\gamma,n)$ equilibrium and prolonged photo-dissociation flows during freeze-out [8], and a "cold" r-process, which does not have photo-disociation during freeze-out [9]. To track abundance composition of nuclei during freeze-out, we use a reaction network as outlined in [10]. In this contribution our nucleosynthesis calculations use the ETFSI nuclear masses for computation of separation energies and neutron capture rates [11][1]. Our calculations include β-decay rates from [12].

3. Constraining Conditions

We use three features found in the rare earth solar data to elucidate favorable r-process conditions. (1) To ensure rare earth peak formation we compare the peak region ($159 \leq A \leq 167$) to solar data. (2) Elemental yields of the $A = 195$ peak are correlated to rare earths in metal-poor halo star data which is believed to be indicative of a small number of r-process events, so we use the ratio of the rare earth peak to $A = 195$ peak as a second feature. (3) Lastly, too much neutron capture during freeze-out can shift material between isotopes which leads to overproduction of the heaviest rare earth elements. Further details on this procedure can be found in [7].

The results of using these three features to isolate favorable r-process conditions is shown in Fig. 1. Constraint (1) is shown by a red contour, (2) by a yellow contour and (3) by a green con-

[1] We have considered a variety of nuclear models in other publications [6, 7, 10].

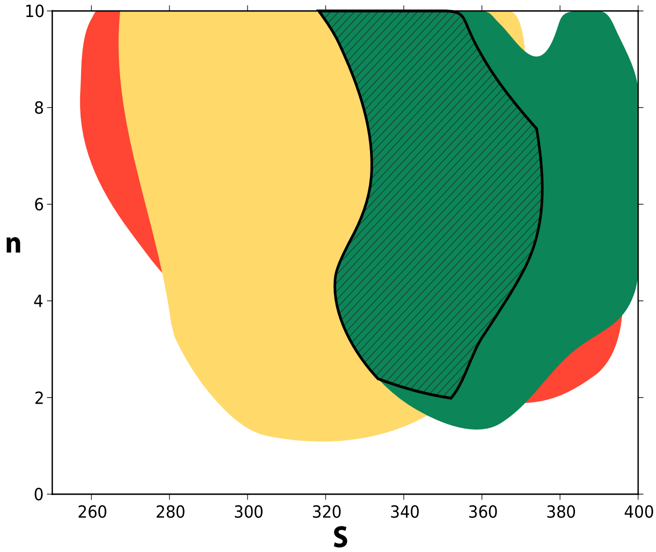

Figure 1: Constraining astrophysical conditions using the rare earth peak leads to a tighter constraint region (shaded) than using the neutron-to-seed ratio (entire plot area predicted to be favorable). The entropy, S, measures the amount of heating and the parameter, n, controls the rate of change of conditions during freeze-out. Large values ($n \gtrsim 5$) correspond to a "cold" r-process while lower values ($n \lesssim 5$) correspond to "hot" a r-process. Red represents conditions where rare earth peak matches solar data [13], yellow, where the ratio of the rare earth peak to the $A = 195$ peak matches solar data and green, where the late time neutron capture effect is weak.

tour. The intersection of these three regions (shaded) produces a tighter constraint on astrophysical conditions than the neutron-to-seed ratio alone (entire plot area predicted to be favorable).

To contrast the difference between these two methods we show final abundances along with error bars in Fig. 2. Error bars were calculated at each value of A by computing the standard deviation of all of the final abundances from the intersection region in the case of the rare earth procedure, or over the entire plot for the neutron-to-seed ratio procedure. Using the rare earth as a diagnostic for favorale r-process conditions produces final abundances which better match data and reduces the size of the error bars.

4. Nuclear Physics Uncertainties

We previously found [7] that the variation among nuclear models contributes the most to the error bars in Fig. 2. To account for uncertainties in neutron capture rates in the rare earth region using the ETFSI nuclear model, we performed sensitivity studies under both hot and cold conditions. The results are shown in Fig. 3.

The distribution of important neutron capture rates differs as the thermodynamic conditions change. This difference arises because the most abundant nuclei are influenced by what nuclear flow is dominate during freeze-out. In a hot freeze-out, the nuclei are coming out of a prolonged $(n,\gamma) \rightleftarrows (\gamma,n)$ equilibrium which prevents changes in capture rates from influencing final abun-

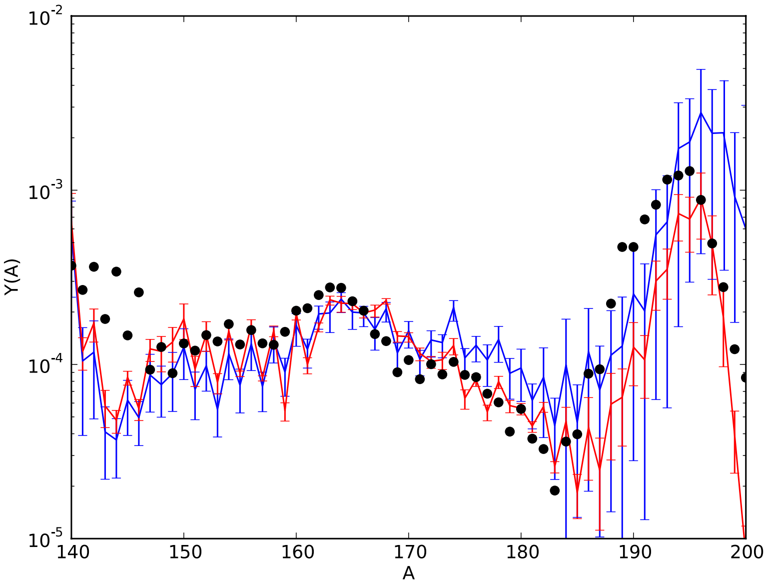

Figure 2: Final abundance patterns with uncertainties better match solar data (black) when using the rare earth peak to probe favorable *r*-process conditions (red) than when using the neutron-to-seed ratio (blue).

dances, see bottom right of panel (a). In a cold freeze-out, the nuclear flow is balanced by a competition between neutron capture and β-decay rates. This results in the population of mostly even-N nuclei.

5. Conclusions

We used three features of a successful rare earth region to explore the types of astrophysical conditions that produce abundance patterns that best match the solar isotopic data. This procedure complements the neutron-to-seed ratio by shedding light on the appropriate conditions needed during the last stage of the *r*-process known as freeze-out. We explored the sensitivity of the final abundances in the region to neutron capture rates and showed that the distribution of influential nuclei depends on the thermodynamic conditions during freeze-out. Uncertainties in nuclear physics such as neutron capture rates result in the largest variance of predicted final abundances. If more constraints can be placed on nuclear models then the usefulness of the rare earth peak as an *r*-process diagnostic will increase.

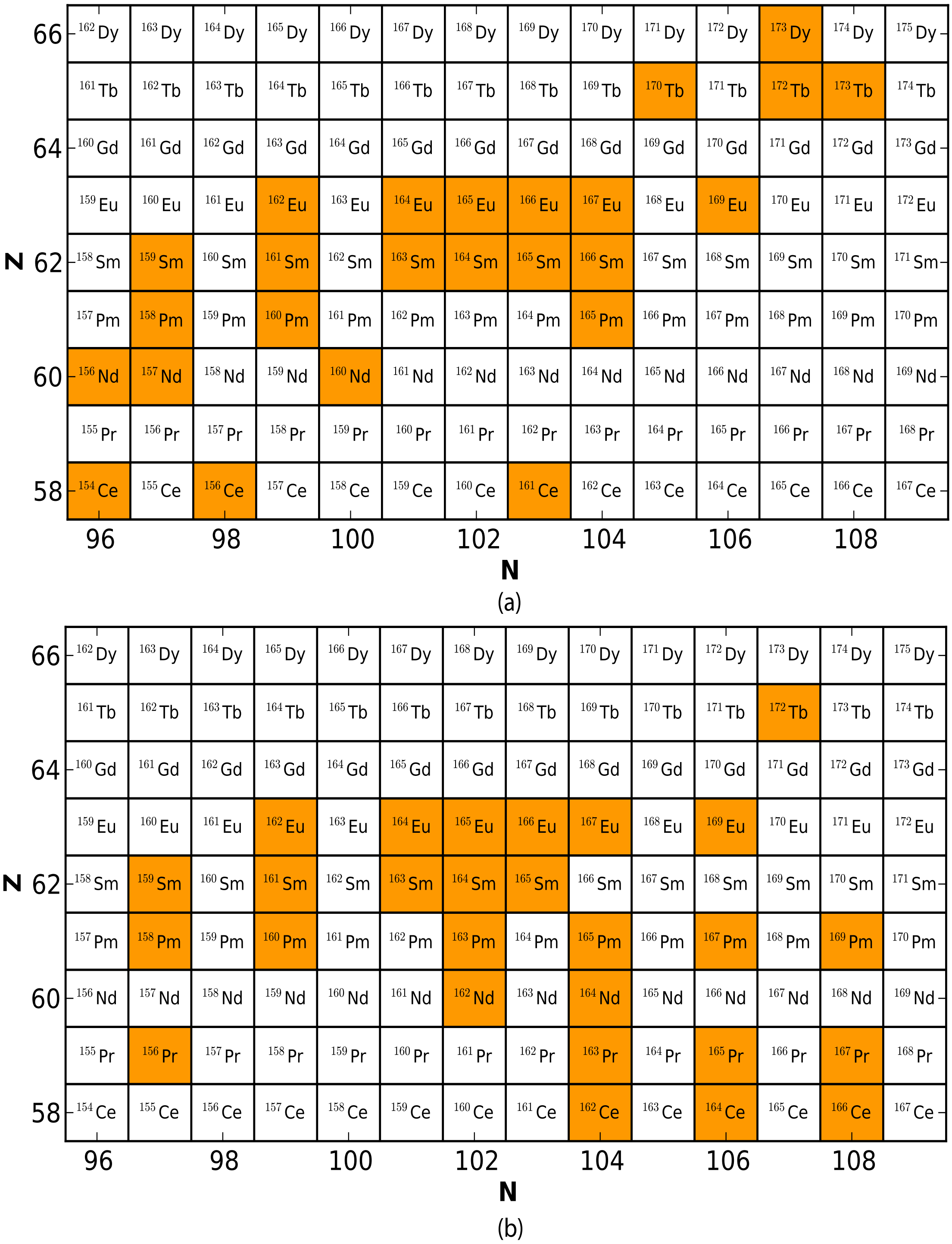

Figure 3: Single neutron capture rates (shaded) that significantly influence the final abundance pattern when the rate is increased by a factor of 5. The sensitivities of rates are shown to both hot (a) and cold (b) freeze-out conditions. Nuclei shaded white have no effect on final abundances when the capture rate was changed.

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References

[1] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle. Synthesis of the Elements in Stars. *Reviews of Modern Physics*, 29:547–650, 1957.

[2] B. S. Meyer, G. J. Mathews, W. M. Howard, S. E. Woosley, and R. D. Hoffman. R-process nucleosynthesis in the high-entropy supernova bubble. ApJ, 399:656–664, November 1992.

[3] J. M. Lattimer, F. Mackie, D. G. Ravenhall, and D. N. Schramm. The decompression of cold neutron star matter. ApJ, 213:225–233, April 1977.

[4] J. W. Truran, J. J. Cowan, C. A. Pilachowski, and C. Sneden. Probing the Neutron-Capture Nucleosynthesis History of Galactic Matter. PASP, 114:1293–1308, December 2002.

[5] D. Argast, M. Samland, F.-K. Thielemann, and Y.-Z. Qian. Neutron star mergers versus core-collapse supernovae as dominant r-process sites in the early Galaxy. *Astronomy and Astrophysics*, 416:997–1011, March 2004.

[6] M. R. Mumpower, G. C. McLaughlin, and R. Surman. Formation of the rare-earth peak: Gaining insight into late-time r-process dynamics. Phys. Rev. C, 85(4):045801, April 2012.

[7] M. Mumpower, G. McLaughlin, and R. Surman. The Rare Earth Peak: An Overlooked r-Process Diagnostic. *ApJ*, February 2012.

[8] B. S. Meyer. r-Process Nucleosynthesis without Excess Neutrons. *Physical Review Letters*, 89(23):231101–+, November 2002.

[9] S. Wanajo. Cold r-Process in Neutrino-driven Winds. *The Astrophysical Journal*, 666:L77–L80, September 2007.

[10] M. R. Mumpower, G. C. McLaughlin, and R. Surman. Influence of neutron capture rates in the rare earth region on the r-process abundance pattern. Phys. Rev. C, 86(3):035803, September 2012.

[11] J. M. Pearson, R. C. Nayak, and S. Goriely. Nuclear mass formula with Bogolyubov-enhanced shell-quenching: application to r-process. *Physics Letters B*, 387:455–459, February 1996.

[12] P. Möller, B. Pfeiffer, and K.-L. Kratz. New calculations of gross β-decay properties for astrophysical applications: Speeding-up the classical r process. Phys. Rev. C, 67(5):055802–+, May 2003.

[13] K. Lodders, H. Palme, and H.-P. Gail. Abundances of the Elements in the Solar System. In J. E. Trümper, editor, *"Landolt-Börnstein - Group VI Astronomy and Astrophysics Numerical Data and Functional Relationships in Science and Technology Volume*, page 44, 2009.