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# The rare earth peak and the astrophysical location of the *r*-process


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## Introduction

### The *r*-Process And The Rare Earth Peak

The rapid neutron capture or *r*-process is believed to be an integral component of heavy element nucleosynthesis.

*The astrophysical location where the r-process takes place is not known at this time, one of the most challenging open questions in all of physics. The two leading candidates are supernovae or compact object mergers.*

The rare earth peak seen in the solar residuals (**Figure 1**) has been proposed to originate from a pile-up of material during the end of the *r*-process. The formation of this abundance feature occurs near the *end* of the *r*-process (freeze-out phase), and so is sensitive to the *uncertain* thermodynamic conditions and *uncertain* nuclear physics inputs [1].

**We introduce a new Monte Carlo method which constrains theoretical nuclear physics inputs in the rare earth region by matching to the rare earth peak found in the solar isotopic abundances.**

**For each scenario, we find that the change in the mass surface has qualitatively different features, thus future measurements can shed light on the type of environment in which the *r*-process occurred [2].**

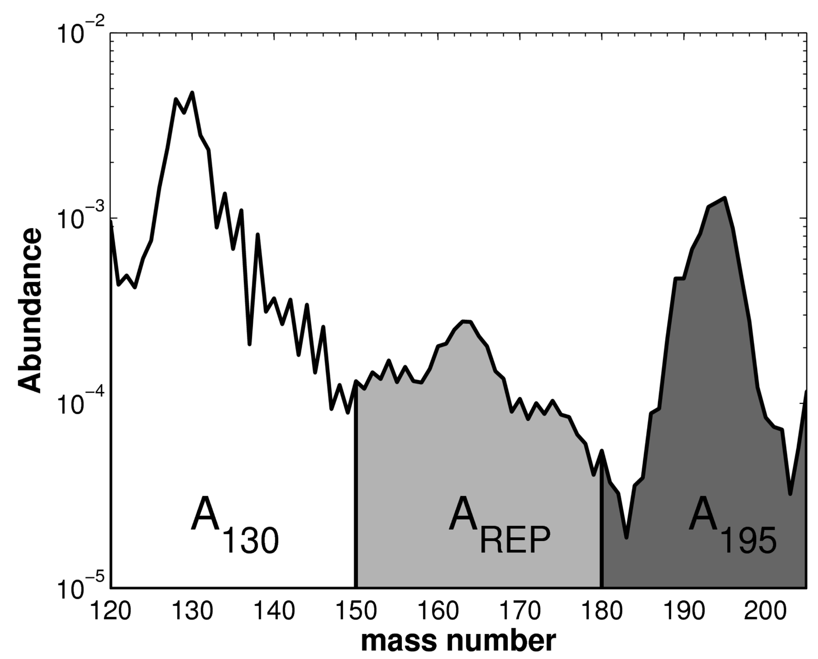


**Figure 1.** Shows the solar *r*-process abundance pattern versus atomic mass with three important regions highlighted.

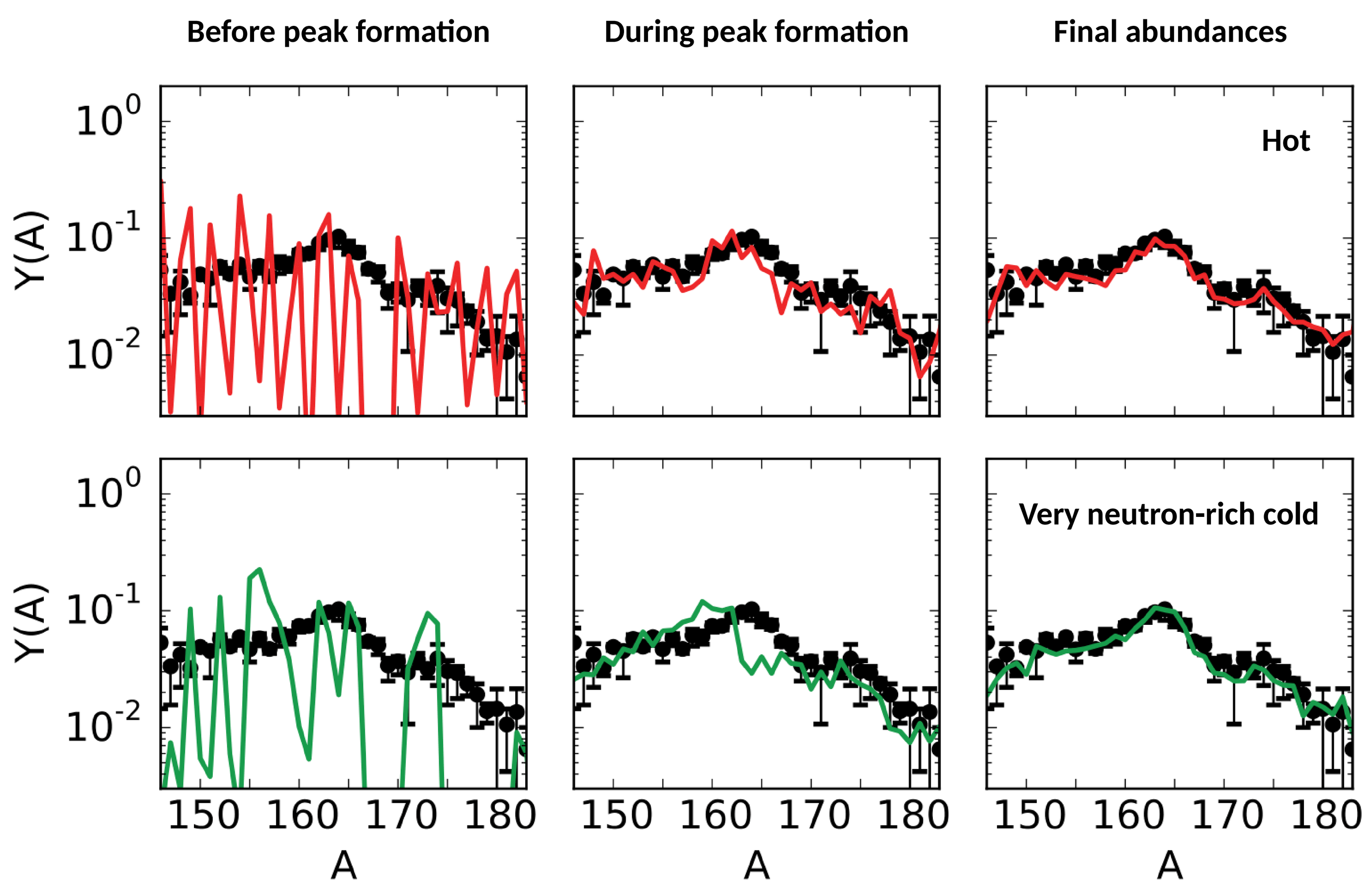


**Figure 3**. The evolution of abundances using hot (top) and cold (bottom) astrophysical conditions. Peak formation varies with conditions due to the difference in nuclear physics inputs that are important in the two scenarios.

## Calculations

### A New Monte Carlo Approach

Astrophysical conditions at the end of the *r*-process can be broken down into two broad categories: hot [long duration (n,γ) ⇆ (γ,n) equilibrium] and cold [limited or nonexistent (n,γ) ⇆ (γ,n) equilibrium]. The choice of hot or cold is fixed at the start of our calculation.

We start from the baseline predictions of the Duflo-Zuker (DZ) mass model, which does not reproduce the rare earth peak.

At each step, the mass surface is then varied and all nuclear properties (for instance β-decays and neutron capture rates) are recalculated self-consistently as in Ref. [3].

The Metropolis algorithm is used to determined whether or not the change to the mass surface better reproduces the rare earth peak, or makes it worse.

The final prediction of rare earth abundances from this procedure can be seen for the two astrophysical conditions in **Figure 2**.

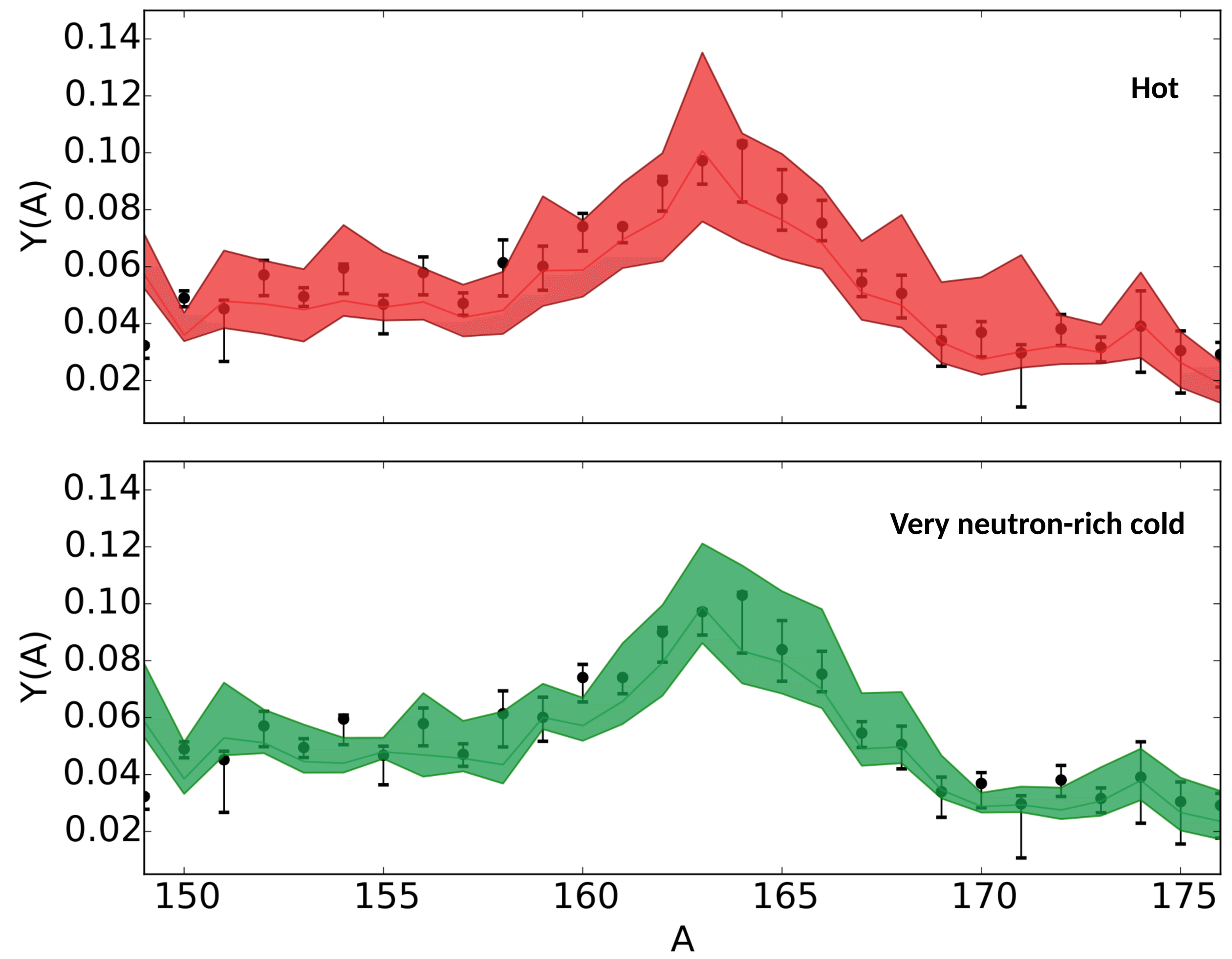


**Figure 2**. The final predicted rare earth peak using our Monte Carlo method for hot (top) and very neutron-rich cold (bottom) conditions.

## Formation Of The Rare Earth Peak

### Ways To Form the Peak During Freeze-out

Depending on the astrophysical conditions (hot vs cold), the rare earth peak forms dynamically during freeze-out by two distinct mechanisms: funneling or trapping [1]. This difference can be seen in the evolution of abundances in **Figure 3**.

In the case of a hot *r*-process, the material is funneled into the peak region as nuclei fall out of (n,γ) ⇆ (γ,n) equilibrium. In the case of a cold *r*-process the material becomes trapped by slower neutron capture rates at lower A, which then shift the material over to higher A during the decay back to stability (third panel of **Figure 3**).

Because of this difference in formation mechanisms we suspect that different mass surfaces will be required for various conditions.

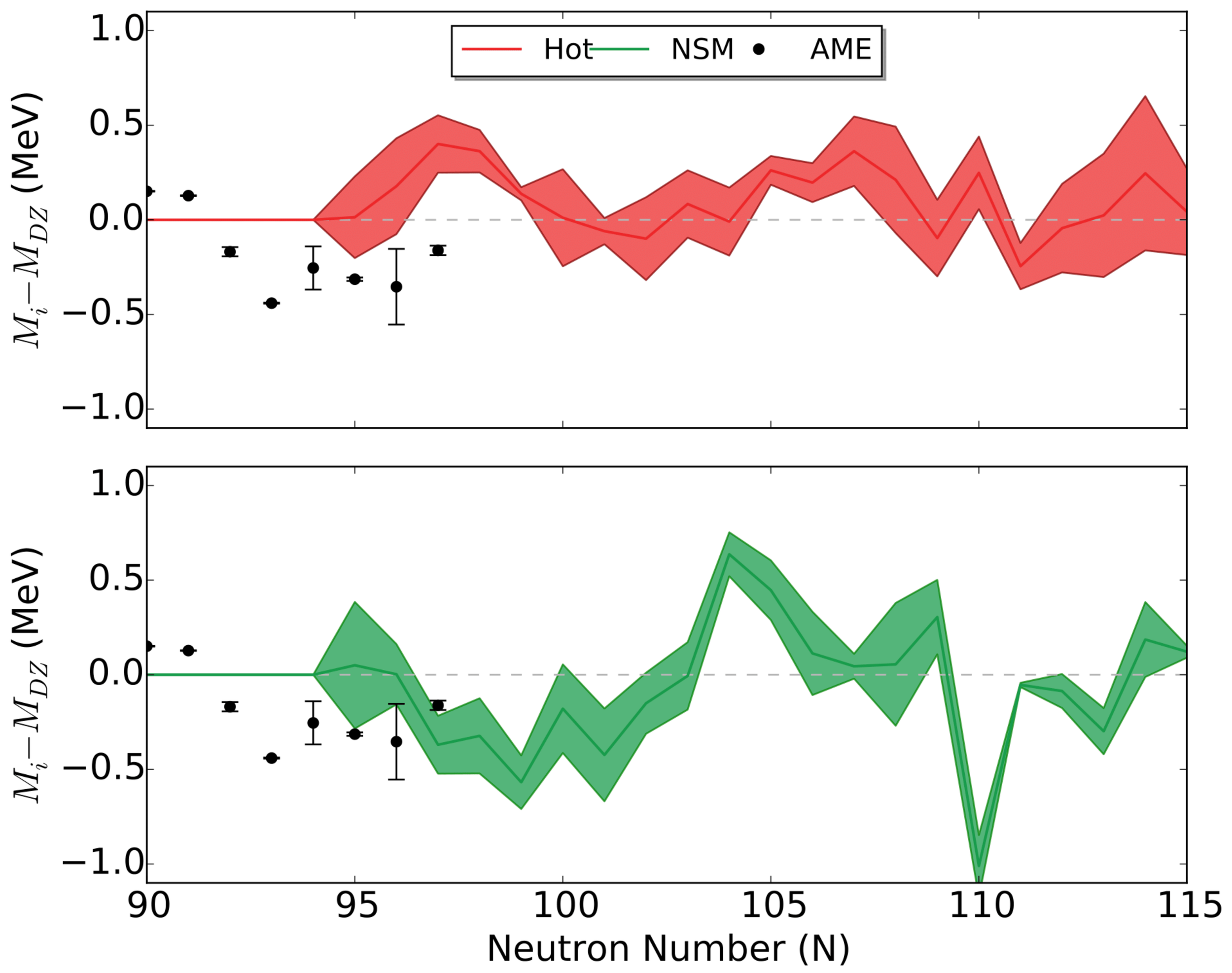


**Figure 4**. Shows the predicted mass surface relative to the DZ mass model along the Z=60 (Nd) isotopic chain.

## Results

### A New Prediction For Unknown Masses

We find that the shape of the mass surface is indeed distinguishable between the two astrophysical conditions, see **Figure 4**.

In the case of a hot *r*-process the change to the masses from DZ is rather small. The local minimum around N~100 is at even-N nuclei and the overall change to the masses requires covers roughly 10 units in N.

In the case of a cold *r*-process the change to masses from DZ is more substantial and the local minimum around N~100 is at odd-N nuclei. We further require a strong modification at N~110 to produce the rare earth peak.

Future measurement campaigns at radioactive beam facilities will help to discover between or rule out these predictions. If measurements fail to find the predicted structure then the only option to form the rare earth peak is via fission recycling, which occurs in compact object mergers. *Thus, future measurements are critical to shed light on the location of the r-process.*

## Summary

- We present a new Monte Carlo method which can be applied to the *r*-process to "reverse engineer" unknown nuclear properties.
- We use this procedure to find the masses necessary to form the rare earth peak in the solar *r*-process abundances.
- We find different mass surfaces depending on the conditions at late-times during freeze-out, see **Figure 4**.
- Future measurements in this region will shed light on the type of environment in which the *r*-process occurred.

## References


[1] M. R. Mumpower, G. C. McLaughlin, and R. A. Surman, Phys. Rev. C **85**, 045801 (2012)
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