



The rare earth peak and the astrophysical location of the r process

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The question of astrophysical site(s) for the rapid neutron capture or r process of nucleosynthesis remains one of the most challenging open problems in all of physics. Neutron star mergers and core collapse supernovae are the leading candidates, but conclusions regarding both are limited by our knowledge of nuclear physics far from stability. Current and future radioactive beam facilities will aid in this endeavor by providing a plethora of new nuclear data information to be used in theoretical simulations. We present a new theoretical framework which, if used in combination with future measurements, will give strong clues to the astrophysical site of the r process.

KEYWORDS: rare earth peak, r -process, nucleosynthesis, nuclear masses, β -decay

1. Introduction

The astrophysical site(s) of the r process still remains an open question which necessitates answers from both nuclear and astrophysics. The uncertain nuclear inputs to the r process are of utmost importance in predicting the final abundances observed in nature [1]. One way to move forward in solving this difficult problem is to try to elucidate the uncertain nuclear physics far from stability which is responsible for key abundance features. A prime candidate for such a study is the rare earth peak (REP), which is believed to be formed during the freeze-out or last stage of the r process when nuclei decay back to stability. The formation of the REP has been shown to be sensitive to both astrophysical conditions and nuclear physics inputs [2–5]. Recently, Monte Carlo studies of nuclear masses have been used in the region to explore the trends required to reproduce the solar REP [6, 7]. In these studies, other nuclear properties (e.g. neutron capture rates and β -decay properties) important during the freeze-out stage of the r process are updated when the mass surface changes. The observational constraint to match the solar isotopic abundances provides an additional benchmark for the uncertain nuclear physics properties where no experimental data exists. The assumptions, approximations and details of the calculations for reverse engineering nuclear properties in the rare earth region responsible for the formation of the peak have been discussed extensively in Refs. [6, 7]. Neutron-rich β -decay rates in the rare earth region play an important role in REP formation. Modern predictions of these rates are in fairly good agreement, showing roughly a factor of 2 deviation between model calculations [8, 9]. We explore the uncertainties in rare earth β -decay rates by re-running our algorithm with systematic rate shifts by a factor of 2 (which is in addition to the modifications of the algorithm based on changes in Q_β). We discuss the influence of systematically slower or faster rare earth β -decay rates on the relative height of the REP and the impact on the predicted mass surface.



2. Results

The relative height of the REP is sensitive to shifts in β -decay rates of the rare earth region as shown in Fig. 1. We find that a systematic shift of a factor of 2 faster β -decay rates in the rare earth region under produces the REP relative to the $A = 195$ peak in both a low entropy hot and very neutron-rich cold trajectories, see [6] for details of the trajectories. In the hot r process, the shift in β -decay rates increases the ratio of $A = 195$ peak to REP to a value of ~ 14 , which is well beyond the solar ratio of ~ 4.7 . In a very neutron-rich cold r process, a slight systematic shift to faster rates, much smaller than a factor of 2 for nuclei in the region, may help to improve the ratio of these two peaks. Slower β -decay rates in the rare earth region are not favored in either case as shown by the squares. We note that the extent fission recycling can also impact the ratio of the heights of the main r -process peaks, see e.g. Refs. [10–14].

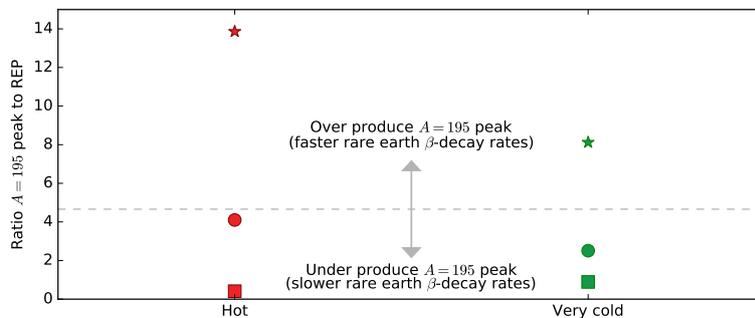


Fig. 1. The ratios of the last two r -process peaks for hot and very neutron-rich cold scenarios. Baseline rare earth β -decay rates shown by circles, stars represents a systematic speed up of the β -decay rates by a factor of 2, and squares a systematic slow down of the β -decay rates by a factor of 2. Solar ratio shown by dotted line.

The β -decay rates of rare earth nuclei also impact the resultant mass surface prediction from reverse engineering as shown in Fig. 2. These two calculations show the mass predictions for the neodymium isotopic chain with a systematic increase of β -decay rates by a factor of 2 and Monte Carlo parameter $C = 60$ held fixed. We find the overall trends in neutron number remain the same as our previous predictions [6, 7], which means the dynamical mechanism for peak formation does not change with faster β -decay rates. However, a more extreme change in the mass surface (larger deviations from DZ) is required to produce the REP which counteracts the faster β -decay rates.

If the Monte Carlo parameter C is allowed to vary with systematically faster rare earth β -decay rates, we find that the center of the mass feature responsible for REP formation shifts further from stability to $C \sim 56 \pm 2.0$. This occurs because the dynamical mechanism for a persistent feature ($f = 40$) seeks to extend the duration of the local pile-up of material in the region as long as possible.

3. Conclusions

We have shown that the formation of the rare earth peak is sensitive to systematic shifts in rare earth β -decay rates. Shifts in β -decay rates can impact the relative height of the rare earth peak as well as the predicted mass surface from our reverse engineering framework. A slight preference is found for faster regional β -decay rates compared to our assumed baseline calculations for both a low entropy hot and very neutron-rich cold r -process. We show that this implies a stronger feature in the rare earth region is required to form the peak. Therefore, future β -decay measurements in this region

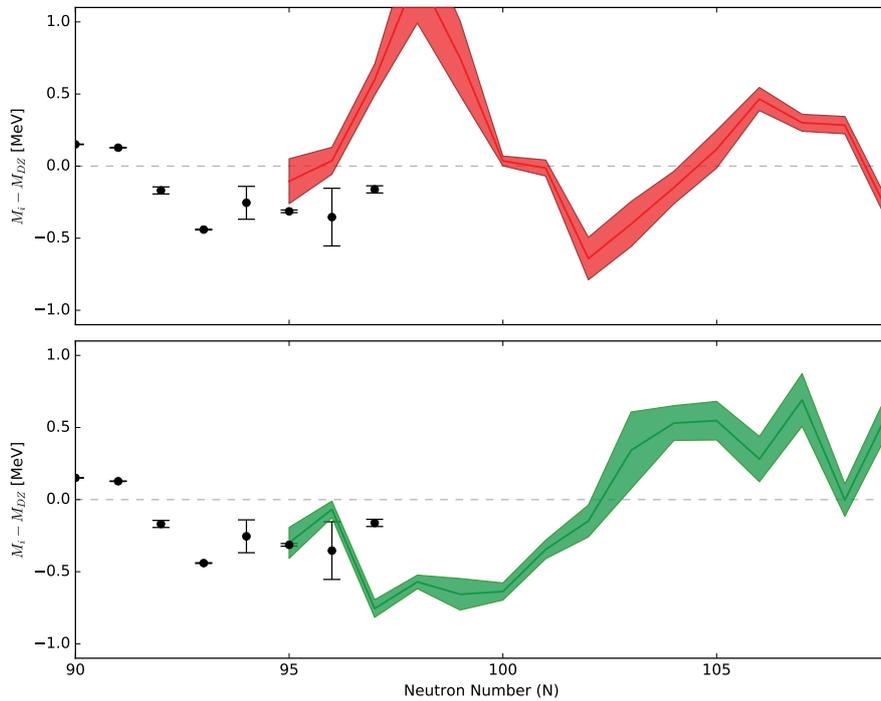


Fig. 2. A more extreme change is needed to the mass surface to produce the rare earth peak for both hot (top) and very neutron-rich cold (bottom) r -process conditions if β -decay rates in the rare earth region are systematically faster by a factor of 2 with Monte Carlo parameter $C = 60$ held constant. Measured masses and their uncertainties from the 2012 AME shown in black [15].

may give the first hints at how the rare earth elements are formed in nature.

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