

## Difficulties in Probing Nuclear Physics: A Study of $^{44}\text{Ti}$ and $^{56}\text{Ni}$

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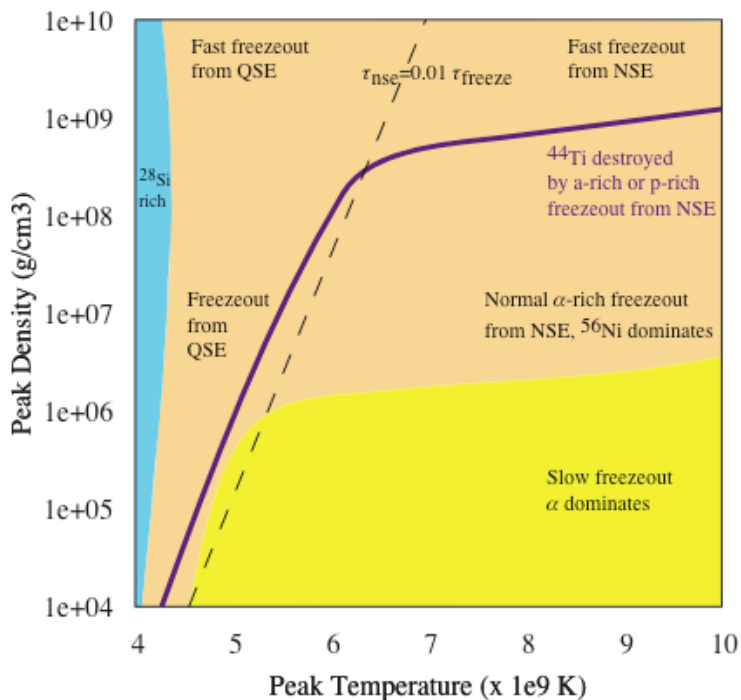
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The nucleosynthetic yield from a supernova explosion depends upon a variety of effects: progenitor evolution, explosion process, details of the nuclear network, and nuclear rates. Especially in studies of integrated stellar yields, simplifications reduce these uncertainties. But nature is much more complex, and to actually study nuclear rates, we will have to understand the full, complex set of processes involved in nucleosynthesis. Here we discuss a few of these complexities and detail how the NuGrid collaboration will address them.

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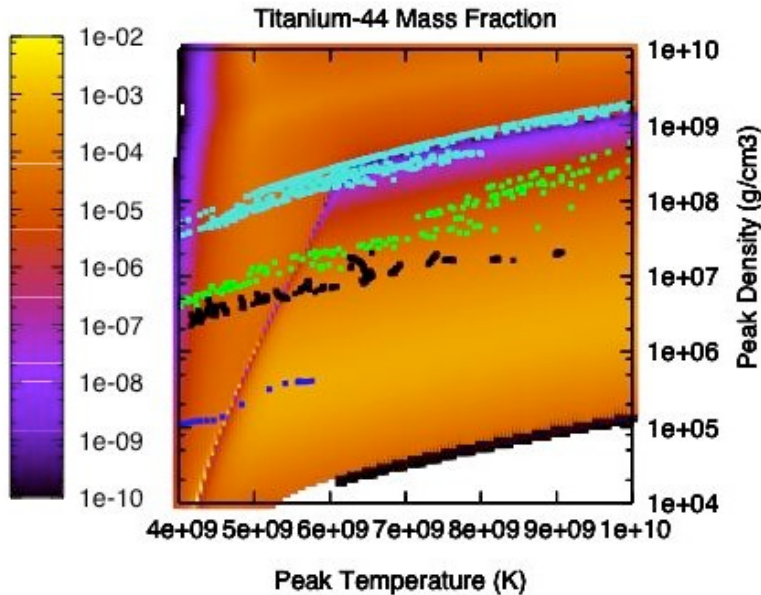


**Figure 1:** A cartoon displaying the key effects in nucleosynthesis for shocked elements focusing on the  $^{44}\text{Ti}$  and  $^{56}\text{Ni}$  yields [2]. Note that the position of the particles determines which effects (fast freezeout, slow freezeout,  $\alpha$ -rich freezeout) occur and this determines the important rates for these yield calculations. The position of the particle used in the The et al. [1] study ( $\rho = 10^7 \text{gcm}^{-3}$ ,  $T = 5.5 \times 10^9 \text{K}$ ) led them to believe one rate was important, but in reality, the trajectories vary tremendously.

## 1. Understanding Key Rates in Astrophysics

The field of nuclear astrophysics is predicated on the belief that astronomers can cull from the tens of thousands of rates a handful of critical rates that define the nuclear yields in astronomy. Although at some level, this is true: rates at some critical weighting points do make a big difference in the yields; for the most part, complications in nucleosynthesis make it very difficult to pick out a single rate. Early astrophysics success in pinpointing specific rates has driven the nuclear physics community to expect that if they solve the rates surrounding a few tens of isotopes, they can solve nuclear astrophysics. But many of these successes that pinpointed specific rates did so because they focused on very specific points in the density/temperature evolution. In nature, the rate pinpointed by these studies may be important for only a small amount of material and, when comparing to observations, they may be completely negligible.

Here we present some of the pitfalls that can occur in determining key rates using our study of the production of  $^{44}\text{Ti}$  and  $^{56}\text{Ni}$  as an example. But the complexity of understanding the role nuclear rates plays on nucleosynthesis spans all discussions of nuclear astrophysics and we present an r-process example as well. Finally, we conclude with the approach that will be taken by the NuGrid team.

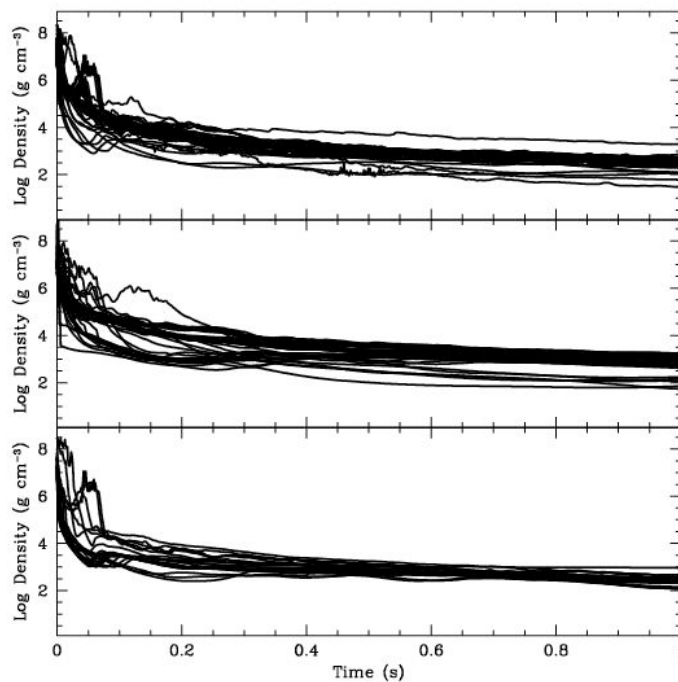


**Figure 2:** A plot of  $^{44}\text{Ti}$  yield on a peak density/temperature grid with points from simulated explosions showing where they lie on this grid. From top to bottom, the points correspond to a magnetohydrodynamic explosion of a collapsar model [3, 4], a rotating 2-dimensional explosion [5], and 2 weak-strong models mimicking fallback gamma-ray bursts [6]. Note that the peak values span the entire trajectory space.

## 2. Understanding $^{44}\text{Ti}$ and $^{56}\text{Ni}$ Production

One example of the complexities in understanding nucleosynthesis is the study of  $\alpha$ -element production and, in particular, the production of  $^{44}\text{Ti}$  and  $^{56}\text{Ni}$ . Let's make the simplifying assumption that the yield of a piece of matter is determined solely by its peak temperature and density. Figure 1 is a cartoon of the peak density/temperature space generally studied in explosive nucleosynthesis. The et al. [1] did exactly this analysis, focusing on a single peak temperature/peak density: ( $\rho = 10^7 \text{gcm}^{-3}$ ,  $T = 5.5 \times 10^9 \text{K}$ ). This density/temperature pair lies directly on the boundary of two different effects. As such, a single rate might change the yield by a large amount and The et al. [1] found that the triple- $\alpha$  rate changed the yield dramatically. But elsewhere on this diagram, the triple- $\alpha$  rate is unimportant. Unless we can assume all explosions produce elements only at a single point, studying that single point will provide us with a skewed set of important rates.

We have begun a more systematic study of this entire grid. A first step might be to determine what peaks are common in supernova explosions. Figure 2 again shows a plot of our peak density/temperature grid with overlying points for 4 different explosion calculations. As one can see, they span a wide part of this grid. Not only are the points from different explosion models spread in peak temperatures and densities, the points within each explosion model possess a range of electron fractions for the fluid element represented. Magkotsios et al. 2008 provide a more detailed view of the added complication from variation in electron fraction (these proceedings.) It appears that the supernova conditions will not permit a narrowing of the important parameter space and an understanding of the entire space is ultimately needed.

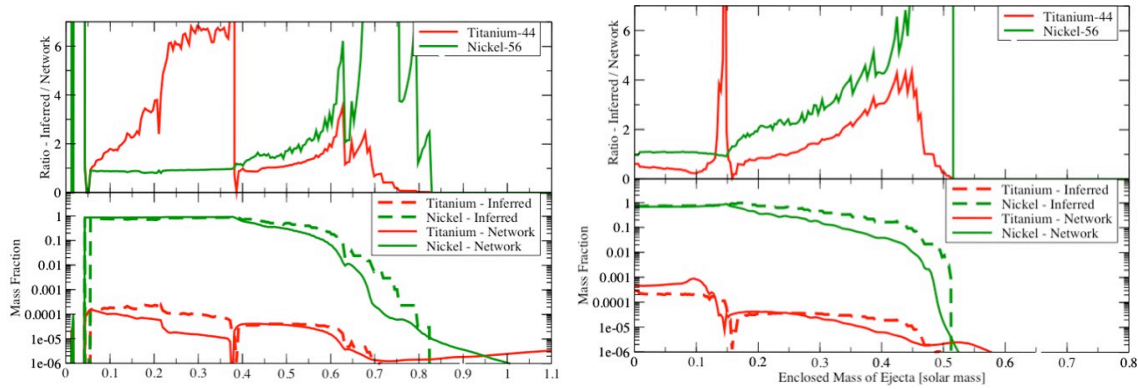


**Figure 3:** Density versus time for 3 sets of particles: high entropy (top), low entropy (middle) and particles that produced reasonable amounts of third r-process peak isotopes (bottom). The zero point on the time axis is set to the time when the density reaches its maximum value (generally corresponding to the peak temperature as well). It is very difficult to distinguish the peak densities from each other and it has not yet been determined what path is required to make the r-process.

With our simplifying assumption that we can determine everything from a single peak density/temperature pair, the problem of determining a yield (and the most crucial rates for that yield) presents us with considerable work studying the entire grid space. But, for some problems, the work doesn't end there. Our simplifying assumption is not true for all nucleosynthetic problems. In the study of nuclear rates of r-process, most scientists have focused on the reactions and trajectories behind wind-driven supernovae. Again, this is a too-narrow view and scientists working outside of this narrow view have discovered an entirely new nucleosynthetic path (or paths) to make r-process [9, 7, 8]. Unfortunately, these new paths depend on the subsequent evolution of the cooling matter as well as the peak temperature/density. Figure 3 shows density trajectories for matter that did not make the r-process peak and matter that did [8]. Matter with the same peaks produced very different yields. Even worse, it is not clear what trajectory is required to make r-process isotopes.

### 3. NuGrid Plans

With all of these complexities, it would seem impossible to actually understand astrophysical explosions and nuclear networks sufficiently well to actually determine what rates are important. But without trying, we will definitely not solve this problem. In many cases, the peak tempera-



**Figure 4:**  $^{56}\text{Ni}$  and  $^{44}\text{Ti}$  yields as a function of enclosed mass for two different stellar explosions. We compare the yields from the standard post-process network (solid lines) to those inferred using peak densities and temperatures. The good agreement means that we can use these peak density/temperature diagrams to improve our intuition about nuclear network yields.

ture/density studies produce results that are very close to studies that follow trajectories (Fig. 4) and we can use these simple studies to develop our intuition. But in the long run, we'll have to approach this from all angles: studies of simplified problems, like the density/temperature peak diagrams and their production tracks, studies of temperature/density evolution tracks to better understand which tracks produce what matter, and finally, integrated yield studies (the more common study) to compare to observations. One approach alone will not work. NuGrid is developing a suite of tools ideally suited for all these studies and our collaboration will approach this problem from all directions.

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