Heavy Element and Neutron-Rich Isotope Production in Neutron Star Mergers

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Abstract:

Background: The commonly accepted process by which elements heavier than iron are formed is through the r-process in supernovae, however it is becoming more and more clear that this accounts for only a small fraction of the abundances of some elements. Due to the neutron-rich environments from the collisions in neutron star mergers, it is hypothesized that they could trigger the nucleosynthesis required to account for the rest of the observed abundances. In addition to helping explain element abundances, neutron star mergers are excellent for studying the production of neutron-rich isotopes. Due to the neutron-rich enviroment, the r-process theoretically proceeds very near the neutron drip line, which is unexplored territory for current Earth-based research. **Purpose:** Determine where the majority of heavy elements are sythesized and study neutron-rich isotopes near the neutron drip line. **Methods:** Currently, nearly all work in this field is theoretical. Models and simulations have been developed that can predict the nucleosynthesis in the aftermath of neutron star mergers. However, with the new era of accelerators, this field may be shifting from theory to application. New accelerators should allow nuclear astrophysicists to study the reactions in neutron star mergers. **Results:** Computational simulations of neutron star mergers show that elements are produced in nearly the same relative abundances as observed in the universe. Coupled with the estimated rate of neutron star mergers, these simulations provide strong evidence that neutrons star collisions are the primary source of many heavy elements. **Conclusions:** From these studies it appears that we have a much better understanding of where heavy elements come from; they are the result of the r-process in neutron star mergers. Once new, more powerful, accelerators are built, we will be able to more accurately test these models.

I. INTRODUCTION

Nuclear fusion in stars produces elements as heavy as iron, however beyond this point energy is required to synthesize heavier elements. Yet elements heavier than iron are present in the universe, and the search for how and where these elements form has been one of the major questions in nuclear physics. These heavier elements are known to be produced in supernovae through the rapid neutron capture process (r-process), but this does not account for the total amount of heavy elements that we observe. In fact, supernovae are responsible for only a fraction of the abundances of many elements and recent studies have shown that neutron star mergers may be responsible for a large portion of the remaining heavy element production (Korobkin et al. 2012).

In addition to potentially explaining the abundances of heavy elements in the universe, neutron stars are an excellent location to search for rare neutron-rich isotopes. Under normal circumstances, extremely neutron-rich isotopes are always unstable and will beta decay into stable and less neutron-rich isotopes. However, neutron star crusts, with their high neutron density and low temperature, have ideal conditions for production of neutron-rich isotopes. Some isotopes that are normally highly unstable on Earth suddenly become stable when placed in the environment of neutron star crusts (Schatz 2008). With the ability to explain the abundances of heavy nuclei and the possibility of studying super neutron-rich isotopes, neutron stars are one of the most promising areas of study in nuclear physics.

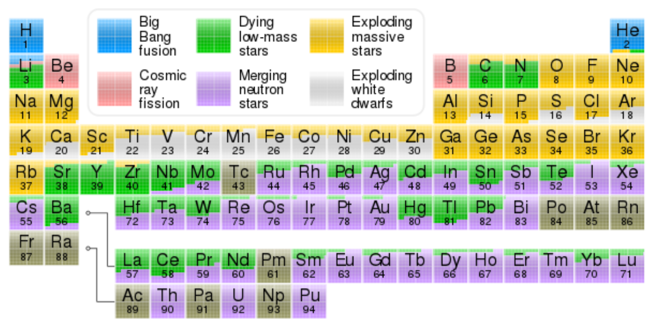

FIG. 1. A periodic table showing the origin of the elements. Supernovae (yellow) produce nearly all of the heavy elements not much more massive than iron, however they contribute very little to elements heavier than rubidium. Recent studies show that neutron star mergers (purple) can account for the observed abundances of the elements heavier than rubidium.

In section II, I will give a brief overview of neutron stars and their structure, highlighting the structure of the crust that allows for the r-process to occur in mergers. In section III, I will explain the process of neutron star mergers and discuss why they are an ideal place for heavy element nucleosynthesis. I will highlight a computaional model that yields relative abundances very near the observed values. In section IV, I will discuss the process by which neutron-rich isotopes are formed in neutron star mergers and the opportunity to study them. In section V, I will provide information on future research attempting to study the processes occuring in neutron star mergers, highlighting the new era of accelerators capable of reaching the energies necessary to study the reactions in neutron star mergers.

II. NEUTRON STAR STRUCTURE

Neutron stars are super dense stars that are the result of the supernovae of massive stars. Despite only having a radius of about 10 km, most neutron stars are between 1.4 and 2.1 solar masses. As their name suggests, neutron stars are composed mainly of neutrons, and are supported from gravitation collapse by neutron degeneracy pressure. Neutron stars are generally divided into five layers: from the core to the surface they are the inner core, outer core, mantle, inner crust, and outer crust.

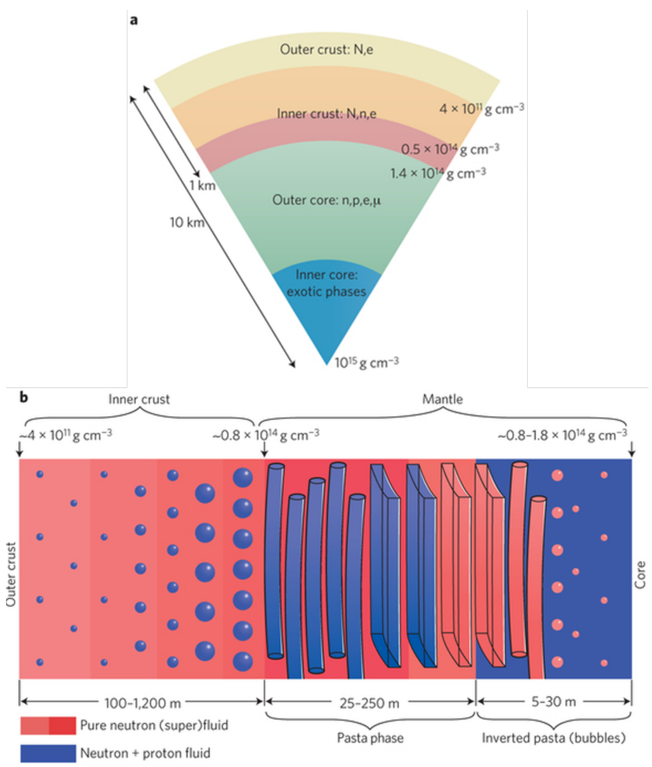

FIG. 2. Neutron star structure. Top: cross section of a neutron star, showing the five layers and what they are composed of. Bottom: enlargement of the mantle and inner crust showing the prevalence of neutrons in the crust, which are critical in the r-process during a merger event.

The inner core is theorized to be composed of exotic phases such as quark-gluon plasma, however this is still just theory. The outer core is composed of neutron-proton fluid. Beyond the core, in the mantle, is a structure called nuclear pasta, where nuclear attraction and Coulomb repulsion are approximately equal (Pons et al. 2013). The inner crust is dominated by neutrons, with some nuclei and electrons also present. Lastly, the outer crust is composed of nuclei that have been compressed into a super strong solid lattice, where electrons are allowed to move throughtout the lattice structure (Beskin 1999). Compared to the rest of the neutron star, the crust is relativley cool. The fact that nuclei are densely packed in the crust at a relatively low temperature is critical for the r-process to occur.

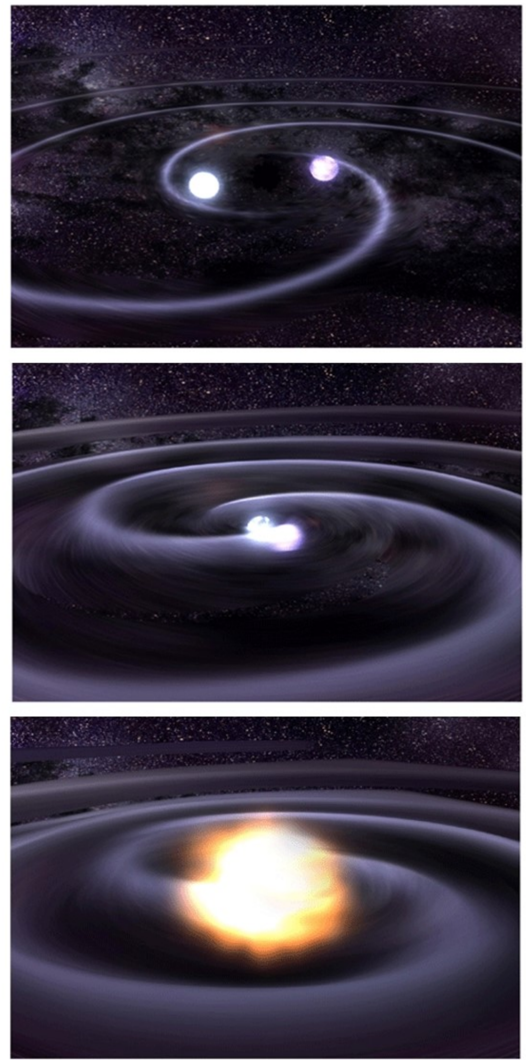

FIG. 3. Artists depiction of the collision of two neutron stars. Top: neutron stars spiraling inward toward each other. Middle: crusts meet as the collision occurs. Bottom: the shower of nuclei and neutrons that begin the r-process.

III. NEUTRON STAR MERGERS

Two neutron stars which are orbiting can begin spirally inward toward their combined center of mass due to gravity. As they both approach the center of mass, the neutron stars will collide violently. This collision ejects a shower of the neutrons and nuclei which made of the crusts of the neutron stars. The nuclei capture the free neutrons and then beta decay, continually growing more massive through the r-process. The r-process is the same process that produces heavy elements in supernovae, however neutron star mergers are the more likely source of many heavy elements. For neutron capture to proceed sufficiently fast for the r-process, the region in which it is occuring must be very neutron rich. Since neutron stars are composed primarily of neutrons, neutron star collisions are theoretically a much better environment for neutron capture than supernovae.

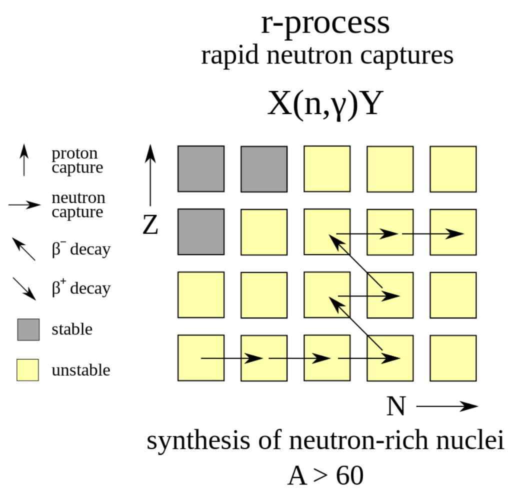

FIG. 4. Diagram showing the r-process. Nuclei capture free neutrons (right on the diagram) until beta decay, where a neutron turns into a proton, occurs (diagonally up to the left on the diagram). These processes keep happening, increasing the atomic number and mass number of the nuclei.

If this is how we are to explain the abundances of heavy elements, then we must answer three questions: (1) How common are neutron star mergers? (2) How much mass is ejected per merger event? and (3) What are the relative abundances of these events? The best estimate for neutron star merger rate is approximately 10^{-5} events per year per galaxy (Bethe et al. 1998). In addition, according to Beniamini et al. (2016), 90 percent of binary neutron star systems collide within 300 million years and 15 percent collide in only 100 million years. Models from Rosswog et al. (1999) predict that about 10^{-3} to 10^{-2} solar masses are ejected in neutron star mergers. The predicted merger rate and ejection mass is sufficient to account for the total abundance of heavy elements, leaving only the relative abundances to be determined.

Computational models of nucleosynthesis in neutron star mergers from Korobkin et al. (2012) match the observed abundances very well. Twenty-one binary neutron star systems, with neutron stars ranging from 1.0 to 2.0 solar masses, were tested. The collisions of these systems were simulated and the nucleosynthesis which followed was tracked throughout the process. The model, which has the ability to discern over 5800 isotopes yielded results that compare favorably with current best estimates

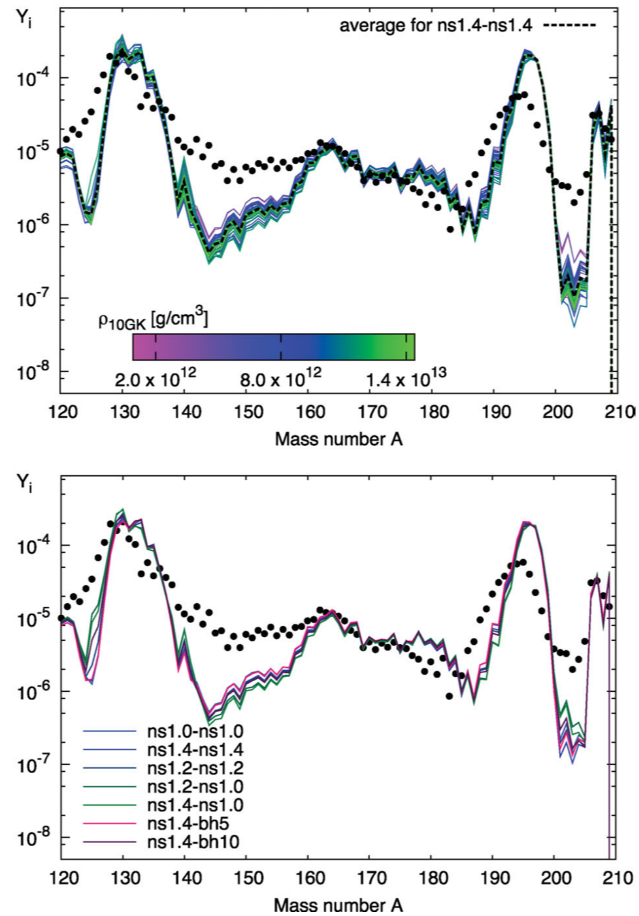

FIG. 5. Results from simulation done by Korobkin et al. (2012). Top: relative abundances of mass number 120 to 210 elements ejected from the collision of two 1.4 solar mass neutron stars. The black dotted line is the observed abundance. Bottom: Same type of plot as above, but this time comparing the relative abundances from different neutron star systems. From the plot, the abundances are not dependant upon the neutron star masses.

of the abundances of elements in the universe. Figure 5 presents the results of this study.

IV. RARE ISOTOPE PRODUCTION

Isotopes are two forms of the same element (defined by the number of protons) that have different numbers of neutrons. About 250 of them are considered stable (black in the chart in figure 6), and so far, about 3000 nuclides have been experimentally confirmed (yellow in the chart in figure 6). However, there is a large region of space between the edge of the experimentally confirmed isotopes and the neutron drip line known as the terra incognita, shown as green in figure 6. In the neutron-rich environment around neutron star collisions, neutron capture happens much faster than beta decay, allowing nuclides in the terra incognita to form.

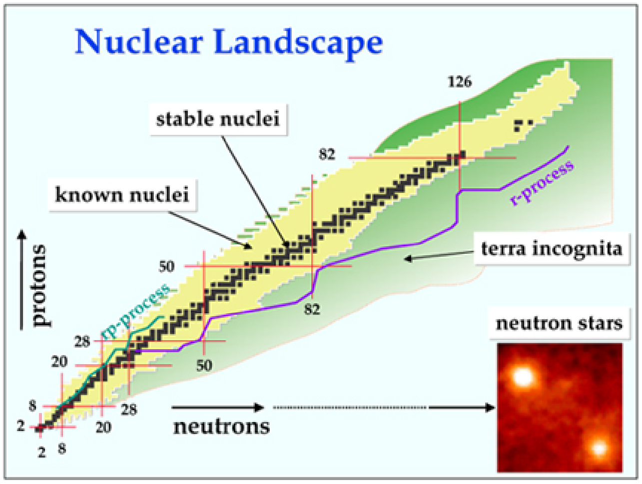

FIG. 6. Current nuclear landscape. Black isotopes are stable, yellow have been experimentally determined, and green is the unexplored region. The r-process travels through this unexplored region, so studying neutron stars will yield information about neutron-rich isotopes in this region.

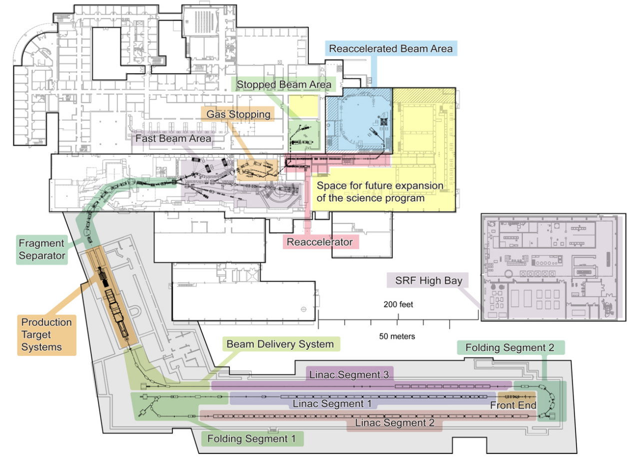

FIG. 7. Diagram of the Facility for Rare Isotope Beams (FRIB). FRIB will help nuclear astrophysicist recreate the environment of neutron star mergers.

The nuclides most likely to form during a neutron star merger will be along the path of the r-process. To determine how the r-process proceeds (its isotope path), we must consider the average neutron separation energy:

$$< S_n >= \frac{\sum_{Z,A} S_n(Z,A)Y(Z,A)}{\sum_{Z,A} Y(Z,A)} \tag{1}$$

Here S_{n}(Z,A) is the neutron separation energy and Y(Z,A) is the abundance. Using the neutron separation energy equation and the model from Korobkin et al. (2012), it is possible to predict the path that the r-process will follow. In this model, the initial neutron separation energy is about 1 MeV, so the r-process proceeds very near the neutron drip line. The process continues along the neutron drip line until it reaches a magic number, where it moves toward larger neutron separation energy through beta decay. This pattern continues for the range of nuclides in the model. Therefore, any tests confirming this model should show a similar pattern.

V. OUTLOOK

Historically, testing the theories and subsequent computational models regarding neutron star mergers has been nearly impossible. Neutron stars are already difficult to observe, and with mergers taking on average over 100 million years to occur, catching a pair of neutron stars in the act is highly unlikely. In addition, our current accelerators are unable to reach the energies required to probe the processes in neutron star collisions.

Fortunately, those times may be in the past, as new accelerators are being built that can reach the necessary energies. The Facility for Rare Isotope Beams (FRIB), which is currently under construction at Michigan State University is one such accelerator. FRIB will have 400 kW, 200 MeV per nuleon heavy-ion linear accelerators with capabilities for fast, stopped, and reaccelerated beam experiments. In terms of energy and diversity of possible experiments, upon its completion in 2022 it will be unmatched anywhere in the world. Using FRIB, nuclear astrophysicists will be able to recreate the environments present in neutron star collisions and test their results against the simulations presented in this paper. Other accelerators under construction are the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany and the Heavy Ion Accelerator Facility (HIAF) in Lanzhou, China. HIAF, once completed is planned to have an intensity four times greater than that of FRIB.

One of the main functions of these accelerators will be to test the theories and models of neutron star mergers. With their help, nuclear astrophysicists will be able to experimentally measure elemental abundances of reactions just like those that occur in the environment around neutron star mergers. In addition, new neutron-rich isotopes will be made along the r-process line, allowing nuclear physicists to study nuclei closer to the neutron drip line than ever before

VI. SUMMARY AND CONCLUSIONS

One of the cornerstone questions in nuclear physics is where did the heavy elements that we observe in the universe come from. It was initially thought that they were mainly the result of supernovae explosions, however recent research has made this claim seem incredibly unlikely. Many super heavy elements are too abundant to be the result of supernovae, so it was hypothesized that neutron mergers were responsible for a large fraction of the abundances of heavy elements. Estimations of neutron star merger rates from (Bethe et al. 1998) and ejecta masses from Rosswog et al. (1999), along with computational models from Korobkin et al. (2012) and others confirm this hypothesis, adequately predicting the observed abundances.

Neutron star mergers are also ideal for the production of super neutron-rich isotopes. Due to the large concentration of neutrons in the aftermath of a neutron star collision, neutron capture happens far quicker than beta decay in the r-process. Therefore, the r-process happens along the neutron drip line in the terra incognita (Roser 2014).

The development of more powerful accelerators in the near future will allow experimental nuclear astrophysicists to probe the processes happening in neutron star mergers, allowing them to better understand where the heavy elements we see in the universe came from. These accelerator should also have enough energy to explore the terra incognita, where the r-process in neutron star mergers occurs. Not only will this add more isotopes to the chart of nuclides, it will allow theorists to improve their models. Without a doubt, the study of neutron star mergers is one of the most exciting and promising fields in nuclear physics, as it attempts to explain the origin of the heavy elements we know and love, as well as help us better understand rare neutron-rich nuclides.

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