Recent Progress in Understanding Nucleosynthesis via Rapid Neutron Capture

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Abstract. I discuss the recent progress in our understanding of nucleosynthesis via rapid neutron capture, the r-process, based on meteoritic data for the early solar system and observations of stars at low metallicities. At present, all data require that there be two distinct kinds of r-process events and suggest that supernovae are associated with these events. The diversity of supernova sources for the r-process may depend on whether a neutron star or black hole is formed in an individual supernova. This dependence, if substantiated by future observations discussed here, has important implications for properties of nuclear matter.

INTRODUCTION

The grand scheme for production of various elements was set down more than forty years ago [1,2]. Within this grand scheme, approximately half of the heavy elements with mass numbers $A > 100$ in the solar system were produced via rapid neutron capture, the r-process. A crude picture for the r-process is as follows. One starts with some seed nuclei and lots of neutrons. The seed nuclei then rapidly capture these neutrons to make very neutron-rich unstable progenitor nuclei. After neutron capture stops, the progenitor nuclei successively $\beta$-decay towards stability and become the r-process nuclei observed in nature. For a given species of seed nuclei with mass number $A_s$, the group of nuclei produced by the r-process are determined by the number of neutrons per seed nucleus, or the neutron-to-seed ratio $n/s$, at the beginning of the r-process. The average mass number of the produced r-process nuclei is $\langle A \rangle = A_s + n/s$.

There are two prominent peaks at $A = 130$ and 195, respectively, in the solar r-process abundance pattern. In order to produce the peak at $A = 130$, we need $n/s \sim 40$ if we start from seed nuclei with $A_s \sim 90$. By comparison, if we start with the same seed nuclei but a higher $n/s \sim 90$, the r-process dominantly produces nuclei with $A > 130$, including the peak at $A = 195$. In general, an astrophysical event would eject, for example, a certain amount of r-process material with $n/s \sim 40$ plus some other amount with $n/s \sim 90$. The ratio of these two amounts then
determines the overall $r$-process abundance pattern produced by this event. A natural question is whether every $r$-process event produces the same abundance pattern or there should be distinct kinds of events producing very different $r$-process abundance patterns. In other words, we would like to know whether the solar $r$-process abundance pattern is produced by every $r$-process event or just reflects a mixture of different patterns produced by distinct kinds of events. In either case, we also would like to know which astrophysical objects are associated with the $r$-process.

Here I discuss the progress that we have made recently in answering the above questions. The answers to these questions have important implications for properties of neutrinos, nuclei far from stability, and nuclear matter. I discuss the implications for properties of nuclear matter in particular.

**METEORITIC DATA AND DIVERSE SUPERNOVA SOURCES FOR THE $R$-PROCESS**

The meteoritic data on the inventory of radioactive nuclei in the interstellar medium (ISM) at the time of solar system formation play an essential role in our understanding of the $r$-process. Because a radioactive species decays after it is produced, a finite abundance ratio of a radioactive species to a stable one in the ISM has to be maintained by a series of production events. Consequently, from the measured abundance ratio of a radioactive species to a stable one, we can infer how frequently the radioactive species was replenished in the ISM. We have data on two radioactive nuclei: $^{129}$I (e.g., [3]) and $^{182}$Hf (e.g., [4]), which are below and above $A = 130$, respectively. If the data indicate that these two species were injected into the ISM at very different frequencies, then the $r$-process nuclei below and above $A = 130$ must be produced by distinct kinds of events. It was found that over the Galactic history of $\approx 10^{10}$ yr before solar system formation, $^{182}$Hf injection occurred at a high frequency $f_H \sim (10^7 \text{ yr})^{-1}$, while $^{129}$I injection occurred at a low frequency $f_L \sim (10^8 \text{ yr})^{-1}$ [5,6]. Therefore, these are distinct kinds of events.

The frequencies of $^{129}$I and $^{182}$Hf injection into the ISM inferred from meteoritic data can be naturally explained by associating supernovae with the $r$-process. A supernova remnant expands to a final radius of $\sim 100$ pc over a period ($\sim 10^6$ yr) much shorter than the lifetime ($\sim 10^7$ yr) of $^{129}$I or $^{182}$Hf. Therefore, if we consider a spherical region of $\sim 100$ pc in radius surrounding an average point in the Galaxy, any supernova within this region can inject fresh radioactive $^{129}$I or $^{182}$Hf to this point after it is produced by the supernova. For a supernova frequency of $\sim (30 \text{ yr})^{-1}$ over the Galactic volume of $\sim 10^3 \text{ kpc}^3$, the corresponding frequency in this spherical region is $\sim (10^7 \text{ yr})^{-1}$. Therefore, the meteoritic data on $^{129}$I and $^{182}$Hf can be explained if we associate the most common supernovae with the $r$-process events producing $^{182}$Hf and a rarer kind with those producing $^{129}$I [5–7].

Because $^{129}$I is produced together with nuclei at $A \leq 130$ and $^{182}$Hf with those at $A > 130$, we conclude that the overall solar $r$-process abundance pattern is
composed of two basic templates characteristic of two distinct kinds of \( r \)-process

events. These are referred to as the \( \mathcal{H} \) and \( \mathcal{L} \) events hereafter, where \( \mathcal{H} \)

stands for the “high” frequency events responsible for “heavy” \( r \)-process nuclei with \( A > 130 \) including \(^{182}\text{Hf} \) and \( \mathcal{L} \) for the “low” frequency events responsible for “light” \( r \)-process nuclei with \( A \leq 130 \) including \(^{129}\text{I} \). An average ISM is enriched in \( r \)-process elements at a frequency \( f_\mathcal{H} \sim (10^7 \text{ yr})^{-1} \) by the \( \mathcal{H} \) events and at a frequency \( f_\mathcal{L} \sim (10^8 \text{ yr})^{-1} \) by the \( \mathcal{L} \) events.

**ABUNDANCES OF \( R \)-PROCESS ELEMENTS IN METAL-POOR STARS**

The influence of the \( \mathcal{H} \) and \( \mathcal{L} \) events is best preserved in metal-poor stars formed very early in the Galaxy when only a small number of supernovae had contributed to the \( r \)-process and “metal” abundances in these stars. The typical heavy \( r \)-process elements observed in these stars are Ba and Eu, and the typical light \( r \)-process elements observed are Pd, Ag, and Cd. The observational data are usually given in the spectroscopic notation, e.g., \( \log \epsilon(\text{Eu}) = \log(\text{Eu}/\text{H}) + 12 \) for Eu, where \( \text{Eu}/\text{H} \) is the number abundance ratio of Eu to hydrogen observed in a star. A typical metal is Fe, and the “metallicity” is defined as \( [\text{Fe}/\text{H}] = \log(\text{Fe}/\text{H}) - \log(\text{Fe}/\text{H})_\odot \), where \( (\text{Fe}/\text{H})_\odot \) is the Fe/H ratio in the sun. As the overall abundance of hydrogen has not changed significantly over the history of the universe, hydrogen is a good reference element for considering chemical enrichment of the ISM.

Over the period of \( \approx 10^{10} \text{ yr} \) before solar system formation, an average ISM was enriched in the heavy \( r \)-process elements by \( \sim 10^3 \mathcal{H} \) events and in the light ones by \( \sim 10^2 \mathcal{L} \) events. The \( r \)-process composition of the ISM at the time of solar system formation is reflected by the corresponding solar abundances. Consequently, the \( r \)-process abundances resulting from a single \( \mathcal{H} \) or \( \mathcal{L} \) event (quantities with the subscript “\( \mathcal{H} \)” or “\( \mathcal{L} \)” can be predicted directly from the solar system data (quantities with the subscript “\( \odot \), \( r \)”). For example, we have \( (\text{Eu}/\text{H})_{\odot,r} \sim 10^3(\text{Eu}/\text{H})_\mathcal{H} \), and hence \( \log \epsilon_\mathcal{H}(\text{Eu}) \sim \log \epsilon_{\odot,r}(\text{Eu}) - 3 \approx -2.5 \). Likewise, we have \( (\text{Ag}/\text{H})_{\odot,r} \sim 10^2(\text{Ag}/\text{H})_\mathcal{L} \), and hence \( \log \epsilon_\mathcal{L}(\text{Ag}) \sim \log \epsilon_{\odot,r}(\text{Ag}) - 2 \approx -0.8 \).

Figure 1 shows the Eu data for many metal-poor stars \([9–12]\). The very low metallicities of these stars indicate that they were formed very early in the Galaxy. The band labeled “1 \( \mathcal{H} \)” corresponds to the Eu abundance resulting from a single \( \mathcal{H} \) event predicted by the meteoritic data on \(^{129}\text{I} \) and \(^{182}\text{Hf} \) as well as the solar \( r \)-process abundances of stable nuclei \([6,8]\). If we pick the centroid of this band, the observed Eu abundances can be explained by contributions from \( \sim 1–30 \mathcal{H} \) events, quite consistent with the corresponding low metallicities.

Figure 2 shows the remarkable data on a number of \( r \)-process elements for one of the stars shown in Figure 1, CS 22892–052 \([13]\). The dashed curve labeled “TS” is the solar \( r \)-process abundance pattern translated to match the data on the heavy \( r \)-process elements. Clearly, this curve cannot match the data on the light \( r \)-process elements. Therefore, the conclusion from the meteoritic data that...
there should be two distinct kinds of r-process events is independently confirmed by stellar observations at low metallicities. The Eu abundance in CS 22892–052 can be explained by \( \sim 30 \) \( r \)-events. However, with a frequency ratio of \( \sim 10 : 1 \)

**FIGURE 1.** Europium data for metal-poor stars (asterisks: [9], squares: [10], triangles: [11,12]) compared with the Eu abundance resulting from a single \( r \)-event (the band labeled “1 \( r \)”)

predicted in [6,8].

**FIGURE 2.** Comparison of data for CS 22892–052 with (1) the solar \( r \)-process abundance pattern translated to match the Eu data (dashed curve), and (2) the result from a mixture of two distinct kinds of \( r \)-process events (solid curve).
between $\mathcal{H}$ and $\mathcal{L}$ events, it is very likely that one $\mathcal{L}$ event also occurred during a period over which $\sim 30 \ \mathcal{H}$ events took place. Indeed, a mixture of $26 \ \mathcal{H}$ events and $1 \ \mathcal{L}$ event (solid curve in Fig. 2) can explain all the data rather well [6].

**NEUTRON STAR/BLACK HOLE FORMATION AND SUPERNOVA $r$-PROCESS NUCLEOSYNTHESIS**

So far, the questions raised in the introduction have been answered. It is found that there are distinct kinds of $r$-process events and that they are associated with supernovae. This leads to a new question: what is causing the difference between these supernova $r$-process events? The answer to the new question may be obtained by further studying $r$-process enrichment of the Galaxy by supernovae. The present Galactic inventory of either the light $r$-process nuclei ($100 \lesssim A \lesssim 130$) or the heavy ones ($A > 130$) is $\sim 4 \times 10^{33} M_\odot$. Assuming a frequency of $\sim (30 \text{ yr})^{-1}$ over the whole Galaxy in its history of $\approx 10^{10}$ yr for the supernovae associated with $\mathcal{H}$ events and a $\sim 10$ times less frequency for those associated with $\mathcal{L}$ events, we find that in order to account for the present Galactic $r$-process inventory, each supernova has to eject only $\sim 10^{-5} M_\odot$ ($\mathcal{H}$ event) to $\sim 10^{-4} M_\odot$ ($\mathcal{L}$ event) of $r$-process material. By comparison, the total amount of ejecta from a supernova is $\sim 10 M_\odot$ and the mass of the neutron star produced in a supernova is $\sim 1 M_\odot$. Despite the striking difference from these comparison mass scales, $\sim (10^{-5} - 10^{-4}) M_\odot$ of material can be naturally ejected by the neutrinos emitted in a supernova.

A supernova occurs when the core of a massive star at the exhaustion of its nuclear fuel collapses into a compact neutron star. The neutron star has a final radius of $\sim 10$ km, and a gravitational binding energy of $\sim 10^{53}$ erg is to be released. Due to the high temperatures and densities encountered during the collapse, the most efficient way to release this energy is to emit all three flavors of neutrinos and antineutrinos mainly through electron-positron pair annihilation. In fact, because of the intense scatterings on neutrons and protons common to all neutrino species, even neutrinos have to diffuse out of the neutron star on a timescale of $\sim 10$ s (as confirmed by the detection of neutrinos from SN 1987A). So the average neutrino luminosity is $\sim 10^{51}$ erg s$^{-1}$ per species.

A few seconds after the core collapse and the subsequent supernova explosion, we have a hot neutron star near the center of the supernova. The neutron star is still cooling by emitting neutrinos. The shock wave which makes the supernova explosion is far away from the neutron star. On its way out to make the explosion, the shock wave has cleared away almost all the material above the neutron star, leaving behind only a thin atmosphere. Close to the neutron star, the temperature is several MeV and the atmosphere is essentially dissociated into neutrons and protons. As the neutrinos emitted by the neutron star free-stream through this atmosphere, some of the $\nu_e$ and $\bar{\nu}_e$ are captured by the neutrons and protons and their energy is deposited in the atmosphere. In other words, the atmosphere is heated by the neutrinos. As a result, it expands away from the neutron star and
eventually develops into a mass outflow — a neutrino-driven “wind” [14].

Because neutrino heating is driving the mass ejection, the fraction of neutrino luminosity absorbed by the wind material determines the rate at which it is being lifted out of the neutron star gravitational potential. As neutrinos interact weakly, the heating rate is small. On the other hand, the neutron star is a compact object and has a deep gravitational potential. Consequently, we expect that the mass ejection rate is small. Indeed, the typical mass ejection rate in the wind was found to be $\sim 10^{-5} M_\odot \ s^{-1}$ [15]. So provided that $r$-process nuclei are produced in the neutrino-driven wind, the wind has to last $\sim 1$ s in an $\mathcal{H}$ event and $\sim 10$ s in an $\mathcal{L}$ event in order to account for the present Galactic $r$-process inventory. Note that neutrino emission from a stable neutron star, and hence the corresponding neutrino-driven wind, last $\sim 10$ s. In order for a wind to last only $\sim 1$ s, neutrino emission has to be terminated $\sim 1$ s after the supernova explosion by transformation of the neutron star into a black hole [7]. Therefore, the difference between the $\mathcal{H}$ and $\mathcal{L}$ events may depend on whether a black hole ($\mathcal{H}$ event) or neutron star ($\mathcal{L}$ event) is formed in an individual supernova.

**CONCLUSIONS**

In summary, meteoritic data on $^{129}$I and $^{182}$Hf require two distinct kinds of $r$-process events: the high frequency $\mathcal{H}$ events responsible for heavy $r$-process nuclei ($A > 130$) and the low frequency $\mathcal{L}$ events responsible for light ones ($100 \lesssim A \leq 130$). The meteoritic data also suggest that supernovae are associated with $\mathcal{H}$ and $\mathcal{L}$ events. These conclusions are either confirmed by or at the very least consistent with observations of $r$-process abundances in metal-poor stars.

If future studies can show that $r$-process nuclei are produced in the neutrino-driven wind in a supernova (see e.g., [15–25] for the current unsatisfactory status), then the amount of material required to account for the present Galactic $r$-process inventory can be adequately provided by the wind. The factor of $\sim 10$ difference in the amount of $r$-process ejecta between the $\mathcal{H}$ and $\mathcal{L}$ events calls for a similar difference in the duration of neutrino emission, and hence that of the neutrino-driven wind, between the corresponding supernovae. In turn, the difference in neutrino emission may require transformation of the initial neutron star into a black hole $\sim 1$ s after the supernova explosion in an $\mathcal{H}$ event and long term stability of the neutron star in an $\mathcal{L}$ event. Consequently, the diversity of supernova sources for the $r$-process may have profound implications for properties of nuclear matter inside the initial neutron star produced in a supernova.

Two possible observational tests for the association of neutron star/black hole formation with supernova $r$-process nucleosynthesis have been proposed [25–27]. One test relies on the occurrence of supernovae in binaries consisting of a massive star and a low mass star. Some binaries would survive the supernova explosion of the massive star and become new systems with a neutron star or black hole orbiting around the low mass star. Furthermore, the surface of the low mass star
would be contaminated by the $r$-process ejecta from the supernova. Therefore, we can test black hole and neutron star formation in $\mathcal{H}$ and $\mathcal{L}$ events, respectively, by looking for $r$-process abundance anomalies on the surface of the binary companion to a neutron star or black hole [25]. This approach is quite promising as large overabundances of O, Mg, Si, and S ejected in supernovae have been observed in the binary companion to a black hole [28].

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