THE \textit{R}-PROCESS: CURRENT UNDERSTANDING AND FUTURE TESTS\textsuperscript{*}

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Current understanding of the \textit{r}-process is summarized in terms of the astrophysical sites, the yield patterns, and the role of neutrinos. The importance of observational and experimental tests is emphasized. A number of future tests regarding the above three aspects of the \textit{r}-process are discussed.

1. Introduction

The goal of this contribution is to present a summary of current understanding of the \textit{r}-process and to suggest a number of observational and experimental tests that can lead to further progress. Three aspects of the \textit{r}-process will be discussed: the astrophysical sites, the yield patterns, and the role of neutrinos. A more detailed review of recent progress in understanding the \textit{r}-process can be found in [1].

2. Astrophysical Sites

Despite decades of studies, we still do not have a self-consistent model that can produce the conditions for \textit{r}-process nucleosynthesis. On the other hand, two major categories of candidate sites have been proposed: core-collapse supernovae (e.g. [2–7]) and neutron star mergers (e.g. [8–12]). A simple argument was made in [13] to favor core-collapse supernovae over neutron star mergers as the major site for the \textit{r}-process based on observations of abundances in metal-poor Galactic halo stars. This argument was borne out by a detailed numerical study on the chemical evolution of

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the early Galaxy [14], which calculated $r$-process abundances in stars for both core-collapse supernova and neutron star merger models and compared them with data. The basic conclusions from these studies are that observations of metal-poor stars are consistent with $r$-process enrichment by core-collapse supernovae (see also [15]) but are in conflict with neutron star mergers being the major $r$-process site. The conclusion regarding neutron star mergers is quite robust so long as the Galactic rate of these events is much lower than that of core-collapse supernovae. For example, with a typical Galactic rate of $\sim (100 \text{ yr})^{-1}$ for core-collapse supernovae and of $\sim (10^5 \text{ yr})^{-1}$ for neutron star mergers, the Fe enrichment of the interstellar medium (ISM) by core-collapse supernovae would be much more frequent than the $r$-process enrichment by neutron star mergers if the latter were the major $r$-process site. In this case, stars with very low Fe abundances formed from an ISM where only a few core-collapse supernovae had occurred would have received no contributions from neutron star mergers and therefore, would have no $r$-process elements such as Eu. This is in strong conflict with the substantial Eu abundances observed in stars having Fe abundances as low as $\sim 10^{-3}$ times solar and also with the substantial Ba abundances observed in stars having Fe abundances as low as $\sim 10^{-4}$ times solar	footnote{At such low metallicities corresponding to early times, only the $r$-process associated with fast-evolving massive progenitors can contribute to the Ba in the ISM.} (e.g. [16]). These observations can be accounted for only if neutron star mergers could make major $r$-process contributions at a rate close to that of Fe enrichment by core-collapse supernovae. Such a high neutron star merger rate is very unlikely and it is much more probable that core-collapse supernovae are responsible for both the $r$-process and Fe enrichment of metal-poor stars. A firm upper limit on the rate of neutron star mergers may be provided by LIGO that is being built to detect gravitational wave signals from such events. In the rest of the discussion, it will be assumed that core-collapse supernovae are the major $r$-process site.

2.1. Diverse $r$-Process Sources

Assuming that core-collapse supernovae are sources of the $r$-process elements and Fe, we still have to answer the following questions: (1) Does $r$-process production vary from event to event? (2) How does $r$-process production correlate with Fe production? (3) How does $r$-process and Fe production depend on the progenitors of core-collapse supernovae? These questions will be addressed mostly from the observational side below.
Several observations support that there are at least two distinct kinds of \(r\)-process sources. Meteoritic data on extinct radioactivities in the early solar system indicate that at least some \(r\)-process events produce \(^{182}\text{Hf}\) but not \(^{129}\text{I}\) (e.g. \([17]\)). In addition, observations of the metal-poor star CS 22892-052 \([18]\) show that while the elements Ba and above with mass numbers \(A > 130\) closely follow the solar \(r\)-process pattern, the elements Rh and Ag with \(A < 130\) fall below the extension of this pattern to the region of \(A < 130\) (see Fig. 1). The \(r\)-process pattern in this star is rather close to that in another metal-poor star CS 31082-001 \([19]\) (see Fig. 4). Both the meteoritic data and observations of metal-poor stars indicate that in order to obtain the overall solar \(r\)-process pattern, there should be a source producing mainly the heavy \(r\)-process nuclei with \(A > 130\) and another producing mainly the light \(r\)-process nuclei with \(A \leq 130\).

![Figure 1](image-url). The observed abundances in CS 22892-052 (filled circles with error bars: \([18]\)) compared with the solar \(r\)-process pattern (solid curve: \([20]\)) that is translated to pass through the Eu data. The data on the heavy \(r\)-process elements from Ba to Ir are in excellent agreement with the translated solar \(r\)-process pattern. However, the data on the light \(r\)-process elements Rh and Ag clearly fall below this pattern. The abundance of element E is given in the spectroscopic notation \(\log \epsilon(E) ≡ \log(E/H) + 12\), where \(E/H\) is the number ratio of E to H atoms in the star.

The relation between production of the heavy \(r\)-process nuclei and that of Fe can be inferred by comparing the abundances in the metal-poor stars CS 31082-001 \([19]\), HD 115444, and HD 122563 \([21]\) (see Fig. 2). While
the heavy $r$-process elements closely follow the solar $r$-process pattern for all three stars, the absolute abundances of these elements differ by a factor of $\sim 100$. However, the absolute abundances of the elements from O to Ge with $A < 75$ are approximately the same for these stars. This clearly demonstrates that the source for the heavy $r$-process nuclei in these stars cannot produce any of the elements from O to Ge including Fe (e.g. [22]).

The core-collapse supernovae associated with this source may have progenitors of $\sim 8$–$10 M_\odot$, which develop O-Ne-Mg cores with very thin shells before collapse [23, 24]. The supernova shock produces essentially no nucleosynthesis as it propagates through the thin shells. So no elements from O to Ge are made. However, production of the heavy $r$-process nuclei could occur in the material ejected from the newly-formed neutron star (e.g. [25]).

This can then explain why these nuclei are not produced together with the elements from O to Ge. In addition, the source for the heavy $r$-process nuclei in the stars shown in Fig. 2 can also be associated with accretion-induced collapse (AIC) of a white dwarf into a neutron star in binaries [26] as no elements from O to Ge are produced in this case, either.

Figure 2. Comparison of the observed abundances in CS 31082-001 (asterisks: [19]), HD 115444 (filled circles), and HD 122563 (squares: [21]). (a) The data on CS 31082-001 are connected with solid line segments as a guide. Missing segments mean incomplete data. The downward arrow at the asterisk for N indicates an upper limit. Note that the abundances of the elements from O to Ge are almost indistinguishable for the three stars. (b) The data on CS 31082-001 to the left of the vertical line are again connected with solid line segments as a guide. In the region to the right of the vertical line, the solid, dot-dashed, and dashed curves are the solar $r$-process pattern translated to pass through the Eu data for CS 31082-001, HD 115444, and HD 122563, respectively. Note the close description of the data by these curves. The shift between the solid and the dashed curves is $\sim 2$ dex.
Observations show that the late-time light curves of some core-collapse supernovae were powered by decay of $^{56}\text{Ni}$ to $^{56}\text{Fe}$ (e.g. [27]). These supernovae have progenitors of $>10\ M_\odot$, which develop Fe cores with extended shells before collapse. The supernova shock in this case produces $^{56}\text{Ni}$ and lighter nuclei through explosive burning in the inner shells. This explosive burning and the hydrostatic burning in the outer shells during the presupernova evolution lead to production of the elements from O to Ni by core-collapse supernovae with progenitors of $>10\ M_\odot$. Such supernovae may be associated with the source responsible for mainly the light $r$-process nuclei (e.g. [22]).

2.2. Tests for $r$-Process Sources

The association of $r$-process sources with different progenitors of core-collapse supernovae can be tested in a number of ways. First, it needs to be shown that a substantial fraction of core-collapse supernovae result from progenitors of $\sim 8–10\ M_\odot$ and AIC events. There are ongoing efforts to identify supernova progenitors by examining the archival images taken with the Hubble space telescope [28, 29]. In one case, a progenitor of $\sim 8–10\ M_\odot$ has been demonstrated [30, 31]. With sufficient statistics to be built up in the future, these efforts will be able to determine the fraction of core-collapse supernovae with low-mass progenitors. Identification of AIC events is more difficult as such events are not expected to have the usual optical display associated with regular supernovae. A firm upper limit on the rate of AIC events may be provided by super Kamiokande and Sudbury Neutrino Observatory, which are capable of detecting the neutrino signals from these events.

The strongest evidence so far for association of $r$-process nucleosynthesis with AIC events was provided by observations of the metal-poor star HE 2148-1247 [32]. The abundances of Fe and lower atomic numbers in this star are typically $\sim 10^{-2}$ times solar. However, the abundances of the neutron-capture elements Ba and above in the star are at the solar level (see Fig. 3). Such high neutron-capture abundances cannot represent the composition of the ISM from which HE 2148-1247 was formed. Instead, they must have resulted from contamination of the surface of this star. As abundances of Ba and above at the solar level must consist of contributions from both the $r$-process and the $s$-process (most of the solar Ba came from the $s$-process while essentially all the solar Eu came from the $r$-process), the explanation for the observed abundances in HE 2148-1247 requires coordi-
nated contamination by both an $r$-process source and an $s$-process source. This coordination may be achieved as follows [26]. If HE 2148-1247 had a more massive binary companion of $\sim 3-8 M_\odot$, this companion would have produced $s$-process elements during its evolution and contaminated the surface of HE 2148-1247 with these elements through mass transfer. The companion eventually became a white dwarf, which then collapsed into a neutron star [33] after accreting some material back from HE 2148-1247. The ejecta from the AIC event would again contaminate the surface of this star, but this time with $r$-process elements. The extremely high contributions from both the $s$-process and the $r$-process to HE 2148-1247 can then be accounted for.

![Figure 3](image.png)

Figure 3. The observed abundances in HE 2148-1247 (squares with error bars: [32]) compared with the solar abundances (solid curve: [34]). The abundances of Fe and lower atomic numbers in HE 2148-1247 are typically $\sim 10^{-2}$ times solar but those of the elements Ba and above are at the solar level. Variations in the radial velocity of HE 2148-1247 have been observed so this star is in a binary [32].

The above AIC scenario has two possible outcomes. If the binary was disrupted by the AIC event, then a single metal-poor star with extremely high neutron-capture abundances would be produced. Indeed, a number of such stars have been observed [35]. On the other hand, if the binary survives, then the metal-poor star with extremely high neutron-capture abundances has a neutron star companion today. The neutron star companion may be revealed through X-ray emission due to its accretion. A number of
metal-poor stars with extremely high neutron-capture abundances, includ-
ing HE 2148-1247, are known to be in binaries. Some loose upper limits on
the X-ray emission due to possible neutron star companions of several stars
were obtained from archival all-sky data [36]. It would be very interesting
to see if dedicated X-ray searches can provide support for the AIC scenario.

The best tests for $r$-process production by core-collapse supernovae
would be direct observations of newly-synthesized $r$-process nuclei in these
events. One possibility is to examine the spectra of an event for atomic lines
of $r$-process elements. The lines of Ba were observed in SN 1987A [37–39].
Combined with Fe production inferred from the light curve, this appears to
indicate that SN 1987A produced both Fe and Ba. As mentioned in Sec.
2.1, Fe producing core-collapse supernovae may be responsible for mainly
the light $r$-process nuclei with $A \leq 130$. So the Ba observed in SN 1987A
may represent the heaviest $r$-process element produced by such supernovae
[40]. Clearly, optical observations of supernovae can provide very valuable
information on the $r$-process.

Perhaps the most direct test for $r$-process production is detection of
$\gamma$-rays from the decay of the unstable progenitor nuclei that are initially
produced by the $r$-process. A number of such nuclei have significant $\gamma$-ray
fluxes for recent or future supernovae in the Galaxy (e.g. [42, 43]). The
most interesting nucleus is $^{126}$Sn with a lifetime of $\sim 10^5$ yr. If the Vela
supernova that occurred $\sim 10^4$ yr ago produced $^{126}$Sn, the $\gamma$-ray flux from
the decay of this nucleus in the Vela supernova remnant may be close to the
detection limit of INTEGRAL [42]. Hopefully, some information on $^{126}$Sn
production by the Vela supernova will be provided by INTEGRAL in the
near future.

3. Yield Patterns and Role of neutrinos

The extensive $r$-process patterns observed in the metal-poor stars CS 22892-
052 [18] and CS 31082-001 [19] are shown in Fig. 4. These two rather
close patterns cover the elements from Sr to Cd with $A = 88–116$ and the
elements Ba and above with $A > 130$. Unfortunately, the elements Te and
Xe with $A \sim 130$ cannot be observed in stellar spectra. On the other hand,
Te and Xe isotopes have been found in presolar diamonds. It is extremely
important to understand the Te and Xe patterns in these diamonds (e.g.
[44, 45]) as they may be the only data outside the solar system on $r$-process
production in the region of $A \sim 130$.

According to the meteoritic data, at least some $r$-process events produce
If these events were responsible for the r-process patterns shown in Fig. 4, they must produce the nuclei with $A = 88$–116 and $A > 130$ but skip those with $A \sim 130$. A fission scenario was proposed in [46] to achieve this. In this scenario, the r-process produces a freeze-out pattern covering $A > 190$ with a peak at $A \sim 195$ and fission of progenitor nuclei during their decay towards stability produces the nuclei with $A < 130$ and $A > 130$ but very little of those with $A \sim 130$. In addition, fission may be significantly enhanced through excitation of the progenitor nuclei by interaction with the intense neutrino flux in core-collapse supernovae [46, 47]. The above fission scenario also accounts for the difference in the Th/Eu ratio between CS 22892-052 and CS 31082-001 (see Fig. 4) that is difficult to explain by the possible difference in the stellar age [46]. In this scenario, Th represents the progenitor nuclei surviving fission whereas Eu represents the nuclei produced by fission. The Th/Eu ratio would then depend on the fraction of the progenitor nuclei undergoing fission, which would in turn depend on, for example, the extent of neutrino interaction in a specific r-process event.

Neutrino interaction can also result in emission of neutrons [48, 49]. In fact, it was shown that the solar r-process abundances of the nuclei with $A = 183$–187 can be completely accounted for by neutrino-induced neutron
emission from the progenitor nuclei in the peak at $A \sim 195$ [48, 50]. Clearly, to test neutrino-induced nucleosynthesis associated with the $r$-process requires a lot of nuclear physics input, such as branching ratios of fission and neutron emission for excited neutron-rich nuclei and the associated fission yields. Perhaps some of this input could be studied at future rare isotope accelerator facilities.

Figure 5. Effects of neutrino-induced neutron emission for the region near the abundance peak at $A \sim 195$ [48, 50]. The abundances before and after neutrino-induced neutron emission (following freeze-out of the $r$-process) are given by the solid and dashed curves, respectively. The filled circles (some with error bars) give the solar $r$-process abundances. The region with $A = 183$–187 is highlighted in the inset.

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