Neutrinos and the Supernova Origin of the Elements

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Intense fluxes of neutrinos are emitted by the hot neutron star produced in a supernova. The average supernova neutrino energies satisfy a robust hierarchy $\langle E_{\nu_e} \rangle < \langle E_{\nu_\mu} \rangle < \langle E_{\nu_\tau} \rangle \approx \langle E_{\bar{\nu}_e} \rangle$. The $\nu_e$ and $\bar{\nu}_e$ capture reactions on neutrons and protons, respectively, provide heating to drive a wind from the hot neutron star. The same reactions also determine the neutron-richness of the wind material. Nucleosynthesis via rapid neutron capture, the $\nu$-process, may occur in the wind material as it expands away from the neutron star. The neutron-richness of the wind material, and hence, the $\nu$-process nucleosynthesis therein, are sensitive to mixing between $\nu_{\mu(\tau)}/\bar{\nu}_{\mu(\tau)}$ and $\nu_e/\bar{\nu}_e$ (or sterile neutrinos $\nu_s/\bar{\nu}_s$) at the level of $\sin^2 2\theta \approx 10^{-4}$ for $\delta m^2 \approx 1$ eV$^2$. Indirect arguments and direct tests for the supernova origin of the $\nu$-process elements are discussed with a goal to establish supernova $\nu$-process nucleosynthesis as an important probe for neutrino mixing.

1. INTRODUCTION TO SUPERNova $\nu$-PROCESS NUCLEOSYNTHESIS

A star lives a luminous life by burning H into successively heavier elements. However, as the Fe group nuclei near mass number $A$ = 56 are most tightly bound, no more nuclear binding energy can be released to power the star by burning “Fe.” Therefore, heavy elements beyond “Fe” have to be made by processes other than normal stellar burning. One such process is the rapid neutron capture process, or the $\nu$-process for short. This process is responsible for approximately half the natural abundance of nuclei with mass numbers $A > 100$. Typical $\nu$-process elements are Cu, Pt, U, and Th. A crude picture for the $\nu$-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 $\nu$-process nuclei observed in nature.

The $\nu$-process has a lot to do with supernova neutrinos. Neutrinos and antineutrinos of all three flavors are emitted by the neutron star produced in a supernova. The individual neutrino species has approximately the same luminosity but very different average energy. As the neutrinos diffuse out of the neutron star, they thermally decouple from the neutron star matter at different radii due to the difference in their ability to exchange energy with such matter. With higher temperatures at smaller radii, $\nu_{\mu}$, $\nu_\tau$, and their antineutrinos decoupling at the smallest radii are imprinted with the highest average energy while $\nu_e$ decoupling at the largest radii are imprinted with the lowest average energy. The average energy of $\bar{\nu}_e$ lies between those of $\nu_{\mu(\tau)}$ and $\nu_e$. Typical average supernova neutrino energies are $\langle E_{\nu_e} \rangle \approx 11$ MeV, $\langle E_{\nu_\mu} \rangle \approx 16$ MeV, and $\langle E_{\nu_\tau} \rangle \approx 25$ MeV. I emphasize that while different supernova calculations give somewhat different numerical values, there is a robust hierarchy of the average supernova neutrino energies: $\langle E_{\nu_e} \rangle < \langle E_{\nu_\mu} \rangle < \langle E_{\nu_\tau} \rangle$. This hierarchy is the most crucial aspect of supernova neutrino emission relevant for our discussion.

A few seconds after the 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”.

The capture reactions $\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$ not only provide heating to drive the wind, but also interconvert neutrons and protons. With a significant excess of $\langle E_{\nu_e}\rangle$ over $\langle E_{\bar{\nu}_e}\rangle$, neutron production by the $\bar{\nu}_e$ dominates neutron destruction by the $\nu_e$. Consequently, the wind material is neutron rich. As this material expands away from the neutron star, its temperature and density decrease and various nuclear reactions take place to change its composition. When the temperature drops to $\approx 0.5$ MeV, essentially all the protons are assembled into $\alpha$-particles and the material at this temperature just contains neutrons and $\alpha$-particles. As the temperature drops further, $\alpha$-particles and neutrons are burned into heavier nuclei (the $\alpha$-process). By the time the Coulomb barrier stops all charged-particle reactions at a temperature of $\approx 0.25$ MeV, nuclei with $A \sim 100$ have been produced. These nuclei then become the seed nuclei to capture the remaining neutrons during the subsequent $r$-process, which occurs at temperatures below $\approx 0.25$ MeV (e.g., $\nu_e$).

2. NEUTRINO OSCILLATIONS AND SUPERNova $r$-PROCESS NUCLEOSYNTHESIS

An absolutely necessary condition for an $r$-process to occur in the neutrino-driven wind is that the wind material must be neutron rich. As $\nu_{\mu(\tau)}$ have the highest average energy, significant mixing between $\nu_{\mu(\tau)}$ and $\nu_e$ would increase the destruction of neutrons by $\nu_e$ and drive the wind material proton rich. (Even in the extreme case of $\langle E_{\bar{\nu}_e}\rangle < \langle E_{\nu_e}\rangle \approx \langle E_{\nu_{\mu(\tau)}}\rangle$, conversion of $\nu_{\mu(\tau)}$ into $\nu_e$ can still drive the wind material proton rich as neutron production by the $\bar{\nu}_e$ is hindered while neutron destruction by the $\nu_e$ is aided by the neutron-proton mass difference.) For $\nu_{\mu(\tau)}$ with a cosmologically significant (vacuum) mass of $\sim 1$–100 eV, matter-enhanced mixing with a lighter $\nu_e$ would occur below the region where the neutron-richness of the wind material is determined. Therefore, such mixing is severely constrained if the $r$-process indeed occurs in the neutrino-driven wind in a supernova. Figure 1 shows the parameters for mixing between $\nu_{\mu(\tau)}$ and $\nu_e$ that are incompatible with supernova $r$-process nucleosynthesis. Note that the $\nu_{\mu(\tau)}-\nu_e$ mixing parameters $\sin^2 2\theta \sim 3 \times 10^{-3} \sim 10^{-2}$ at $\delta m^2 \geq \text{several eV}^2$ reported by the LSND experiment lie in the incompatible region. Thus only the LSND parameters at $\delta m^2 \lesssim \text{several eV}^2$ are compatible with supernova $r$-process nucleosynthesis. The LSND parameters at low $\delta m^2$ are also consistent with the results from the KARMEN experiment.

One may ask what happens if the LSND parameters at $\delta m^2 \gtrsim \text{several eV}^2$ turn out to be true. In this case, supernova $r$-process nucleo-

![Figure 1. Matter-enhanced mixing between $\nu_{\mu(\tau)}$ and $\nu_e$ with parameters in the labeled region drives the material in the neutrino-driven wind proton rich (corresponding to an electron fraction $Y_e > 0.5$), and hence, is incompatible with supernova $r$-process nucleosynthesis.](image-url)
synthesis can still occur if for example, a light sterile neutrino $\nu_s$ is introduced so that $\nu_{\mu(\tau)}$ with the highest average energy will be turned into $\nu_s$ before they can mix with the $\nu_e$. Of course, one can consider many other possibilities of neutrino mixing that are compatible with supernova $r$-process nucleosynthesis. In any case, supernova $r$-process nucleosynthesis provides a potential probe for mixing between $\nu_{\mu(\tau)}/\bar{\nu}_{\mu(\tau)}$ and $\nu_{\tau(\tau)}/\bar{\nu}_{\tau(\tau)}$ at the level of $\sin^2 2\theta \lesssim 10^{-4}$ for $\Delta m^2 \gtrsim 1$ eV$^2$. To establish this probe on a solid basis requires us to check the supernova laboratory against the standards of terrestrial experiments.

A terrestrial neutrino oscillation experiment consists of a known neutrino source and a detector with unambiguous signals for neutrino oscillations. In the supernova laboratory, the hot neutron star is the neutrino source. The most crucial aspect of this source is the robust hierarchy of average neutrino energies. As the neutrinos move away from the neutron star, various scenarios of neutrino mixing can occur. The $\nu_e$ and $\bar{\nu}_e$ emerging from the mixing region are detected by the capture reactions on neutrons and protons, respectively. The signal that we are looking for is the production of $r$-process elements such as Eu and U in supernovae. If this signal is observed, any scenario of neutrino mixing that would cause neutron destruction by the $\nu_e$ to dominate neutron production by the $\bar{\nu}_e$ is forbidden.

Note that the use of supernova nucleosynthesis to study forbidden scenarios of neutrino mixing only relies on the necessary condition for an $r$-process to occur in the neutrino-driven wind — the wind material must be neutron rich. Provided that we can prove the supernova origin of the $r$-process elements, we do not have to understand the exact details of supernova $r$-process nucleosynthesis in order to use the supernova laboratory in the “forbidden” mode for studying neutrino mixing. On the other hand, if we also know the exact characteristics of supernova neutrino emission and of the neutrino-driven wind, we can even determine whether a certain neutrino mixing scenario is required based on the sufficient conditions for supernova $r$-process nucleosynthesis. However, great improvements in our understanding of supernovae have to be made before the supernova laboratory can be used in the “required” mode for studying neutrino mixing. As the supernova origin of the $r$-process elements is the basis for using supernova nucleosynthesis to study neutrino mixing in either the forbidden or the required mode, it will be the focus of the following discussion.

3. SUPERNOVA ORIGIN OF THE $r$-PROCESS ELEMENTS

I first present indirect arguments for the supernova origin of the $r$-process elements based on recent observations of $r$-process elemental abundances in metal-poor stars and consideration of Galactic chemical evolution. Two possible direct tests are discussed next.

3.1. Indirect arguments

The astrophysical site for the $r$-process has to provide a large neutron abundance. This can be achieved by having $\nu_e$ capture on protons dominate $\nu_e$ capture on neutrons in a supernova. Alternatively, neutron-rich material may be obtained in the merger of a neutron star with another neutron star or a black hole. In fact, supernovae and neutron star mergers are considered as the two leading candidate sites for the $r$-process. An important distinction between these two sites is the vast difference in the event rate. Massive stars that explode as supernovae are a small fraction of all stars. The progenitor system for neutron star mergers must have two massive stars in a binary. Furthermore, this binary must survive the two supernova explosions that produce the two compact objects for the eventual merger. A rather high estimate of the neutron star merger rate in the Galaxy is $\sim (3 \times 10^4 \text{ yr})^{-1}$ (e.g., [4]). This is still $\sim 10^3$ times smaller than the Galactic supernova rate.

Let us assume that supernovae are the major source for the $r$-process and consider $r$-process enrichment of the interstellar medium (ISM). The ejecta from each supernova is mixed with an average mass $M_{\text{mix}} \approx 3 \times 10^4 M_\odot$ of ISM (mostly H) swept up by the supernova remnant (e.g., [3]). For a supernova rate that is proportional to the mass of gas, an average ISM in the Galaxy is
enriched by supernova ejecta at a frequency of \( \sim M_{\text{mix}}(f_{\text{SN}}^{\odot}/M_{\text{gas}}) \sim (10^7 \text{ yr})^{-1} \), where the supernova rate per unit mass of gas is estimated using \( f_{\text{SN}}^{\odot} \sim (30 \text{ yr})^{-1} \) and \( M_{\text{gas}} \sim 10^{10} \, M_{\odot} \) for the present Galaxy. Consequently, an average ISM would be enriched with a solar \( r \)-process composition (denoted by the subscript \( \odot, r \)) by \( \sim 10^3 \) supernovae over a period of \( \sim 10^{10} \text{ yr} \). This then determines the \( r \)-process abundances resulting from a single supernova, e.g., \((\text{Eu}/\text{H})_{\text{SN}} \sim 10^{-3} (\text{Eu}/\text{H})_{\odot,r}\) with \( \text{Eu}/\text{H} \) being the abundance ratio of Eu to H. In the spectroscopic notation \( \log \epsilon(\text{Eu}) \equiv \log(\text{Eu}/\text{H}) + 12 \), we have \( \log \epsilon_{\text{SN}}(\text{Eu}) \sim \log \epsilon_{\odot,r}(\text{Eu}) - 3 \approx -2.5 \) \([14–16] \).

The observed Eu abundances in many metal-poor stars \([17–20] \) are shown in Figure 2. The “metallicity” is defined by \([\text{Fe}/\text{H}] \equiv \log (\text{Fe}/\text{H}) - \log (\text{Fe}/\text{H})_{\odot} \). The low values of \([\text{Fe}/\text{H}] \) for the stars indicate that they were formed at very early times when the ISM had been enriched by only a small number of supernovae. The lowest Eu abundances observed in metal-poor stars are in agreement with the \( r \)-process enrichment resulting from a single supernova discussed above.

The ejecta from each neutron star merger is mixed with approximately the same amount of ISM as swept up by a supernova remnant. However, as the Galactic rate of neutron star mergers is \( \sim 10^3 \) times smaller than that of supernovae, an average ISM would be enriched by the ejecta from only \( \sim 1 \) neutron star merger over a period of \( \sim 10^{10} \text{ yr} \). Consequently, the Eu abundance resulting from a single event would be \( \log \epsilon_{\text{NSM}}(\text{Eu}) \sim \log \epsilon_{\odot,r}(\text{Eu}) \approx 0.5 \) if neutron star mergers were the major source for the \( r \)-process. This is in clear disagreement with the data in Figure 2 \([14–16] \).

Supernovae also provided Fe enrichment of the ISM at \([\text{Fe}/\text{H}] \gtrsim -2.5 \) \([13] \). Figure 2 shows that there is a correlation between the abundances of Eu and Fe at \([\text{Fe}/\text{H}] \gtrsim -2.5 \). This can be explained as the result from mixture of the Eu and Fe produced by many supernovae if supernovae are the major source for the \( r \)-process. On the other hand, an average ISM would be enriched in Fe by many supernovae between the occurrence of two successive neutron star mergers due to the vast

\[ \text{Figure 2. Europium data for metal-poor stars (asterisks: [17], squares: [18], triangles: [19,20]). If supernovae are the major source for the } r \text{-process, the Eu abundance resulting from a single event is } \log \epsilon(\text{Eu}) \sim -2.5 \text{ (dashed line). If neutron star mergers were the major source for the } r \text{-process instead, the Eu abundance resulting from a single event would be } \log \epsilon(\text{Eu}) \sim 0.5. \]
difference in the event rate. Consequently, the correlation between the abundances of Eu and Fe, especially its early onset at \([\text{Fe}/\text{H}] \sim -2.5\), would be very difficult to explain if Eu enrichment were provided by neutron star mergers while Fe enrichment was provided by supernovae \[16\]. Therefore, consideration of Galactic chemical evolution and observations of \(r\)-process elemental abundances in metal-poor stars strongly favor supernovae over neutron star mergers as the major source for the \(r\)-process. Furthermore, the total amount of \(r\)-process ejecta required from each supernova to explain the observed \(r\)-process elemental abundances in metal-poor stars is consistent with the amount of material ejected in the neutrino-driven wind \[3,16\]. In summary, there is strong evidence for the supernova origin of the \(r\)-process elements.

### 3.2. Direct tests

As described in the introduction, the \(r\)-process initially produces very neutron-rich unstable progenitor nuclei. During the decay towards stability, some progenitor nuclei decay to the excited states of their daughters. The gamma rays from the de-excitation of the daughters constitute the signal for the presence of these \(r\)-process progenitor nuclei. If such gamma rays are detected from a future supernova, then we will have proven the supernova origin of the \(r\)-process elements. A supernova becomes transparent to gamma rays after approximately one year of expansion. Therefore, the relevant \(r\)-process progenitor nuclei must have lifetimes of \(\gtrsim 1\) yr. Three most promising nuclei are \(^{125}\text{Sb}\), \(^{144}\text{Ce}\), and \(^{194}\text{Os}\). The typical gamma-ray flux from a supernova at a distance of 10 kpc is \(\gtrsim 10^{-7} \, \gamma \, \text{cm}^{-2} \, \text{s}^{-1}\) \[21\]. To detect such fluxes requires a future supernova and a new detector with a sensitivity of \(\sim 10^{-7} \, \gamma \, \text{cm}^{-2} \, \text{s}^{-1}\). Therefore, this is the most direct means to prove \(r\)-process production in supernovae, it is also the hardest.

If we can find suitable \(r\)-process progenitor nuclei with lifetimes much longer than one year, we may search for the decay gamma rays from the remnant of a past supernova. As a longer lifetime means a smaller decay rate, to ensure a substantial gamma-ray flux requires a nearby supernova remnant (SNR). The Vela SNR is at a distance of \(\approx 250\) pc. The age of the pulsar in this SNR is \(\sim 10^4\) yr. The relevant \(r\)-process progenitor nucleus for gamma-ray detection is \(^{126}\text{Sn}\) with a lifetime of \(\sim 10^5\) yr and several prominent decay gamma rays. The expected gamma-ray fluxes due to decay of \(^{126}\text{Sn}\) in the Vela SNR are \(\gtrsim 10^{-7} \, \gamma \, \text{cm}^{-2} \, \text{s}^{-1}\) \[21\]. A new SNR near Vela was discovered recently through its X-ray emission and the gamma rays from decay of \(^{44}\text{Ti}\). As \(^{44}\text{Ti}\) has a lifetime of only \(\approx 90\) yr, the age of the new SNR is \(\lesssim 10^3\) yr. In this case, we can search for decay gamma rays from a number of actinides with lifetimes of \(\sim 10^3\) yr. The expected fluxes are again \(\gtrsim 10^{-7} \, \gamma \, \text{cm}^{-2} \, \text{s}^{-1}\) \[22\].

As we can see, to prove \(r\)-process production in supernovae by gamma-ray astronomy requires a new detector with a sensitivity of \(\sim 10^{-7} \, \gamma \, \text{cm}^{-2} \, \text{s}^{-1}\). By comparison, the sensitivity of the Compton Gamma-Ray Observatory just demissioned was \(\sim 10^{-5} \, \gamma \, \text{cm}^{-2} \, \text{s}^{-1}\), and that of the INTEGRAL experiment to be launched within the next few years is \(\sim 10^{-6} \, \gamma \, \text{cm}^{-2} \, \text{s}^{-1}\). Perhaps a sensitivity of \(\sim 10^{-7} \, \gamma \, \text{cm}^{-2} \, \text{s}^{-1}\) can be reached within the next decade.

There is yet another way to prove \(r\)-process production in supernovae if we take advantage of the occurrence of supernovae in binaries. Approximately half of the stars are in binaries. Some binaries initially consist of a massive star and a low-mass star. After the massive one explodes as a supernova, it is possible for the neutron star or black hole produced in the supernova to remain in orbit around the low-mass star. Furthermore, a fraction of the \(r\)-process ejecta from the supernova would be intercepted by the low-mass star. Therefore, \(r\)-process production in supernovae will be proven if we detect \(r\)-process abundance anomalies on the surface of the binary companion to a neutron star or black hole \[10\]. Large overabundances of supernova products such as O, Mg, Si, and S have been observed recently in the binary companion to a black hole \[23\]. With the use of the Hubble Space Telescope and the Keck Observatory, perhaps this kind of observation can be extended successfully to the \(r\)-process elements within the next few years.
4. CONCLUSIONS

I have discussed the role of neutrinos in heavy element production in supernovae, especially the effects of neutrino mixing on supernova $r$-process nucleosynthesis. The neutron-richness of the material in the neutrino-driven wind in a supernova is sensitive to mixing between $\nu_\mu(\tau)/\bar{\nu}_\mu(\tau)$ and $\nu_e(s)/\bar{\nu}_e(s)$ at the level of $\sin^2 2\theta \lesssim 10^{-4}$ for $\delta m^2 \gtrsim 1$ eV$^2$. A necessary condition for an $r$-process to occur in the wind is that the wind material must be neutron rich. Provided that the supernova origin of the $r$-process elements can be proven, this necessary condition can be used to eliminate any scenario of neutrino mixing that would cause neutron destruction by the $\nu_e$ to dominate neutron production by the $\bar{\nu}_e$.

I have presented indirect arguments for the supernova origin of the $r$-process elements based on recent observations of $r$-process elemental abundances in metal-poor stars and consideration of Galactic chemical evolution. I have also discussed two direct tests for $r$-process production in supernovae: detection of gamma rays due to decay of $r$-process progenitor nuclei from a future supernova or nearby supernova remnant and observation of $r$-process abundance anomalies on the surface of the binary companion to a neutron star or black hole. Hopefully, these tests will prove the supernova origin of the $r$-process elements in the near future, thereby establishing supernova $r$-process nucleosynthesis as an extremely sensitive probe for neutrino mixing.

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