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The Role of Neutrinos in Explosive Nucleosynthesis

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We present a new primary nucleosynthesis process, the νp-process, occurring in supernovae (and possibly gamma-ray bursts) when strong neutrino fluxes create proton-rich ejecta. In this process, antineutrino absorptions in the proton-rich environment produce neutrons that are immediately captured by neutron-deficient nuclei. The capture of these neutrons permits to overcome the long beta-decay lifetimes of proton-rich nuclei like ^{64}Ge, allowing the nucleosynthesis flow to proceed to nuclei with mass numbers $A > 64$. This process is a possible candidate to explain the origin of the solar abundances of the light p-nuclei (such as ^{92,94}Mo and ^{96,98}Ru) and also offers a natural explanation for the large abundance of Sr (and other elements beyond Fe) seen in the very early stage of the galactic evolution.

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1. Introduction

The production of elements beyond Fe has long been postulated by three classical processes, the r- and s-process (caused by rapid or slow neutron capture) and the p-process, standing either for proton capture or alternative means to produce heavy neutron deficient, stable isotopes. The s-process acts during stellar evolution via neutron captures on Fe produced in previous stellar generations (thus being a "secondary process"). The location and/or uniqueness of the r- and p-process in astrophysical sites is still a subject of debate. Most of the p-nuclei are thought to be produced in hot (supernova) environments, via the desintegration of pre-existing heavy elements due to black-body radiation photons (thus also being a secondary process). The r-process is required to be a primary process in stellar explosions. Primary here means that the production of such elements is independent of the initial heavy element content in the star.

Observations of extremely "metal-poor" stars in the Milky Way [1, 2] provide us with information about the nucleosynthesis processes operating at the earliest times in the evolution of our Galaxy. These extremely "metal-poor" stars witness chemical enrichment by the first generation of faint massive supernovae. Such events are in all cases observed to produce Fe. However, the detection of Sr/Fe, exceeding 10 times the solar ratio in the most metal-poor star known to date (HE 1327-2326 with [Fe/H]=-5.4±0.2) [1] suggests the existence of a primary process, producing elements beyond Fe and Zn. Recent galactic chemical evolution studies of Sr, Y, and Zr [3] also suggest the existence of a primary process denoted "lighter element primary process" (LEPP), operating very early in the Galaxy and being independent of the r-process [4, 5]. There exist also problems to account for the correct amount of the light p-elements with mass numbers $A < 100$. Currently, the precise mechanism for the production of the light p-nuclei, ^{92,94}Mo and ^{96,98}Ru, is unknown. The "p-process", occurring in supernovae of a second generation and acting upon pre-existing heavy nuclei, accounts for the heavy p-nuclei but underproduces the light ones (see e.g. [6]). These shortcomings are strengthened by the chemical evolution studies of the cosmochronometer nucleus ^{92}Nb [7] – a light *p*-nucleus shielded from the decay of other *p*-nuclei – which underline the need for a supernova origin and thus represent a problem to present models of supernova nucleosynthesis.

2. Nucleosynthesis in the Innermost Ejecta of Core Collapse Supernovae

As a full understanding of the core collapse supernova mechanism is still pending and successful explosions are difficult to obtain [8], the composition of the innermost ejecta — directly linked to the explosion mechanism — remained to a large extent unexplored. Recent supernova simulations with accurate neutrino transport [9, 10, 11] show the presence of proton-rich neutrino heated matter, both in the inner ejecta [9, 10] and the early neutrino wind from the proto-neutron star [10]. This matter, part of the initially shock-heated material located between the surface of the proto-neutron star and the shock front expanding through the outer layers, is subject to a large neutrino energy deposition that heats the matter, lifting the electron degeneracy and making it possible for the reactions $\nu_e + n \leftrightarrow p + e^-$ and $p + \overline{\nu}_e \leftrightarrow n + e^+$ (i.e. neutrino and antineutrino captures on free nucleons and their inverse reactions electron and positron capture) to drive the composition proton-rich [12, 13, 14], i.e. $Y_e > 0.5$ where Y_e is the electron fraction $< Z/A >$. This effect will always be present in successful explosion with ejected matter irradiated by a strong neutrino flux, independent of the details of the explosion. While this matter expands and cools, nuclei can form resulting in a composition dominated by $N = Z$ nuclei, mainly ^{56}Ni and ^{4}He, and protons. Without the further inclusion of neutrino and antineutrino reactions the composition of this matter will finally consist of protons, alpha-particles, and heavy (Fe-group) nuclei, i.e. a proton- and alpha-rich freeze-out that results in enhanced abundances of ^{45}Sc, ^{49}Ti, and ^{64}Zn [12, 13, 14]. Similar results have been found in the outflow from gamma-ray bursts [15, 16]. The heaviest nuclei synthesized in these calculations have a mass number $A = 64$. The matter flow stops at the nucleus ^{64}Ge which has a small proton capture probability and a beta-decay half-life (64s) that is much longer than the expansion time scale (10s) [13]. We show that the synthesis of nuclei with $A > 64$ can also be obtained at moderate entropies if one takes neutrino interactions in the nucleosynthesis of heavy nuclei into account.

3. Nucleosynthesis beyond A=64: The νp-process

Traditionally, explosive (supernova) nucleosynthesis calculations did not include interactions with neutrinos and antineutrinos. When such reactions are considered for both free and bound nucleons the situation becomes dramatically different [17, 18, 19]. $N \sim Z$ nuclei are practically inert to neutrino capture (converting a neutron into a proton) because such reactions are endoergic for neutron-deficient nuclei located away from the valley of stability. The situation is different for antineutrinos that are captured in a typical time of a few seconds, both in protons and in nuclei, at the distances at which nuclei form ($\sim$ 1000 km). As protons are more abundant than heavy nuclei, antineutrino capture occurs predominantly on protons, causing a residual density of free neutrons of 10^{14} – 10^{15} cm^{-3} for several seconds when the temperatures are in the range 1–3 GK. This effect is clearly seen in Figure 1 (left panel) where the time evolution of the abundances of protons, neutrons, alpha-particles and ^{56}Ni is shown for a trajectory of model B07 of [14]. The solid (dashed) lines display the nucleosynthesis results which include (omit) neutrino and antineutrino absorption interactions after nuclei are formed. ^{56}Ni serves to illustrate when nuclei are formed. The difference in proton abundances between both calculations is due to antineutrino captures on protons producing neutrons which drive the νp-process. Without the inclusion of antineutrino captures the neutron abundance soon becomes too small to allow for any capture on heavy nuclei.

The neutrons produced via antineutrino absorption on protons can easily be captured by neutron-deficient $N \sim Z$ nuclei (for example ^{64}Ge) which have large neutron capture cross sections. While proton capture, (p,γ), on ^{64}Ge takes too long or is impossible, the (n,p) reaction dominates, permitting the matter flow to continue to nuclei heavier than ^{64}Ge via subsequent proton captures with freeze-out close to 1 GK.

Figure 1 (right panel) shows the results for the composition of supernova ejecta from one hydrodynamical model described in [14] which includes neutrino absorption reactions in the nucleosynthesis calculations (filled circles) that lead initially to proton-rich conditions in the innermost zones, experiencing afterwards the νp-process. These abundances are compared to an older set of nucleosynthesis calculations [20] (open circles) that did not include neutrino interactions and therefore did not produce the proton-rich matter resulting in models with accurate neutrino transport [9, 10, 11].

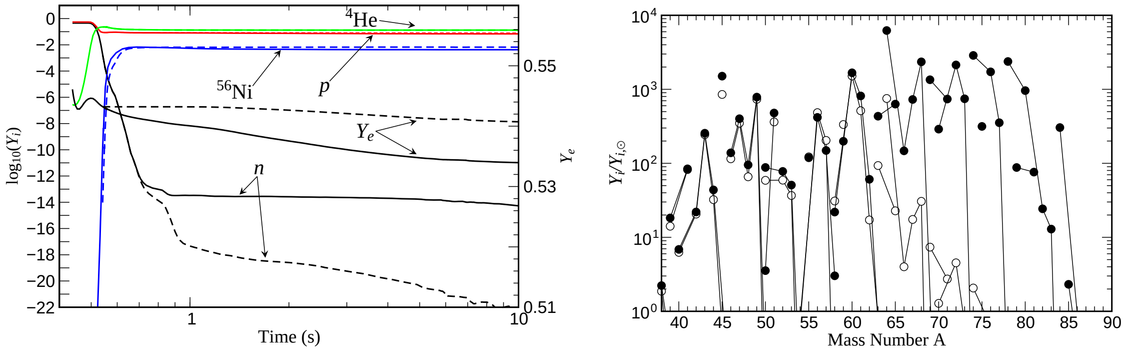

Figure 1: Left: Evolution of the abundance of neutrons, protons, alpha-particles, and ^{56}Ni in a nucleosynthesis trajectory resulting from model B07 of reference [14]. **Right:** Isotopic abundances for model B07 of reference [14] relative to solar abundances [21] (filled circles), compared with earlier predictions [20] (open circles). The filled circles represent calculations where (anti)neutrino absorption reactions are included in the nucleosynthesis while for the open circles neutrino interactions are neglected. The effect of neutrino interactions is clearly seen for nuclei above $A > 64$ where enhanced abundances are obtained.

In order to understand the abundance variability in observation and simulation one has to consider the dependence of the νp-process on the conditions during the ejection of matter in supernova explosions. There are several essential parameters in addition to the entropy s. The entropy is set during the explosion and determines the nature of the alpha-rich freeze-out of explosive nucleosynthesis. An important parameter is the Y_e-value of the matter when nuclei are formed. The larger Y_e, the larger is the residual proton abundance, producing a larger neutron abundance for the same antineutrino flux during the νp-process. This permits a more efficient bridging of beta-decay waiting points by (n, p)-reactions in the flow of proton captures to heavier nuclei. The location (radius r) of matter during the formation of nuclei and the ejection velocity also influence the νp-process by determining the intensity and duration of the antineutrino flux. Finally, the long-term evolution of the neutrino luminosities during the cooling phase of the proto-neutron star plays an essential role. Many of these factors are poorly known, still related to existing uncertainties in the supernova explosion mechanism. However, as discussed in [22], mixing before fallback will always lead to the ejection of elements synthesised even in the innermost layers.

To explore the sensitivity of the nucleosynthesis on these parameters we have also carried out parametric calculations based on adiabatic expansions similar to those used in [23, 24] but for a constant realistic entropy per nucleon $s = 50\ k_B$ (where k_B is the Boltzmann constant). In all cases we assumed a Fermi-Dirac spectrum for both neutrinos and antineutrinos with temperatures that are varied to obtain different degrees of proton richness, Y_e, which is the main parameter determining the resulting nucleosynthesis. For an example of the dependence of the p-nuclei see Figure 2. For values of Y_e close (and below) 0.5 essentially no nuclei heavier than $A = 64$ are produced. The production of these nuclei sets in for $Y_e > 0.5$, showing a very strong dependence on Y_e in the range 0.5–0.6. Even though the production of the light p-nuclei, ^{92,94}Mo and ^{96,98}Ru, increases as Y_e gets larger they are still underproduced by a factor of 10 compared to ^{84}Sr.

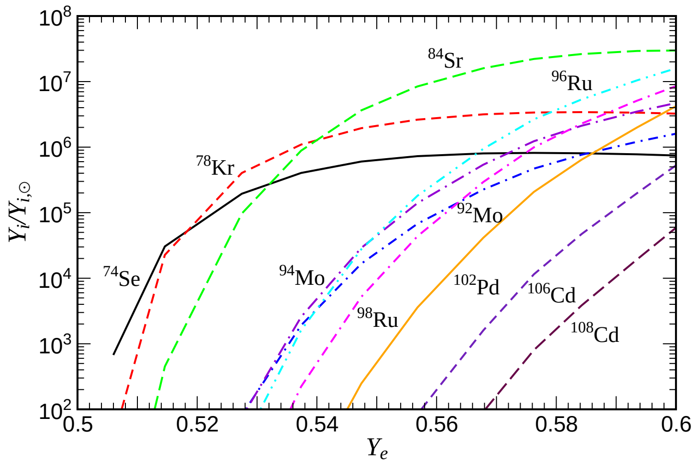

Figure 2: Light p-nuclei abundances in comparison to solar abundances as a function of Y_e. The Y_e-values given are the ones obtained at a temperature of 3 GK that corresponds to the moment when nuclei are just formed and the νp-process starts to act.

4. Summary and Conclusions

All core collapse supernova explosions, independent of existing model uncertainties, will eject hot, explosively processed matter subject to neutrino irradiation. Thus, in all cases the νp-process will operate in the innermost ejected layers. The parameters discussed above might vary widely from supernova to supernova (e.g. as a function of stellar mass, rotation, etc.), and with them the amount of nuclei up to $A \approx 100$. The final amount of matter ejected will also depend on the intensity of the fallback (see for example [22]). Our studies of the νp-process show that the elements between Zn and Sr should be co-produced together with Sr. The observation of these elements, which with the exception of Ge and Rb are not detectable from the ground in optical lines, but possible from space in the infrared or near ultraviolet (e.g. the Hubble Space and Spitzer Space telescopes), can provide support for the occurrence of the νp-process at early times in the Galaxy and contribute valuable information about the conditions experienced by the inner supernova ejecta in order to constrain current theoretical models of supernova explosions. Further studies are required to fully understand the νp-process contribution to the chemical evolution of the Galaxy.

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