Neutrino-induced nucleosynthesis of \( A > 64 \) nuclei: The \( \nu p \)-process

C. Fröhlich, 1 G. Martínez-Pinedo, 2, 3 M. Liebendörfer, 1, 4, 5 F.-K. Thielemann, 1 E. Bravo, 5 W. R. Hix, 6 K. Langanke, 3 and N. T. Zinner 7

1 Departement für Physik und Astronomie, Universität Basel, CH-4056 Basel, Switzerland
2 ICREA and Institut d’Estudis Espacials de Catalunya, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain
3 Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany
4 Canadian Institute for Theoretical Astrophysics, Toronto, ON M5S 3H8, Canada
5 Departamento de Física i Enginyeria Nuclear, Universitat Politècnica de Catalunya, E-08034 Barcelona, Spain
6 Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831
7 Institute for Physics and Astronomy, University of Arhus, DK-8000 Arhus C, Denmark

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We present a new nucleosynthesis process, that we denote \( \nu p \)-process, which occurs 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. This allows for the nucleosynthesis of nuclei with mass numbers \( A > 64 \). Making this process a possible candidate to explain the origin of the solar abundances of \( ^{92,94}\text{Mo} \) and \( ^{96,98}\text{Ru} \). This process also offers a natural explanation for the large abundance of Sr seen in an hyper-metal-poor star.

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Supernova explosions (the cataclysmic endpoint of stellar evolution) produce iron and neighboring nuclei, underlined by their lightcurves powered by radioactive decay of \( ^{56}\text{Ni} \). The production of elements beyond Fe has long been postulated by three classical processes, the \( r \)- and the \( s \)-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 \( [1, 2] \). 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 operation and uniqueness of the \( r \) - and \( p \)-process in astrophysical sites are still a subject of debate. The \( r \)-process is required to be a primary process in stellar explosions \( [3] \), meaning that the production of such elements is independent of the initial heavy element content in the star. Recent galactic chemical evolution studies of Sr, Y, and Zr \( [4] \) suggest the existence of a \( p \)-process, denoted “lighter element primary process” (LEPP), that is independent of the \( r \)-process \( [4, 5] \) and operates very early in the Galaxy. Most of the \( p \)-nuclei are thought to be produced in hot (supernova) environments, where disintegration of pre-existing heavy elements (thus being also a secondary process) due to black-body radiation photons can account for the heavy \( p \)-nuclei but underproduces the light ones (see e.g. ref. \( [6, 7, 8] \)). Currently, the mechanism for the production of the light \( p \)-nuclei, \( ^{92,94}\text{Mo} \) and \( ^{96,98}\text{Ru} \), is unknown, however chemical evolution studies of the cosmochronometer nucleus \( ^{92}\text{Nb} \ [5] \), imply a primary supernova origin for these light \( p \)-nuclei.

Observations of extremely “metal-poor” stars in the Milky Way provide us with information about the nucleosynthesis processes operating at the earliest times in the evolution of our Galaxy. They are thus probing supernova events from the earliest massive stars, the fastest evolving stellar species. The recently discovered hyper-metal-poor stars in the Milky Way \( [10, 11] \) may witness chemical enrichment by the first generation of faint massive supernovae which experience extensive matter mixing (due to instabilities) and fallback of matter after the explosion \( [12] \). However, the detection of Sr/Fe, exceeding 10 times the solar ratio, in the most metal-poor star known to date \( [12] \) suggests the existence of a primary process, producing elements beyond Fe and Zn.

In this Letter, we present a new nucleosynthesis process that will occur in all core-collapse supernovae and could explain the existence of Sr and other elements beyond Fe in the very early stage of galactic evolution. We denote this process “\( \nu p \)-process” and suggest it as a candidate for the postulated lighter element primary process LEPP \( [4] \). It can also contribute to the nucleosynthesis of light \( p \)-process nuclei. Here, we consider only the inner ejecta of core-collapse supernovae, but the winds from the accretion disk in the collapsar model of gamma-ray bursts \( [13, 14, 15, 16] \) may also be a relevant site for the \( \nu p \)-process. The \( \nu p \)-process is primary and is associated with explosive scenarios. It occurs when strong neutrino fluxes create proton-rich ejecta. After the production of Fe-group elements, continued antineutrino absorptions by free protons produce free neutrons subject to immediate capture on neutron-deficient nuclei with small proton-capture cross sections and long beta-decay half-lives. This is distinct from earlier suggestions for the production of \( p \)-nuclei in the so-called neutrino wind that develops in later phases of a supernova explosion \( [17, 18] \), because the captured neutrons are directly delivered by antineutrino absorption on free protons in a proton-rich

\[ 2 \nu_e + p \rightarrow n + 2 \nu_e \]

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environment.

As a full understanding of the core collapse supernova mechanism is still pending and successful explosion simulations are difficult to obtain \cite{19}, 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 \cite{20, 21, 22} show the presence of proton-rich neutrino-heated matter, both in the inner ejecta \cite{20, 21} and in the early neutrino wind from the proto-neutron star \cite{21}. This matter is subject to a large neutrino energy deposition by the absorption of neutrinos and antineutrinos with initially similar intensities and energy spectra. As soon as the heating lifts the electron degeneracy, the reactions $\nu_e + n \rightarrow p + e^-$ and $\nu_e + p \rightarrow n + e^+$ drive the composition proton-rich due to the smaller mass of the proton \cite{23, 24}, $(n, p, e^-, e^+, \nu_e, \bar{\nu}_e$ denote the neutron, proton, electron, positron, neutrino, and antineutrino respectively). Such proton-rich matter with $Y_e$, the number of electrons or protons per nucleon, larger than 0.5 will always be present in core-collapse supernovae explosions with ejected matter irradiated by a strong neutrino flux, independently of the details of the explosion \cite{23}. As this proton-rich 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 (in nucleosynthesis terms a proton- and alpha-rich freeze-out), with enhanced abundances of $^{45}$Sc, $^{49}$Ti, and $^{64}$Zn \cite{23, 24}. In these calculations the matter flow stops at $^{64}$Ge with a small proton capture probability and a beta-decay half-life (64 s) that is much longer than the expansion time scale ($\sim 10$ s) \cite{24}.

Synthesis of nuclei heavier than $A = 64$ is possible in proton rich ejecta if the entropy per nucleon is in the range $s \approx 150-170 \, k_B$ (where $k_B$ is the Boltzmann constant) \cite{25}. Such large entropies are, however, not attained in core-collapse supernovae simulations with detailed neutrino transport which give $s \approx 50-75 \, k_B$ \cite{23, 24}. Here we show that the synthesis of nuclei with $A > 64$ can also be obtained with realistic entropies, if one explores the previously neglected effect of neutrino interactions on the nucleosynthesis of heavy nuclei. When interactions with neutrinos and antineutrinos are considered for both free and bound nucleons the situation becomes dramatically different. $N \sim Z$ nuclei are practically inert to neutrino capture (converting a neutron in 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 on protons and nuclei, at the distances at which nuclei form ($\sim 1000$ km). This time is much shorter than the beta-decay half-life of the most abundant heavy nuclei reached without neutrino interactions (e.g. $^{56}$Ni, $^{64}$Ge). 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 where the time evolution of the abundances of protons, neutrons, alpha-particles and $^{56}$Ni is shown ($^{56}$Ni serves to illustrate when nuclei are formed). The dashed lines shows the results for a calculation where neutrino absorptions are neglected once the temperature drops below 6 GK. This allows to study the effect of neutrino absorptions in the latter phase of nucleosynthesis when the $\nu p$-process acts without changing the initial phases where $Y_e$ is determined. Without the inclusion of antineutrino capture the neutron abundance soon becomes too small to allow for any capture on heavy nuclei. The figure also compares the evolution of $Y_e$.

In our studies we use the detailed neutrino spectral information provided by neutrino radiation hydrodynamical calculations to determine the neutrino antineutrino absorption rates at each point of the nucleosynthesis trajectory (temperature, density and radius). Our network calculations follow the detailed abundances of 1435 isotopes between $Z = 1$ and $Z = 54$, which allows an accurate treatment of the changes in composition induced by neutrino interactions. However, our network calculations follow the $Y_e$ evolution of the hydrodynamical calculations only till the moment when alpha particles form. At this time, the determination of the $Y_e$ value in the hydrodynamical studies is plagued by an error in the Lattimer-Swesty equation of state \cite{20, 23}, which we had
adopted in the hydrodynamical calculations. This error results in an underproduction of alpha particles which suppresses the occurrence of an alpha-effect which drives the $Y_e$ value closer to 0.5 \cite{17, 28}. While such alpha effect does not occur in the hydrodynamical calculations as the computed alpha abundance is too low, it is present in the network calculations. However, we stress that, in contrast to expectation \cite{24}, the alpha effect is no obstacle for the nucleosynthesis of heavy nuclei, because once heavy nuclei form the neutrons are captured by heavy neutron-deficient nuclei instead of forming deuterium and later alpha particles.

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. The amount of nuclei with $A > 64$ produced is then directly proportional to the number of antineutrinos captured. While proton capture, $(p, \gamma)$, on $^{64}$Ge takes too long, the $(n, p)$ reaction dominates (with a lifetime of 0.25 s at a temperature of 2 GK), permitting the matter to flow to heavier nuclei than $^{64}$Ge via subsequent proton captures with freeze-out at temperatures around 1 GK. This is different to $r$-process environments with $Y_e < 0.5$, i.e. neutron-rich ejecta, where neutron capture on neutrons provides protons that interact mainly with the existing neutrons, producing alpha-particles and light nuclei. Their capture by heavy nuclei is suppressed because of the large Coulomb barriers \cite{17, 28}. Consequently, in $r$-process studies an enhanced formation of the heaviest nuclei does not take place when neutrino interactions are included. In proton-rich ejecta, however, antineutrino absorption produces neutrons that do not suffer from Coulomb barriers and are captured preferentially by heavy neutron-deficient nuclei.

Figure 2 shows the composition of supernova ejecta obtained with the hydrodynamical model B07 described in detail in ref. \cite{22}. In addition to the proton-rich conditions in the innermost ejected zones visible in simulations by different groups \cite{20, 21, 22}, our models consistently include neutrino-absorption reactions in the nucleosynthesis calculations allowing for the occurrence of the $\nu p$-process. However, in our stratified spherically symmetric models the accretion rate is rapidly reduced (and with this the neutrino luminosities) with the onset of the explosion. In a more realistic scenario considering convective turnover in the hot mantle, continued accretion is expected to maintain a large neutrino luminosity beyond the onset of the explosion and to further support the $\nu p$-process.

In order to understand the sensitivity of our results one must consider the dependence of the $\nu p$-process on the conditions during the ejection of matter in supernova explosions. There are several essential parameters in addition to the entropy $s$. One is the $Y_e$-value of the matter when nuclei are formed. The larger the $Y_e$-value, the larger is the proton abundance, producing a larger neutron abundance for the same antineutrino flux during the $\nu p$-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 $\nu p$-process by determining the intensity and duration of the antineutrino flux which the matter will experience. A location closer to the surface of the proto-neutron star and/or a slow ejection velocity leads to an extended antineutrino exposure that allows for an increased production of heavy elements. Finally, the long-term evolution of the neutrino luminosities and energy spectra during the cooling phase of the proto-neutron star plays an important role. These factors are poorly known due to existing uncertainties in the supernova explosion mechanism.

To test the dependence of the nucleosynthesis on these parameters we have also carried out parametric calculations based on adiabatic expansions similar to those used in refs. \cite{22, 23} but for a constant realistic entropy per nucleon $s = 50 \, k_B$. This allows exploration of the sensitivity of the nucleosynthesis without the need to perform full radiation-hydrodynamical calculations. An example is given in figure 3 which shows the dependence of the $p$-nuclei abundances as a function of the $Y_e$ value of the ejected matter. The different $Y_e$ values have been obtained by varying the temperatures of the neutrino and antineutrino spectra assuming Fermi-Dirac distributions for both. Close to $Y_e = 0.5$ (and below) essentially no nuclei beyond $A = 64$ are produced. Nuclei heavier than $A = 64$ are only produced for $Y_e > 0.5$, showing a very strong dependence on $Y_e$ in the range 0.5–0.6. A clear increase in the production of the light $p$-nuclei, $^{92, 94}$Mo and $^{96, 98}$Ru, is observed as $Y_e$ gets larger. However, addi-
the moment when nuclei are just formed and the ones obtained at a temperature of 3 GK that corresponds to the $p$-process. We argue that in all cases the $νp$-process will initially be proton-rich but will turn neutron-rich in its later phases allowing for the synthesis of $r$-process nuclei. The variations in the production of Sr, Y, and Zr and the $r$-process (producing the heaviest elements up to Th and U) can shed light on the connection of both of these processes and provide information about the class of supernovae that produce the heavy $r$-process nuclei.

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