

## Neutrino-Induced Nucleosynthesis of $A > 64$ Nuclei: The $\nu p$ Process

C. Fröhlich,<sup>1</sup> G. Martínez-Pinedo,<sup>2,3</sup> M. Liebendörfer,<sup>4,1</sup> F.-K. Thielemann,<sup>1</sup> E. Bravo,<sup>5</sup>  
W. R. Hix,<sup>6</sup> K. Langanke,<sup>3,7</sup> and N. T. Zinner<sup>8</sup>

<sup>1</sup>*Departement für Physik und Astronomie, Universität Basel, CH-4056 Basel, Switzerland*

<sup>2</sup>*ICREA and Institut d'Estudis Espacials de Catalunya, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain*

<sup>3</sup>*Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany*

<sup>4</sup>*Canadian Institute for Theoretical Astrophysics, Toronto, Ontario M5S 3H8, Canada*

<sup>5</sup>*Departament de Física i Enginyeria Nuclear, Universitat Politècnica de Catalunya, E-08034 Barcelona, Spain*

<sup>6</sup>*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*

<sup>7</sup>*Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*

<sup>8</sup>*Institute for Physics and Astronomy, University of Århus, DK-8000 Århus C, Denmark*

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We present a new nucleosynthesis process that we denote as the  $\nu p$  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 <sup>92,94</sup>Mo and <sup>96,98</sup>Ru. This process also offers a natural explanation for the large abundance of Sr seen in a hyper-metal-poor star.

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Supernova explosions (the cataclysmic end point of stellar evolution) produce iron and neighboring nuclei. The production of elements beyond Fe has long been postulated by three classical processes: the  $r$  and  $s$  processes (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]. The  $s$  process acts during stellar evolution via neutron captures on Fe produced in previous stellar generations (thus being a “secondary process”). The location, operation, and uniqueness of the  $r$  and the  $p$  process in astrophysical sites are still a subject of debate. The  $r$  process is required to be a primary process [2], 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 [3] suggest the existence of a *primary process*, denoted the “lighter element primary process” (LEPP), which is independent of the  $r$  process [2,4] and operates very early in the Galaxy. Most of the  $p$  nuclei are thought to be produced in hot (supernova) environments, where disintegration of preexisting heavy elements due to blackbody radiation photons can account for the heavy  $p$  nuclei while the light ones are underproduced (see, e.g., Refs. [5–7]). Currently, the mechanism for the production of the light  $p$  nuclei, <sup>92,94</sup>Mo and <sup>96,98</sup>Ru, is unknown. However, chemical evolution studies of the cosmochronometer nucleus <sup>92</sup>Nb [8] 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 [9,10] 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 [11]. However, the detection of Sr/Fe (exceeding 10 times the solar ratio) in the most metal-poor star known to date [9] 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 the “ $\nu p$  process” and suggest it as a candidate for the postulated lighter element primary process LEPP [3]. 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 [12–14] may also be a relevant site for the  $\nu p$  process. This process is distinct from previous nucleosynthesis processes involving neutrinos. The production of light  $p$  nuclei by neutrino absorption on nuclei in alpha-rich freeze-outs resulting from the neutron-rich neutrino wind that develops in later phases of a supernova explosion [15,16]. The neutrino process, involving neutrino-induced spallation of nucleons, has been discussed [17–19] for the production of some selected nuclei. And finally, it has been suggested that antineutrino absorption on protons may be a source of neutrons for the production of light nuclei up to Li [17].

As a full understanding of the core-collapse supernova mechanism is still pending and successful explosion simulations are difficult to obtain [20], the composition of the

innermost ejecta—directly linked to the explosion mechanism—remains to a large extent unexplored. Recent supernova simulations with accurate neutrino transport [20–22] show the presence of proton-rich neutrino-heated matter, both in the inner ejecta [20,21] and in the early neutrino wind from the protoneutron star [20]. 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 and expansion lifts the electron degeneracy, the reactions  $\nu_e + n \rightleftharpoons p + e^-$  and  $\bar{\nu}_e + p \rightleftharpoons n + e^+$  drive the composition proton rich due to the smaller mass of the proton [23,24] ( $n, p, e^-, e^+, \nu_e$ , and  $\bar{\nu}_e$  denote the neutron, proton, electron, positron, neutrino, and antineutrino, respectively). As this proton-rich matter expands and cools, nuclei can form resulting in a composition dominated by  $N = Z$  nuclei, mainly  $^{56}\text{Ni}$  and  $^4\text{He}$ , 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  $^{45}\text{Sc}$ ,  $^{49}\text{Ti}$ , and  $^{64}\text{Zn}$  [23,24]. In these calculations the matter flow stops at  $^{64}\text{Ge}$  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) [23].

Synthesis of nuclei heavier than  $A = 64$ , including light  $p$  nuclei, is possible in proton-rich ejecta if the entropy per nucleon is in the range  $s \approx 150\text{--}170k_B$  (where  $k_B$  is the Boltzmann constant) [25]. Such large entropies are, however, not attained in core-collapse supernovae simulations with detailed neutrino transport which give  $s \approx 50\text{--}75k_B$  [23,24]. Here we show that the synthesis of nuclei with  $A > 64$  can also be obtained with realistic entropies, if one

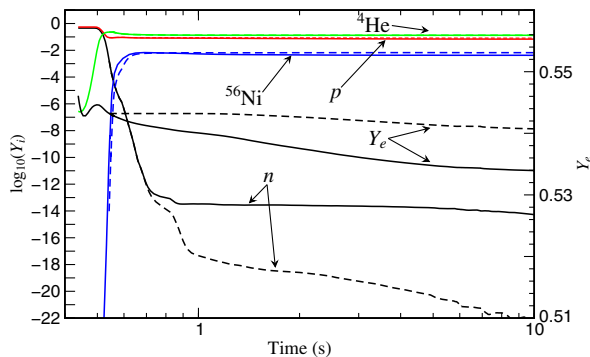


FIG. 1 (color online). Evolution of the abundances of neutrons, protons, alpha particles, and  $^{56}\text{Ni}$  in a nucleosynthesis trajectory resulting from model B07 of Ref. [24]. The abundance,  $Y_i$ , is defined as the number of nuclei of the species  $i$  present divided by the total number of nucleons which is conserved during the calculation. The solid (dashed) lines display the nucleosynthesis results which include (omit) neutrino and antineutrino absorption interactions after nuclei are formed. The abscissa measures the time since the onset of the supernova explosion.

explores the previously neglected effect of neutrino interactions on the nucleosynthesis of heavy nuclei.  $N \sim Z$  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 scale is much shorter than the beta-decay half-life of the most abundant heavy nuclei reached without neutrino interactions (e.g.,  $^{56}\text{Ni}$  and  $^{64}\text{Ge}$ ). As protons are more abundant than heavy nuclei, antineutrino capture occurs predominantly on protons, causing a residual density of free neutrons of  $10^{14}\text{--}10^{15}\text{ cm}^{-3}$  for several seconds, when the temperatures are in the range 1–3 GK. This effect is clearly seen in Fig. 1, where the time evolution of the abundances of protons, neutrons, alpha particles, and  $^{56}\text{Ni}$  is shown ( $^{56}\text{Ni}$  serves to illustrate when nuclei are formed). The dashed lines show the results for a calculation where neutrino absorptions are neglected once the temperature drops below 6 GK. 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  $Y_e$  (defined as the number of electrons per nucleon).

In our studies we use the detailed neutrino spectral information provided by neutrino radiation-hydrodynamical calculations [24] to determine the neutrino and 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  $Z = 54$  plus neutrons, which allows an accurate treatment of the changes in composition induced by neutrino interactions.

The neutrons produced via antineutrino absorption on protons can easily be captured by neutron-deficient  $N \sim Z$  nuclei (for example,  $^{64}\text{Ge}$ ), which have large neutron capture cross sections. The amount of nuclei with  $A > 64$  produced is then proportional to the number of antineutrinos captured. While proton capture ( $p, \gamma$ ) on  $^{64}\text{Ge}$  takes too long, the  $(n, p)$  reaction dominates (with a lifetime of 0.25 s at a temperature of 2 GK), permitting the matter flow to continue to nuclei heavier than  $^{64}\text{Ge}$  via subsequent proton captures with freeze-out at temperatures around 1 GK. This is different from  $r$ -process environments with  $Y_e < 0.5$ , i.e., neutron-rich ejecta, where neutrino 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 [15,26]. 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, in contrast to expectation [23], 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. [24]. In addition to the proton-rich conditions in the innermost ejected zones visible in simulations by different groups [20–22], 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) after 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. Finally, the long-term evolution of the neutrino luminosities and energy spectra during the cooling phase of the protoneutron 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

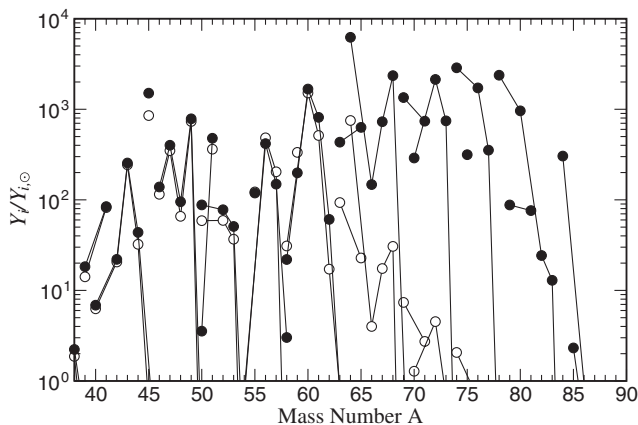


FIG. 2. The panel shows the isotopic abundances for model B07 of Ref. [24] relative to solar abundances [29]. The solid circles represent calculations where (anti)neutrino-absorption reactions are included in the nucleosynthesis while for the open circles neutrino interactions are neglected.

Refs. [25,27] but for a constant realistic entropy per nucleon  $s = 50k_B$ . This allows exploration of the sensitivity of the nucleosynthesis without the need to perform full radiation-hydrodynamical calculations. An example is given in Fig. 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 produced only 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,  $^{92,94}\text{Mo}$  and  $^{96,98}\text{Ru}$ , is observed as  $Y_e$  gets larger. However, the abundances of these nuclei are still a factor 10 smaller than the ones of  $^{84}\text{Sr}$ . Similar results have been recently obtained by Pruet *et al.* [28], in a study of the nucleosynthesis that occurs in the early proton-rich neutrino wind. These authors suggest that the production of  $^{92}\text{Mo}$  is sensitive to the experimentally unknown masses of nuclei around  $^{92}\text{Pd}$ . Future experimental determinations of these masses will help to decide if the solar system abundances of light  $p$  nuclei can be due to the  $\nu p$  process.

All core-collapse supernova explosions, independent of existing model uncertainties, will eject hot, proton-rich explosively processed matter subject to strong neutrino irradiation. We argue that in all cases the  $\nu p$  process will operate in the innermost ejected layers producing neutron-deficient nuclei above  $A = 64$ . As the innermost ejecta, this matter is most sensitive to the details of individual explosions, thus their abundances will vary noticeably from supernova to supernova (e.g., as a function of stellar mass, rotation, etc.). The final amount of matter ejected will also depend on the intensity of the fallback, but as discussed in Ref. [11], mixing before fallback will always

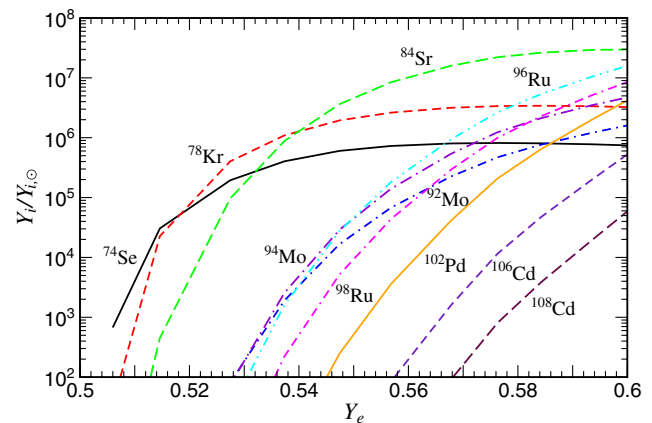


FIG. 3 (color online). Light  $p$ -nuclei abundances in comparison to solar abundances as a function of  $Y_e$ . The  $Y_e$  values given are the ones obtained at a temperature of 3 GK that corresponds to the moment when nuclei are just formed and the  $\nu p$  process starts to act.

lead to the ejection of elements synthesized, even in the innermost layers. Reference [11] explains the abundances seen in hyper-metal-poor stars by the ejecta of faint or weak core-collapse supernovae. Such faint supernova will generally have small expansion velocities favoring an enhanced production of  $\nu p$  elements, offering an explanation for the presence of Sr in the star HE 1327-2326 [9]. Our studies of the  $\nu p$  process show that the elements between Zn and Sr should be coproduced 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 may be 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  $\nu p$  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  $\nu p$  process contribution to the chemical evolution of the Galaxy. In this Letter, we have discussed the innermost proton-rich supernova ejecta before the emergence of the neutrino wind from the proton-neutron star. This neutrino wind will initially be proton rich [23] but will turn neutron rich in its later phases allowing for the synthesis of  $r$ -process nuclei [15,16,26]. The variations in the contribution of the  $\nu p$  process (represented by Sr, Y, and Zr) and the  $r$  process (producing the heaviest elements up to Th and U) [2,4] 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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