Neutrinos and Nucleosynthesis

The effect of neutrinos on nucleosynthesis in core-collapse supernovae

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1 Introduction

Scientists all over the world try to solve the question why the universe looks the way it does today. The formation of heavy elements like the ones found on earth is one big aspect of this search because it is expected to give great insight into the evolution process of our universe. Especially, the process and place of origination are in question. Some fundamental questions can be partly or completely answered nowadays, thanks to advanced measurements, e.g. masses and transition strengths, and the improvement of theoretical models and the possibility to run much more complex simulations. Today one knows that elements are produced in a process which is called nucleosynthesis. There are different types of nucleosynthesis. One type is the supernova nucleosynthesis. During a supernova nucleosynthesis elements heavier than ^{56}Fe are produced through different processes, which are determined by the given surroundings and its properties. One scenario where supernova nucleosynthesis is happening is a core-collapse supernova, which is the fate of a massive star. When a massive star runs out of burning fuel it starts to collapse under its own gravitational pressure. A possible remnant of such a supernova is a neutron star. In this environment, after the supernova has happened, the nucleosynthesis process starts. Two possible sites for nucleosynthesis are determined in a core-collapse supernova.

On the one hand, nucleosynthesis can happen in the so called neutrino driven winds, which is a matter outflow coming from near the neutron star and is driven outwards by neutrino matter interactions. The neutrinos needed to heat the material in order to cause the mass outflow are produced within the neutron star in large numbers through various reactions. As they leave the neutron star they take away energy and therefore cool the neutron star. This energy they take away can be transferred onto nucleons and nuclei by neutrino matter interactions while the neutrinos travel through matter. In the neutrino driven winds there is the possibility to have a νp-process and a weak r-process which denominate a proton capture and neutron capture process respectively. On the other hand the nucleosynthesis can happen in the outer shells, which remain further outward around the neutron star after the supernova explosion. Here, the operating process is the so called ν-process, which means the interaction of neutrinos with mainly nuclei that are abundant prior to the nucleosynthesis process. Therefore, only certain elements are produced during this process.

Two of the processes, namely the νp-process and the ν-process, involve neutrino matter interactions directly. This indicates, that the neutrinos emitted by the neutron star in the center of the exploded star can influence and even induce nucleosynthesis. Therefore neutrino matter interactions change the nucleosynthesis outcome and composition of the matter. Furthermore, neutrino matter interactions influence the proton-to-nucleon ratio, which determines the processes that can operate in different regions, and therefore can influence their occurrences.

2 Nucleosynthesis and Core-Collapse Supernovae

During the evolution of the universe elements were produced through different processes. This production of elements is called nucleosynthesis. Nucleosynthesis can happen at different stages of the evolution of the universe as well as in different environments. An identified nucleosynthesis site is the core-collapse supernova.

2.1 Nucleosynthesis

One distinguishes three different types of nucleosynthesis: the big bang nucleosynthesis, the stellar nucleosynthesis and the supernova nucleosynthesis. The big bang nucleosynthesis happened during the first three minutes after the big bang. Here light elements, mainly hydrogen and helium, were produced, see *Big Bang* in fig. 1. These light elements then assembled into stars. Here the stellar nucleosynthesis takes place, known as well as stellar burning. In a multiple step process ^{56}Fe is produced. The first step is hydrogen burning, where helium is produced. After completing the subsequent burning stages ^{56}Fe is produced from silicon burning. This process is indicated by the *stellar burning* process in fig. 1.
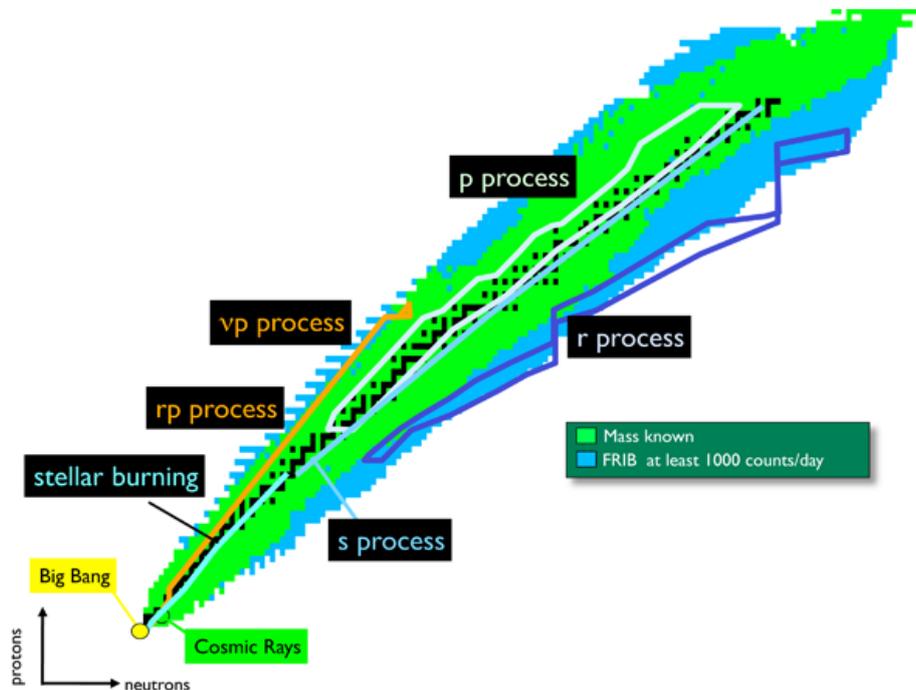
Figure 1: Elements can be produced by various nucleosynthesis processes, the relevant processes for supernova nucleosynthesis are the νp-process and a weak r-process [3].

^{56}Fe has the highest binding energy and therefore the fusion process in stars is not able to produce elements heavier than iron. Fig. 2 shows the resulting shell structure of a star after nuclear shell burning has stopped. Depending on the mass and size of the star, it can explode, which is called supernova. In such a scenario supernova nucleosynthesis happens, where elements heavier than iron can be produced by various processes. In a core-collapse supernova the nucleosynthesis is happening after the actual explosion has taken place. Important for the nucleosynthesis during a core-collapse supernova are the weak *r-process*, the *vp-process* and the *v-process*, while the last one is not shown in fig. 1, because it only produces abundances of a few nuclei. A detailed discussion of the relevant processes for the core-collapse supernova can be found in chap. 5. All nucleosynthesis processes that are possible are shown in fig. 1. It emphasizes, that elements heavier than ^{56}Fe cannot be produced during big bang nucleosynthesis and stellar nucleosynthesis.
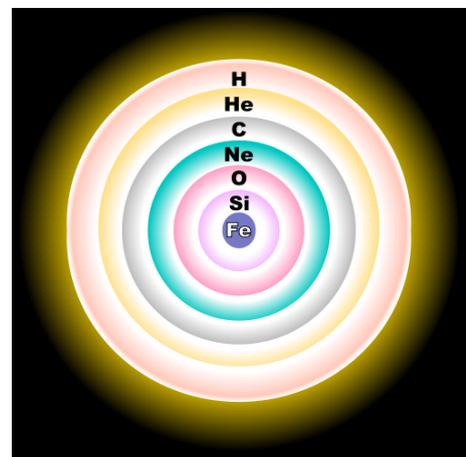
Figure 2: Shells of elements in a star produced during stellar nucleosynthesis [2].

A core-collapse supernova happens, when a massive star has burned all its fuel, leading to an onion like structure of the star. Due to the deficiency in burning material the star is not able to counterbalance the gravitational pressure pushing inwards. This leads to a compression of the core of the massive star up to nuclear densities, during this process a neutron star is formed in the center of the old star. There is also the possibility to produce a black hole in the center, but this case won't be considered here. During the collapse of the star a shock wave is launched outwards which triggers the explosion of the star. As the shock wave passes through matter it dissociates the heavy nuclei into free neutrons and protons. This is why after the explosion the matter close to the neutron star is mainly composed of nucleons, so neutrons and protons, while heavier nuclei can be found further away form the neutron star in the outer shells. Because the neutron star is really hot and dense, there are a lot of reactions going on in the center. As the neutron star matter consists mainly of free protons and neutrons two possible reactions are electron or positron capture, $p + e^- \rightarrow n + \nu_e$ and $n + e^+ \rightarrow p + \bar{\nu}_e$, producing electron neutrinos and antineutrinos. All other sorts of neutrino flavors are produced by various additional processes. As the cross section for neutrino matter interactions is very small, they leave the neutron star eventually and take away energy, which cools the neutron star. Approximately 10^{58} neutrinos with an average neutrino energy of 10 MeV per neutrino leave the neutron star, carrying away almost 99% of the gravitational binding energy. The neutrinos leaving the neutron star interact with the surrounding matter and an outcome of this are the neutrino driven winds, which are low-mass outflows coming from near the neutron star, caused by matter heating through neutrino matter interactions. Furthermore, these neutrinos can interact with the matter in the outer shells. Through these interactions with matter in the neutrino driven winds and the outer shells of the star the neutrinos can influence the ongoing nucleosynthesis happening in these two locations. The different paths neutrinos can take to interact with matter are discussed in the next section.

3 Neutrino Matter Interactions

There are two different channels through which neutrinos can interact with matter. One distinguishes charged-current interactions and neutral-current interactions. They are characterized by the exchange boson, that mediates the reaction. The charged-current interactions are mediated by either the W^+ or the W^- boson. During the interaction the charge of the participators is changed, like shown in fig. 3. The left Feynman diagram is an example for a charged-current interaction, where a neutrino, charge zero, changes into an electron, charge e, and the electron changes into a neutrino. Such a charge change is not possible during a neutral-current interaction mediated by a Z_0 boson. Like shown in the right Feynman diagram of fig. 3 the flavors of the participators remain unchanged. Only electron neutrinos and antineutrinos can interact via the charged-current interactions, while all neutrino flavors can interact via the neutral-current interactions.
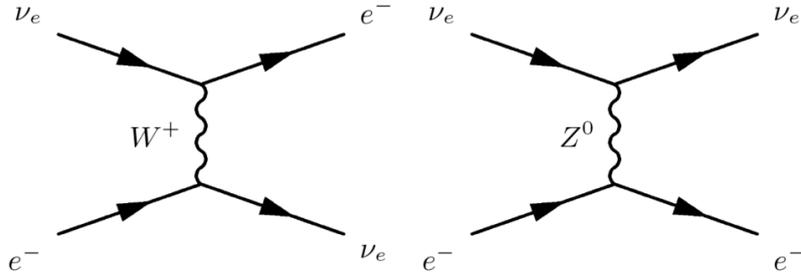
Figure 3: The left Feynman diagram shows a charged-current interaction, where a W^+ boson is exchanged, while the right Feynman diagram shows a neutral-current interaction mediated by the Z^0 boson [1].

The possible charged-current interactions are

$$n + \nu_e \longleftrightarrow p + e^- \quad \text{and} \quad p + \bar{\nu}_e \longleftrightarrow n + e^+ \quad .$$

These interactions happen mainly near the neutron star as there the composition is mainly neutrons and protons due to the dissociation by the shock wave. Moving further outwards there are two similar charged-current interactions happening,

$$\nu_e + A(Z,N) \rightarrow A(Z+1, N-1) + e^- \quad \text{and} \quad \bar{\nu}_e + A(Z,N) \rightarrow A(Z-1, N+1) + e^+,$$

these two reactions are similar to the two above, because there are still neutrinos captured by nucleons but now the interaction partners are bound in a nucleus $A(Z,N)$. Here A is the mass number of the nucleus, N gives the number of neutrons and Z gives the number of protons bound in the nucleus. As heavier nuclei just exist in the outer shells around the neutron stars these interactions can happen there. Theoretically, muons can be produced as well during charged-current interactions, but during a core-collapse supernova this is not the case as the energy of the neutrinos leaving the

neutron star is around 10 MeV and therefore not high enough to create a muon, which has a mass of 105 MeV/c^2. Through the neutral current interactions all three flavors of neutrinos and antineutrinos can interact with matter. One distinguishes neutrino Bremsstrahlung,

$$N + N \rightarrow N + N + \bar{\nu} + \nu \quad ,$$

where a neutrino antineutrino pair is produced during an interaction between two nucleons, neutrino pair production,

$$A^*(Z,N) \rightarrow A(Z,N) + \bar{\nu} + \nu \quad ,$$

where a neutrino antineutrino pair is produced during the deexciation of a nucleus, and finally there can be neutrino scattering,

$$\nu + A \rightarrow \nu + A^* \quad ,$$

where a neutrino or antineutrino transfers energy onto a nucleus during a scattering incident. If the energy transferred onto the nucleus by the neutrino is high enough, the nucleus is excited into a state in the continuum and can therefore deexcite by emission of either a neutron, a proton or an alpha-particle. If the energy transferred is not sufficient to lift the nucleus into the continuum, the nucleus will decay under emission of a photon.

In the following the energies the neutrinos have when they leave the neutron star and possible differences in energy between the different flavors are discussed. As already mentioned the neutrinos have an average energy of 10 MeV when they leave the neutron star. But the question is if this average energy is valid for all different flavors. Imagine a neutrino being produced in the neutron star. If the neutrino is a μ- or τ-neutrino or -antineutrino it can only interact with the surrounding matter via neutral-current interactions. This means, the $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ will have a certain number of interactions with matter, due to the given interaction rates, before it diffuses out of the neutron star. If the neutrino is an e^--neutrino or -antineutrino, it can interact via neutral- and charged-current with the neutron star matter. Assuming the same production point for a $\nu_{\mu,\tau}$ or $\bar{\nu}_{\mu,\tau}$ and a ν_e or $\bar{\nu}_e$ the number of interactions with the neutron star matter is much higher for the e^--neutrino and -antineutrino than for the μ- or τ-neutrino or -antineutrino as ν_e and $\bar{\nu}_e$ can interact via charged-current and neutral-current interactions before they diffuse out of the neutron star. This means due to more interactions of e^--neutrinos and -antineutrinos they are trapped for a longer distance and time in the neutron star and thus have less energy when they leave the neutron star compared to the μ- or τ-neutrino or -antineutrino.
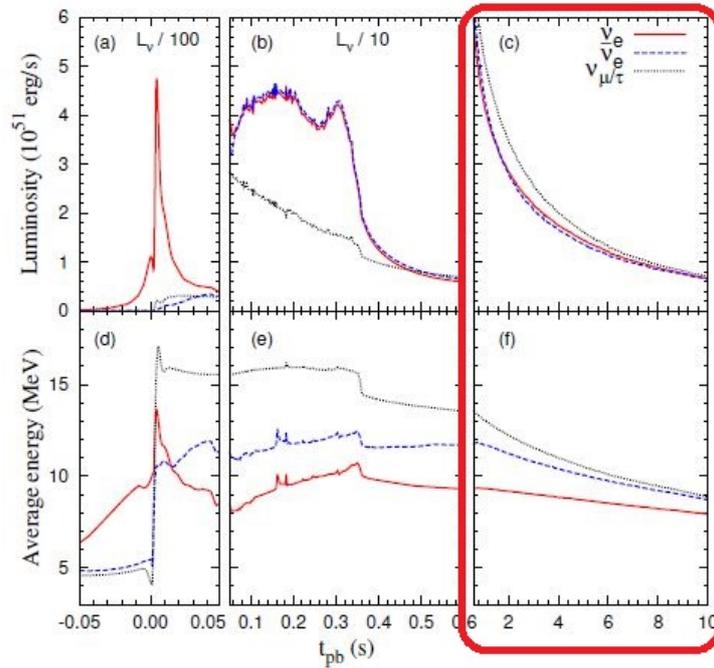
Figure 4: Shown are the neutrino luminosities and average energies for the different flavors. The red area is the time frame relevant for nucleosynthesis and for neutrino influences on nucleosynthesis. The picture was derived from a simulation of a 18 M$_\odot$ supernova model [9].

Furthermore, one has to distinguish between e^--neutrino and -antineutrino. As the matter of the neutron star consists mainly of neutrons the probability of a ν_e absorption on neutrons is bigger than the probability of a $\bar{\nu}_e$ absorption on a proton. Therefore, the electron neutrino will interact more often with the matter than the e^--antineutrino before

diffusing out of the neutron star and the electron neutrino will therefore have a lower energy.
This leads to an energy hierarchy for the different neutrino flavors leaving the neutron star:

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_{\mu,\tau}, \bar{\nu}_{\mu,\tau}} \rangle \quad .$$

This hierarchy derived by the theoretical considerations is confirmed by simulations as shown in fig. 4, framed plot region. The specific simulation was done using a $18\,\mathrm{M}_\odot$ supernova model [9]. It reproduces the expected energy differences at the beginning of the cooling process of the neutron star, so when the neutron star becomes translucent to neutrinos after the collapse has stopped. With progressing time the simulation shows that the energies become quiet similar.

4 Proton-to-Nucleon Ratio

A variable to determine different locations for nucleosynthesis processes is the so called proton-to-nucleon ratio Y_e. Its value is determined by charged-current interactions near the neutron star and therefore depends on the following interactions:

$$n + \nu_e \longleftrightarrow p + e^- \quad \text{and} \quad p + \bar{\nu}_e \longleftrightarrow n + e^+ \quad .$$
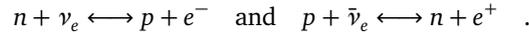
Depending on the reactions rates for these two processes $\lambda_{\nu_e n}$, for the electron neutrino absorption on neutrons, and $\lambda_{\bar{\nu}_e p}$, for the electron antineutrino absorption on protons, one distinguishes between two cases. On the one hand one considers the case where Y_e is larger than 0.5 and the case where Y_e is smaller than 0.5. If $Y_e > 0.5$ the matter is called proton-rich, as the absorption rate for neutrinos is bigger than for antineutrinos and therefore more proton than neutrons are produced. For the matter to be called neutron-rich Y_e has to be smaller than 0.5 and therefore $\lambda_{\bar{\nu}_e p}$ is bigger than $\lambda_{\nu_e n}$. Assuming that electron and positron capture ceases much earlier, the change of Y_e is determined only by the charged-current interactions and the associated absorption rates,

$$\dot{Y}_e = \lambda_{\nu_e n} Y_n - \lambda_{\bar{\nu}_e p} Y_p \quad ,$$

with Y_n and Y_p as the neutron and proton abundance respectively. When matter is exposed to high neutrino fluxes over a long period of time, as this is the case during a core-collapse supernova, the value of Y_e reaches an equilibrium value which can be calculated by assuming $Y_p = Y_e$, $Y_n = 1 - Y_e$ and setting $\dot{Y}_e = 0$. With this the equilibrium proton-to-nucleon ratio

$$Y_{e,eq} = \frac{\lambda_{\nu_e n}}{\lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p}}$$

is derived. This means, that the value is only dependent on the absorption rates

$$\lambda_{\nu_e n} = \Phi_{\nu_e} \cdot \sigma_{\nu_e n} \quad \text{and} \quad \lambda_{\bar{\nu}_e p} = \Phi_{\bar{\nu}_e} \cdot \sigma_{\bar{\nu}_e p}$$

with the neutrino fluxes Φ and the cross sections σ for ν_e and $\bar{\nu}_e$ given by

$$\Phi_\nu = \frac{L_\nu}{4\pi r^2 \langle E_\nu \rangle} \quad \text{and} \quad \sigma_\nu = \frac{\sigma_0}{m_e c^2}(E_\nu + \Delta)^2 \quad ,$$

with L_ν as the luminosity, $\sigma_0 = 2.569 \times 10^{-44}\,\mathrm{cm}^2$ and Δ as the mass difference between protons and neutrons. If the expression for the cross section is averaged over the whole neutrino spectrum one derives

$$\lambda_{\nu_e n} = \frac{L_{\nu_e}}{4\pi r^2 (m_e c^2)} \frac{\sigma_0}{(m_e c^2)} \left(\epsilon_{\nu_e} + 2\Delta + \frac{\Delta^2}{\langle E_{\nu_e} \rangle} \right) \quad \text{and}$$

$$\lambda_{\bar{\nu}_e p} = \frac{L_{\bar{\nu}_e}}{4\pi r^2 (m_e c^2)} \frac{\sigma_0}{(m_e c^2)} \left(\epsilon_{\bar{\nu}_e} - 2\Delta + \frac{\Delta^2}{\langle E_{\bar{\nu}_e} \rangle} \right) \quad ,$$

with $\epsilon_\nu = \frac{\langle E_\nu^2 \rangle}{\langle E_\nu \rangle}$ as the ratio between the second moment of the neutrino spectrum and the average neutrino energy.
After having derived an expression for the different absorption rates it can easily be calculated an equation predicting when matter in proton-rich or neutron-rich simply by comparison of the value of ϵ for neutrinos and antineutrinos. Considering the requirement for neutron-rich matter $\lambda_{\bar{\nu}_e p} > \lambda_{\nu_e n}$, one can derive a condition for ϵ_ν to obtain neutron-rich conditions:

$$\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} > 4\Delta - \left[\frac{L_{\bar{\nu}_e}}{L_{\nu_e}} - 1 \right] \left(\epsilon_{\bar{\nu}_e} - 2\Delta \right) \quad .$$

The condition above is an indirect condition for the energy difference between ν_e and $\bar{\nu}_e$, as $\epsilon_\nu = \frac{\langle E_\nu^2 \rangle}{\langle E_\nu \rangle}$. As the mass difference between neutrons and protons is 2 MeV, the energy difference between ν_e and $\bar{\nu}_e$ has to be bigger than 8 MeV without the correction term. As the luminosities for the two neutrino flavors are almost equal, the correction term $\left(\epsilon_{\bar{\nu}_e} - 2\Delta\right)$ only gets important for a high $\bar{\nu}_e$ energy, which is the case during the early times of the cooling phase. This means that the energy limit is depressed to smaller energy differences during the early times of the nucleosynthesis process, meaning the energy difference between ν_e and $\bar{\nu}_e$ can be smaller in order to get neutron-rich conditions. Simulations suggest, that these requirements might be met during the early neutrino driven wind phase, but won't be fulfilled during later times, as the average energies of neutrinos and antineutrinos become similar and the average energies decreases generally. Therefore the neutrino driven wind ejecta can be neutron-rich at the early start but will be proton-rich for most of the time [6–8].

5 Nucleosynthesis Sites

In a core-collapse supernova there are two different sites identified where nucleosynthesis happens: the outer shells of the exploded star and the neutrino driven winds, which consist of material that was heated near the neutron star and driven outwards by neutrino matter interactions. Depending on the proton-to-nucleon ratio in the neutrino driven winds two different processes can happen, the νp-process or the weak r-process, whereas in the outer shells just the ν-process operates.

5.1 Neutrino driven Winds

To understand what happens in neutrino driven winds during nucleosynthesis one might first consider the neutrinos emitted by the neutron star and second think about the neutrino matter interaction and the consequences when this matter is driven further outwards. All kinds of neutrino flavors leave the neutron star.
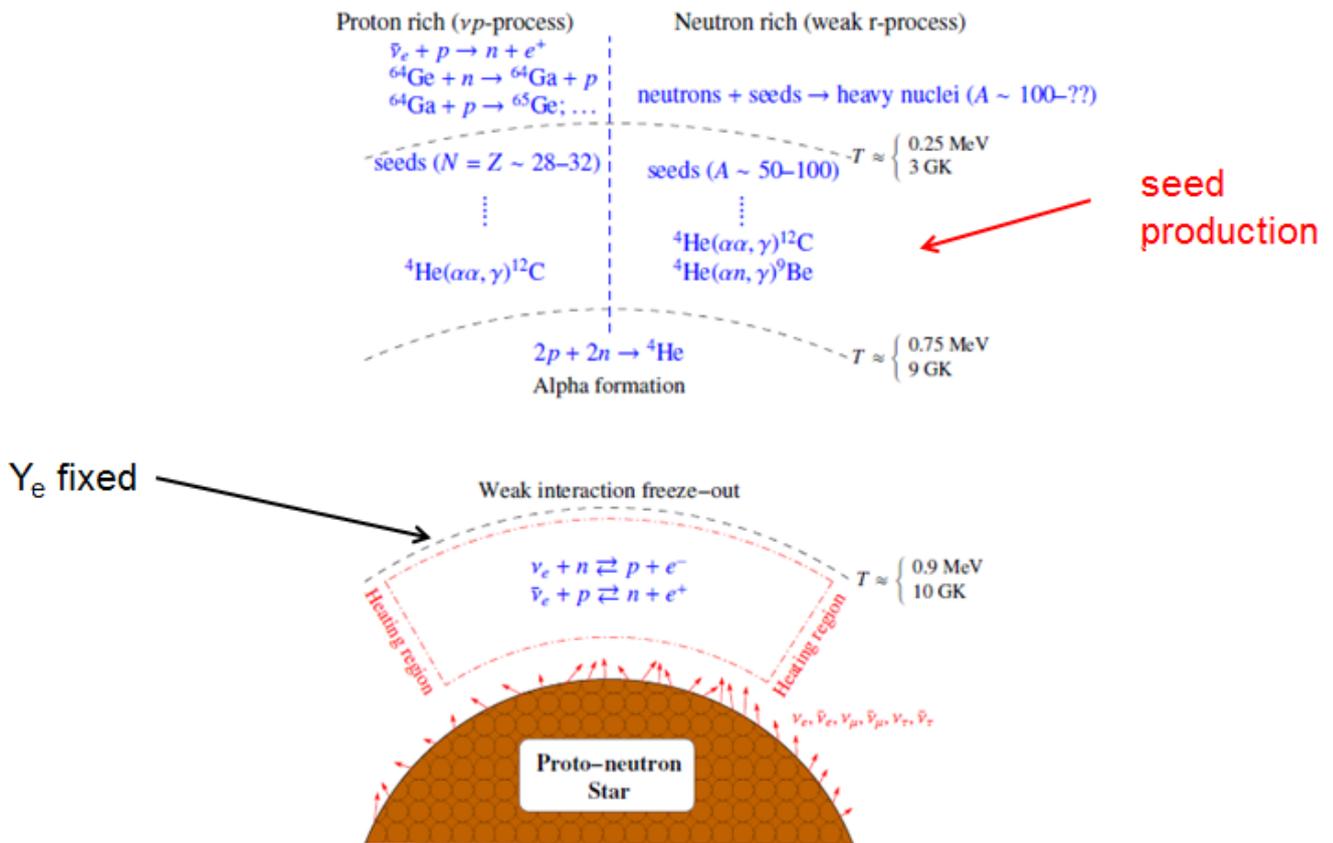
Figure 5: When the neutrino driven matter moves to cooler reagions, heavier elements are formed which act as seed for the subsequent nucleosynthesis processes. There are two possible processes, the νp-process and the weak r-process which operate in proton-rich or neutron-rich surroundings respectively [8].

But as the composition near the neutron is star is mainly neutrons and protons, there are more interactions of ν_e and $\bar{\nu}_e$ with matter via absorption processes than interactions with $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$. This area, where charged current interactions dominate is called heating region. During this heating phase the two absorption reactions of ν_e and $\bar{\nu}_e$ are in equilibrium,

but moving further outwards the reaction rates for these two processes decrease until they are finally smaller than the Hubble expansion rate, which characterizes the expansion of the universe. This leads then to the weak interaction freeze-out, which means, that the absorption processes of neutrinos on neutrons and protons vanish, which fixes Y_e to a certain value. Moving even further outwards nucleons start to form nuclei. First Helium nuclei are created and by α-particle capture even higher elements are formed, which then function as seeds for the νp-process or the weak r-process.

The νp-process is a proton capture process. Nuclei with equal neutron and proton number act as seeds for this process. These nuclei capture protons until the Coulomb barrier is too high and until the β^+-half-life of a nucleus is longer than the expansion time of the winds. If just the coulomb barrier is too high to add another proton, the nucleus could decay via β^+-decay and then start capturing protons again. Therefore the β^+-decay acts as a supplier of nuclei for proton capture. The nuclei where the coulomb barrier is too high but as well the β^+-halflife is too long are called waiting-point nuclei, as here the proton capture process stagnates(e.g. ^{64}Ge, see fig. 6). At the point where the proton capture halts, the neutrinos play an important role. As the ejecta is proton-rich, there is a high probability for $\bar{\nu}_e$ capture on protons. This way free neutrons are produced which can be captured by the waiting-point nuclei. Fig. 6 shows, that the produced neutrons are captured by the waiting-point nuclei under emission of a proton, thus changing the composition of the nucleus and as well the coulomb barrier. Therefore it is possible for the created nucleus to start the proton capture process again. This makes it possible to bypass the waiting-point nuclei and proceed to higher elements by further proton capture. Simulations show, that this bypassing is actually happening.
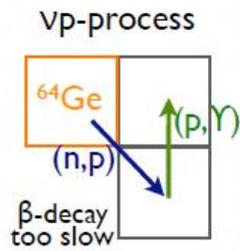
Figure 6: Waiting point nuclide ^{64}Ge, nucleosynthesis only continues due to neutron capture.
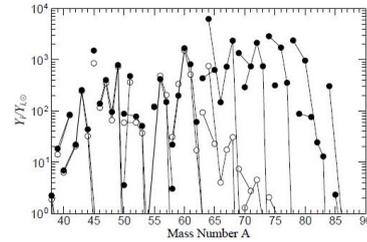
Figure 7: Proton capture abundances with neutrino matter interactions taken into account, black circles, and without, white circles [5].

The results of such a simulation are shown in fig. 7. Here, the abundances of elements produced solely by proton capture, marked with white circles, and with the supply of neutrons by the $\bar{\nu}_e$ capture on protons, marked with black circles, are compared. Obviously, the nucleosynthesis without taking neutrinos into account ceases much earlier, while it is possible to produce higher elements, when neutrinos are taken into account. The efficiency of this process is highly depending on the proton-to-neutron ratio as well as the antineutrino luminosity.
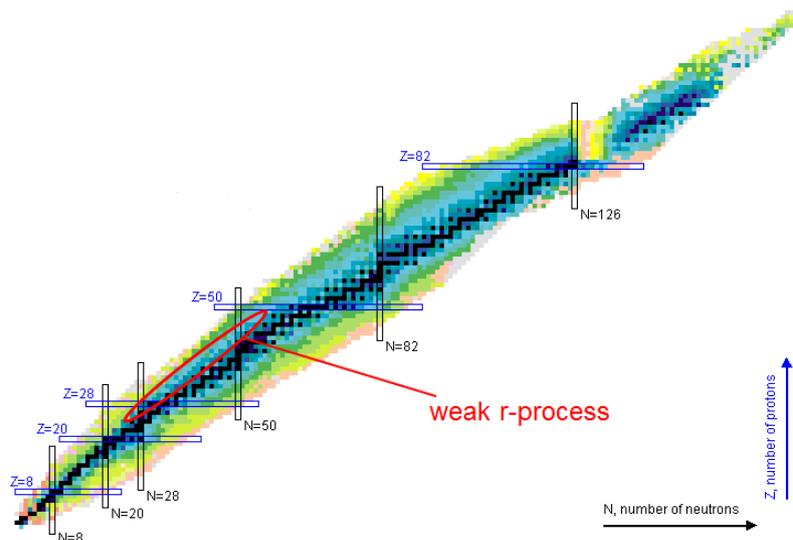
Figure 8: The weak r-process operates on the proton-rich side of the nuclear chart, as the proton-to-nucleon ratio can only be slightly smaller than 0.5 [4].

If the matter in the neutrino driven winds is slightly neutron-rich, which can be the case in the early wind phase, which was shown in sec. 4, it is also possible for the weak r-process to happen. The weak r-process is an extinction of the r-process which is based on neutron capture of nuclei via

$$N(A, Z) + n \rightarrow N(A + 1, Z) + \gamma \quad .$$

The actual r-process is a neutron capture process running along the neutron-rich side of the nuclear chart, as indicated in fig. 1. As the weak r-process is an extinction of this process it is not necessarily running along the neutron-rich side of the nuclear chart and it doesn't produce neutron-rich nuclei, especially not to such a high mass number as the actual r-process does. The weak r-process produces nuclei up to mass number A~90 on the proton-rich side of the nuclear chart. This is due to the fact, that the proton-to-nucleon ratio is just slightly smaller than 0.5. Simulations suggest, that the value is around 0.48 [8]. This means that by the neutron capture just nuclei up to a proton-to-nucleon ratio of 0.48 can be produced, these types of nuclei lie on the proton-rich side of the nuclear chart. As there are not many free neutrons available for capture reactions, the weak r-process will mainly cause major abundances of nuclei with closed neutron shells and therefore a neutron number of N=50. Nevertheless, it is quite unsure if this process really happens, as the supernova ejecta is proton-rich over most of the time and it is not proven yet, that it really can be slightly neutron-rich at the earlier times.

5.2 Outer Shells

Another possible site of nucleosynthesis are the outer layers of the star which survive the supernova explosion, here the so called ν-process takes place. For this process all kinds of neutrino matter interactions are important. Neutrinos can interact via charged-current or neutral-current interactions with matter leading to distinct abundance peaks for several nuclei. The nuclei neutrinos interact with are abundant prior to the happening nucleosynthesis. It is expected that the ν-process mainly causes abundance peaks for the rare isotopes ^{7}Li, ^{11}B, ^{19}F, ^{138}La and ^{180}Ta and the long lived radioactive isotopes ^{22}Na and ^{26}Al.
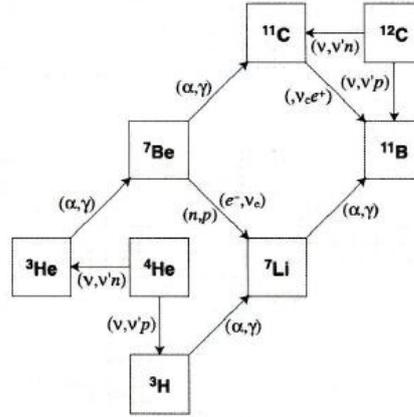
Figure 9: Production of light elements during the ν-process by induced reactions on ^{4}He and on ^{12}Ca [8].

Neutrino induced reactions on ^{4}He and on ^{12}Ca cause a small reaction sequence which produces light nuclei and especially ^{7}Li and ^{11}B via

$$^4He(\nu, \nu'p)^3He(\alpha, \gamma)^7Li \quad , \quad ^4He(\nu, \nu'n)^3He(\alpha, \gamma)^7Be(e^-, \nu_e)^7Li \quad \text{and}$$

$$^{12}C(\nu, \nu'p)^{11}B \quad ,$$
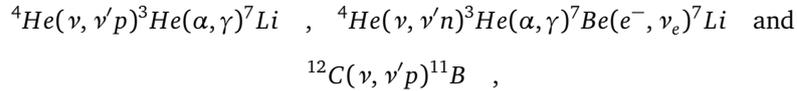
where the last interaction is mainly happening with $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$. For both cases there are as well charged-current interactions contribution to the abundances. Fig. 9 shows the reaction sequence responsible for the formation of ^{7}Li and ^{11}B. Another reaction where $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ are involved is the production of ^{19}F via

$$^{20}Ne(\nu, \nu'n)^{19}F \quad ,$$
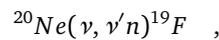
the contribution of this reaction to the total ^{19}F abundance is strongly dependent on the progenitor mass and the stellar evolution, as simulations suggest. The two elements ^{138}La and ^{180}Ta are solely produced by ν_e and $\bar{\nu}_e$ interactions:

$$^{238}Ba(\nu, e^-)^{138}La \quad \text{and} \quad ^{180}Hf(\nu, e^-)^{180}Ta \quad .$$
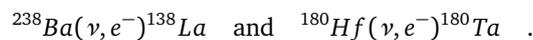
In addition to that simulations also suggest, that the two radioactive nuclei ^{22}Na and ^{26}Al are as well produced directly or indirectly by neutrino-induced reactions which provide an abundance of light particles [8].

6 Summary and Outlook

Elements can be produced during a core-collapse supernova in two different environments. One are the neutrino driven winds, where either the weak r-process or the νp-process can happen. Concerning the weak r-process it is not really sure to what extend and if it really happens during neutrino driven winds. Recent simulations suggest, that the neutrino driven wind ejecta can be slightly neutron-rich in the beginning. Future simulations have to be done in order to confirm or falsify this result, therefore models have to be improved in order to be able to perform better simulations to decide whether the weak r-process is really likely to happen during early wind phases.

Furthermore, there is the production of elements via the ν-process in the outer shells. Here simulations are very advanced due to good measuring possibilities of transition strengths and cross sections. One can tell to which extend certain nuclei are produced in the outer shells via neutrino matter interactions and what percentage might be due to different interactions in different surroundings. To improve all supernova models there is as well a need to measure more masses and transition strengths in order to be able to improve the different simulations that were already performed.

As the nucleosynthesis outcome depends on the neutrinos involved in the interactions as well as on the energies of the neutrino flavors, there are very recent studies which suggest that neutrino oscillations could change the nucleosynthesis outcome. This is due to the fact, that these oscillations cause a swap in energy and luminosity spectra of the neutrinos. It is possible that these oscillations may have an impact on the nucleosynthesis in neutrino driven winds as well as the nucleosynthesis occuring in the outer supernova shells.

As this whole research area is mainly theoretical it is important to collect as much experimental data as possible as an input to modify existing models and simulations to make more reliable predictions of what can happen during nucleosynthesis in core-collapse supernovae.

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