

Implication of the Steady State Equilibrium Condition for Electron-Positron Gas in the Neutrino-driven Wind from Proto-Neutron Star

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Abstract: Based on the steady state equilibrium condition for neutron-proton-electron-positron gas in the neutrino-driven wind from protoneutron star, we estimate the initial electron fraction in the wind in a simple and effective way. We find that the condition in the wind might be appropriate for the r-process nucleosynthesis.

Keywords: r-process; neutrino-driven wind; steady equilibrium condition

It is well known that approximately half of the heavy elements ($A > 60$) are produced by the r-process nucleosynthesis. There are two favorite sites for the r-process nucleosynthesis: one is the neutrino-driven wind of the core-collapse supernovae (CC-SNe); the other is the neutron star (NS) mergers. The observations of the metal-poor stars in recent years strongly favor the neutrino-driven wind over the neutron stars mergers as the major source of the r-process. On the one hand, neutrino-driven wind of CCSNe can not produce any significant amount of the low- A elements; on the other hand, the explosion rate of CCSNe is larger than that of NS-NS mergers^[1]. Here we only investigate the neutrino-driven wind that is produced two seconds after the bounce as the shock wave rushes out of the iron core for a successful CCSNe explosion. Neutrino-driven wind is first proposed by Duncan et al. in 1986^[2]. Later, many detailed analysis for this process including the general relativity hydrodynamics, rotation, magnetic field, the different composition of the wind, and the termination shock [3, 4, 5, 6, 7] have been done by many authors. There are also some excellent reviews, e.g. Martínez-Pinedo(2008)^[8]. Here we give a brief introduction to the r-process nucleosynthesis in the neutrino-driven wind. Soon after the birth of protoneutron star, lots of neutrinos(including e , μ and τ neutrinos and the corresponding antineutrinos) escape from the surface of PNS. Because of the photodisintegration in the shock wave, the main ingredients near the surface of PNS are proton, neutron, electron

and positron (npe^-e^+ gas). The main reactions in this region are the absorption of neutrino and antineutrino by neutrons and protons, so the region is called as neutrino heat region. At the outer boundary of the neutrino heat region, the weak interactions are freeze-out (i.e. electron fraction Y_e keeps as a constant) at temperature about 0.9MeV. Above this region, protons and neutrons begin to combine into α particles, and for the further region, heavier nuclides, such as ^{12}C , ^9Be and the other seed nuclei are produced. Abundant neutrons can captured by the seed nuclei in neutrino-driven wind, but this process only sustains about 10 seconds. Since the different regions have almost invariable composition and physical states in such a short timescale, it can be dealt as a steady process for a good approximation. The final products of this process are the r-elements. Usually, four parameters are essential for a success r-element pattern. They are: (1) the neutron-seed ratio, (2)the electron fraction, (3)the entropy and (4) the expansion timescale. It is very difficult to satisfy all those conditions self-consistently. We here discuss one of those important parameters: electron fraction Y_e , which varies very quickly from the neutrino sphere to the position where α particles form. For example, Y_e increases from 0.03 to 0.47 only through 3km in the $1.4M_\odot$ PNS model(of course the result is model-dependent)[7]. So we here main care the region close to the surface of PNS. The evolution of Y_e is obtained by solving a set of differential equations with the input of the EoS, neutrino reaction rate, hydrodynamic frame and so on. In addition, the initial conditions and boundary conditions are also necessary. As to the initial electron fraction Y_{ei} , there exits many methods to dertermine. Because the neutrinos emit from the neutrino sphere where the wind origin, the electron fraction at the neutrino sphere can be regarded as the initial electron fraction.

One of methods to calculate Y_{ei} is applying the steady equilibrium condition at the neutrino sphere, which is suggested by Arcones et al.[9] In the following part, we give a simple introduction to the steady equilibrium condition with composition of proton, neutron and electron under the different conditions. One can refer Yuan (2005) for more detailed analysis [10]. If neutrinos are trapped in a system of npe^-e^+ gas, the following reactions can take place:



Other reactions such as $\gamma + \gamma \leftrightarrow e^- + e^+$ also exist, but they do not influence the electron fraction. Note that all reactions(1-3) are the reversible reactions, when all the reactions reach the equilibrium, according to the theory of thermodynamics, it is well known that the chemical equilibrium condition is

$$\mu_p + \mu_e = \mu_n + \mu_\nu. \quad (4)$$

If the neutrino can escape freely from the system, the generally steady equilibrium condition is written by

$$\lambda_{e-p} = \lambda_{e+n} + \lambda_n. \quad (5)$$

Now we consider two special cases.

CASE1: When the temperature of the gas is comparative low, that the neutrinos are trapped in the system or not does give the same equilibrium condition, because the number density of the “trapped” neutrinos can be neglected, as $n_\nu \propto T^3$. As argued in Shapiro and Teukolsky (1983)^[11], the chemical potential of the ‘trapped’ neutrinos $\mu_\nu \approx T$, the chemical potential of neutrinos can be ignored in equation (4), i.e. $\mu_\nu = 0$, therefore, the corresponding chemical equilibrium condition for cold npe^- gas under β -equilibrium is

$$\mu_p + \mu_e = \mu_n. \quad (6)$$

The above equilibrium condition can be obtained in the another way [10], based on equation (5). When the temperature of the gas is low, there is few positron in the npe^- gas, λ_{e+n} is negligible, $\lambda_{e+n} \approx 0$, then equation (5) becomes

$$\lambda_{e-p} = \lambda_n. \quad (7)$$

As argued in Yuan (2005)^[10], we can re-obtain equation (6) from equation (7).

CASE2: If the temperature is very high and the neutrinos can escape freely in a system of npe^-e^+ gas (i.e. “hot” β equilibrium npe^-e^+ gas), the rate of neutron decay can be ignored comparing with that of positron capture by neutron, then equation (5) becomes

$$\lambda_{e-p} = \lambda_{e+n}. \quad (8)$$

Based on the theory of the weak interaction, the corresponding steady chemical equilibrium condition is (the detailed derivation can be found in reference[10]),

$$\mu_p + 2\mu_e = \mu_n. \quad (9)$$

Return to the issue of PNS, we find that at the inner region of PNS, the neutrinos are almost trapped, but at the neutrino sphere, the situation have been changed

CASE	Y_{ei}	Y'_{ei}
1	0.063	0.065 ^[9]
2	0.031	0.03 ^[7]

Table 1: Comparison of the initial electron fractions Y_{ei} in the neutrino-driven wind by using the different steady equilibrium conditions for a model of $1.4 M_\odot$ PNS. CASE1 corresponds to the equilibrium condition $\mu_p + \mu_e = \mu_n$; CASE2 corresponds to the equilibrium condition $\mu_p + 2\mu_e = \mu_n$. Y'_{ei} are the reference values from the previous references.

completely. Neutrino from the inner region will be absorbed by baryons and then re-emit quickly; the luminosity of neutrino and anti-neutrino is similar; the temperature of PNS is very high (it can even be larger than 10^{11} K), and the neutrinos can escape freely. All those physical conditions indicate that the “hot” β equilibrium is valid, not as that in the inner region of PNS. The chemical potentials are functions of densities, temperatures and electron fractions. When the density and temperature at the neutrino sphere is fixed, the electron fraction can be determined. so we obtain a simple method to calculate the electron fraction at neutrino sphere, i.e. the initial electron fraction of the wind,

$$\mu_p(\rho, T, Y_{ei}) + 2\mu_e(\rho, T, Y_{ei}) = \mu_n(\rho, T, Y_{ei}), \quad (10)$$

where ρ, T, Y_{ei} are the density, temperature, electron fraction at the neutrino sphere respectively. We here give an example for a typical PNS with mass $\sim 1.4M_{\odot}$ (following data are chosen from the reference[7, 9]). At $t=2s$ after the bounce, the neutrino sphere radius $R_v \sim 10km$, temperature $T \sim 8MeV$, $\rho \sim 3 \times 10^{12}g\text{ cm}^{-3}$. The results from Table 1 show that the difference of the electron fraction under the different equilibrium conditions is significant. Y_{ei} is 0.63 for CASE1 and 0.31 for CASE2. Electron fraction in CASE2 is about two times less than the fiducial result which results from CASE1. Moreover, comparing with reference[7], we find the results from the steady state equilibrium condition accord with those from the other methods well. So this is a simple and effective method.

Due to the significant difference from CASE1 and CASE2, the initial electron fraction of neutrino-driven wind is changed, which results in the variation of the initial condition of the wind. Such variation must influence the nuclear reaction paths, final products and the position of the r-process nucleosynthesis. Recent research by Wanajo et al.(2009) shows that only 0.005-0.01 increase of Y_e can significantly change the fraction of r-elements[12]. So applying an accurate and simple method to calculate electron fraction in neutrino-driven wind and r-process nucleosynthesis is necessary.

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