Neutrinos and Nucleosynthesis in Supernova *

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The type II supernova is considered as a candidate site for the production of heavy elements. The nucleosynthesis occurs in an intense neutrino flux, we calculate the electron fraction in this environment.

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I. NUCLEOSYNTHESIS IN SUPERNOVA

A star lives a luminous life by burning $H$ into successively heavier elements. However, as the Fe group nuclei near mass number $A = 56$ are most tightly bound, no more nuclear binding energy can be released to power the star by burning Fe. Therefore, heavy elements beyond Fe have to be made by process other than normal stellar burning. One such process is the rapid neutron capture process, or the r-process.

One starts with some nuclei and lots of neutrons, the nuclei rapidly capture these neutrons to make very neutron-rich unstable progenitor nuclei. After neutron capture stops, the progenitor nuclei successively beta-decay towards stability and become the r-process nuclei observed in nature. This process is responsible for approximately half the natural abundance of nuclei with mass number $A > 100$ [1].

There is as yet no consensus for the site or sites of r-process nucleosynthesis. The high neutron densities $10^{20}$ cm$^{-3}$ and temperatures of $10^9$ K associated with r-process suggest astrophysical sites as core-collapse type II or Ib supernovae. The most plausible environment yet proposed is the neutrino-heated ejecta from the nascent neutron star. Close to the neutron star, the temperature is several Mev and the atmosphere is essentially dissociated into neutrons and protons. As the neutrinos emitted by the neutron star free-stream through this atmosphere, some of the $\nu_e$ and $\overline{\nu}_e$ are captured by the nucleons and their energy is deposited in the atmosphere. The atmosphere is heated and, as a result, it expands away from the neutron star and eventually develops into a mass outflow, a neutrino-driven wind [2]. After the shock wave has propagated out to several hundred kilometers, condition behind the shock at 100 to 200 km are suitable for neutrino heating. The neutrino heating blows a hot bubble above the proton-neutron star.

II. NEUTRINO-NUCLEON INTERACTION

Neutrinos and antineutrinos of all three flavors are emitted by the neutron star produced in a supernova. The individual neutrino species has approximately the same luminosity but very different average energy. As the neutrinos diffuse out of the neutron star, they thermally decouple from the neutron star matter at different radii due to the difference in their ability to exchange energy with such matter. Neutrinos species of all flavors have identical neutral current interactions but, due to energy threshold effects, the $\nu_\mu$, $\nu_\tau$, and their antiparticles lack the charged current capture reactions analogous to

$$\nu_e + n \rightarrow p + e$$  \hspace{1cm} (1)
$$n + e^+ \rightarrow p + \nu_e.$$ \hspace{1cm} (2)

The result is that $\nu_\tau$, $\nu_\mu$, and their antiparticles, have identical spectra and decouple at a higher density, and thus temperature, than the electron neutrinos and antineutrinos [3].

We require the neutron-to-nuclei ratio $R > 100$ to effect a good r-process yield for heavy nuclear species, but the models with conventional equations of state for nuclear matter all give smaller values of $R$. In all models $R$ is determined by the net neutron-proton ratio; the entropy-per-baryon in the ejecta, $s$; and the dynamic expansion time scale, $t_{\text{dyn}}$ . The neutron-to-proton ratio
is \( n/p = Y_e^{-1} - 1 \), where \( Y_e \) is the number of electrons per baryon. The \( r \)-process is only possible when \( Y_e < 0.5 \) at freeze-out from nuclear statistical equilibrium. The value of \( Y_e \) in the region above the neutrinosphere is determined by the interactions in Eq. (1) and (2). We can write the rate of change of \( Y_e \) with time as

\[
\frac{dY_e}{dt} = \lambda_1 - \lambda_2 Y_e,
\]

where \( \lambda_1 = \lambda_{\nu e} + \lambda_{\nu n} \) and \( \lambda_2 = \lambda_1 + \lambda_{\nu e} + \lambda_{\nu p} \), are the rates in (1) and (2), (see Ref[4]).

III. ELECTRON FRACTION

The general solution to the above equation is given by

\[
Y_e = \frac{\lambda_1}{\lambda_2} - \int_0^t I(t, t') \left[ \frac{d}{dt'} \left( \frac{\lambda_1(t')}{\lambda_2(t')} \right) \right] dt',
\]

with the integrating factor given by

\[
I(t, t') = Exp \left( -\int_{t'}^t \lambda_2(t'') dt'' \right)
\]

and \( \lambda_1/\lambda_2 \equiv Y_{eq} \). The functional form for the weak-interaction rates are given by:

\[
\lambda_{\nu n} = \frac{B L_\nu}{r^2 < E_\nu >} \times \frac{1}{T_\nu^3 F_2(0)} \int_0^\infty (1 - f_\nu) E_\nu^2 P_{\nu e} dE_\nu,
\]

\[
\lambda_{\nu p} = \frac{B L_\nu}{r^2 < E_{\nu} >} \times \frac{1}{T_\nu^3 F_2(0)} \int_{\Delta m}^\infty (1 - f_\nu) E_\nu^2 P_{\nu e} dE_\nu,
\]

\[
\lambda_{\nu e} = A \int_{\Delta m}^\infty (1 - P f_\nu) E_{\nu}^2 f_{\nu e} dE_{\nu}^-,
\]

\[
\lambda_{\nu p} = A \int_{\Delta m}^\infty (1 - \bar{P} f_{\nu}) E_{\bar{\nu}}^2 f_{\bar{\nu} e} dE_{\bar{\nu}}^-,
\]

where \( B = 9.6 \times 10^{-44} \text{cm}^2/\text{MeV}^2 \), \( L_\nu = 1 \times 10^{51} \text{erg/seg} \) and \( L_{\bar{\nu}} = 1.3 \times 10^{51} \text{erg/seg} \) are the neutrino luminosity, \( < E_\nu >= 3.15 T_\nu \), \( F_2(0) = 1.8 \), \( f = E^2/(e^{E/T} + 1) \) is the distribution function of the neutrinos or electrons and positrons. \( (1 - f_\nu) \) and \( (1 - f_{\nu}) \) are the Pauli blocking factor and \( r \) is evaluated in 10 km. and \( A = \frac{G c^2}{2\pi^2} (g_{\nu}, g_{\bar{\nu}}^2 + 3g_{\nu}A^2) \). \( g_{\nu} \) is the Fermi coupling constant, and \( P (Q) \) is a factor of survival probability (<1) for neutrinos (antineutrinos). In this work, we assume the energy spectrum of each neutrino species, electron and positron is approximated by a Maxwell-Boltzmann distribution, following Bernstein[7] and Enqvist[8]. We changed to the variable \( y = \Delta m/T \) and the solution is function of the temperature, the integrating factor now becomes

\[
I(y, y') = Exp \left( -\int_{y'}^y \left[ \frac{dt''}{dy''} \right] \lambda_2(y'') dy'' \right).
\]

To evaluate the integrating factor we assume the neutrino-driven wind model, the radius of an outflowing mass element is related to time \( t \) by \( r = r_0 \exp \{ (t - t_0)/t_{dyn} \} \) this implies an outflow velocity proportional to the radius, \( v = r/t_{dyn} \). In the model, \( \rho r^{-3} = T \alpha r^{-1} \). We set \( T_n = T_p = T_e = T_{e+} = T \), but we assume that the neutrino and antineutrino temperatures remain nearly constant. We finally compute the integrals in the solution for a range of \( y \) values, we obtain the curve for \( Y_e(y) \) and \( P \). Numerical supernova neutrino transport calculations show that \( T_{\nu e} = 5.1 \text{ Mev}, \ n_{\nu e} = 4.5 \text{ Mev} \) and we set for \( t_{dyn} = 0.3 \text{ s} \). Neutrino oscillations add a new complication to the diagnostic of supernova neutrinos, the factor \( P \) will be the survival probability of the electron neutrinos and antineutrinos.

IV. CONCLUSIONS

In Figures (a) and (b) show that difference between \( Y_e \) (dotted line) and \( Y_{eq} \) (solid line) is very little. That is, the integral in the equation (4) not contribute significantly to \( Y_e \). Calculations made for \( t_{dyn} \) between 0.01 s and 1 s confirm the last.

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FIG. 1: In (a) the electron fraction $Y_e$ (dotted line) and $Y_{eq}$ (solid line) is plotted against $y = (m_n - m_p)/T$ with $P = Q = 0.2, 0.4, 0.6, 0.8, 1.0$. In (b) the same but assuming that no exist antineutrino oscillations, i.e. $Q = 1$.

(2000).