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Emissivity of Neutrinos in Supernova via the pair-annihilation process beyond the Standard Model

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Abstract. We calculate the emissivity due to neutrino-pair production in e^+e^- annihilation in the context of a 331 model and a left-right symmetric model in a way that can be used into realistic supernova model to evaluate the energy lost in the form of neutrinos.

1. Introduction

Gamow [1] and Pontecorvo [2] were the first to recognize the important role played by neutrinos in the evolution of stars. The neutrino emission processes may affect the properties of matter at high temperatures, and hence affect stellar evolution.

Neutrino emission is known to play an important role in stellar evolution, especially in the late stages when the rate of evolution is almost fully dependent on energy loss via neutrinos.

The explosion energy of the core-collapse is typically $10^{53}\, erg$ which makes it one of the most impressive violent events in the universe. This energy comes from the explosion of the progenitor star, and only partly manifests itself in the shock wave that is launched somewhere at the boundary between the iron core and the inner most regions, collapsing into a neutron star. Even when the mechanism of the core-collapse is not yet understood in great detail, the most distinctive feature is the enormous energy of $(3-5)\times 10^{53}\, erg$ radiated in the form of neutrinos and antineutrinos of all flavors $(\nu_e, \nu_\mu, \nu_\tau)$ during a burst of about 10 seconds.

The detection of neutrinos from SN1987A by the Kamiokande II [3] and Irvine-Michigan-Brookhaven [4] detectors confirmed the standard model of core-collapse (type II) supernovae [5] and provided a laboratory to study the properties of neutrinos [6] and exotic particles such as axions. The collapse of stellar iron-core into a neutron star is preceded by a high-power pulse of neutrino emission.

The energy loss rate due to neutrino emission receives contributions from both weak nuclear reactions and purely leptonic processes. However, for the large values of density and temperature which characterize the final stage of stellar evolution, the latter are largely dominant, and are mainly produced by four possible interaction mechanisms:

$$\begin{aligned}
e^+ + e^- &\rightarrow \nu + \bar{\nu} \ \ \text{(pair annihilation)},\\
\gamma + e^\pm &\rightarrow e^\pm + \nu + \bar{\nu} \ \ (\nu\text{-photoproduction}),\\
\gamma^* &\rightarrow \nu + \bar{\nu} \ \ \text{(plasmon decay)},\\
e^\pm + Z &\rightarrow e^\pm + Z + \nu + \bar{\nu} \ \ \text{(bremsstrahlung on nuclei)}.
\end{aligned}$$

Our main objective in this work is to provide suitable expressions for the emissivity of pair production of neutrinos via the process $e^+e^- \rightarrow \nu\bar{\nu}$ in the context of a 331 model [7] and a left-right symmetric model (LRSM) [8] and in a form which can be easily incorporated into realistic supernova models to evaluate the energy lost in the form of neutrinos.

2. Process $e^+ + e^- \rightarrow \nu + \bar{\nu}$ in the 331 model

The amplitude of transition for the process

$$e^+(p_1) + e^-(p_2) \rightarrow \bar{\nu}(k_1, \lambda_1) + \nu(k_2, \lambda_2). \tag{1}$$

is given by

$$\mathcal{M} = -\frac{g^2 ab}{2\cos^2\theta_W}\left[\bar{u}\left(k_2, \lambda_2\right)\gamma^\mu\left(g_V^\nu - g_A^\nu\gamma_5\right)v\left(k_1, \lambda_1\right)\right]\left[\bar{v}\left(p_1\right)\gamma_\mu\left(ag_V^e - bg_A^e\gamma_5\right)u\left(p_2\right)\right], \tag{2}$$

where the constant a and b depend only on the parameters of the 331 model [7]

$$a = \cos\phi - \frac{\sin\phi}{\sqrt{3 - 4\sin^2\theta_W}} \quad \text{and} \quad b = \cos\phi + \frac{1 - 2\sin^2\theta_W}{\sqrt{3 - 4\sin^2\theta_W}}, \tag{3}$$

where ϕ is the mixing parameter of the 331 model [7], u and v are the usual Dirac spinors, and the electron and positron helicity indexes have been suppressed since they will be averaged over.

3. Process $e^+ + e^- \rightarrow \nu + \bar{\nu}$ in the left-righ symmetric model

The amplitude of transition for the process (1) is given by

$$\mathcal{M} = \frac{g_Z^2}{2M_Z^2}\left[\bar{u}\left(k_2, \lambda_2\right)\gamma^\mu\frac{1}{2}\left(a'g_V^\nu - b'g_A^\nu\gamma_5\right)v\left(k_1, \lambda_1\right)\right]\left[\bar{v}\left(p_1\right)\gamma_\mu\frac{1}{2}\left(a'g_V^e - b'g_A^e\gamma_5\right)u\left(p_2\right)\right], \tag{4}$$

where the constant a' and b' depend only on the parameters of the LRSM model [9, 10]

$$a' = \cos\phi' - \frac{\sin\phi'}{\sqrt{\cos 2\theta_W}} \quad \text{and} \quad b' = \cos\phi' + \sqrt{\cos 2\theta_W}\sin\phi', \tag{5}$$

where ϕ' is the mixing parameter of the LRSM.

We calculate the emissivity associated with neutrino pair production only in the case of the 331 model, which is given by [9, 11]

$$Q_{\nu\bar{\nu}} = \frac{4}{(2\pi)^8}\int\frac{d^3\mathbf{p}_1}{2E_1}\frac{d^3\mathbf{p}_2}{2E_2}\frac{d^3\mathbf{k}_1}{2\epsilon_1}\frac{d^3\mathbf{k}_2}{2\epsilon_2}(E_1 + E_2)F_1F_2\delta^{(4)}(p_1 + p_2 - k_1 - k_2)|\mathcal{M}|^2, \tag{6}$$

where the quantities $F_{1,2} = [1 + \exp(E_{e^-} \pm \mu_{e^-})/T]^{-1}$ are the Fermi-Dirac distribution functions for $e^\pm$, μ_e is the chemical potential for the electrons and T is the temperature. From the transition amplitude Eq. (2) and the formula of the emissivity Eq. (6) the partial emissivities are obtained:

$$
\begin{aligned}
Q^{[1]}_{\nu\bar{\nu}} &= G_F^2 a^2 b^2 \left[(g_V^e)^2 + (g_A^e)^2 + 2g_V^e g_A^e\right]\left[I_1^{10} + I_1^{01}\right], && (7)\\
Q^{[2]}_{\nu\bar{\nu}} &= G_F^2 a^2 b^2 \left[(g_V^e)^2 + (g_A^e)^2 - 2g_V^e g_A^e\right]\left[I_2^{10} + I_2^{01}\right], && (8)\\
Q^{[3]}_{\nu\bar{\nu}} &= G_F^2 a^2 b^2 \left[(g_V^e)^2 - (g_A^e)^2\right] m_e^2 \left[I_3^{10} + I_3^{01}\right]. && (9)
\end{aligned}
$$

where

$$
\begin{aligned}
I_1^{nm} &= I_2^{nm} = \frac{m_e^{n+m+8}}{6(2\pi)^5}\Bigg[3G^-_{\frac{n}{2}}G^+_{\frac{m}{2}} + 2G^-_{\frac{n+1}{2}}G^+_{\frac{m+1}{2}} + G^-_{\frac{n-1}{2}}G^+_{\frac{m-1}{2}} \\
&\quad + \frac{4}{9}\left(G^-_{\frac{n+1}{2}} - G^-_{\frac{n-1}{2}}\right)\left(G^+_{\frac{m+1}{2}} - G^+_{\frac{m-1}{2}}\right)\Bigg], && (10)\\
I_3^{nm} &= \frac{m_e^{n+m+6}}{(2\pi)^5}\left[G^-_{\frac{n-1}{2}}G^+_{\frac{m-1}{2}} + G^-_{\frac{n}{2}}G^+_{\frac{m}{2}}\right], && (11)
\end{aligned}
$$

and

$$
G_s^{\pm} = \frac{1}{m_e^{3+2s}}\int_{m_e/KT}^{\infty} E^{2s+1}\frac{\sqrt{E^2 - m_e^2}}{1 + e^{(E\pm\mu_e)/KT}}dE. \qquad (12)
$$

Finally, the expression for the emissivity of neutrino pair production via the process $e^+e^- \to \nu\bar{\nu}$ in the context of a 331 model is given by

$$
Q^{331}_{\nu\bar{\nu}}(\phi,\beta) = Q^{[1]}_{\nu\bar{\nu}}(\phi,\beta) + Q^{[2]}_{\nu\bar{\nu}}(\phi,\beta) + Q^{[3]}_{\nu\bar{\nu}}(\phi,\beta), \qquad (13)
$$

where the dependence of the ϕ mixing parameter of the 331 model is contained in the constants a and b.

4. Conclusions

We have determined analytical expressions for the emissivity due to neutrino-pair production via the process $e^+e^- \to \nu\bar{\nu}$ in the context of a 331 model and in a form which can be easily incorporated into realistic supernova models to evaluate the energy lost in the form of neutrinos. It is noteworthy that to determine the emissivity in the context of a left-right symmetric model should be performed a similar procedure as in the case of the 331 model.

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