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Production of unstable heavy neutrinos in proto-neutron stars

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A R T I C L E I N F O

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A B S T R A C T

We discuss the production of a class of heavy sterile neutrinos ν_h in proto-neutron stars. The neutrinos, of mass around 50 MeV, have a negligible mixing with the active species but relatively large dimension-5 electromagnetic couplings. In particular, a magnetic dipole moment $\mu \approx 10^{-6}$ GeV^{-1} implies that they are thermally produced through $e^+e^- \to \bar{\nu}_h \nu_h$ in the early phase of the core collapse, whereas a heavy–light transition moment $\mu_{\text{tr}} \approx 10^{-8}$ GeV^{-1} allows their decay $\nu_h \to \nu_i \gamma$ with a lifetime around 10^{-3} s. This type of electromagnetic couplings has been recently proposed to explain the excess of electron-like events in baseline experiments. We show that the production and decay of these heavy neutrinos would transport energy from the central regions of the star to distances $d \approx 400$ km, providing a very efficient mechanism to enhance the supernova shock front and heat the material behind it.

1. Introduction

Neutrinos define a sector of the Standard Model that still presents some important unknowns. The current scheme of mass differences and mixings seems able to explain most of the existing data [1], but the absolute value of their masses, their Dirac or Majorana nature [2] or the presence of additional sterile modes [3,4] are yet to be determined. In particular, the production of sterile neutrinos ν_s, through collisions with standard matter or through flavor oscillations has important implications both in particle physics and astrophysics [5–8]. The mixing with an active neutrino ν may provide sterile modes with small couplings to the W and Z gauge bosons that translate into dimension-6 operators of type

$$-\mathcal{L}_{\text{eff}} = \frac{G_F \sin\theta}{\sqrt{2}} \bar{f} \gamma_\mu (C_V - C_A \gamma_5) f \, \bar{\nu}_s \gamma^\mu (1 - \gamma_5) \nu + \text{h.c.} \qquad (1)$$

In addition, the low-energy effective Lagrangian may also include dimension-5 operators from loops involving heavy particles. Although these operators are usually overlooked, they could mediate the dominant reactions of sterile neutrinos in a star under favorable thermodynamical conditions. Here we will study this possibility in the context of supernova explosions.

When a supernova goes off a proto-neutron star can be formed having a typical initial radius of (20–60) km and a mass of (1–1.5) $M_\odot$. It is believed that most of the gravitational binding energy ($E_{\text{grav}} \approx 3 \times 10^{53}$ erg) is released in a ∼20 second neutrino burst [9]. The neutrino spectrum from supernova SN1987A detected at SuperK and IMB indicated a weak decoupling from baryonic matter, confirming that neutrino transparency sets in as their temperature falls below a few MeV [10] in the dense core. At earlier phases of the collapse, however, computational simulations [11,12] reveal internal peak temperatures exceeding 20 MeV in the central high density regions of the star. At such temperatures and densities the evolution of these astrophysical objects becomes sensitive to the fundamental properties of neutrinos and to the presence of hypothetical weakly-coupled particles. In this context, a lot of effort has been devoted to the cooling through neutrino emission in the nuclear medium [13], to the matter opacity [14] and revival of the stalled shock that arises in the standard paradigm of supernova core collapse [15], or to the synthesis of heavy nuclei taking place in the hot bubble behind the shock [16,17].

In this work we will focus on the astrophysical consequences of the production of a heavy sterile neutrino ν_h whose dominant interactions are *not* the weak ones in Eq. (1) but of electromagnetic kind. This type of particles have been proposed as a possible explanation [18] for the excess of electron-like events in baseline experiments [19]. Let us briefly show how the required couplings could be generated. Consider an $SU(2)_L$-singlet Dirac neu-

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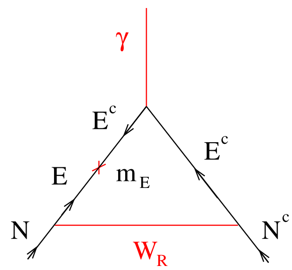

Fig. 1. Diagram contributing to the magnetic dipole moment μ of ν_h.

trino, ν_h, of mass $m_h = 50$ MeV. We will denote by N and N^c the (2-component) neutrino and antineutrino spinors defining ν_h,

$$\nu_h = \begin{pmatrix} N \\ \bar{N}^c \end{pmatrix}. \tag{2}$$

Let us also suppose that at TeV energies the gauge symmetry is $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ and that ν_h is accommodated within two $SU(2)_R$ doublets together with a charged lepton,

$$L = \begin{pmatrix} N \\ E \end{pmatrix} \quad L^c = \begin{pmatrix} E^c \\ N^c \end{pmatrix}. \tag{3}$$

In order to avoid collider bounds [20], the breaking of the left–right symmetry must be such that the charged lepton (E, E^c) gets a mass $m_E \geq 300$ GeV while ν_h remains light. Loop diagrams of heavy gauge bosons and fermions (see Fig. 1) will then generate the operator

$$-\mathcal{L}_{\rm eff} = \mu\, \bar{\nu}_h \sigma_{\mu\nu} \nu_h\, \partial^\mu A^\nu\,, \tag{4}$$

where A^ν is the electromagnetic field and μ is a magnetic dipole moment of order [21]

$$\mu \approx e\, \frac{g_R^2}{16\pi^2}\, \frac{m_E}{M_R^2} \approx 10^{-6}\ {\rm GeV}^{-1}\,. \tag{5}$$

In addition, the possible mixing of the sterile and the active neutrinos will be parametrized by an angle θ, so that the mass eigenstates read $N' = \cos\theta\, N + \sin\theta\, \nu$ and $\nu' = -\sin\theta\, N + \cos\theta\, \nu$. This mixing will generate electromagnetic transitions through the same type of diagrams (we drop the prime to indicate mass eigenstates):

$$\mathcal{L}_{\rm eff} = \frac{1}{2}\, \mu_{\rm tr}\, \bar{\nu}_h\, \sigma_{\mu\nu}\, (1-\gamma_5)\, \nu\, \partial^\mu A^\nu + {\rm h.c.}\,, \tag{6}$$

with $\mu_{\rm tr} \approx \sin\theta\mu$ being the transition dipole moment. This operator may imply that the dominant decay mode of the heavy neutrino is $\nu_h \to \nu\gamma$. Notice also that the presence of additional heavy singlets ($\nu_{h'}$ with $m_{h'} \approx m_E$) mixed both with ν and ν_h will give additional contributions to $\mu_{\rm tr}$. Therefore, at this point we will treat μ and $\mu_{\rm tr}$ as independent parameters.

This type of sterile neutrinos could change substantially the evolution of a proto-neutron star. We will show that sterile pairs can be produced abundantly during the $\sim$20 second neutrino burst, escape the star core more easily than standard neutrinos, and finally decay within a few hundred km from the core. The very energetic photons from the decay could deposit energy, helping revive the stalled accretion shock formed during the collapse and change the thermal environment in the vicinity of the star. Our scenario could be considered a different realization of the *eosphoric* neutrino hypothesis proposed in [22].

2. Decay rate, production and scattering cross sections

Let us first describe the dominant decay and production channels for the heavy neutrino ν_h in vacuum. Later we will discuss how the hot and dense medium in a proto-neutron star (including populations of neutrons, protons, electrons and muons) affects these processes.

To be definite in our calculation we will take as reference values $m_h = 50$ MeV, $\mu = 10^{-6}$ GeV^{-1} $= 3.3 \times 10^{-9} \mu_B$, and $\mu_{\rm tr} \approx 10^{-8}$ GeV^{-1}. We use $\hbar = c = 1$. For these values of the mass and the transition moment, the heavy neutrino will decay into $\nu\gamma$ with a lifetime

$$\tau_h = \frac{16\pi}{\mu_{\rm tr}^2\, m_h^3} = \frac{(50\ {\rm MeV})^3}{m_h^3} \times \frac{(10^{-8}\ {\rm GeV}^{-1})^2}{\mu_{\rm tr}^2} \times 0.0026\ {\rm s}\,. \tag{7}$$

We will also assume that the mass mixing, i.e., the active component in ν_h, is smaller than $\sin^2\theta < 10^{-3}$ and only along the muon and/or the tau flavors. In that case, the radiative decay will dominate over the weak processes $\nu_h \to \nu e^+ e^-$, $\nu \nu_i \bar{\nu}_i$, which appear with a branching ratio

$$\begin{aligned} &{\rm BR}(\nu_h \to \nu e^+ e^-) \\ &\approx \frac{\sin^2\theta}{10^{-3}} \times \frac{(10^{-8}\ {\rm GeV}^{-1})^2}{\mu_{\rm tr}^2} \times \frac{m_h^2}{(50\ {\rm MeV})^2} \times 0.05\%\,. \end{aligned} \tag{8}$$

This type of sterile neutrino avoids cosmological bounds since it decays before primordial nucleosynthesis. At colliders it is hardly detectable: even if it were produced in 1% of kaon or muon decays, ν_h is too long lived to decay inside the detectors and too light to change significantly the kinematics of the decay [23]. Actually, more elaborate setups with two sterile modes have been proposed to explain the excess of electron-like events at MiniBooNE in terms of the photon that results from its decay [18].

The dominant production channels of ν_h will also be electromagnetic. In particular, electron–positron annihilation into ν_h pairs, $e^+e^- \to \bar{\nu}_h \nu_h$, will be mediated by a photon through the magnetic dipole moment coupling in Eq. (4). The differential cross section is given by

$$\begin{aligned} \frac{{\rm d}\sigma}{{\rm d}t} &= \frac{\alpha \mu^2}{s^2 - 4 s m_e^2} \\ &\times \left(-t + 2m_h^2 + m_e^2 - \frac{t^2 - 2(m_h^2 + m_e^2)t + (m_h^2 - m_e^2)^2}{s} \right), \end{aligned} \tag{9}$$

where α is the fine structure constant, m_e is the electron mass, and s and t are the usual Mandelstam variables ($\sqrt{s}$ is the center-of-mass energy). In Fig. 2 (left panel) we plot the total cross section for this process. Muon pair annihilation will give an analogous but subleading contribution, since muons are less abundant than electrons in the star core.

The active to sterile transition mediated by a photon can be catalyzed by the presence of charged particles $X = p, e$: $\nu X \to \nu_h X$ (see right panel in Fig. 2). This contribution, however, can be neglected here due to the smaller value of the transition coupling that we have assumed, $\mu_{\rm tr} \approx 10^{-2}\mu$. The weak channels which dominate the production of active neutrinos [24] give also a subleading contribution due to the small mixing $\sin^2\theta < 10^{-3}$ of our sterile, whereas other processes like plasmon decay [25] are irrelevant for heavy neutrino masses around 50 MeV (i.e., much larger than the electron mass).

In addition to its production and decay, the collisions of ν_h with charged matter will be essential in order to understand its propagation in the dense medium and estimate how efficiently these