Radiative decay of keV-mass sterile neutrinos in strongly magnetized plasma

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Introduction

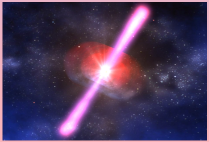
- Critical Schwinger value $B_e = m_e^2/e = 4.41 \times 10^{13}$ Gauss
- Magnetars (SGRs and AXPs)

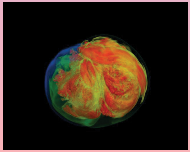
  [S. A. Olausen and V. M. Kaspi, Astrophys. J. Suppl. 212, 6 (2014)]
- Core-collapse supernova explosions

  [A. Heger et al, ApJ 626, 350 (2005);
  G. S. Bisnovatyi-Kogan et al, Acta Polytech. Proc. 1, 181 (2014);
  H. Sawai and S. Yamada, Astrophys. J. 817, 153 (2016)]
- Accretion discs at merger of compact objects in close binary systems

  [M. V. Barkov and S. S. Komissarov, MNRAS 401, 1644 (2010);
  I. Zalamea and A. Beloborodov, MNRAS 410, 2302 (2011)]

Neutrino Sources





$B \sim 10^{15}$ G

$\nu \to \nu + \gamma$ in active medium

- In vacuum
  P. Pal and L. Wolfenstein, Phys. Rev. D25, 766 (1982)
- In plasma
  V. N. Tsytovich, Sov. Phys. JETP 18, 816 (1964);
  V. N. Oraevsky et al., JETP Lett. 43, 709 (1986);
  J. C. D'Olivo et al., Phys. Rev. Lett. 64, 1088 (1990);
  C. Giunti et al., Phys. Rev. D43, 164 (1991);
  R. Sawyer, Phys. Rev. D46, 1180 (1992);
  J. C. D'Olivo et al., Phys. Lett. B365, 178 (1996);
  S. Hardy and D. Melrose, Phys. Rev. D54, 6491 (1996)
- In magnetic field
  D. V. Galtsov and N. S. Nikitina, Sov. Phys. JETP 35, 1047 (1972);
  V. V. Skobelev, Sov. Phys. JETP 44, 660 (1976);
  A. N. Ioannisian and G. G. Raffelt, Phys. Rev. D55, 7038 (1997);
  A. A. Gvozdev et al., Phys. Rev. D54, 5674 (1996);
  A. A. Gvozdev et al., Phys. Lett. B410, 211 (1997)
- In magnetized plasma
  M. V. Chistyakov and N. V. Mikheev, Phys. Lett. B467, 232 (1999);
  A. I. Ternov and P. A. Eminov, Phys. Rev. D87, 113001 (2013);
  A. A. Dobrynina et al., Phys. Rev. D90, 113015 (2014)

Strongly magnetized plasma

- Strongly magnetized plasma $\Rightarrow$ electrons occupy the lowest Landau level
- Magnetic field is directed along the third axis $\vec{B} = (0, 0, B)$
- Hierarchy of plasma parameters

$$2eB > \mu_e^2 - m_e^2 \gg T^2$$

  m_e is the electron mass, e is the elementary charge,
  μ_e is the electron chemical potential, T is plasma temperature

- Strong magnetic field and degenerate plasma $\Rightarrow$
  photon becomes a particle with the effective mass Ω_0
  [H. Pérez Rojas and A. E. Shabad, Ann. Phys. (1979), Ann. Phys. (1982)]

$$\Omega_0^2 = \frac{2\alpha}{\pi} eB \frac{p_F}{\sqrt{p_F^2 + m_e^2}}$$

  α is the fine-structure constant, p_F is the electron Fermi momentum

Plasma frequency

- Electron number density in strong magnetic field

$$n_e = \frac{eBp_F}{2\pi^2} \Rightarrow p_F = 2\pi^2 \frac{n_e}{eB}$$

- Plasma frequency Ω_0 can be presented in the form

$$\Omega_0 \simeq 37.1 \text{ keV} \left[\frac{n_{30}^2 b^2}{b^2 + 1.3\, n_{30}^2} \right]^{1/4}$$

- $b = B/B_e, \quad n_{30} = n_e / \left(10^{30} \text{cm}^{-3}\right)$
- Critical Schwinger value of electron

$$B_e = \frac{m_e^2}{e} = 4.41 \times 10^{13} \text{ G}$$

- Benchmark number density $n = 10^{30}$ cm^{-3} corresponds to matter mass density $\rho \simeq 10^6$ g/cm^3
- Degenerate electrons would still be nonrelativistic, $V_F \ll 1$

Neutrino

- Standard neutrino with sub-eV masses $m_\nu \lesssim 1$ eV

$$\Omega_0 \gg m_\nu \quad \Rightarrow \quad \nu_i \to \nu_j \, \gamma \text{ decay is kinematically forbidden}$$

- Sterile neutrino with keV-mass m_s
[M. Drewes et al., arXiv:1602.04816]

  Bound from cosmology

$$0.4\,\text{keV} < m_s < 50\,\text{keV}$$

  [S. Tremaine and J. E. Gunn, Phys. Rev. Lett. (1979);
  A. Boyarsky et al., Ann. Rev. Nucl. Part. Sci. (2009);
  M. Laine and M. Shaposhnikov, JCAP (2008)]

Mixing

- Sterile neutrino ν_s can mix with active species
  $\Rightarrow$ can interact with matter in this way
- Restriction: sterile neutrino is mixing with one active neutrino; similar to two-flavor scheme of active-neutrino mixing
- Neutrino mass states

$$|\nu_1\rangle = \cos\theta_s|\nu_a\rangle - \sin\theta_s|\nu_s\rangle$$
$$|\nu_2\rangle = \sin\theta_s|\nu_a\rangle + \cos\theta_s|\nu_s\rangle$$

- One mixing angle θ_s
- The mixing angle θ_s is assumed to be very small; supported by experimental data

$$|\nu_1\rangle \simeq |\nu_a\rangle, \qquad |\nu_2\rangle \simeq |\nu_s\rangle$$

- Upper limit on θ_s from radiative decay $\nu_s \to \nu_a\gamma$
  [A. Boyarsky et al., Ann. Rev. Nucl. Part. Sci. 59 (2009)]

$$\theta_s^2 \lesssim 1.8 \times 10^{-5} \left(\frac{1\ \text{keV}}{m_s}\right)^5$$

Strongly magnetized plasma

- In plasma active neutrino can interact with photons via real electrons

$$\mathcal{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} \left[\bar{\Psi}_e \, \gamma^{\alpha} \, (C_V + C_A \gamma_5) \, \Psi_e\right] j_{\alpha}$$

- Vector and axial-vector coefficients

$$C_V = \pm 1/2 + 2 \sin^2 \theta_W , \qquad C_A = \pm 1/2$$

  θ_W is the Weinberg angle $\quad (\sin^2 \theta_W \simeq 0.23)$;
  upper sign is for ν_e, lower one is for ν_μ and ν_τ

- Neutrino current describes sterile-to-active neutrino transition

$$j_\alpha = j_\alpha^{(s \to a)} = \cos \theta_s \sin \theta_s \, [\bar{\nu}_a \gamma_\alpha \, (1 + \gamma_5) \, \nu_s]$$

- We consider the active neutrino with fixed flavor — electron neutrino
- Modifications in dispersion relations of both neutrino are very small
  $\Rightarrow$ safely neglected

Effective Lagrangian

- Effective Lagrangian of neutrino-electron interaction

$$\mathcal{L}_{\rm eff} = -\frac{G_F}{\sqrt{2}} \left[C_V \left(\bar{\Psi}_e \gamma^\alpha \Psi_e \right) j_\alpha + C_A \left(\bar{\Psi}_e \gamma^\alpha \gamma_5 \Psi_e \right) j_\alpha \right]$$

- Axial-vector electron current can be transformed into vector current

$$\bar{\Psi}_e \gamma_\alpha \gamma_5 \Psi_e \Rightarrow \bar{\Psi}_e (\tilde{\varphi}\gamma)_\alpha \Psi_e$$

- Dimensionless tensor of the external magnetic field and its dual

$$\varphi_{\alpha\beta} = \frac{F_{\alpha\beta}}{B}, \qquad \tilde{\varphi}_{\alpha\beta} = \frac{1}{2} \varepsilon_{\alpha\beta\rho\sigma} \varphi^{\rho\sigma}$$

- Lagrangian becomes

$$\mathcal{L}_{\rm eff} = e \left(\bar{\Psi}_e \gamma^\alpha \Psi_e \right) V_\alpha$$

- Local vector operator

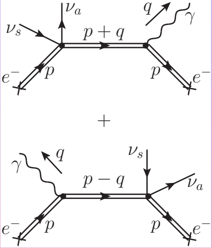
$$V_\alpha = -\frac{G_F}{e\sqrt{2}} \left[C_V \, (\tilde{\varphi}\tilde{\varphi} j)_\alpha - C_A \, (\tilde{\varphi} j)_\alpha \right]$$

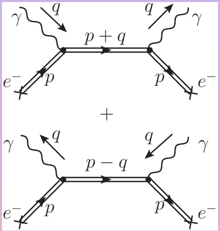
- Formally coinsides with usual electromagnetic Lagrangian

$$\mathcal{L}_{\rm EM} = e \left(\bar{\Psi}_e \gamma^\alpha \Psi_e \right) A_\alpha$$

Amplitude of $\nu_s \to \nu_a + \gamma$ decay

- Feynman diagrams of $\nu_s \to \nu_a + \gamma$ decay in strongly magnetized plasma are identical to the Compton scattering diagrams, after one of the photon lines is replaced by the local vector operator V_α





- Photon polarization operator $\Pi_{\alpha\beta}$ in electron plasma is determinated by the amplitude of $\gamma \to \gamma$ transition

$$M_{\gamma\to\gamma} = -\mathcal{E}^*_\alpha\, \Pi^{\alpha\beta}\, \mathcal{E}_\beta$$

- Similar, sterile-neutrino decay amplitude

$$M_{\mathrm{pl+f}} = -\mathcal{E}^*_\alpha \Pi^{\alpha\beta}\, V_\beta$$

Photon polarization operator in strongly magnetized plasma

- In strongly magnetized plasma, there are only two photon physical states [M. V. Chistyakov and D. A. Rumyantsev, JETP 107, 533 (2008)]

$$\mathcal{E}_\alpha^{(1)} \approx \frac{(q\varphi)_\alpha}{\sqrt{q_\perp^2}}\,, \qquad \mathcal{E}_\alpha^{(2)} \approx \frac{(q\tilde{\varphi})_\alpha}{\sqrt{q_\parallel^2}}$$

- Eigenvalues of polarization operator Π_λ $(\lambda = 1, 2)$

$$\Pi_{\alpha\beta}\, \mathcal{E}_\beta^{(\lambda)} = \Pi_\lambda\, \mathcal{E}_\alpha^{(\lambda)}$$

- Eigenvalues Π_1 and Π_2 under kinematical condition $\omega \lesssim m_s \ll m_e$

$$\Pi_1 \approx -\frac{2\alpha}{\pi}\, \frac{\omega V_F \mu_e \sqrt{q^2}}{\sqrt{q_\parallel^2}}\,, \quad \Pi_2 \approx \frac{2eB\alpha}{\pi}\, \frac{q_\parallel^2 V_F}{\omega^2 - V_F^2 k_3^2}$$

- ω is photon energy, k_3 is photon momentum projection on field direction, V_F is the Fermi velocity of electron plasma
- Contribution of Π_2 in sterile-neutrino decay amplitude dominates

$$\left|\frac{\Pi_1}{\Pi_2}\right| \lesssim \frac{m_s}{\mu_e} \ll 1$$

Photons of mode 2 are mainly produced in this decay

$\nu_s \to \nu_a + \gamma$ decay width

- Sterile-neutrino decay amplitude in strongly magnetized plasma

$$M_{\rm pl+f} = \frac{G_F\,\Omega_0^2}{e\sqrt{2}}\,\sqrt{q_\parallel^2}\,\frac{C_V\,(q\tilde{\varphi}j) + C_A\,(q\tilde{\varphi}\tilde{\varphi}j)}{\omega^2 - V_F^2 k_3^2}$$

- Rest frame of sterile neutrino is chosen: $p_s^\mu = (m_s, \vec{0})$
- Decay width of $\nu_s \to \nu_a + \gamma$ process

$$W_{\rm pl+f} = \frac{1}{32\pi^2 m_s}\int \frac{d^3 p_a}{E_a}\,\frac{d^3 k}{\omega}\,\delta^{(4)}(p_s - p_a - q)\,|M_{\rm pl+f}|^2$$

- Four-momenta of active neutrino $p_a^\mu = (E_a, \vec{p}_a)$ and photon $q^\mu = (\omega, \vec{k})$; neutrino assumed to be massless: $E_a = |\vec{p}_a|$
- Non-trivial photon dispersion relation in strongly magnetized plasma [Ω_0 is photon "effective mass"]

$$q^2 = \Pi_2 \qquad \Rightarrow \qquad \omega^2 = k_3^2 + k_\perp^2 + \Omega_0^2\,\frac{\omega^2 - k_3^2}{\omega^2 - V_F^2 k_3^2}$$

- Analytical results are available in limiting cases only

Unmagnetized electron plasma

- Effective local Lagrangian

$$\mathcal{L}_{\rm eff} = -\frac{G_F}{\sqrt{2}} \left[C_V \left(\bar{\Psi}_e \, \gamma^\alpha \Psi_e\right) j_\alpha^{(s\to a)} + C_A \left(\bar{\Psi}_e \, \gamma^\alpha \gamma_5 \Psi_e\right) j_\alpha^{(s\to a)} \right]$$

- Vector part of $\mathcal{L}_{\rm eff}$ is similar to the standard electromagnetic Lagrangian

$$\mathcal{L}_{\rm EM} = e \left(\bar{\Psi}_e \gamma_\alpha \Psi_e\right) A^\alpha$$

- Vector part of $\nu_s \to \nu_a + \gamma$ decay amplitude $M_{\rm pl} = M_{\rm pl}^V + M_{\rm pl}^A$ can be expessed through the photon polarization operator $\Pi_{\alpha\beta}$

$$M_{\rm pl}^V = \frac{C_V \, G_F}{e\sqrt{2}} \, (j \Pi \varepsilon^*)$$

- Axial-vector contribution is much smaller in both nonrelativistic and relativistic electron plasma
- In nonrelativistic plasma, suppression by neutrino-to-electron mass ratio

$$\frac{M_{\rm pl}^A}{M_{\rm pl}^V} \sim \frac{C_A}{C_V} \, \frac{m_s}{m_e} \ll 1$$

Photon dispersion in unmagnetized plasma

- Plasma frequency in nonrelativistic plasma

$$\omega_0^2 = \frac{4\pi\alpha n_e}{m_e}$$

- For degenerate electrons $n_e = p_F^3/3\pi^2$
- Photons in plasma have three polarization modes: one longitudinal ε^ℓ_α and two transverse ε^t_α, where $t = 1, 2$
- In nonrelativistic plasma, PO eigenvalues are well known [G. Raffelt, Stars as Laboratories for Fundamental Physics (1996)]:

$$\Pi_t \approx \omega_0^2\,, \qquad \Pi_\ell \approx \omega_0^2\left(1 - \frac{k^2}{\omega^2}\right)$$

- Modified photon dispersion relation can be obtained from equation

$$q^2 = \omega^2 - k^2 = \Pi_\lambda$$

- Solutions for longitudinal and transverse modes, respectively

$$\omega \simeq \omega_0, \qquad \omega = \sqrt{\omega_0^2 + k^2}$$

Decay width in unmagnetized electron plasma

- Decay width of $\nu_s \to \nu_a + \gamma$ decay in nonrelativistic electron plasma

$$W^t_{\rm pl} = W_{\rm vac} \frac{16\pi^2}{9\alpha^2} \, x_0^4 (1 - x_0^2)^2$$

$$W^\ell_{\rm pl} = W_{\rm vac} \frac{32\pi^2}{9\alpha^2} \, x_0 (1 - x_0)^2$$

- Scaled plasma frequency $x_0 = \omega_0 / m_s$
- Normalized to vacuum decay width

$$W_{\rm vac} = \frac{9\alpha G_F^2}{2048\pi^4} \, m_s^5 \sin^2(2\theta_s)$$

- For parameter values of interest, lifetime of sterile neutrino

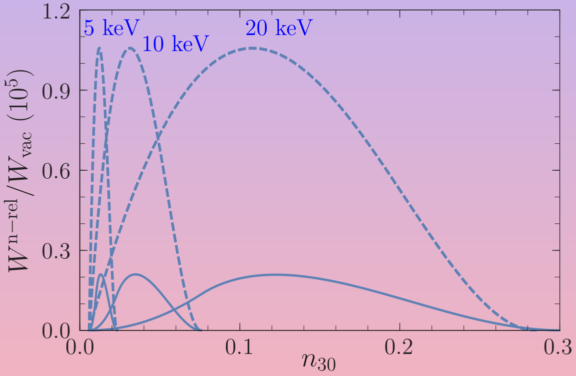
$$\tau_{\rm vac} = 1.2 \times 10^{26} \text{ years} \left(\frac{10 \text{ keV}}{m_s} \right)^5 \left(\frac{10^{-11}}{\theta_s^2} \right)$$

- Age of the Universe

$$\tau_{\rm Univ} = 1.37 \times 10^{10} \text{ years}$$

Comparison of magnetized and unmagnetized plasma

Sterile-neutrino radiative decay rate for fixed mass values
as a function of electron density $n_{30} = n_e/(10^{30}\ \mathrm{cm}^{-3})$



Dashed lines: unmagnetized plasma.
Solid lines: strongly magnetized plasma with $B = B_e = 4.41 \times 10^{13}$ G

Conclusions

- Radiative decay of sterile neutrino with mass of order of ten keV is studied in presence of both strongly magnetized and unmagnetized electron plasma
- Photon dispersion modified by electron plasma is taken into account in analysis of the sterile neutrino decay width
- Strong magnetic field suppresses the catalyzing influence of electron plasma on the sterile-neutrino decay rate

Nonrelativistic magnetized plasma

- For $m_s = 2 - 20$ keV and $B = 1 - 100\, B_e$,
  strongly magnetized electron plasma is nonrelativistic, $V_F \ll 1$

$$W_{\mathrm{pl+f}}^{\mathrm{n-rel}} = W_{\mathrm{vac}} \frac{32\,\pi^2}{2835\,\alpha^2} \left(C_V^2 + C_A^2\right) \left[\theta(2x_0 - 1)\right.$$
$$\times \left(-\frac{11}{x_0} + 129x_0 - 210x_0^2 + 168x_0^3 - 84x_0^4 - 24x_0^6 + 32x_0^8\right)$$
$$\left. + \theta(1 - 2x_0)\, 4x_0^4 \left(21 + 6x_0^2 - 8x_0^4\right)\right]$$

- Dimensionless plasma frequency $\quad x_0 = \Omega_0 / m_s$
- Normalized on the vacuum decay width

$$W_{\mathrm{vac}} = \frac{9\alpha G_F^2}{2048\pi^4}\, m_s^5 \sin^2(2\theta_s)$$

- At $x_0 \ll 1$ and $C_V = C_A = 1/2$

$$\left.\frac{W_{\mathrm{pl+f}}^{\mathrm{n-rel}}}{W_{vac}}\right|_{x_0 \ll 1} = \frac{256}{135} \frac{\pi^2}{\alpha^2} x_0^4$$

[A. I. Ternov and P. A. Eminov, Phys. Rev. D87 (2013)]

Relativistic magnetized plasma

- In the case of relativistic strongly magnetized plasma: chemical potential μ_e of electron plasma is large, $\mu_e \gg m_e$

$$V_F \simeq \sqrt{1 - m_e^2/\mu_e^2} \to 1$$

- Plasma frequency has root dependence on magnetic field strength

$$\Omega_0 \simeq 34.7 \text{ keV} \sqrt{B/B_e}$$

- Small $x_0 = \Omega_0/m_s \quad (x_0 \ll m_e/\mu_e)$

$$W_{\mathrm{pl+f}}^{\mathrm{rel}} \simeq \frac{(G_F \Omega_0^2)^2}{64\pi^2\alpha} m_s \sin^2(2\theta_s) \left(C_V^2 + C_A^2\right) \frac{\ln(2\mu_e/m_e) - 5/4}{1 - e^{-m_s/(2T)}}$$

- Large $x_0 \quad (m_e/\mu_e \ll x_0 < 1)$

$$W_{\mathrm{pl+f}}^{\mathrm{rel}} \simeq \frac{(G_F m_s^2)^2}{64\pi^2\alpha} m_s \sin^2(2\theta_s) \frac{\left(C_V^2 + C_A^2\right) x_0^4}{1 - e^{-m_s\left(1+x_0^2\right)/(2T)}} \times \left[\left(1 + x_0^2\right) \ln\frac{1}{x_0} - \frac{1}{8}\left(1 - x_0^2\right)\left(3 + x_0^2\right)\right]$$