Neutrino oscillations in a magnetic field: The three-flavor case

Alexey Lichkunov, Artem Popov, Alexander Studenikin
Lomonosov Moscow State University and
Joint Institute for Nuclear Research, Dubna

ICHEP 2020, PRAGUE
28 JULY - 6 AUGUST 2020

A.Popov, A. Studenikin, Eur. Phys. J. C (2019) 79:144

Supported by the Russian Foundation for Basic Research under grants No. 20-52-53022-GFEN-a

Main idea

Using equation:

Dirac equation:

$$(\gamma_\mu p^\mu - m_i - \mu_i \boldsymbol{\Sigma B})\nu_i^s(p) = 0$$

transform it: $\hat{H}_i \nu_i^s = E \nu_i^s$

Where "Hamiltonian" is:

$$\hat{H}_i = \gamma_0 \boldsymbol{\gamma p} + \mu_i \gamma_0 \boldsymbol{\Sigma B} + m_i \gamma_0$$

Also we use this spin operator:

$$\hat{S}_i = \frac{m_i}{\sqrt{m_i^2 \boldsymbol{B}^2 + \boldsymbol{p}^2 B_\perp^2}} \cdot \left[\boldsymbol{\Sigma B} - \frac{i}{m_i}\gamma_0\gamma_5[\boldsymbol{\Sigma} \times \boldsymbol{p}]\boldsymbol{B}\right]$$

The resulting energy spectrum:

$$E_i^s = \sqrt{m_i^2 + p^2 + \mu_i{}^2 \mathbf{B}^2 + 2\mu_i s \sqrt{m_i^2 \mathbf{B}^2 + p^2 B_\perp^2}}$$

Stationary state

Spin operator commutes with hamiltonian:

$$\hat{S}_i \left|\nu_i^s\right\rangle = s\left|\nu_i^s\right\rangle, s = \pm 1, \langle \nu_i^s | \nu_k^{s'} \rangle = \delta_{ik}\delta_{ss'}$$

Thus, we can build projective operator:

$$\hat{P}_i^\pm = \frac{1 \pm \hat{S}_i}{2}$$

$$\nu_i^L(t) = c_i^+ \nu_i^+(t) + c_i^- \nu_i^-(t)$$
$$\nu_i^R(t) = d_i^+ \nu_i^+(t) + d_i^- \nu_i^-(t)$$

$$|c_i^\pm|^2 = \langle \nu_i^L | \hat{P}_i^\pm | \nu_i^L \rangle$$
$$|d_i^\pm|^2 = \langle \nu_i^R | \hat{P}_i^\pm | \nu_i^R \rangle$$
$$(d_i^\pm)^* c_i^\pm = \langle \nu_i^R | P_i^\pm | \nu_i^L \rangle$$

General formulae for neutrino flavor and spin-flavor oscillations

$$P_{\nu_e^L \to \nu_i^L} = \left|\langle \nu_i^L | \nu_e^L \rangle\right|^2 = \left| \sum_{j=1}^{3} \left(|c_j^+|^2 e^{-iE_j^+ t} + |c_j^-|^2 e^{-iE_j^- t} \right) U_{1j} U_{ij}^* \right|^2$$

$$P_{\nu_e^L \to \nu_i^R} = \left|\langle \nu_i^R | \nu_e^L \rangle\right|^2 = \left| \sum_{j=1}^{3} \left(|d_j^+|^2 e^{-iE_j^+ t} + |d_j^-|^2 e^{-iE_j^- t} \right) U_{1j} U_{ij}^* \right|^2$$

Case 2-flavor example:

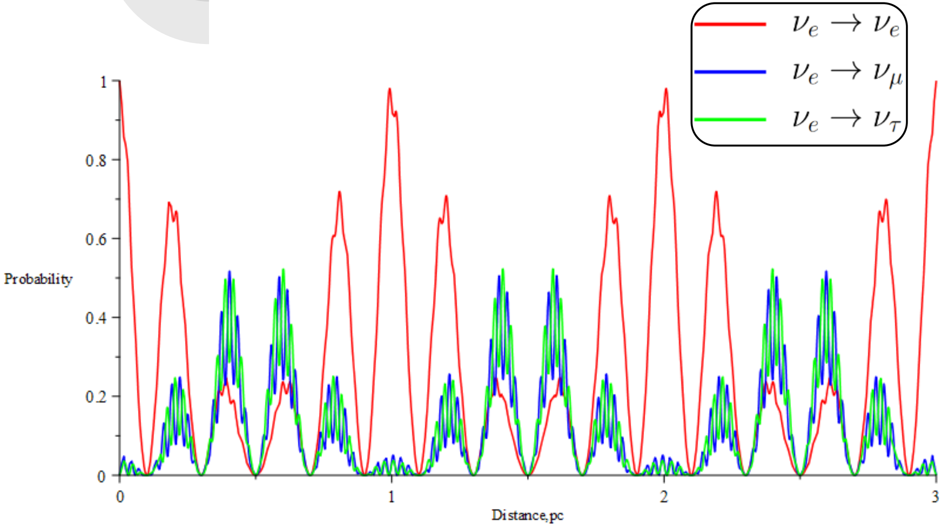
$$P_{\nu_e^L \to \nu_\mu^R} = \sin^2(\mu B_\perp t) \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4p} t$$

A.Popov, A. Studenikin, Eur. Phys. J. C (2019) 79:144

Weak field approximation:

$$E_i^s \approx p + \frac{m_i^2}{2p} + \frac{\mu_i^2 B^2}{2p} + \mu_i s B_\perp$$

Cosmic neutrino flavor oscillations



B = 2.9 μG, μ1=μ2=μ3=μ=10^(-20)μB, normal mass ordering, zero CP-phase, p=10^19 eV

Conclusions: We have confirmed that in the three-flavor neutrino case there is an inherent interplay between neutrino flavor oscillations on corresponding frequencies and neutrino spin (or spin-flavor) oscillations in the presence of a magnetic field. These phenomena should be accounted when neutrino oscillations are considered in magnetized astrophysical environments.