Back-to-back pair correlation of Majorana neutrinos with transit magnetic moments

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The pair production of Majorana neutrinos with transit magnetic moments from the annihilation of charged particles in colliding experiments is discussed using the Pauli interaction, through which the neutral neutrinos with magnetic moments can be probed by the photon. The pair of neutrinos with different flavors are produced due to the transit magnetic moment coupling. We discuss the correlations of flavors in pairs produced back-to-back in the center of the mass frame, where the angular distribution peaks at $\theta = \pi/2$ with respect to the beam direction. We demonstrate that the flavor mixing angle can be inferred by measuring the flavor correlation in pairs.

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Among the fundamental building blocks of the Universe in the standard model, neutrinos are electrically neutral particles with spin $1/2$, which are interacting only weakly being classified as an upper component of weak left-handed doublets. The atmospheric and solar neutrino observations [1,2] as well as reactor experiments [3] show the evidences of oscillations between different flavors of neutrinos, which are only possible if neutrinos are massive and flavors are mixed in the mass eigenstates. Neutrinos do not have electric charges, but they are found to have nonvanishing mass, and it is natural to ask the possibility of magnetic moments [4] through which they can interact with photons directly. We assume, in this work, the case where the massive neutrinos have nonvanishing magnetic moments or the transition magnetic moments, which can induce a spin-dependent coupling to photons.

The bounds for the neutrino magnetic moments obtained from the experiments [5–8] and theoretical considerations [9] are varying in wide range of $10^{-15} - 10^{-7}\mu_B$, where μ_B is the Bohr magneton. In the standard model, the neutrino magnetic moment induced by the one-loop effect [10] is $\mu_\nu = 3 \times 10^{-19}(\frac{m_\nu}{\mathrm{eV}})\mu_B$, which is much smaller than the above bounds. It is also worth mentioning that the upper bound for the magnetic moments are less stringent for Majorana neutrinos than for Dirac neutrinos.

In the lowest order of the standard model, the neutrino pair production by the annihilation of charged particles is through the Z^0 channel. However, if neutrinos have nonvanishing magnetic moments[1] they can also be produced through the photon channel as well[13–15]. When we adopt the Pauli interaction [16] as an effective interaction as for beyond standard model physics, the cross section of pair production becomes dominated by the Pauli interaction over the standard process through Z^0 channel as the energy is increasing. For example, if magnetic moments are not much smaller than $10^{-10} - 10^{-9}\mu_B$, substantial increases of pair production rates at the Large Hadronic Collider (LHC, $E^{\mathrm{CM}}_{\mathrm{LHC}} > 10$ TeV) and Ultra High Energy Cosmic Ray experiments (UHECR, $E^{\mathrm{CM}}_{\mathrm{GZK}} \sim 100$ TeV) are expected[17].

Majorana neutrinos are known to have only transit magnetic moments, which implies that the lepton flavor numbers are not conserved in this process. Therefore, if the neutrinos produced are Majorana type, then the pairs should be produced with different flavors. It gives us an interesting possibility to figure out which type of neutrinos is involved, Majorana or Dirac. In this work, we discuss the flavor correlations in a pair of neutrinos, which can be used to infer the flavor mixing angles for Majorana neutrinos. Since the angular distribution of produced pairs through magnetic moment coupling peaks at $\theta = \pi/2$ with respect to the beam direction, the events observed at the right angle in the center of mass frame can be easily distinguished from those of the standard model process.

The Majorana field is basically represented by two-component spinor, χ. For a free particle, the Lagrangian of two-component Majorana field is given by

$$\mathcal{L} = \chi^\dagger \bar{\sigma} \cdot \partial \chi - \frac{m}{2}[(\chi^C)^\dagger \chi + \chi^\dagger \chi^C], \tag{1}$$

where

$$i\bar{\sigma} \cdot \partial \chi - im\sigma^2 \chi^* = 0. \tag{2}$$

Using the four-component Majorana field, $\Psi(x)$, the interaction Lagrangian for the Majorana neutrino with Pauli interaction can be written down,

$$\mathcal{L}_{\mathrm{int}} = i\frac{\mu_{ij}}{2}\bar{\Psi}^i_M \sigma_{\mu\nu}\Psi^j_M F^{\mu\nu}, \tag{3}$$

where $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$ and $g_{\mu\nu} = (+, -, -, -)$. μ_{ij} is a transition magnetic moment which is antisymmetric for a Majorana neutrino, $\mu_{ij} = -\mu_{ji}$.

[1]It is interesting to note that the effect of magnetic moments of neutrinos on the vacuum instability has been recently investigated in the presence of a strong external magnetic field to find out that with a nonvanishing magnetic moment there appears vacuum instability beyond critical field strength, $B_c = \frac{m_\nu}{\mu_\nu}$ against the pair production of neutrinos [11,12]

The process we are considering is the annihilation of a charged fermion into the neutrino pair through a photon channel with Pauli interaction at very high energy. In the high-energy region, where the particle masses are very small compared to the energy scale, $m_i \ll E$, the differential cross section and total cross section, respectively, converge to simple expressions [17]:

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{\alpha Q^2 \mu_{12}^2}{4\pi} \sin^2\theta \tag{4}$$

and

$$\sigma = \frac{2\alpha Q^2 \mu_{12}^2}{3}, \tag{5}$$

which are similar to the results for a Dirac neutrino with a magnetic moment [13]. One can see that the angular distribution peaks at $\theta = 1/2$. It is compared to the angular distribution of the standard model process, which has a maximum for $\theta = 0$ and π and a minimum for $\theta \sim \pi/2$. These features are quite different from those with Pauli interaction. To get some idea of the energy scale for which the magnetic moment coupling is dominant, we can define the energy scale, $E_{0.1}$, for which the total cross section becomes $\sim 10\%$ of the standard model,

$$E_{0.1} \sim 10^2 \left(\frac{10^{-10}\mu_B}{\mu}\right) \text{TeV}. \tag{6}$$

Then the detectors located around the right angle to the beam direction can measure the back-to-back correlations in pair production, where the production rate is supposed to be maximum. Most of the detectors are using electromagnetic triggers at the end stations, which implies electrons or muons are those to be detected finally. The Majorana pairs in mass eigenstates, ν_1 and ν_2, are produced and interact weakly with other particles to produce charged leptons to be detected. We consider only two mass eigenstates to simplify the situation. ν_1 and ν_2 are linear combinations of weak eigenstates, ν_α and ν_β,

$$\nu_1 = \cos\delta\nu_\alpha + \sin\delta\nu_\beta \quad \nu_2 = -\sin\delta\nu_\alpha + \cos\delta\nu_\beta, \tag{7}$$

where δ is a mixing angle and α and β, for example, can be electron and muon. Now consider two targets A and B placed at the opposite side of the center of mass at the right angle to the beam direction. Suppose ν_1 hits the target A, then the rates, $N_A^{(1)}(\alpha)$ and $N_A^{(1)}(\beta)$ for detecting l_α and l_β, respectively, at the detectors surrounding A are proportional to the mixing angles,

$$N_A^{(1)}(\alpha) = N\cos^2\delta, \qquad N_A^{(1)}(\beta) = N\sin^2\delta, \tag{8}$$

where N is introduced as an overall normalizing factor. The second neutrino, ν_2, produced in the opposite direction hits the target B to produce leptons,

$$N_B^{(2)}(\alpha) = N\sin^2\delta, \qquad N_B^{(2)}(\beta) = N\cos^2\delta. \tag{9}$$

On the other hand, when ν_2 hits the target A we get

$$N_A^{(2)}(\alpha) = N\sin^2\delta, \qquad N_A^{(2)}(\beta) = N\cos^2\delta, \tag{10}$$

and

$$N_B^{(1)}(\alpha) = N\cos^2\delta, \qquad N_B^{(1)}(\beta) = N\sin^2\delta. \tag{11}$$

Since the rate of producing ν_1 in the direction A is the same as for ν_2 simply because they are simultaneous events, the rates of producing l_α or l_β at each targets are not depending on the mixing angle,

$$\begin{aligned} N_A(\alpha) &= N_A^{(1)}(\alpha) + N_A^{(2)}(\alpha) = N \\ N_B(\alpha) &= N_B^{(1)}(\alpha) + N_B^{(2)}(\alpha) = N \end{aligned} \tag{12}$$

and the same for l_β.

However, the back-to-back correlation, R, defined by the product of the rates of l_α at A and l_β at B,

$$\begin{aligned} R &\equiv [N_A^{(1)}(\alpha) \times N_B^{(2)}(\beta) + N_A^{(2)}(\alpha) \times N_A^{(1)}(\beta)]/N \\ &= \cos^4\delta + \sin^4\delta = \frac{1}{2}(1 + \cos^2 2\delta), \end{aligned} \tag{13}$$

turns out to be strongly dependent on the mixing angle, δ, to be measured. The maximum value, $R = 1$, is obtained for the cases of no-mixing, $\delta = \frac{n\pi}{2}(n = 0, 1, 2, \ldots)$. But interestingly the minimum value, $R = 1/2$, is obtained when the mixing angle is $\pi/4$ for the maximal mixing. And for moderate mixing, $\delta = \pi/8$, one can get $R = 3/4$.

In summary, we discuss an observational possibility of mixing angle of Majorana neutrinos by measuring back-to-back correlation of flavors in the pairs produced assuming that the Majorana neutrinos have nonvanishing transit magnetic moments and they are produced in pairs from the annihilation of charged particles through Pauli interaction. It turns out that because of the periodicity of the correlation R with a period of $\pi/2$ in mixing angle it can measure δ effectively modulo between 0 and $\pi/4$ for which R ranges from 1 to 1/2, which can be of interest particularly for the moderate mixing angles up to maximal mixing. Although the present energy scale might not be sufficiently high enough to be effective in measuring the correlations for the magnetic moment smaller than $\sim 10^{-10}\mu_B$ and moreover most of the present experimental systems are not sensitive enough for the neutrino detections, we suggest that the neutrino magnetic moment with Pauli coupling can open an interesting channel in the future experiments at higher energy with more sensitive detecting systems of neutrinos. Finally, it should be noted that the Pauli coupling is a kind of effective interaction term which might be valid only up to some scale, which we assume to be higher than the scale we are considering in this work.

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