Astrophysical probes of electromagnetic neutrinos

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Abstract. Electromagnetic properties of massive neutrinos and current best astrophysical bounds on neutrino magnetic moment and millicharge are outlined. Future probes of electromagnetic neutrinos from a core-collapse supernova with JUNO are discussed.

1. Introduction
In 1930, Pauli not only postulated the existence of neutrino but also discussed the possibility that it might have electromagnetic properties, namely a magnetic moment \cite{1}. Systematic theoretical studies of neutrino electromagnetic properties started after it was shown that in the extended standard model with right-handed neutrinos the magnetic moment of a massive neutrino is, in general, nonvanishing and that its value is determined by the neutrino mass. In spite of many efforts in the search of neutrino electromagnetic interactions, up to now there is no positive experimental indication in favor of their existence. Electromagnetic interactions of neutrinos can generate important effects, especially in astrophysical environments, where neutrinos propagate over long distances in magnetic fields in vacuum and in matter. In the present work we emphasize the potential of searches for electromagnetic properties of massive neutrinos in astrophysics.

The paper is organized as follows. Section 2 gives a short overview of neutrino electromagnetic properties. In section 3, current theoretical bounds and future experimental studies with JUNO on the effects of electromagnetic interactions of neutrinos in astrophysics are discussed.

2. Electromagnetic properties of massive neutrinos
A detailed review of neutrino electromagnetic properties and interactions can be found in \cite{2–4}. Below we briefly outline the general form of the electromagnetic interactions of Dirac and Majorana neutrinos. There are at least three massive neutrino fields $\nu_i$ with respective masses $m_i$ ($i = 1, 2, 3$), which are mixed with the three active flavor neutrinos $\nu_e$, $\nu_\mu$, $\nu_\tau$. Therefore, the effective electromagnetic interaction Hamiltonian can be presented as

$$\mathcal{H}_{em}^{(\nu)} = j_\mu^{(\nu)} A^\mu = \sum_{i,f=1}^{3} \mathcal{A}_f^{i} \nu_i \nu_\ell A^\mu,$$ (1)
where we take into account possible transitions between different massive neutrinos. The physical effect of $\mathcal{H}_\text{em}$ is described by the effective electromagnetic vertex, which in momentum-space representation depends only on the four-momentum $q = p_i - p_f$ transferred to the photon and can be expressed as follows:

$$\Lambda_{\mu}(q) = (\gamma_{\mu} - q_{\mu} g / q^2) \left[ f_Q(q^2) + f_A(q^2) q^2 \gamma_5 \right] - i \sigma_{\mu\nu} q^\nu \left[ f_M(q^2) + i f_E(q^2) \gamma_5 \right].$$

Here $\Lambda_{\mu}(q)$ is a $3 \times 3$ matrix in the space of massive neutrinos expressed in terms of the four Hermitian $3 \times 3$ matrices of form factors

$$f_Q = f_Q^\dagger, \quad f_M = f_M^\dagger, \quad f_E = f_E^\dagger, \quad f_A = f_A^\dagger,$$

where $Q, M, E, A$ refer respectively to the real charge, magnetic, electric, and anapole neutrino form factors. The Lorentz-invariant form of the vertex function (2) is also consistent with electromagnetic gauge invariance that implies four-current conservation.

For the coupling with a real photon in vacuum ($q^2 = 0$) one has

$$f_Q^{\dagger}(0) = e_f, \quad f_M^{\dagger}(0) = \mu_f, \quad f_E^{\dagger}(0) = \epsilon_f, \quad f_A^{\dagger}(0) = a_f,$$

where $e_f, \mu_f, \epsilon_f$ and $a_f$ are, respectively, the neutrino charge, magnetic moment, electric moment and anapole moment of diagonal ($f = i$) and transition ($f \neq i$) types.

3. Effects of neutrino electromagnetic interactions in astrophysics

Studies of neutrino propagation and interactions in astrophysical environments allow obtaining strong limits on neutrino electromagnetic properties. Magnetic moment plasmon decay $\gamma^* \rightarrow \nu\nu$ enhances the standard model photo-neutrino cooling of a red giant star. From this consideration one obtains the best astrophysical limit [5]

$$\mu_\nu \leq 3 \times 10^{-12} \mu_B,$$

which is by an order of magnitude stronger than the best limit obtained so far in laboratory measurements of elastic $\nu - e^-$ scattering with reactor antineutrinos, $\mu_{\nu_e} \leq 2.9 \times 10^{-12} \mu_B$ [6].

A strong limit on the neutrino millicharge $e_\nu$ can be obtained by considering the influence of millicharged neutrinos on the rotation of a magnetized star which is undergoing a core-collapse supernova explosion (the neutrino star turning mechanism, $\nu ST$) [7],

$$|e_\nu| \leq 1.3 \times 10^{-19} e.$$

This limit is by seven orders of magnitude stronger than the best limit from reactor experiments on elastic $\nu - e^-$ scattering, $|e_{\nu_e}| \leq 1.5 \times 10^{-12} e$ [8].

Detection of neutrinos from astrophysical sources, such as a supernova (SN), can provide another excellent probe of their electromagnetic properties. It remains an open question in modern astrophysics how a massive star of more than eight solar masses ends its life in a gravitational collapse, which subsequently turns to be a spectacular and violent explosion [9]. Such a core-collapse SN is expected to give birth to neutron stars, and provides an ideal place to produce heavy nuclear elements that cannot be found in the ordinary stellar evolution. In the paradigm of the delayed neutrino-driven SN explosion, it is neutrinos that carry away 99% of the total gravitational binding energy (i.e., $\sim 3.0 \times 10^{53}$ erg) released during the core collapse, and revive the shock wave that was halted by a rapid energy loss in disassociating heavy nuclei in the outer core. Therefore, a high-statistics detection of SN neutrinos and a precise determination of their flavor content and energy spectra are of crucial importance to establish the true mechanism
of SN explosions [10]. On the other hand, the SN offers us an intensive neutrino source and serves an extraordinary laboratory to probe the intrinsic properties of neutrinos themselves.

The Jiangmen Underground Neutrino Observatory (JUNO) [11], which is under construction in Guangdong Province in China, has been designed to precisely measure the energy spectrum of reactor antineutrinos by using a 20 kiloton liquid-scintillator detector with an unprecedented energy resolution of 3%/√E/MeV. The primary goals of JUNO are to unambiguously determine neutrino mass ordering (i.e., either \( m_1 < m_2 < m_3 \) or \( m_3 < m_1 < m_2 \)) and precisely measure neutrino oscillation parameters (e.g., sub-percent precisions for \( \Delta m^2_{21} \), \( \theta_{12} \) and \( |\Delta m^2_{ee}| \)). At the same time, JUNO will be able to register more than 5000 electron antineutrino events via the inverse beta decay process \( \nu_e + p \rightarrow e^+ + n \), if a galactic SN is exploding at a distance of 10 kpc away. In addition, the elastic neutrino-proton scattering \( \nu + p \rightarrow \nu + p \) takes place for neutrinos and antineutrinos of all three flavors, and contributes to another 2000 events at JUNO. Using all possible reaction channels, including both charged-current and neutral-current neutrino interactions on the carbon nuclei, it has been found in Ref. [10] that the average energy of SN neutrinos can be measured at a precision of 1.4% for \( \nu_e \), 12% for \( \nu_x \) and 4.6% for \( \nu_x \), respectively, where \( \nu_x \) collectively denote muon and tau neutrinos and their antineutrinos.

Although it was pointed out long time ago that the neutrino-neutrino refraction in the SN environment may be very important for neutrino flavor conversions, the nonlinear evolution of neutrino flavors has recently been found to dramatically change the neutrino energy spectra [13]. Depending on the initial neutrino fluxes and energy spectra, a complete swap between neutrino spectra of electron and non-electron flavors can take place in the whole or a finite energy range, as a direct consequence of collective neutrino oscillations. Furthermore, the impact of nonzero transition magnetic moments for massive Majorana neutrinos on collective neutrino oscillations has been explored in Refs. [14, 15]. For a magnetic field of \( 10^{12} \) G and the transition magnetic moment at the level of \( 10^{-22} \mu_B \), which is just two orders of magnitude larger than the standard-model prediction corresponding to neutrino masses of the order of 0.1 eV, the pattern of spectral splits of SN neutrinos may be observed in future experiments, such as JUNO. The identification of the spectral splits will allow probing values of the neutrino magnetic moments which are extremely small and impossible to detect in other terrestrial experiments.

Acknowledgments

This work was supported by the joint project of the Russian Foundation for Basic Research (RFBR) under grant no. 15-52-53112 GFEN\_a and National Natural Science Foundation of China (NSFC) under grant no. 11511130016. K.A.K, A.V.L and A.I.S also acknowledge support from RFBR under grant nos. 14-22-03043 ofi\_m and 16-02-01023 A.

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