Neutrino spin states in moving matter and the effect of neutrino spin light ⋆

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Abstract. In this short note we discuss the potential of the developed method of neutrino treatment in external conditions (external fields and matter) for description of neutrino processes in astrophysics. As an example of its application we consider the spin light of neutrino in the transversal matter current.

Keywords: Neutrino electromagnetic properties

Neutrino electromagnetic properties and its interaction with matter are the key questions in physics of neutrino propagation in astrophysical media. The electromagnetic properties are represented by neutrino electromagnetic form factors [1] and the interaction with matter on the quantum level can be accounted for by the modified Dirac equation [2]. Combining these two research lines gives the so-called "method of exact solutions" [2, 3] which makes it possible to describe several new effects of neutrino propagation under the influence of external conditions (background matter and external electromagnetic fields). The method implies the use of the modified Dirac equation solutions to calculate amplitudes for particular processes.

The most important neutrino electromagnetic characteristic is the magnetic moment. In the minimally extended Standard Model with right-handed neutrinos its value is calculated to be $\mu \approx 3.2\times 10^{-19}\mu_{\rm B}(m/1\ {\rm eV})$, where m is the neutrino mass and $\mu_{\rm B}$ is the Bohr magneton [4]. Severe upper limits obtained in neutrino scattering experiments with the reactor and solar neutrino fluxes are at the level of $\mu \leq (2.8-2.9)\times 10^{-11}\mu_{\rm B}$ [5, 6]. Quite recently significant progress has been made [7] in verifying the neutrino magnetic moments by analyzing data on the direct detection of dark matter in experiments.

In the present short note we aim to demonstrate the potential of the exact solution method which encompasses description of various phenomena related to the neutrino propagation in external media and the neutrino electromagnetic properties. On this basis the following important phenomena were predicted and studied.

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1. The neutrino energy quantization in the case of neutrinos moving in a rotating matter [8].

2. When applied to millicharged neutrinos moving in a magnetized pulsar a new mechanism (*the neutrino star turning*, νST) that disturbers the star rotation angular velocity was predicted [9]. The comparison of the νST impact with the observed pulsars angular velocities provides the most stringent astrophysical bound on the neutrino millicharge $q_\nu < 1.3 \times 10^{-19} e_0$ (e_0 is the elementary charge).

3. The neutrino spin and spin-flavour oscillations can be engendered by neutrino interaction with the background moving matter in the case when there is the transversal matter current or matter polarization [10, 11].

4. A consistent treatment of neutrino oscillations in a magnetic field with account for massive neutrino helicity [12]. This approach reveals modulations of the neutrino oscillation amplitude owing to the interplay between vacuum and magnetic field oscillation frequencies.

5. The phenomenon of neutrino electromagnetic radiation in matter owing to its magnetic moment, called the Spin Light of Neutrino ($SL\nu$) [2, 13]. The process was studied for the case of non-moving matter and the higher the density of the matter and the neutrino energy, the more effective it is. Due to the latter fact it can be substantial in ultra-dense astrophysical environments (e.g., NSs, third-family compact stars, GRBs). For instance, for the case of third-family compact stars, assuming the baryon density as high as $n_b \sim 10^{41}$ cm^{-3} and neutrino energy $E \sim 10$ PeV, the radiation time is about $\tau_{SL\nu} \sim 10^{-4}$ s [14].

Here we show how the method of exact solutions can easily be adopted to asses the effect of transversal matter motion on $SL\nu$. This settings are peculiar for GRB models. Note that the $SL\nu$ photon is emitted between different neutrino helicity states. In the limit of massless neutrinos they become the chiral states: ν_L for the initial neutrino and ν_R for the final one which is sterile. For the initial neutrino moving with momentum p and matter moving at a speed v along the third and first axes, respectively, we have the effective Dirac equation:

$$\big\{\gamma_0 E - \gamma_3 p - \tilde{n}(1-\gamma_5)(\gamma_0 - v\gamma_1)\big\}\Psi_i(x) = 0, \tag{1}$$

where matter is composed of electrons the density parameter is $\tilde{n} = \frac{1}{2\sqrt{2}} G_F(1 + 4\sin^2\theta_W)n$ with $n = \gamma n_0$ being the number density in the laboratory frame ($\gamma = 1/\sqrt{1-v^2}$ is the Lorentz gamma factor). For densities peculiar to matter of neutron stars ($n \sim 10^{38}$ cm^{-3}) one has $\tilde{n} \sim 1$ eV, so that $\tilde{n}$ is very small compared to p. Then the neutrino energy leading from (1) can be written as $E = \sqrt{p^2 + 4\tilde{n}^2 v^2} + 2\tilde{n} \approx p + 2\tilde{n} + 2\tilde{n}^2 v^2/p$, and, for the standard representation of gamma-matrices, the solution to equation (1) has the form:

$$\Psi_i(x) = \frac{1}{\sqrt{2}p}\,(-\tilde{n}v, -p, \tilde{n}v, p)^T e^{-iEt+ipz}. \tag{2}$$

For the final neutrino, the solution of the free Dirac equation is used.

Solving the kinematical problem with respect to the photon energy ω, while neglecting its dispersion for simplicity, gives: $\omega = \frac{2\tilde{n}p}{p(1-\cos\theta)+2\tilde{n}}$. The amplitude of the process is defined by the vertex $(\hat{\mathbf{\Gamma}}\mathbf{e}^*)$, where vector $\mathbf{e}$ describes the photon polarization and $\mathbf{\Gamma} = i\big\{\big[\mathbf{\Sigma}\times\mathbf{k}\big] + i\omega\gamma^5\mathbf{\Sigma}\big\}$ [2].

Within the straightforward calculation for the total rate and the power of $SL\nu$, which in the limit $\tilde{n}/p \ll 1$ we obtain, respectively,

$$\Gamma = 4\mu^2\tilde{n}^2(p - 2\tilde{n} + \tilde{n}v^2) \quad I = \frac{4}{3}\mu^2\tilde{n}^2 p(p + 2\tilde{n}v^2). \tag{3}$$

For the case of non-moving matter, $v = 0$, these formulas fit perfectly the results obtained before in [14]. Expressions (3) show that the $SL\nu$ in moving matter is γ^2 times more efficient than in the case of the resting one given that p and n_0 are the same. As a result, the $SL\nu$ radiation time is appeared to be γ^2 times less, which for high matter velocities in the real GRB conditions can give additional reduction by an order of magnitude.

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