Neutrino magnetic moment: a window to new physics

A. Studenikin\textsuperscript{a} *

\textsuperscript{a}Department of Theoretical Physics, Moscow State University, 119991 Moscow, Russia

A short review on a neutrino magnetic moment is presented.

Introduction. Experimental and theoretical studies of flavour conversion in solar, atmospheric, reactor and accelerator neutrino fluxes give strong evidence of non-zero neutrino mass. A massive neutrino can have non-trivial electromagnetic properties \cite{1}. For a recent review on neutrino electromagnetic properties see \cite{2}.

The neutrino dipole magnetic moment (along with the electric dipole moment) is the most well studied among neutrino electromagnetic properties. The effective Lagrangian, that is in charge of neutrino electromagnetic properties see \cite{2}. A Dirac neutrino may have non-zero diagonal magnetic moment within a minimal extension of the Standard Model, as it follows from (3), is

\begin{equation}
\mu_{ij}^D = \frac{eG_F m_i}{8\sqrt{2}\pi^2} \left(1 + \frac{m_j}{m_i}\right) \sum_{l=\epsilon, \mu, \tau} f(a_l) U_{ij} U_{il}^*, \quad (2)
\end{equation}

where $U_{ii}$ is the neutrino mixing matrix. The correspondent result in the absence of mixing was confirmed in \cite{5}. For the diagonal magnetic moment of the Dirac neutrino, from (2) in the limit $a_l \ll 1$ the result \cite{1} can be obtained

\begin{equation}
\mu_{ii}^D = \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \left(1 - \frac{1}{2} \sum_{l=\epsilon, \mu, \tau} a_l |U_{ii}|^2 \right). \quad (3)
\end{equation}

The magnetic moment for hypothetical heavy neutrino was studied in \cite{6}. In particular, it was obtained

\begin{equation}
\mu_{\nu} = \frac{eG_F m_{\nu}}{8\sqrt{2}\pi^2} \begin{cases} 
3 + \frac{5}{3} b, & m_\ell \ll m_{\nu} \ll M_W, \\
1, & m_\ell \ll M_W \ll m_{\nu}.
\end{cases} \quad (4)
\end{equation}

Note that the LEP data set a limit on number of light neutrinos coupled to $Z$ boson.

The numerical value of the Dirac neutrino magnetic moment within a minimal extension of the Standard Model, as it follows from \cite{9}, is

\begin{equation}
\mu_{ii}^D \approx 3.2 \times 10^{-19} \left(\frac{m_i}{1\,\text{eV}}\right) \mu_B, \quad (5)
\end{equation}

This is several orders of magnitude smaller than the present experimental limits if to account for the existed constraints on neutrino masses.

\*e-mail: studenik@srd.sinp.msu.ru

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Neutrino magnetic moment in other extensions of Standard Model. Much larger values for a neutrino magnetic moments can be obtained in different other extensions of the Standard Model (see [7], the first paper of [1] and, for instance, [8]). However, there is a general problem [9,10,11] for a theoretical model how to get a large magnetic moment for a neutrino and simultaneously to avoid unacceptable large contribution to the neutrino mass. If a contribution to the neutrino magnetic moment of an order $\mu_\nu \sim \frac{\Lambda}{\Lambda}$ is generated by physics beyond a minimal extension of the Standard Model at an energy scale characterized by $\Lambda$, then the correspondent contribution to the neutrino mass is

$$\delta m_\nu \sim \frac{\Lambda^2}{2m_e} \mu_\nu = \mu_\nu \frac{10^{-18} \mu_B (\frac{\Lambda}{\text{Tev}})^2}{eV}. \quad (6)$$

Therefore, a particular fine tuning is needed to get a large value for the neutrino magnetic moment while keeping the neutrino mass within experimental bounds.

Different possibilities to have a large magnetic moment for a neutrino were considered in the literature (see, for instance, [12]).

Bounds on neutrino magnetic moment. The constraints on the neutrino magnetic moment in the direct laboratory experiments so far obtained from unobservant distortions in the recoil electron energy spectra. The best upper bounds on the neutrino magnetic moment are obtained in the recently carried reactor experiments: $\mu_\nu \leq 9.0 \times 10^{-11} \mu_B$ (MUNU collaboration [13]), $\mu_\nu \leq 7.4 \times 10^{-11} \mu_B$ (TEXONO collaboration [14]), and $\mu_\nu \leq 5.8 \times 10^{-11} \mu_B$ (GEMMA collaboration [15]). Stringent limits also obtained in the solar neutrino scattering experiments: $\mu_\nu \leq 1.1 \times 10^{-10} \mu_B$ (Super-Kamiokande collaboration [17]) and $\mu_\nu \leq 5.4 \times 10^{-11} \mu_B$ (Borexino collaboration [18]).

Note that the global fit [19] of the magnetic moment data from the reactor and solar neutrino experiments for the Majorana neutrinos produces limits on the neutrino transition moments $\mu_{\nu_3}$, $\mu_{\nu_1}$, $\mu_{\nu_2} < 1.8 \times 10^{-10}$. Upper limits on magnetic moments for the muon and $\tau$-neutrino neutrinos ($\mu_{\nu_\mu} \leq 1.5 \times 10^{-10} \mu_B$ and $\mu_{\nu_\tau} \leq 1.9 \times 10^{-10} \mu_B$, respectively) were found [20] in an independent analysis of the first release of the Borexino experiment data.

It should be mentioned [9] that what is measured in scattering experiments is an effective magnetic moment $\mu_\nu^{\text{exp}}$, that depends on the flavour composition of the neutrino beam at the detector located at a distance $L$ from the source, and which value is a rather complicated function of the magnetic (transition) moments $\mu_{ij}$:

$$\mu_\nu^{\text{exp}} = \mu_\nu^2 (\nu_i, L, E_\nu) = \sum_j \left| \sum_i U_{ij} e^{-iE_i L} \mu_{ji} \right|^2.$$

The dipole electric (transition) moments, if these quantities not vanish, can also contribute to $\mu_\nu^{\text{exp}}$.

A general and model-independent upper bound on the Dirac neutrino magnetic moment, that can be generated by an effective theory beyond the standard model, have been derived [11]: $\mu_\nu \leq 10^{-14}$ (the limit in the Majorana case is much weaker).

Neutrino magnetic moment interaction effects. If a neutrino has non-trivial electromagnetic properties, notably non-vanishing magnetic (and also electric (transition) dipole moments or non-zero millicharge and charge radius), then a direct neutrino couplings to photos becomes possible and several important for applications processes exist [21]. A set of typical and most important neutrino electromagnetic processes involving the direct neutrino couplings with photons is: 1) a neutrino radiative decay $\nu_1 \rightarrow \nu_2 + \gamma$, neutrino Cherenkov radiation in external environment (plasma and/or electromagnetic fields), spin light of neutrino, $SL\nu_\nu$, in the presence of medium [22]; 2) photon (plasmon) decay to a neutrino-antineutrino pair in plasma $\gamma \rightarrow \nu \bar{\nu}$, 3) neutrino scattering off electrons (or nuclei), 4) neutrino spin (spin-flavor) precession in magnetic field. Note that resonant neutrino spin-flavour oscillations in matter were considered in [23].

The tightest astrophysical bound on a neutrino magnetic moment is provided by observed properties of globular cluster stars. For a large enough neutrino magnetic moment the plasmon decay rate can be enhanced so that a reasonable delay of helium ignition would appear. From lack
observation evidence of anomalous stellar cooling due to the plasmon decay the following limit has been found [21]
\[
\left( \sum_{i,j} | \mu_{ij} |^2 \right)^{1/2} \leq 3 \times 10^{-12} \mu_B. \tag{7}
\]
This is the most stringent astrophysical constraint on a neutrino magnetic moment, applicable to both Dirac and Majorana neutrinos.

**Conclusion.** There is a huge gap of many orders of magnitude that does exist between the present limits \( \propto 10^{-11+14} \mu_B \) on a neutrino magnetic moment \( \mu_\nu \) and the prediction of a minimal extension of the Standard Model. Therefore, if any direct experimental confirmation of non-zero neutrino magnetic moment were obtained within a reasonable time in the future, it would open a window to new physics.

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