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Overview on neutrino electromagnetic properties

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Abstract. There is a short overview on the selected issues of neutrino electromagnetic properties with focus on existed experimental constraints and on the effect of neutrino spin precession in the transversal magnetic field and transversal matter current.

1. Introduction. It has been known since quite many years [1] that massive neutrinos should have nonzero magnetic moments. Although up to now there are no indications in favour of nonzero neutrino electromagnetic properties, neither from terrestrial experiments nor from astrophysical observations, the electromagnetic properties is one of popular issues related to neutrinos and this problem has been discussed many times in recent literature (see, for instance, [2]-[9]). A complete review on neutrino electromagnetic properties and neutrino electormagnetic interactions is given in [10]. In [11, 12] an addendum to previous reviews are provided and the most recent new aspects and prospects related to neutrino electromagnetic interactions that have appeared after publication of the review paper [10] are discussed.

In this note below we focus on discussions of theoretical predictions and experimental constraints for neutrino electromagnetic characteristics and on the effect of neutrino spin precession in the transversal magnetic fields and transversal matter currents.

2. Magnetic moment in minimal extension of Standard Model. Consider the magnetic moment as the most well theoretically appreciated and experimentally studied (constrained) electromagnetic characteristic of neutrinos. Within the initial formulation of the Standard Model neutrinos are massless particles with zero magnetic moment. Thus, the would be nonzero neutrino magnetic moment regardless of its value should indicate the existence of *new physics* beyond the Standard Model. Indeed, as it has been shown in [1] a minimal extension of the Standard Model with right-handed neutrinos yields for the diagonal magnetic moment of a Dirac neutrino to be proportional to the neutrino mass m_i,

$$\mu^D_{ii} = \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19}\Big(\frac{m_i}{1 \text{ eV}}\Big)\mu_B, \tag{1}$$

where μ_B is the Bohr magneton. For Majorana neutrinos the diagonal magnetic moments are zero in the neutrino mass basis and only transition (off-diagonal) magnetic moments μ^M_{ij} $(i \neq j)$ can be nonzero in this case.

The value of neutrino magnetic moment (1) has to be several orders of magnitude smaller than the present experimental limits if to account for the existed constraints on neutrino masses. Transition magnetic moments are even smaller due to the GIM cancelation mechanism.

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3. Constraints on neutrino magnetic moment. The best laboratory upper limit on neutrino magnetic moment has been obtained by the GEMMA collaboration that investigates the reactor antineutrino-electron scattering at the Kalinin Nuclear Power Plant (Russia) [13]. Within the presently reached electron recoil energy threshold of $T \sim 2.8$ keV the neutrino magnetic moment is bounded from above by the value $\mu_\nu < 2.9 \times 10^{-11}\mu_B$ (90% C.L.). This limit, obtained from unobservant distortions in the recoil electron energy spectra, is valid for both Dirac and Majorana neutrinos and for both diagonal and transition moments. The most recent stringent constraint on the electron effective magnetic moment $\mu_{\nu_e} \leq 2.8 \times 10^{-11}\mu_B$ has been reported by the Borexino Collaboration [14].

A strict astrophysical bound on the neutrino magnetic moment is provided by the observed properties of globular cluster stars and amounts to [15] (see also [16, 17]) $\left(\sum_{i,j} |\mu_{ij}|^2\right)^{1/2} \leq (2.2{-}2.6) \times 10^{-11}\mu_B$. This stringent astrophysical constraint on neutrino magnetic moments is applicable to both Dirac and Majorana neutrinos.

There is a huge gap of many orders of magnitude between the present experimental limits on neutrino magnetic moments and the prediction of a minimal extension of the Standard Model. If any direct experimental confirmation of nonzero neutrino magnetic moment were obtained in a reasonable future, it would open a window to *new physics* beyond a minimal extension of the Standard Model.

4. Large neutrino magnetic moment in extensions of Standard Model. Much larger values for a neutrino magnetic moments are predicted in different other extensions of the Standard Model. However, there is a general problem for a theoretical model of how to get large magnetic moment for a neutrino and simultaneously to avoid an unacceptable large contribution to the neutrino mass (see the corresponding discussion in [10] and references therein). If a contribution to the neutrino magnetic moment of an order $\mu_\nu \sim \frac{eG}{\Lambda}$ is generated by physics beyond a minimal extension of the Standard Model at an energy scale characterized by Λ, then the corresponding contribution to the neutrino mass is $\delta m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} = \frac{\mu_\nu}{10^{-18}\mu_B}\left(\frac{\Lambda}{1\ Tev}\right)^2 eV$. Therefore, a particular fine tuning is needed to get large value for a neutrino magnetic moment while keeping the neutrino mass within experimental bounds. Different possibilities to have large magnetic moment for a neutrino were considered in the literature (see in [10]).

A general and termed model-independent upper bound on the Dirac neutrino magnetic moment, that can be generated by an effective theory beyond a minimal extension of the Standard Model, has been derived in [18]: $\mu_\nu \leq 10^{-14}\mu_B$. Note that the corresponding limit for transition moments of Majorana neutrinos is much weaker [19]. The value of a neutrino magnetic moment once observed experimentally at the level not less than $\mu_\nu \sim 10^{-14}\mu_B$ would provide information on the nature of neutrinos.

5. Neutrino electric moment. From the most general form of the neutrino electromagnetic vertex function $\Lambda_{ij}(q^2)$ (see for detailed discussion [10]) there are three other sets (in addition to the magnetic moments μ_{ij}) of electromagnetic characteristics that determine a neutrino coupling with real photons ($q^2 = 0$). They are namely the dipole electric moments ϵ_{ij}, anapole moments a_{ij} and millicharges q_{ij}. In the theoretical framework with CP violation a neutrino can have nonzero electric moments ϵ_{ij}. In the laboratory neutrino scattering experiments for searching the neutrino magnetic moment (like, for instance, the mentioned above GEMMA experiment) the electric moment contributions interfere with those due to magnetic moments. Thus, these kind of experiments also provide constraints on ϵ_{ij}. The astrophysical bounds (**??**) are also applicable for constraining ϵ_{ij} [15]- [17].

6. Neutrino electric millicharge and charge radius. There are extensions of the Standard Model that allow for nonzero neutrino electric millicharges. This option can be provided by not excluded experimentally possibilities for hypercharhge dequantization or another *new physics* related with an additional $U(1)$ symmetry peculiar for extended theoretical frameworks.

Neutrino millicharges are strongly constrained on the level $q_\nu \sim 10^{-21}e_0$ (e_0 is the value of an electron charge) from neutrality of the hydrogen atom.

A nonzero neutrino millicharge q_ν would contribute to the neutrino electron scattering in the terrestrial experiments. Therefore, it is possible to get bounds on q_ν in the reactor antineutrino experiments GEMMA. The most stringent constraint using the GEMMA data is $q_\nu \leq 1.5 \times 10^{-11}e_0$ [20] (see also [21]).

A neutrino millicharge might have specific phenomenological consequences in astrophysics because of new electromagnetic processes are opened due to a nonzero charge. Following this line, the most stringent astrophysical constraint on neutrino millicharges $q_\nu \leq 1.3 \times 10^{-19}e_0$ was obtained in [22]. This bound follows from the impact of the neutrino star turning mechanism ($ST\nu$) [22] that can be charged as a *new physics* phenomenon end up with a pulsar rotation frequency shift engendered by the motion of escaping from the star neutrinos on curved trajectories due to millicharge interaction with a constant magnetic field.

Even if a neutrino millicharge is vanishing, the electric form factor $f^q_{ij}(q^2)$ can still contain nontrivial information about neutrino electromagnetic properties. The corresponding electromagnetic characteristics is determined by the derivative of $f^q_{ij}(q^2)$ over q^2 at $q^2 = 0$ and is termed neutrino charge radius, $r^2_{ij} = -6\frac{df^q_{ij}(q^2)}{dq^2}\mid_{q^2=0}$. A neutrino charge radius (that is indeed the charges radius squared) contributes to the neutrino scattering cross section on electrons and thus can be constrained by the corresponding laboratory experiments [23]. In all (see, for instance, [10]) but one previous studies it was claimed that the effect of the neutrino charge radius can be included just as a shift of the vector coupling constant g_V in the weak contribution to the cross section. However, as it has been recently illustrated, in [24] within the direct calculations of the cross section accounting for all possible neutrino electromagnetic characteristics and neutrino mixing, this is not the fact. The neutrino charge radius dependence of the cross section indeed is more complicated and there is, in particular, the dependence on the interference terms of the type $g_V r^2_{ij}$ that can't be obtained just only by the corresponding shift of the constant g_V.

7. Neutrino spin precession and oscillations in electromagnetic fields. One of the most important phenomenon of nontrivial neutrino electromagnetic interactions is the neutrino magnetic moment precession and the corresponding spin oscillations in presence of external electromagnetic fields. The origin of these effects is the neutrino magnetic moment interaction with a transversal magnetic field determined by $\mu_\nu B_\perp$. The neutrino spin precession in a transverse magnetic field can result in the neutrino helicity flip that can have important phenomenological consequences because an active neutrino ν_{eL} can be converted to a sterile one ν_{eR} in invironments with a magnetic field.

The precession $\nu_{eL} \to \nu_{eR}$ in the magnetic field of the Sun was first considered in [25], a similar effect in magnetic fields of supernovae and neutron stars came into sight for the first time in [1]. Then spin-flavor oscillations $\nu_{eL} \Leftrightarrow \nu_{\mu R}$ in $\mathbf{B}_\perp$ in vacuum were discussed in [26], the importance of the matter effect was emphasized in [27]. The effect of the resonant amplification of neutrino spin oscillations in $\mathbf{B}_\perp$ in the presence of matter was proposed in [28, 29], the impact of the longitudinal magnetic field $\mathbf{B}_{||}$ was discussed in [30]. The neutrino spin oscillations in the presence of constant twisting magnetic field were considered in [31]-[36].

Recently a new approach to description of neutrino spin and spin-flavor oscillations in the presence of an arbitrary constant magnetic field have been developed [36, 12]. Within the new approach exact quantum stationary states in the magnetic field are used for classification of neutrino spin states, rather than the neutrino helicity states that have been used for this purpose within the customary approach in many published papers. Recall that the helicity states are not stationary in the presence of a magnetic field.

In [37] neutrino spin oscillations were considered in the presence of arbitrary constant electromagnetic fields $F_{\mu\nu}$. A neutrino spin oscillations in the presence of the field of circular and linearly polarized electromagnetic waves and superposition of an electromagnetic wave and constant magnetic field were considered in [38]-[40].

More general case of neutrino spin evolution in the case when neutrino is subjected to general types of non-derative interactions with external scalar s, pseudoscalar π, vector V_μ, axial-vector A_μ, tensor $T_{\mu\nu}$ and pseudotensor $\Pi_{\mu\nu}$ fields was considered in [41]. From the general neutrino spin evolution equation, obtained in [41], it follows that electromagnetic (tensor) and weak (axial-vector) interactions can contribute to the neutrino spin evolution.

Recently we consider in details [42, 12] neutrino mixing and oscillations in arbitrary constant magnetic field that have $\mathbf{B}_\perp$ and $\mathbf{B}_{||}$ nonzero components in mass and flavour bases and derived an explicit expressions for the effective neutrino magnetic moments for the flavour neutrinos in terms of the corresponding magnetic moments introduced in the neutrino mass basis.

8. **Neutrino spin precession and oscillations in transversal matter currents**. There is a phenomenon of *new physics* related to the neutrino spin precession in magnetic fields. For many years, until 2004, it was believed that a neutrino helicity precession and the corresponding spin oscillations can be induced by the neutrino magnetic interactions with the transversal magnetic field. A new and very interesting possibility for neutrino spin (and spin-flavour) oscillations engendered by the neutrino interaction with matter background was proposed and investigated in [43]. It was shown that neutrino spin oscillations can be induced not only by the neutrino interaction with a magnetic field but also by neutrino interactions with matter in the case when there is a transversal matter current (or a transversal matter matter polarization). The is no need for neutrino magnetic moment interaction in this case. The origin of the oscillations $\nu_L \Leftrightarrow \nu_R$ in the transversal matter currents $j_\perp$ is the neutrino weak interactions with moving matter and the corresponding mixing between neutrino states ν_L and ν_R is determined by $G_F j_\perp$. This new effect has been explicitly highlighted in [43, 44], recently the existence of this effect was confirmed in [45]. For historical notes reviewing studies and the detailed derivation of the discussed effect see [11, 12] and [46].

9. **Conclusions**. The foreseen progress in constraining neutrino electromagnetic characteristics is related, first of all, with the expected new results from the GEMMA experiment measurements of the reactor antineutrino cross section on electrons at Kalinin Power Plant. The new set of data is expected to arrive next year. The electron energy threshold will be as low as 350 eV (or even lower, $\sim 200\ eV$). This will provide possibility to test the neutrino magnetic moment on the level of $\mu_\nu \sim 0.9 \times 10^{-12}\mu_B$ and also to test the millicharge on the level of $q_\nu \sim 1.8 \times 10^{-13}e_0$ [20]. For the next future, presently it seems unclear whether further progress in constraining the neutrino electromagnetic characteristics would be achievable with this type of the reactor antineutrino experiment. A rather promising claim was made in [47, 48]. It was shown that even much smaller values of the Majorana neutrino transition moments would probably be tested in future high-precision experiments with the astrophysical neutrinos. In particular, observations of supernova fluxes in the JUNO experiment (see [49]- [51]) may reveal the effect of collective spin-flavour oscillations due to the Majorana neutrino transition moment $\mu_\nu^M \sim 10^{-21}\mu_B$.

To conclude, the existing current constraints on the flavour neutrino charge radius $r^2_{e,\mu,\tau} \leq 10^{-32} - 10^{-31}\ cm^2$ from the scattering experiments differ only by 1 to 2 orders of magnitude from the values $r^2_{e,\mu,\tau} \leq 10^{-33}\ cm^2$ calculated within the minimally extended Standard Model with right-handed neutrinos [23]. This indicates that the minimally extended Standard Model neutrino charge radii could be experimentally tested in the near future. Note that there is a need to re-estimate experimental constraints on $r^2_{e,\mu,\tau}$ from the scattering experiments following new derivation of the cross section [24] that properly accounts for the interference of the weak and charge radius electromagnetic interactions and also for the neutrino mixing.

Finally, the effect of neutrino spin precession engendered by the transversal matter currents or transversal matter polarization predicted in [43, 44], that has recently attracted a lot of interest (see [45, 46] and references therein), opens a promising field for the active neutrino ν_L

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conversion to the sterile neutrino state ν_R that can proceed in the corresponding astrophysical environments.

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