Electromagnetic neutrino properties: New constraints and new effects

Alexander I. Studenikin[1,2]

[1] Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia; [1] Joint Institute for Nuclear Research, Dubna 141980, Moscow Region, Russia

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

1. Neutrino magnetic and electric dipole moments. The most well understood and studied among the neutrino electromagnetic properties [1–3] are the dipole magnetic and electric moments. In a minimal extension of the Standard Model the diagonal magnetic moment of a Dirac neutrino is given [4] by $\mu^D_{ii} = \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19}\left(\frac{m_i}{1\text{ eV}}\right)\mu_B$, μ_B is the Bohr magneton. The Majorana neutrinos in the mass basis can have only transition (off-diagonal) magnetic moments $\mu^M_{i\neq j}$.

The most stringent constraints on the effective neutrino magnetic moment are obtained with the reactor antineutrinos (GEMMA Collaboration [5]) $\mu_\nu < 2.9 \times 10^{-11}\mu_B$, and solar neutrinos (Borexino Collaboration [6]) $\mu_{\nu_e} \leq 2.8 \times 10^{-11}\mu_B$. It should be noted, that in general in scattering experiments the neutrino is created at some distance from the detector as a flavor neutrino, which is a superposition of massive neutrinos. Therefore, the magnetic and electric moments measured in these experiments are not those of massive neutrinos, but they are effective moments and they account for the neutrino mixing and oscillations during the propagation between source and detector [7,8]. For the recent and detailed study of the neutrino electromagnetic characteristics dependence on neutrino mixing see [9].

An astrophysical bound (for both Dirac and Majorana neutrinos) is provided [10] by observations of the properties of globular cluster stars: $\left(\sum_{i,j}|\mu_{ij}|^2\right)^{1/2} \leq (2.2–2.6) \times 10^{-12}\mu_B$. 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 [11]: $\mu_\nu \leq 10^{-14}\mu_B$, the corresponding limit for transition moments of Majorana neutrinos is much weaker.

In the theoretical framework with CP violation a neutrino can have nonzero electric moments ϵ_{ij}. In the laboratory neutrino scattering experiments for searching μ_ν (for instance, in the GEMMA experiment) the electric moment ϵ_{ij} contributions interfere with those due to μ_{ij}. Thus, these kind of experiments also provide constraints on ϵ_{ij}. The astrophysical bounds on μ_{ij} are also applicable for constraining ϵ_{ij} (see [10] and [12]).

2. Neutrino electric millicharge. 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 (for the detailed discussion and corresponding references see [1]). 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. The most stringent reactor antineutrino constraint $q_\nu \leq 1.5 \times 10^{-12}e_0$ is obtained in [13] (see also [14]) with use of the GEMMA experimental data [5].

A neutrino millicharge might have specific phenomenological consequences in astrophysics because of new electromagnetic processes are opened due to a nonzero charge (see [1,15]). Following this line, the most stringent astrophysical constraint on neutrino millicharges $q_\nu \leq 1.3 \times 10^{-19}e_0$ was obtained in [16]. This bound follows from the impact of the *neutrino star turning* mechanism ($ST\nu$) [16] that can be considered as a *new phenomenon* end up with a pulsar rotation frequency shift engendered by the motion of escaping from the star neutrinos along curved trajectories due to millicharge interaction with a constant magnetic field of the star.

3. Neutrino charge radius and anapole moment. Even if a neutrino millicharge is vanishing, the electric form factor $f^{ij}_Q(q^2)$ can still contain nontrivial information about neutrino electromagnetic properties. The corresponding electromagnetic characteristics is determined by the derivative of $f^{ij}_Q(q^2)$ over q^2 at $q^2 = 0$ and is termed neutrino charge radius, $\langle r^2_{ij}\rangle = -6\frac{df^{ij}_Q(q^2)}{dq^2}\mid_{q^2=0}$ (this is indeed the charge radius squared, see [1] for the detailed discussions). Note that for a massless neutrino the neutrino charge radius is the only electromagnetic characteristic that can have nonzero value. In the Standard Model the neutrino charge radius and the anapole moment are not defined separately, and there is a relation between these two values: $a = -\frac{\langle r^2\rangle}{6}$.

A neutrino charge radius contributes to the neutrino scattering cross section on electrons and thus can be constrained by the corresponding laboratory experiments [17]. In all papers, published before our study [9], 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 demonstrated in [9] within the direct calculations of the elastic neutrino-electron scattering 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 is more complicated and there are, in particular, the dependence on the interference terms of the type $g_V\langle r^2_{ij}\rangle$ and also on the neutrino mixing.

4. Future prospects. 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 the Kalinin Power Plant. A new set of data is expected to arrive next year. The electron energy threshold will be as low as $350\ eV$ (or even lower, up to $\sim 200\ eV$). 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 $q_\nu \sim 1.8 \times 10^{-13}e_0$ [13].

The current constraints on the flavour neutrino charge radius $\langle r^2_{e,\mu,\tau}\rangle \leq 10^{-32} - 10^{-31}\ cm^2$ from the scattering experiments differ only by 1 to 2 orders of magnitude from the values $\langle r^2_{e,\mu,\tau}\rangle \leq 10^{-33}\ cm^2$ calculated within the minimally extended Standard Model with right-handed neutrinos [17]. 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 $\langle r^2_{e,\mu,\tau}\rangle$ from the scattering experiments following new derivation of the cross section [9] that properly accounts for the interference of the weak and charge radius electromagnetic interactions and also for the neutrino mixing.

Recently constraints on charged radii have been obtained [18] from the analysis of the data on coherent elastic neutrino-nucleus scattering obtained in the COHERENT experiment [19]. In addition to the customary diagonal charge radii $\langle r^2_{e,\mu,\tau}\rangle$, also the neutrino transition (off-diagonal) charge radii have been constrained in [18] for the first time: $\left(|\langle r^2_{\nu_{e\mu}}\rangle|, |\langle r^2_{\nu_{e\tau}}\rangle|, |\langle r^2_{\nu_{\mu\tau}}\rangle|\right) < (22, 38, 27) \times 10^{-32}\ \text{cm}^2$. These constraints have been included to the recent update of the Review of Particle Properties [14].

Quite recently the potential of current and next generation of coherent elastic neutrino-nucleus scattering experiments in probing neutrino electromagnetic interactions has been also explored [20]. In [21] constraints on the neutrino charges (in particular, the diagonal charge of ν_μ and the $\nu_\mu - \nu_\tau$ transition charges) are obtained with coherent neutrino-nucleus elastic scattering data the first time.

For the future progress in studying (or constraining) neutrino electromagnetic properties a rather promising claim was made in [22]. It was shown that even tiny 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 [23]) may reveal the effect of collective spin-flavour oscillations due to the Majorana neutrino transition moment $\mu^M_\nu \sim 10^{-21}\mu_B$. There are indeed other new possibilities for neutrino magnetic moment visualization in extreme astrophysical environments considered recently [24,25].

In the most recent paper [26] we have proposed an experimental setup to observe coherent elastic neutrino-atom scattering using electron antineutrinos from tritium decay and a liquid helium target. In this scattering process with the whole atom, that has not been observed so far, the electrons tend to screen the weak charge of the nucleus as seen by the electron antineutrino probe. Finally, we study the sensitivity of this apparatus to a possible electron neutrino magnetic moment and we find that it is possible to set an upper limit of about $\mu_\nu < 7 \times 10^{-13}\mu_B$, at $90\%\ C.L.$, that is more than one order of magnitude smaller than the current experimental limits from GEMMA [5] and Borexino [6].

5. New neutrino oscillations in transversal matter current. In the presence of a magnetic field the neutrino flavour oscillations pattern is modified. The presence of a magnetic field can engender neutrino spin and also spin-flavour oscillations. A review on this issue can be found in [1] (see also [27]). As it has been shown in [27] in the presence of a magnetic field it is not possible to consider the neutrino flavour and spin oscillations as separate phenomena. On the contrary, there is an inherent communication between two. In particular, the amplitude of the neutrino flavour oscillations is modulated by the magnetic frequency $\omega_B = \mu B_\perp$.

It was shown in [28] that neutrino spin oscillations can be induced not only by the neutrino interaction with a magnetic field, as it was believed before, but also by neutrino interactions with matter in the case when there is a transversal matter current or matter polarization. A detailed study of the effect is given in [29]. The main result of the discussions in [28,29] is the conclusion on the equal role that the transversal magnetic field $\boldsymbol{B}_\perp$ and the transversal matter current $\boldsymbol{j}_\perp$ plays in generation of the neutrino spin and spin-flavour oscillations.

From these observations, and also taking into account the mentioned above inherent communication between flavour and spin oscillations [27], **we predict [31] a new phenomenon of the modification of the flavour neutrino oscillations probability in moving matter under the condition of non-vanishing matter transversal current** $\boldsymbol{j}_\perp = n\boldsymbol{v}_\perp$. Given the similarity of the action of the magnetic field $B_\perp$ and transversal matter current $\boldsymbol{j}_\perp$ the flavour neutrino oscillation probability accounting for the effect of moving matter can be expressed as follows: $P^{(j_{||}+j_\perp)}_{\nu^L_e\to\nu^L_\mu}(t) = \left(1 - P^{(j_\perp)}_{\nu^L_e\to\nu^R_e} - P^{(j_\perp)}_{\nu^L_e\to\nu^R_\mu}\right)P^{(j_{||})}_{\nu^L_e\to\nu^L_\mu}$, where $P^{(j_{||})}_{\nu^L_e\to\nu^L_\mu}(t) = \sin^2 2\theta_{eff}\sin^2\omega_{eff}t$ is the flavour oscillation probability in moving matter [30], $\omega_{eff} = \frac{\Delta m^2_{eff}}{4p^\nu_0}$, θ_{eff} and Δm^2_{eff} are the corresponding quantities modified by the presence of moving matter (note that in the definition of θ_{eff} and Δm^2_{eff} only the longitudinal component of matter motion matters). Following an analogy with the studies performed in [28,29], we derive the probability of the neutrino spin and spin-flavour oscillations engendered by the transversal current $\boldsymbol{j}_\perp$:

$$P^{j_\perp}_{\nu^L_e\to\nu^R_k}(t) = \frac{\left(\frac{\eta}{\gamma}\right)^2_{ek}v^2_\perp}{\left(\frac{\eta}{\gamma}\right)^2_{ek}v^2_\perp + \left(\frac{\Delta M}{\tilde{G}n}(1-\delta_{ek}) - (1-\boldsymbol{v\beta})\right)^2}\sin^2\omega^{j_\perp}_{ek}t,$$

where $k = e, \mu$, $\delta_{ee} = 1, \delta_{e\mu} = 0$, for the notations used see [29]. The discussed new effect of the modification of the flavour oscillations $\nu^L_e \Leftarrow (j_{||}, j_\perp) \Rightarrow \nu^L_\mu$ probability is the result of an interplay of oscillations on a customary flavour oscillation frequency in moving matter ω_{eff} and two additional oscillations with changing the neutrino polarization (the neutrino spin $\nu^L_e \Leftarrow (j_\perp) \Rightarrow \nu^R_e$ and spin-flavour $\nu^L_e \Leftarrow (j_\perp) \Rightarrow \nu^R_\mu$ oscillations) that are governed by two characteristic frequencies : $\omega^{j_\perp}_{ek} = \tilde{G}n\sqrt{\left(\frac{\eta}{\gamma}\right)^2_{ek}v^2_\perp + \left(\frac{\Delta M}{\tilde{G}n}(1-\delta_{ek}) - (1-\boldsymbol{v\beta})\right)^2}$, $k = e, \mu$. The interplay of neutrino oscillations on the introduced different frequencies can have important consequences for neutrino fluxes in astrophysical environments.

6. Conclusions. For completeness, we mention other of the main manifestations of neutrino electromagnetic interactions (see [1] for a review) not indicated above, such as: 1) the neutrino radiative decay in vacuum, in matter and in a magnetic field, 2) the neutrino Cherenkov radiation, 3) the plasmon decay to neutrino-antineutrino pair, 4) the neutrino spin light in matter, 5) the neutrino energy quantization in a magnetic field and/or a rotating matter. The most preferred conditions for the manifestation of these effects can be realized in various astrophysical environments. Finally, we will point to our most recent research [32] on the quantum decoherence of astrophysical neutrinos, which could arise due to the process of radioactive decay of neutrinos.

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