# Overview of neutrino electromagnetic properties

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**1. The theory.** The most well understood and studied among neutrino electromagnetic characteristics are the neutrino magnetic moments. However, in the Standard Model with massless neutrinos magnetic moments of neutrinos are zero. In a minimal extension of the Standard Model the diagonal magnetic moment of a massive Dirac neutrino is given **[1]** by $\mu^D_{ii} = \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \approx 3.2\times 10^{-19}\left(\frac{m_i}{1\text{ eV}}\right)\mu_B$, $\mu_B$ is the Bohr magneton. Therefore, it is believed that the studies of neutrino electromagnetic properties open a window to *new physics* beyond the Standard Model **[2]**. Note that the Majorana neutrinos can have only transition (off-diagonal) magnetic moments $\mu^M_{i\neq j}$.

In the most general form the neutrino electromagnetic vertex function $\Lambda^{ij}_\mu(q)$ can be expressed **[2,3]** in terms of four form factors $\Lambda^{ij}_\mu(q) = (\gamma_\mu - q_\mu \not{q}/q^2)\left[f^{ij}_Q(q^2) + f^{ij}_A(q^2)q^2\gamma_5\right] - i\sigma_{\mu\nu}q^\nu\left[f^{ij}_M(q^2) + if^{ij}_E(q^2)\gamma_5\right]$, where $q = p_i - p_f$ is 4-momentum of a real photon coupled to neutrinos, $\Lambda_\mu(q)$ and form factors $f_{Q,A,M,E}(q^2)$ are $3\times 3$ matrices in the space of massive neutrinos.

In the case of coupling with a real photon ($q^2 = 0$) the form factors $f(q^2)$ provide four sets of neutrino electromagnetic characteristics: 1) the electric millicharges $q_{ij} = f^{ij}_Q(0)$, 2) the dipole magnetic moments $\mu_{ij} = f^{ij}_M(0)$, 3) the dipole electric moments $\epsilon_{ij} = f^{ij}_E(0)$ and 4) the anapole moments $a_{ij} = f^{ij}_A(0)$. Different interesting aspects of neutrino electromagnetic properties (including the direct one-loop calculations of electromagnetic characteristics in different models, the relation between anapole and toroidal decomposition of the vertex function etc) are discussed in **[4-9]**.

A Majorana neutrino does not have diagonal electric charge and dipole magnetic and electric form factors, only a diagonal anapole form factor can be nonzero. At the same time, a Majorana neutrino can also have nonzero off-diagonal (transition) form factors.

**2. Neutrino electromagnetic properties in scattering experiments.** So far, there are no any evidence in favour of neutrino nonzero electromagnetic properties either from laboratory measurements of neutrinos from ground-based sources or from observations of neutrinos from astrophysical sources **[10,11]**. Only constraints (the upper bounds on neutrino electromagnetic characteristics) are obtained in different experiments. The available constraints are discussed in the review paper **[2]** (see also **[11-15]** for the latest progress in this field). A widely used method to probe the neutrino electromagnetic properties is based on the direct measurements of low-energy elastic (anti)neutrino-electron scattering **[16]** in reactor, accelerator, and solar neutrino experiments. The recent and most comprehensive study of neutrino electromagnetic properties in the neutrino electron scattering with account for neutrino mixing and oscillations can be found in **[17]**. Consider the most stringent constraints on the effective neutrino magnetic moments that are obtained with the reactor antineutrinos: $\mu_\nu \leq 2.9\times 10^{-11}\mu_B$ (GEMMA Collaboration **[18]**), and solar neutrinos: $\mu_\nu \leq 2.8\times 10^{-11}\mu_B$ (Borexino Collaboration **[19]**).

**3. Neutrino electromagnetic processes.** Neutrinos with nonzero electromagnetic characteristics, due to their couplings with real and virtual photons, generate processes that can occur in various astrophysical conditions and be the cause of important phenomena that are fundamentally observable. The most important are the following (see also **[2,10]**): 1) a heavier neutrino decay to a lighter mass state in vacuum, 2) the Cherenkov radiation by a neutrino in matter or an external magnetic field, 3) the spin-light of neutrino in matter, 4) the plasmon decay to a neutrino-antineutrino pair in matter, 5) the neutrino scattering on an electron or a nuclei, and 6) the neutrino spin precession in an external magnetic field or the transversally moving (or the transversally polarized) matter. All of these processes can be of great interest in astrophysics, and registration of possible consequences of these processes in experiments allows us to obtain information about the values of the electromagnetic characteristics of neutrinos and also set appropriate limits. Indeed, astrophysics can be considered as a laboratory for studying the electromagnetic properties of neutrinos (see **[2,10,11]**).

**4. Neutrino radiative decay.** A heavier neutrino mass state $\nu_i$ in case the neutrino have nonzero electric charges (millicharges) or the magnetic and electric (the diagonal and transition) dipole moments can decay into a lighter state $\nu_f$, $m_i > m_f$, with emission of a photon. For the first time this kind of processes were discussed in **[20]** and in the concrete applications to neutrinos can be found in **[21,22]**. For more recent papers and detailed discussions of neutrino radiative decay $\nu_i \to \nu_f + \gamma$ see **[2]**. In case one neglects the effect of nonzero neutrino millicharges ($q_\nu = 0$) the neutrino electromagnetic vertex function reduces to $\Lambda^{if}_\mu = -i\sigma_{\mu\nu}q^\nu(\mu_{if} + i\epsilon_{if}\gamma_5)$. The decay rate in the rest frame of the decaying neutrino $\nu_i$ is given by $\Gamma_{\nu_i\to\nu_f+\gamma} = \frac{1}{8\pi}\left(\frac{m_i^2-m_f^2}{m_i}\right)^3(|\mu_{fi}|^2 + |\epsilon_{fi}|^2)$. Note that due to $m_i \neq m_f$ only the transition magnetic and electric dipole moments contribute. Therefore this expression is equally valid for both Dirac and Majorana neutrinos. In the simplest extensions of the Standard Model for both Dirac and Majorana neutrinos we have **[23]** $\Gamma_\nu \approx 5\left(\frac{\mu_{eff}}{\mu_B}\right)^2\left(\frac{m_i^2-m_f^2}{m_i}\right)^3\left(\frac{m_i}{1\ eV}\right)^3\ s^{-1}$, where $\mu^2_{eff} = |\mu_{fi}|^2 + |\epsilon_{fi}|^2$. The corresponding life time of neutrinos in respect to the radiative decay is indeed huge $\tau_{\nu_i\to\nu_j+\gamma} \approx 0.19\left(\frac{m_i^2}{m_i^2-m_j^2}\right)^3\left(\frac{eV}{m_i}\right)\left(\frac{\mu_B}{\mu^2_{eff}}\right)s$. This is because the neutrino transition moments are suppressed by the Glashow–Iliopoulos-Maiani cancellation mechanism.

The neutrino radiative decay has been constrained from the absence of decay photons in studies of the solar, supernova and reactor (anti)neutrino fluxes, as well as from the absence of the spectral distortions of the cosmic microwave background radiation. However, the corresponding upper bounds on the effective neutrino magnetic moments **[24]** are in general less stringent than the astrophysical bounds from the plasmon decay to $\boldsymbol{\nu}$-$\bar{\boldsymbol{\nu}}$ pair.

**5. Plasmon decay to $\boldsymbol{\nu}$-$\bar{\boldsymbol{\nu}}$ pair.** For constraining neutrino electromagnetic properties, and obtaining upper bounds on neutrino magnetic moments in particular, the most interesting process is the plasmon decay into a neutrino-antineutrino pair **[25,26]**. This plasmon process becomes kinematically allowed in media where the photon behaves as a particle with an effective mass $\omega_\gamma$. In the case of nonrelativistic plasma the dispersion relation for a photon (plasmon) is $\omega^2_\gamma + \vec{k}^2_\gamma = \omega^2_p$, where $\omega_p = 4\pi N_e/m_e$ is the plasmon frequency. The plasmon decay rate is given by $\Gamma_{\gamma^*\to\nu\bar{\nu}} = \frac{\mu^2_{eff}}{24\pi}Z\frac{(\omega^2_\gamma - k^2_\gamma)^2}{\omega_\gamma}$, where $Z$ is a factor which depends on the polarization of the plasmon. A plasmon decay into a neutrino-antineutrino pair transfers the energy $\omega_\gamma$ to neutrinos that can freely escape from a star and thus can fasten the star cooling. The corresponding energy-loss rate per unit volume is $Q_{\gamma^*\to\nu\bar{\nu}} = \frac{g}{(2\pi)^3}\int\Gamma_{\gamma^*\to\nu\bar{\nu}}f_{k_\gamma}\omega_\gamma d^3k_\gamma$, where $f_{k_\gamma}$ is the photon Bose-Einstein distribution function and $g = 2$ is the number of polarization states. The magnetic moment plasmon decay enhances the Standard Model photo-neutrino cooling by photon polarization tensor, and more fast star cooling slightly reduces the core temperature. These nonstandard energy losses can delay the helium ignition in low-mass red giants. This, in turn, can be related to astronomically observable luminosity of stars before and after the helium flash. And in order not to delay the helium ignition in an unacceptable way (a significant brightness increase is constraint by observations) the upper bound on the effective neutrino magnetic was obtained in **[26]** $\mu_{eff} = \left(\sum_{fi}|\mu_{fi}|^2 + |\epsilon_{fi}|^2\right)^{\frac{1}{2}} \leq 3\times 10^{-12}\mu_B$. Recently new analysis **[27-29]** of the observed properties of globular cluster stars provides new upper bounds on the effective neutrino magnetic moment $\mu_{eff} \leq (1.2{-}2.6)\times 10^{-12}\mu_B$ that is valid for both cases of Dirac and Majorana neutrinos.

It is interesting to compare these astrophysical bounds on the effective neutrino magnetic moments with constraints obtained in investigations of the elastic scattering of a flavour neutrino $\nu_l + e^- \to \nu_l + e^-$, $l = e, \mu, \tau$ (or an antineutrino $\bar{\nu}_l$ ) in the laboratory experiments. For a detailed discussion of this issue see **[2,16]**.

The plasmon decay considered in the vicinity of red giants can also be used to constrain neutrino millicharges $q_\nu$ **[24]**. The plasmon decay to neutrino-antineutrino pair due to the neutrino millicharge $q_\nu$ is described by the Lagrangian $L = -iq_\nu\bar{\psi}_\nu\gamma_\mu\psi_\nu A^\mu$. In order to avoid the delay of helium ignition in low-mass red giants the millicharge should be constraint at the level $q_\nu \leq 2\times 10^{-14}e_0$, and from the absence of the anomalous energy-dependent dispersion of the SN1987A neutrino signal it should be $q_\nu \leq 3\times 10^{-17}e_0$ ($e_0$ is the value of an electron charge).

The most stringent astrophysical constraint on neutrino millicharges $q_\nu \leq 1.3\times 10^{-19}e_0$ was obtained **[30]** in consideration of the impact of the *neutrino star turning* (**$\boldsymbol{\nu}$ST**) mechanism that can shift a magnetised pulsar rotation frequency. Note the most sever upper bound on the neutrino millicharges $q_\nu \sim 10^{-21}e_0$ arrives from neutrality of the hydrogen atom.

**6. Neutrino spin conversion.** One of the most important for astrophysics consequences of neutrino nonzero effective magnetic moments (see **[2,24,14]**) is the neutrino helicity change $\nu_L \to \nu_R$ with the appearance of nearly sterile right-handed neutrinos $\nu_R$ . In general, this phenomena, the helicity change $\nu_L \to \nu_R$, can proceed in two different electromagnetic mechanisms: 1) the helicity change in the neutrino magnetic moment scattering on electrons (or protons and neutrons), 2) the neutrino spin and spin-flavour precession in an external magnetic field (the resonance amplification of these kind of oscillations was considered in **[31]**).

As it was investigated for the firs time in **[32]** and then studied in **[33,34]**, there is also nonelectromagnetic mechanism of the neutrino helicity change $\nu_L \to \nu_R$: the neutrino spin and spin-flavour precession in the transversally moving matter currents or in the transversally polarized matter at rest. The existence of the proposed phenomenon **[32]** has been confirmed and applied in studies of astrophysical neutrino fluxes in **[35-38]**.

The detection of the SN 1987A neutrinos provides the energy-loss limits on the effective neutrino magnetic moments related to the observed duration of the neutrino signal (see **[2,24]**). In the magnetic scattering on electrons due to the change of helicity $\nu_L \to \nu_R$ the proto-neutron star formed in the core-collapse SN can cool faster since $\nu_R$ are sterile and are not trapped in a core like $\nu_L$ are trapped for a few seconds. The escaping $\nu_R$ will cool the core very efficient and fast ($\sim 1\ s$). However, the observed $5 - 10\ s$ pulse duration in Kamioka II and IMB experiments is in agreement with the standard model $\nu_L$ trapping and cooling of the star. From this it was concluded that for the Dirac neutrinos the effective magnetic moment $\mu_D \geq 10^{-12}\mu_B$ is inconsistent with the SN1987A observed cooling time.

There is another approach to constrain the neutrino magnetic moment from the data on SN1987A neutrinos related to the observed neutrino energies **[2,24]**. The right-handed neutrinos $\nu_R$, that appear due to the helicity change in the magnetic scattering in the inner SN core, have larger energies than $\nu_L$ emitted from the neutrino sphere. Then in the magnetic moment precession process $\nu_R \to \nu_L$ the higher-energy $\nu_L$ would arrive to the detector as a signal of SN1897A. And from the absence of the anomalous high-energy neutrinos again the bound on the level $\mu_D \leq 10^{-12}\mu_B$ can be settled.

**7. Future prospects.** A new phase of the GEMMA project for measuring the neutrino magnetic moment is now underway at the Kalinin Power Plant in Russia. The discussed **[39]** next GEMMA-3 experiment, called $\nu$GEN, is aimed at the detection of coherent Neutrino–Ge Nucleus elastic scattering. It is also expected that this experiment will further increase sensitivity to the neutrino magnetic moment and will reach the level of $\mu_{\nu_e} \sim (5{-}9)\times 10^{-12}\mu_B$. To reach the claimed limit on the neutrino magnetic moment the $\nu$GEN experiment setup reasonably improves characteristics in respect to those of the previous editions of the GEMMA project. The most important are the following: 1) a factor of 2 increase in the total neutrino flux at the detector because of much closer location of the detector to the reactor core, 2) a factor of 3.7 increase in the total mass of the detector, 3) the energy threshold is improved from $2.8\ keV$ to $200\ eV$. Furthermore, the $\nu$GEN experimental setup is located in the new room at the Kalinin Power Plant with much better (by an order of magnitude) gamma-background conditions and on a moveable platform.

Here we recall that the first observation of the coherent elastic neutrino-nucleus scattering at the COHERENT experiment at the Spallation Neutron Source **[40]** can be also used for constraining neutrino electromagnetic properties. However, as it was shown in **[41]** and then confirmed in recent studies (see, for instance, **[42]**), the bounds for the magnetic moments are of the order $\mu_e, \mu_\mu \sim 10^{-8}\mu_B$. New possibilities to constrain other neutrino electromagnetic characteristics, including the electric millicharges and charge radii, were discussed in **[43]**.

In the recent studies **[44]** it is shown that the puzzling results of the XENON1T collaboration **[45]** at few keV electronic recoils could be due to the scattering of solar neutrinos endowed with finite Majorana transition magnetic moments of the strengths lie within the limits set by the Borexino experiment with solar neutrinos **[19]**. The comprehensive analysis of the existing and new extended mechanisms for enhancing neutrino transition magnetic moments to the level appropriate for the interpretation of the XENON1T data and leaving neutrino masses within acceptable values is provided in **[46]**.

In a recent paper **[47]** 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 $\mu_\nu \leq 7\times 10^{-13}\mu_B$, that is about two orders of magnitude smaller than the current experimental limits from GEMMA and Borexino. A corresponding experiment involving the of an intense $1kg$ tritium antineutrino source is currently being prepared in the framework of the research program of the National Center for Physics and Mathematics in Sarov (Russia). The work is supported by the Interdisciplinary Scientific and Educational School of Moscow University "Fundamental and Applied Space Research" and by the Russian Science Foundation under grant No.22-22-00384.

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