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Overview on neutrino electromagnetic properties

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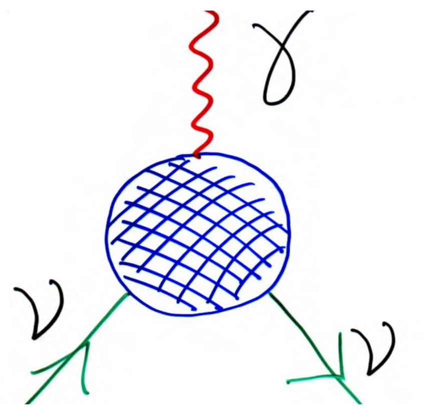
1. Introduction

The importance of neutrino electromagnetic properties was first mentioned by Wolfgang Pauli just in 1930 when he postulated the existence of this particle and discussed the possibility that the neutrino might have a magnetic moment. The most complete review on neutrino electromagnetic properties is given in [1] and the recent update can be found in [2]. Systematic theoretical studies of neutrino electromagnetic properties have started with calculations of the one-loop electromagnetic vertex of a fermion in the minimal extension of the Standard Model with right-handed neutrinos [3]. The magnetic and electric moments of neutrinos have been explicitly calculated in [4] and then in [5] and also in [6] by evaluating the one-loop radiative diagrams.

In spite of reasonable efforts in studies of neutrino electromagnetic properties, up to now there is no experimental confirmation in favour of nonvanishing neutrino electromagnetic characteristics. However, studies of neutrino electromagnetic properties are of particular importance because they provide a kind of bridge (or "open a window") to new physics beyond the Standard Model.



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2. Neutrino electromagnetic vertex function

The neutrino electromagnetic properties are determined by the neutrino electromagnetic vertex function $\Lambda_\mu(q,l)$ that is related to the matrix element of the electromagnetic current between the neutrino initial state $\psi(p)$ and final state $\psi(p')$ can be presented in the form

$$\langle\psi(p')|J_\mu^{\rm EM}|\psi(p)\rangle = \bar{u}(p')\Lambda_\mu(q,l)u(p), \qquad (1)$$

where $q_\mu = p'_\mu - p_\mu,\ l_\mu = p'_\mu + p_\mu.$ Lorentz and electromagnetic gauge invariance imply [1,7] (see also [2]) that the electromagnetic $\Lambda_\mu(q,l)$ vertex function (Fig.1) can be written in terms of four form factors

$$\Lambda_\mu(q) = f_Q(q^2)\gamma_\mu + f_M(q^2)i\sigma_{\mu\nu}q^\nu + f_E(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 + f_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5, \qquad (2)$$

where $f_Q(q^2),\ f_M(q^2),\ f_E(q^2)$ and $f_A(q^2)$ are charge, dipole magnetic and electric and anapole neutrino form factors. Note that the form factors are Lorentz invariant and they depend only on q^2, which is the only independent Lorentz invariant dynamical quantity.

The matrix element of the electromagnetic current can be considered also between neutrino initial $\psi(p)$ and final $\psi(p')$ states with different masses, $p^2 = m_i^2$ and $p'^2 = m_j^2$. The corresponding vertex function can be written in the form

$$\Lambda_\mu(q) = \Big(f_Q(q^2)_{ij} + f_A(q^2)_{ij}\gamma_5\Big)(q^2\gamma_\mu - q_\mu \not{q}) + f_M(q^2)_{ij}i\sigma_{\mu\nu}q^\nu + f_E(q^2)_{ij}\sigma_{\mu\nu}q^\nu\gamma_5, \qquad (3)$$

where the form factors are matrices in the space of neutrino mass eigenstates [1] .

In the case of Dirac neutrinos, the assumption of *CP* invariance combined with the hermiticity of the electromagnetic current J_μ^{EM} implies that the electric dipole form factor vanishes. In the case of Majorana neutrinos, regardless of whether *CP* invariance is violated or not, the charge, dipole magnetic and electric form factors vanish [1,7, 8] ,

$$f_Q = f_M = f_E = 0 \qquad (4)$$

the anapole moment can be nonvanishing, see also [9] , as well as transition magnetic and electric moments. Since Dirac and Majorana neutrinos exhibit quite different electromagnetic properties, the investigation of neutrino electromagnetic interactions provides a tool for specifying the neutrino nature.

It is interesting to note that the effective diagonal magnetic moment of flavour neutrinos in case of mixing of Majorana neutrinos can be not zero [1,10] .

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3. Neutrino magnetic and electric moments

The neutrino dipole magnetic moment (along with the electric dipole moment) is the most well studied among neutrino electromagnetic properties. A Dirac neutrino may have non-zero diagonal electric moments in models where *CP* invariance is violated. For a Majorana neutrino the diagonal magnetic and electric moments are zero.

The explicit evaluation of the one-loop contributions to the Dirac neutrino dipole moments in the leading approximation over the small parameters $b_i = m_i^2/m_W^2$ (m_i are the neutrino masses, *i* = 1, 2, 3), that however exactly accounts for $a_l = m_l^2/m_W^2$, leads to the following result [5,6] :

$$\left.\begin{matrix}\mu_{ij}^D \\ \epsilon_{ij}^D\end{matrix}\right\} = \frac{eG_F m_i}{8\sqrt{2}\pi^2}\Big(1\pm\frac{m_j}{m_i}\Big)\sum_l f(a_l)U_{lj}U_{li}^*,\ \ f(a_l) = \frac{3}{4(1-a_l)^3}\Big(2-7a_l+6a_l^2-a_l^3-2a_l^2\ln a_l\Big), \qquad (5)$$

where U_{li} is the neutrino mixing matrix. From (5) in the limit $a_l \ll 1$, the diagonal magnetic moment of a Dirac neutrino is given by [4]

$$\mu_{ii}^D = \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \approx 3.2\times 10^{-19}\Big(\frac{m_i}{1\ eV}\Big)\mu_B. \qquad (6)$$

On the other hand, the magnetic moment of a hypothetical heavy neutrino $(m_\ell \ll m_W \ll m_\nu)$ is [6] :

$$\mu_\nu = \frac{eG_F m_\nu}{8\sqrt{2}\pi^2}. \qquad (7)$$

Note that much larger values for the neutrino magnetic moments can be obtained in various extensions of the Standard Model (see, for instance, [1]).

4. Bounds on neutrino magnetic moments

The most sensitive and established method for the experimental investigation of the neutrino magnetic moment is provided by direct laboratory measurements of electron neutrino(antineutrino)–electron scattering at low energies in solar, accelerator and reactor experiments. A detailed discussion and references can be found in [1] . The cross section for electron neutrino (antineutrino) scattering on electrons can be written [11] as a sum of the Standard Model contribution and the neutrino magnetic moment contribution:

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_{\rm SM} + \left(\frac{d\sigma}{dt}\right)_\mu. \qquad (8)$$

The Standard Model contribution is:

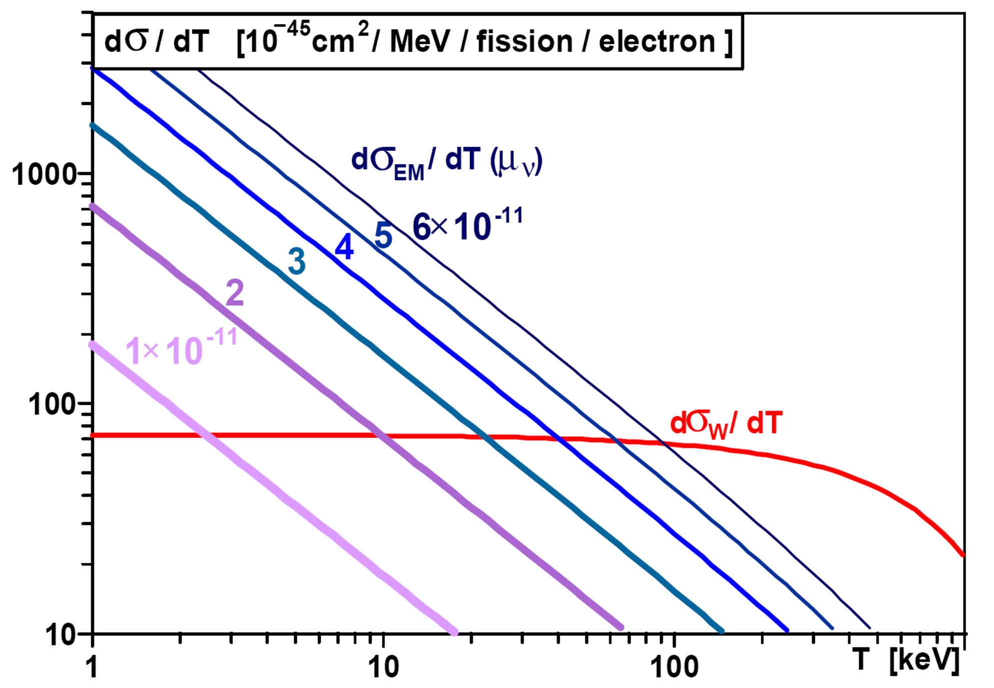
$$\left(\frac{d\sigma}{dt}\right)_{SM} = \frac{G_F^2 m_e}{2\pi}\left[(g_V+g_A)^2 + (g_V-g_A)^2\Big(1-\frac{T}{E_\nu}\Big)^2 + (g_A^2-g_V^2)\frac{m_e T}{E_\nu^2}\right], \qquad (9)$$

where E_ν is the initial neutrino energy and ***T*** is the electron recoil energy, which is measured in experiments. The coupling constants are:

$$g_V = \begin{cases} 2\sin^2\theta_W + \frac{1}{2}, & \text{for } \nu_e, \\ 2\sin^2\theta_W - \frac{1}{2}, & \text{for } \nu_\mu,\nu_\tau, \end{cases} \qquad g_A = \begin{cases} \frac{1}{2}, & \text{for } \nu_e, \\ -\frac{1}{2}, & \text{for } \nu_\mu,\nu_\tau. \end{cases} \qquad (10)$$

The neutrino magnetic moment contribution to the cross section is

$$\left(\frac{d\sigma}{dt}\right)_\mu = \frac{\pi\alpha_{em}^2}{m_e^2}\Big(\frac{1-T/E_\nu}{T}\Big)\Big(\frac{\mu_\nu}{\mu_B}\Big)^2. \qquad (11)$$



The dependence of two terms in the cross section on the electron recoil energy ***T*** is shown in **Fig.** [12] for six fixed values of the neutrino magnetic moment, $\mu_\nu^{(N)} = N\times 10^{-11}\mu_B$, *N* = 1, 2, 3, 4, 5, 6 . These two terms exhibit a quite a different dependence on the experimentally observable electron recoil energy ***T***. The constraints on the neutrino magnetic moment in such direct laboratory experiments are obtained from the lack of any observable distortion of the recoil electron energy spectrum.

The best upper limits on the neutrino magnetic moment have been obtained in recent reactor experiments are: $\mu_\nu \le 9.0\times 10^{-11}\mu_B$ (MUNU collaboration [13]), $\mu_\nu \le 7.4\times 10^{-11}\mu_B$ (TEXONO collaboration [14] , $\mu_\nu \le 3.2\times 10^{-11}\mu_B$ (GEMMA collaboration [15]) . A stringent limit has been recently obtained in the Borexino solar neutrino scattering experiment: $\mu_\nu^{eff} < 2.8{\cdot}10^{-11}\ \mu_B$ [16].

An attempt to reasonably improve the expected experimental bound on a neutrino magnetic moment has been undertaken in [17]. It was claimed that the account for the electron binding in atom (the "atomic ionization effect" in neutrino interactions on ***Ge*** target) can significantly increase the electromagnetic contribution to the cross section in respect to the case when the free electron approximation is used in calculations of the cross section. However, as it has been shown in a series of recent papers [18,19] the free electron approximation is quite appropriate for interpretation of the present reactor neutrino experiments such as performed by GEMMA and TEXONO collaborations.

It should be mentioned that what is measured in experiments is an effective magnetic moment μ_ν^{exp} whose value is a rather complicated function of the magnetic (transition) moments [2, 10].

The dipole electric (transition) moments, if these quantities do not vanish, could also contribute to μ_ν^{exp} . In addition, the measured value for the neutrino magnetic moment depends on the flavour composition of the neutrino beam at the detector (for the detailed discussion see the recent studies in [19]).

Note that within various extensions of the Standard Model [20, 21] magnetic moment of the Majorana neutrino could be at the level of the recent experimental bounds irrespective to the neutrino mass. At the same time, as it was shown in [22] from naturalness arguments, the magnetic moment of the Dirac neutrino could not exceed the value $\mu_\nu \sim 10^{-14}\mu_B$.

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5. Neutrino electric form factor

It is usually believed that the neutrino electric charge is zero. This is often thought to be attributed to gauge invariance and anomaly cancellation constraints imposed in the Standard Model. In the Standard Model of $SU(2)_L\times U(1)_Y$ electroweak interactions it is possible to get [23] a general proof that neutrinos are electrically neutral which is based on the requirement of electric charges quantization.

The direct calculations of the neutrino charge in the Standard Model for massless (see, for instance [24] and references therein) and massive neutrino [9] also prove that, at least at the one-loop level, the neutrino electric charge is gauge independent and vanishes. However, if the neutrino has a mass, the statement that a neutrino electric charge is zero is not so evident as it meets the eye. As a result, neutrinos may become electrically millicharged particles [23] .

The most severe experimental constraints on the electric charge of the neutrino,

$$q_\nu \le 10^{-21}e, \qquad (12)$$

are obtained assuming electric charge conservation in neutron beta decay $n \to p + e^- + \nu_e$, from the neutrality of matter (from the measurements of the total charge $q_p + q_e$) [25] . The most stringent constraint on the neutrino millicharge obtained in the scattering experiments is [26]

$$q_\nu < 1.1\times 10^{-12}e \qquad (13)$$

A detailed discussion of different constraints on the neutrino electric charge can be found in [1, 25] .

Even if the electric charge of a neutrino is vanishing, the electric form factor $f_Q(q^2)$ can still contain nontrivial information about neutrino static properties. A neutral particle can be characterized by a superposition of two charge distributions of opposite signs so that the particle's form factor $f_Q(q^2)$ can be non zero for $q^2 \ne 0$. The mean charge radius (in fact, it is the charged radius squared) of an electrically neutral neutrino is given by

$$< r_\nu^2 > = -6\frac{df_Q(q^2)}{dq^2}|_{q^2=0} \qquad (14)$$

The charge radius is determined by the second term in the expansion of the neutrino charge form factor

$$f_Q(q^2) = f_Q(0) + q^2\frac{df_Q(q^2)}{dq^2}|_{q^2=0} \qquad (15)$$

in series of powers of q^2 . Note that there is a long standing discussion (see [1] for details) in the literature on the possibility to obtain (calculate) for the neutrino charged radius a gauge independent and infinite quantity. In the corresponding calculations, performed in the one-loop approximation including additional terms from the $\gamma - Z$ boson mixing and the box diagrams involving *W* and *Z* bosons, the following gauge-invariant result for the neutrino charge radius have been obtained [27] :

$$< r_{\nu_l}^2 > = \frac{G_F}{4\sqrt{2}\pi^2}\Big[3 - 2\log\big(\frac{m_l^2}{m_W^2}\big)\Big] \qquad (16)$$

where m_l and m_W are the *W* boson and lepton masses $(l = e,\mu,\tau)$. This result, however, received the discussion [28] on the definition of the neutrino charge radius as a physical observable. Numerically, for the electron neutrino electroweak radius it yields

$$< r_{\nu_e}^2 > = 4\times 10^{-33}\,cm^2 \qquad (17)$$

This theoretical result differs at most by one order of magnitude from the available experimental bounds on $< r_{\nu_i}^2 >$. Therefore, one may expect that the experimental accuracy will soon reach the value needed to probe the neutrino effective charge radius.

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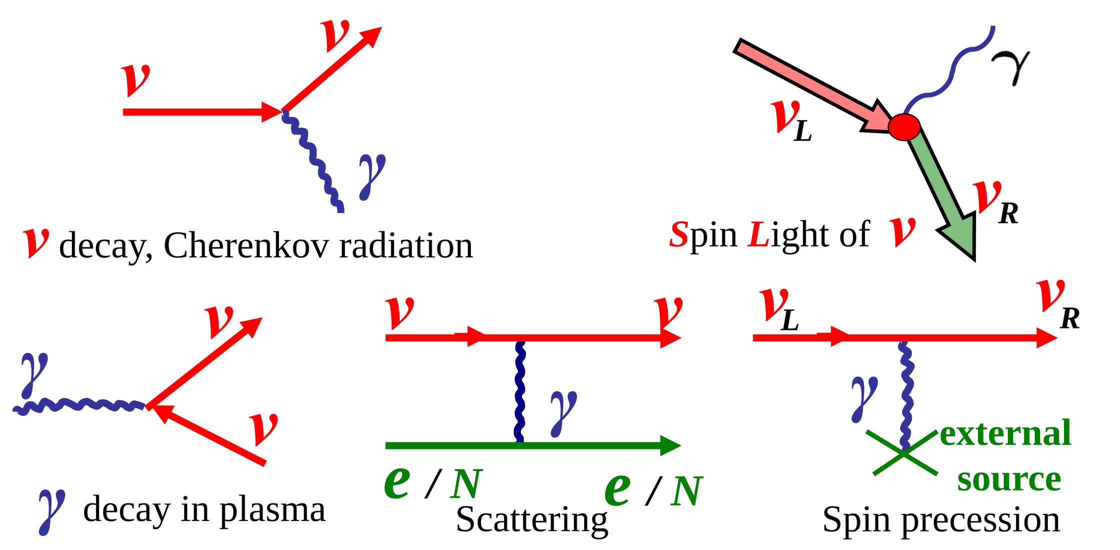
6. Neutrino-electron scattering within three-neutrino mixing

A thorough account of electromagnetic interactions of massive neutrinos in the theoretical formulation of low-energy elastic neutrino-electron scattering is given [10]. The formalism of neutrino charge, magnetic, electric, and anapole form factors defined as matrices in the mass basis is employed under the assumption of three-neutrino mixing. The flavor change of neutrinos traveling from the source to the detector is taken into account and the role of the source-detector distance is inspected. The effects of neutrino flavour transition millicharges and charge radii in the scattering experiments are pointed out.

7. Effects of neutrino electromagnetic properties

If a neutrino has the non-trivial electromagnetic properties discussed above, a direct neutrino coupling to photons is possible and several processes important for applications exist [1,25] . A set of most important neutrino electromagnetic processes is: 1) neutrino radiative decay $\nu_1 \to \nu_2 + \gamma$, neutrino Cherenkov radiation in an external environment (plasma and/or electromagnetic fields), spin light of neutrino (***SLν***) in the presence of a medium [29]; 2) photon (plasmon) decay to a neutrino-antineutrino pair in plasma $\gamma \to \nu\bar{\nu}$; 3) neutrino scattering on electrons (or nuclei); 4) neutrino spin (spin-flavour) precession in a magnetic field (see [19]) and resonant neutrino spin-favour oscillations in matter [30] .



The tightest astrophysical bound on a neutrino magnetic moment is provided by observed properties 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 anomalous stellar cooling due to the plasmon decay the following limit has been found [25, 31]

$$\big(\textstyle\sum_{i,j} \mid \mu_{ij} \mid^2\big)^{1/2} \le 3\times 10^{-12}\mu_B, \qquad (18)$$

This is the most stringent astrophysical constraint on a neutrino magnetic moment, applicable to both Dirac and Majorana neutrinos.

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8. Neutrino spin and flavour oscillations in magnetic field

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 later effect has been studied in numerous papers published during several passed decades. Within this scope the neutrino spin oscillations $\nu^L \Leftrightarrow \nu^R$ induced by the neutrino magnetic moment interaction with the transversal magnetic field $\mathbf{B}_\perp$ was first considered in [32]. Then spin-flavor oscillations $\nu_e^L \Leftrightarrow \nu_\mu^R$ in $\mathbf{B}_\perp$ in vacuum were discussed in [8], the importance of the matter effect was emphasized in [33]. The effect of the resonant amplification of neutrino spin oscillations in $\mathbf{B}_\perp$ in the presence of matter was proposed in [30], the impact of the longitudinal magnetic field $\mathbf{B}_{||}$ was discussed in [34]. The neutrino spin oscillations in the presence of constant twisting magnetic field were considered in [35].

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Consider two favour and two mass neutrinos with two chiralities accounting for mixing

$$\begin{aligned}\nu_e^{L(R)} &= \nu_1^{L(R)}\cos\theta + \nu_2^{L(R)}\sin\theta, \\ \nu_\mu^{L(R)} &= -\nu_1^{L(R)}\sin\theta + \nu_2^{L(R)}\cos\theta,\end{aligned} \qquad (19)$$

For the relativistic neutrinos the chiral states approximately coincide with the helicity states. Then the probability of neutrino spin-flavour oscillations $\nu_e^L \leftrightarrow \nu_\mu^R$ in the transversal magnetic field $B_\perp$ is

$$P_{\nu_e^L\to\nu_\mu^R} = \sin^2(\mu B_\perp t)\sin^2 2\theta \sin^2\frac{\Delta m^2}{4p}t. \qquad (20)$$

It is supposed the neutrino mass states have equal magnetic moments $\mu_1 = \mu_2 = \mu$. This result can be expressed as a product of two probabilities that are the probability of neutrino spin [36-38]

$$P^{cust}_{\nu_e^L\to\nu_e^R} = \sin^2(\mu B_\perp t) \qquad (21)$$

and flavour oscillations, respectively,

$$P^{cust}_{\nu_e^L\to\nu_\mu^L} = \sin^2 2\theta\sin^2\frac{\Delta m^2}{4p}t. \qquad (22)$$

Finally, there is very interesting possibility for neutrino spin (and spin-flavour) oscillations engendered by the neutrino interaction with the transversal (in respect to the direction of neutrino propagation) matter current that was proposed and investigated for first time in [39], for the recent developments see [40]. The existence of this effect was confirmed in [40-43].

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