New bounds on neutrino electric millicharge from limits on neutrino magnetic moment

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Abstract – Using the new limit on the neutrino anomalous magnetic moment recently obtained by the GEMMA experiment on measurements of the cross-section for the reactor antineutrino scattering on free electrons, we get, by comparing the neutrino magnetic moment and millicharge contributions to the total cross-section at the electron recoil energy threshold of the experiment, an order-of-magnitude estimation for a possible new direct upper bound on the neutrino electric millicharge \(|q_\nu| \sim 1.5 \times 10^{-12} e_0\) (\(e_0\) is the absolute value of the electron charge). This estimation is confirmed by the performed analysis of the GEMMA data using established statistical procedures and a new direct bound on the neutrino millicharge absolute value \(|q_\nu| < 2.7 \times 10^{-12} e_0\) (90% C.L.) is derived. This limit is more stringent than the previous one obtained from the TEXONO reactor experiment data that is included to the Review of Particle Properties 2012. We also predict, in an order-of-magnitude estimation, that with data from the ongoing new phase of the GEMMA experiment (GEMMA-II) the upper bound on the neutrino millicharge will reach an expected level of about \(|q_\nu| \sim 1.5 \times 10^{-12} e_0\) within two years. We also predict that, with the next phase of the considered experiment (GEMMA-III), the upper bound on the millicharge will be reduced by an order of magnitude over the present bound and reach the level \(|q_\nu| \sim 1.8 \times 10^{-13} e_0\) within approximately four years.

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Introduction. – The discovery of the Higgs boson provides a convincing experimental confirmation of the solid status of the Standard Model. Therefore, now one can consider the neutrino to be the only particle that really exhibits properties beyond the Standard Model. In addition to the experimentally confirmed nonzero mass, flavour mixing and oscillations the neutrino nontrivial electromagnetic properties, once confirmed, would provide a clear indication for physics beyond the Standard Model.

Within the Standard Model neutrinos are massless and have “zeroth” electromagnetic properties. However, it is well known that in different extensions of the Standard Model a massive neutrino has nontrivial electromagnetic properties (for a review of the neutrino electromagnetic properties see [1–4]). That is why it is often claimed that neutrino electromagnetic properties open “a window to new physics” [5].

The neutrino electromagnetic interactions, in addition to being a powerful tool in exploring beyond the Standard Model frontier, can generate important effects when neutrinos propagate for long distances in the presence of magnetic fields and media. Therefore, there are two main approaches for studying the neutrino electromagnetic properties. The first approach is based on the consideration of possible electromagnetic contributions to neutrino processes in extreme astrophysical environments. A detailed discussion of the astrophysical option of constraining neutrino electromagnetic properties can be found in [6].

The second approach assumes high-precision measurements of neutrino interaction cross-section in the terrestrial laboratory experiments in which the electromagnetic interaction contributions are hoped to be observed in addition to the main contributions due to weak interactions. An updated review on the relevant present results on the
upper bounds on the neutrino effective magnetic moment can be found in [4].

Note that there are several attempts in the literature aimed to investigate new promising possibilities for providing more stringent constraints on the neutrino electromagnetic properties based on the existing experimental data on the $\bar{\nu} - e$ scattering. For instance, an interesting possibility for getting a more stringent bound on the neutrino magnetic moment from $\bar{\nu} - e$ scattering experiments based on the “dynamical zeros” that appear in the Standard Model scattering cross-section was discussed in [7]. Another possibility was discussed in [8] where it was claimed that electron binding in atoms (the “atomic ionization” effect in neutrino interactions on a Ge target) can significantly increase the electromagnetic contribution to the differential cross-section with respect to the free electron approximation. However, detailed considerations of the atomic ionization effect in (anti)neutrino atomic electron scattering experiments presented in [9–13] show that the effect is by far too small to have measurable consequences even in the case of the low energy threshold of 2.8 keV reached in the GEMMA experiment [14].

In this letter we discuss the possibility to obtain constraints on the neutrino electromagnetic properties using the recent data as well as the expected results from the GEMMA Collaboration on measurements of the re-actor antineutrino scattering off electrons. The goal of the GEMMA experiment is to constrain from above (or discover) the neutrino anomalous magnetic moment $\mu^\nu_q$. Using the bound on the neutrino magnetic moment recently reported [14] by the GEMMA Collaboration, we get, by comparing the corresponding neutrino magnetic moment and millicharge contributions to the total cross-section, an order-of-magnitude estimation for possible new direct upper bound on the neutrino electric millicharge $|q_\nu| \sim 1.5 \times 10^{-12} e_0$, where $e_0$ is the absolute value of the electron charge. This estimation is confirmed by performing an analysis of GEMMA data using established statistical procedures, and we derive a new direct bound on the neutrino millicharge absolute value $|q_\nu| < 2.7 \times 10^{-12} e_0$ (90% C.L.).

These estimation and bound are more stringent constraints than the previous bound [15] obtained from the TEXONO reactor experiment data [16] and included by the Particle Data Group Collaboration to the Review of Particle Physics 2012 [17].

As a matter of fact, the scale on which the millicharge is probed within the used scheme depends on the attained scale of the magnetic moment $\mu^\nu_q$ and the electron recoil energy threshold of the experiment. With the expected future progress of the new ongoing phase of the experiment (GEMMA-II) [18] we predict that, in approximately two years, the neutrino electric charge will be bound on the level of $|q_\nu| \sim 3.7 \times 10^{-13} e_0$, and even on the level $|q_\nu| \sim 1.8 \times 10^{-13} e_0$ with the next planned phase of this experiment (GEMMA-III) within approximately four years from now.

Note that the possibility to constrain neutrino charge from the results of experiments searching for neutrino magnetic moment was considered in [19]. It has been shown, using results of the Big European Bubble Chamber beam dump experiment, that from the consideration of the elastic scattering $\nu e^- \rightarrow \bar{\nu} e^+$ the tau-neutrino electric charge may be bound by $|q_\nu| < 4 \times 10^{-4} e_0$. A direct experimental limit on the electric charge of the electron antineutrino $|q_\nu| < 3.7 \times 10^{-12} e_0$ has been obtained as a by-product result in [15] where constraints on millicharged hypothetical particles from the TEXONO reactor experiment were derived. This limit is presently included by the Particle Data Group Collaboration to the Review of Particle Physics [17].

The discussed above constraints should be compared with those obtained from direct accelerator searches, charged leptons anomalous magnetic moments, stellar astrophysics and primordial nucleosynthesis (some of that can be in general less stringent) [20,21]:

$$q_\nu \leq 10^{-6} - 10^{-17} e_0.$$  \hfill (1)

Recently, a more stringent astrophysical bound,

$$q_\nu \leq 1.3 \times 10^{-19} e_0,$$  \hfill (2)

has been obtained [22] from implication of the neutrino Neutron Star Turning (\(\nu ST\)) mechanism on star rotation. The most severe indirect constraints on the electric charge of the neutrino,

$$q_\nu \leq 10^{-21} e_0.$$  \hfill (3)

are obtained assuming electric charge conservation in neutron beta decay $n \rightarrow p + e^- + \nu_e$, from the neutrality of matter (from the measurements of the total charge $q_p + q_e$) [23] and from the neutrality of the neutron itself [24]. A detailed discussion of different constraints on the neutrino electric charge can be found in [4,6,25].

**Electrically millicharged neutrino.** – It is usually believed that the neutrino has a zero electric charge. This can be attributed to gauge invariance and anomaly cancelation constraints imposed in the Standard Model. However, if the neutrino has a mass, the statement that the neutrino electric charge is zero is not so evident as it meets the eye. In theoretical models with the absence of hypercharge quantization the electric charge also gets “dequantized” and as a result neutrinos may become electrically millicharged particles. A detailed discussion of theoretical models predicted the millicharged neutrinos as well as possible experimental aspects of this problem can be found in many papers [26,27]. See also [4] for a review on this topic.

**Bound on neutrino millicharge from the GEMMA experiment.** – Consider a massive neutrino with nonzero electric millicharge $q_\nu$ that induces an additional electromagnetic interaction of the neutrino with other particles of the Standard Model. Such a neutrino...
behaves as an electrically charged particle with the direct neutrino-photon interactions, additional to one produced by possible neutrino nonzero (anomalous) magnetic moment \( \mu_\nu \) that is usually attributed to a massive neutrino.

If there is no special mechanism of “screening” of these new electromagnetic interactions, then the neutrino will get a normal magnetic moment predicted within the Dirac theory of an electrically charged spin-\( \frac{1}{2} \) particle

\[
\mu_\nu^D = \frac{q_\nu}{2m_\nu}, \quad (4)
\]

that is proportional to the neutrino millicharge \( q_\nu \), here \( m_\nu \) is the neutrino mass. In general, this new contribution to the neutrino magnetic moment should be added to the neutrino anomalous magnetic moment \( \mu_\nu^a \) that can be generated by the vacuum polarization loop interactions within different theoretical models beyond the Standard Model. We recall here that, in the initial formulation of the Standard Model, a neutrino is the massless particle and its magnetic moment is zero. Within the easiest generalization of the \( SU(2)_L \times U(1)_Y \) Standard Model for a massive neutrino the contribution to the anomalous magnetic moment is produced by the \( \nu-W-e \) loop diagramme.

Thus, for a millicharged massive neutrino one can expect that the magnetic moment contains two terms,

\[
\mu_\nu = \mu_\nu^D + \mu_\nu^a, \quad (5)
\]

where, in the case of the Dirac neutrino \([28]\),

\[
\mu_\nu^D = \mu_\nu^D = \frac{e_G G_F m_\nu}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19} \left( \frac{m_\nu}{1 \text{ eV}} \right) \mu_B \quad (6)
\]

is a tiny value for any reasonable scale of \( m_\nu \) consistent with the present neutrino mass limits (\( \mu_B = \frac{e}{2m_e} \) is the Bohr magneton).

Here we recall that there is a hope of both theorists and experimentalists that new interactions beyond the Standard Model might reasonably increase the anomalous part of the neutrino magnetic moment to the level that could be checked by new terrestrial laboratory experiments in the near future.

Now we consider the direct constraints on the neutrino millicharge obtained using data on the neutrino electromagnetic cross-section in the GEMMA experiment. It is important to note that although in the case of a millicharged neutrino two terms, i.e. normal and anomalous magnetic moments, sum up in the total expression (5) for the magnetic moment, however these two contributions should be treated separately when one considers the electromagnetic contribution to the scattering cross-section. The point is that the normal magnetic moment contribution is accounted for automatically when one considers the direct neutrino millicharge to the electron charge interaction.

The prescription to obtain the bound on the neutrino millicharge from the experimental data on the \( \bar{\nu} - e \) cross-section is as follows. One first compares the magnetic moment cross-section \( (\frac{d\sigma}{dT})_{\bar{\nu}e} \) with the Standard Model weak contribution to the cross-section \( (\frac{d\sigma}{dT})_{\text{weak}} \). From the fact that the experimental data on the cross-section, for the presently achieved electron recoil energy threshold \( T \), shows no deviation from the predictions of the Standard Model a limit on the neutrino magnetic moment is obtained. Then one should compare the magnetic moment contribution to the cross-section, \( (\frac{d\sigma}{dT})_{\nu e} \), and the contribution due to the neutrino millicharge, \( (\frac{d\sigma}{dT})_{\nu e} \), and account that the latter is also not visible in the present experiment. In order not to contradict the experimental data the cross-section \( (\frac{d\sigma}{dT})_{\nu e} \) should not accede the cross-section \( (\frac{d\sigma}{dT})_{\nu e} \) anyway. Thus, the obtained upper limit on the neutrino millicharge depends on the achieved upper limit on the neutrino (anomalous) magnetic moment and the electron recoil energy threshold of the \( \bar{\nu} - e \) experiment.

Consider the latest results \([14]\) of the GEMMA Collaboration on the neutrino magnetic moment. Within the presently reached electron recoil energy threshold of

\[
T \sim 2.8 \text{ keV}, \quad (7)
\]

the neutrino magnetic moment is bounded from above by the value

\[
\mu_\nu^a < 2.9 \times 10^{-11} \mu_B. \quad (8)
\]

In order to get from these data the limit on the neutrino millicharge we compare the two mentioned above cross-sections, \( (\frac{d\sigma}{dT})_{\nu e} \) and \( (\frac{d\sigma}{dT})_{\nu e} \). The expression for the neutrino magnetic moment cross-section can be found in \([29]\), for our present needs only the term proportional to \( \frac{1}{T^2} \) matters,

\[
\frac{d\sigma}{dT} \approx \pi \alpha^2 \frac{1}{m_e^2 T^2} \frac{\mu_\nu^a}{\mu_B}^2, \quad (9)
\]

here \( \alpha \) is the fine structure constant. For the corresponding neutrino millicharge-to-charge cross-section we obtain (see also \([30]\))

\[
\frac{d\sigma}{dT} \approx 2\pi \alpha \frac{1}{m_e T^2 q_\nu^2}. \quad (10)
\]

For the ratio \( R \) of the mentioned above cross-sections (10) and (9) we have

\[
R = \frac{\frac{d\sigma}{dT} \nu e}{\frac{d\sigma}{dT} \nu e} = \frac{2m_\nu}{T} \left( \frac{q_\nu}{q_e} \right)^2 \frac{\mu_\nu^a}{\mu_B}^2. \quad (11)
\]

In case there are no observable deviations from the weak contribution to the neutrino scattering cross-section it is possible to get the upper bound for the neutrino millicharge demanding that possible effect due to \( q_\nu \) does not exceed one due to the neutrino (anomalous) magnetic moment. This implies that \( R < 1 \) and from (11) we get an estimation

\[
q_\nu^2 < \frac{T}{2m_e} \left( \frac{\mu_\nu^a}{\mu_B} \right)^2 c_0^2. \quad (12)
\]

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Thus, we predict that from the present GEMMA experiment data (7) and (8) the neutrino millicharge can be probed on the level

$$|q_\nu| \sim 1.5 \times 10^{-12} e_0.$$

(13)

The obtained constraint on a neutrino millicharge (13) should be treated as a rough order-of-magnitude estimation, while the exact values should be evaluated using the corresponding statistical procedures. This is because the limits on the neutrino magnetic moment are derived from the GEMMA experiment data taken over an extended energy range from about 2.8 keV to 55 keV, rather than at a single electron energy-bin at threshold.

To justify the obtained estimation (13) we undertake a more complete analysis of the published data set [14,18] from the GEMMA experiment, and evaluate the corresponding limit using established statistical procedures. While performing an analysis and deriving the limit on $q_\nu$ we use the GEMMA data and follow the statistical procedures that have been used [14,18] in derivation of the limit on the neutrino magnetic moment. In order to get an electron recoil energy spectrum (that is the only measured value in the experiment) the differential method is used that implies the comparison of the spectra measured at the reactor operation and shut down periods, $S_{on}$ and $S_{off}$ respectively. Note that here $S_{on}$ and $S_{off}$ are the measured spectra correspondingly normalized by the reactor operation and shut down data taking periods, $T_{on}$ and $T_{off}$. Up to now there is not any indication in the experimental data in favour of the existence of the electromagnetic contribution (including the effect of the millicharge $q_\nu$) to the antineutrino-electron cross-section. To evaluate the limit on $q_\nu$ we use the final spectra from GEMMA experiment (the data from [14] is shown in fig. 1). The difference between $S_{on}$ and $S_{off}$ taking into account the contribution of weak interaction to the spectrum $S_{weak}$ (see, for instance, [14]) normalized by the theoretical electromagnetic spectra $S_{\nu_{\mu}}^{th}$ derived from (9) and/or (10) can be interpreted for evaluation of $\mu_\nu$ and/or $q_\nu$ for each energy-bin from the region of interest. The detailed procedure of data processing and obtaining the final result on $\mu_\nu$ is discussed in [14]. Following the same prescription and applying a conventional renormalization procedure recommended by the Particle Data Group [31] and described in [32], we obtain the following upper limit on the neutrino millicharge

$$|q_\nu| < 2.7 \times 10^{-12} e_0 \text{ (90\% C.L.).}$$

(14)

Thus, the limit evaluated using the statistical procedures is of the same order of magnitude as one given by (13).

It is interesting to estimate the range of the neutrino millicharge that can be probed in a few years with the GEMMA-II experiment that is now in the final stage of preparation and is expected to get data in 2015. It is planned (for details, see in [14,18]) that the effective threshold will be reduced to $T = 1.5$ keV and the sensitivity to the neutrino anomalous magnetic moment will be at the level $\mu_\nu \sim 1 \times 10^{-11} \mu_B$. Then, in the case no indications for effects of new physics were observed, from a preliminary analysis we predict that the upper limit on the neutrino millicharge will be of order

$$|q_\nu| \sim 3.7 \times 10^{-13} e_0.$$  

(15)

It is also planned that the GEMMA-III experiment will reach the threshold $T = 350$ eV and the sensitivity to $\mu_\nu$ at the level $\mu_\nu \sim 9 \times 10^{-12} \mu_B$ approximately to the year 2018\footnote{Victor Brudanin, Vyacheslav Egorov and Alexander Starostin, private communication.}. Then, if again there were no deviations from the Standard Model cross-section observed, the upper limit to the neutrino millicharge can reach the level

$$|q_\nu| \sim 1.8 \times 10^{-13} e_0.$$  

(16)

The above new bounds on the neutrino millicharge are more stringent than many other bounds previously discussed in the literature [20,21].

Conclusions. – We consider the possibility, provided in various extensions of the Standard Model, that a neutrino is an electrically millicharged particle. The corresponding nonstandard electromagnetic interactions of such a neutrino generates the additional contribution to the neutrino electromagnetic scattering off electrons that depends on the millicharge. A new upper limit on the neutrino magnetic moment recently obtained by the GEMMA experiment allows us, by comparing the neutrino magnetic moment and millicharge contributions to the total cross-section at the electron recoil energy threshold of the experiment, to get an order-of-magnitude estimation for possible new direct upper bound on the neutrino electric millicharge $|q_\nu| \sim 1.5 \times 10^{-12} e_0$. This estimation is confirmed by performing an analysis of the GEMMA data using established statistical procedures that yields the new limit $|q_\nu| < 2.7 \times 10^{-12} e_0 \text{ (90\% C.L.).}$

We also predict that with the expected for 2015 new phase of the experiment (GEMMA II) the neutrino millicharge will be probed at the level of $|q_\nu| \sim 3.7 \times 10^{-13} e_0$.
Then in a few more years with the expected data of the next phase of the experiment (GEMMA III) the neutrino millicharge will be probed at the level of $|q_\nu| \sim 1.8 \times 10^{-13} e_0$. The obtained bounds are in general independent of the neutrino mass and will become stronger with the progress of the neutrino-electron scattering experiments that can be reached with decreasing of the attained electron recoil energy threshold and further improvements of the experimental setup.

The obtained bound (14) on the neutrino millicharge from the recent experimental data of the GEMMA Collaboration is more stringent than the reactor neutrino scattering constraint included by the Particle Data Group Collaboration to the Review of Particle Physics [17] and that was obtained by [15] from the TEXONO reactor experiment data [16]. Accordingly, we predict that a new bound on the millicharge that can be obtained in future with the new GEMMA experiment data will be a factor of about 10 more stringent than one from the present GEMMA data.

Note that the prediction to obtain, in a few years, a reasonable improvement (on the level of (16)) in constraining the neutrino millicharge over the present limit (14) will be with no doubt attained in case the GEMMA Collaboration reaches the declared sensitivity in probing the neutrino magnetic moment. The bound on the neutrino millicharge on the level of (16) will be reached irrespectively of whether any deviation from the Standard Model in the cross-section $\bar{\nu} - e$ were observed or not.

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