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New bounds on neutrino electric millicharge from GEMMA experiment on neutrino magnetic moment

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Neutrino electromagnetic properties

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. Systematic theoretical studies of neutrino electromagnetic properties have started after it was shown that in the extended Standard Model with right-handed neutrinos the magnetic moment of a massive neutrino is, in general, nonvanishing and that its value is determined by the neutrino mass **[1]**.

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. The available experimental data in the field do not role out the possibility that neutrinos have "zero" electromagnetic properties. However, in the course of the recent development of knowledge on neutrino mixing and oscillations, supported by the discovery of flavour conversion of neutrinos from different sources, nontrivial neutrino electromagnetic properties seems to be very plausible. Studies of neutrino electromagnetic properties are in fact of particular importance because they provide a kind of bridge (or "open a window") to new physics beyond the Standard Model. For a review on the neutrino electromagnetic properties see **[2].**

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 **[3,4]** (see also **[2]**) that the electromagnetic $\Lambda_\mu(q,l)$ vertex function 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.

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[2] C.Giunti, A.Studenikin, arXiv: 1403.6344; C.Broggini, C.Giunti, A.Studenikin, *Adv. High Energy Phys.* **2012**, 459526 (2012); C.Giunti, A.Studenikin, *Phys.Atom.Nucl.* **72** (2009) 1089; A.Studenikin, *Nucl.Phys.Proc.Suppl.* **188** (2009) 220
[3] B.Kayser, *Phys.Rev.* **D 26** (1982) 1662; J.F.Nieves, *Phys.Rev.* **D 26** (1982) 3152
[4] M.Nowakowski, E.Paschos, J.Rodriguez, *Eur.J.Phys.* **26** (2005) 545

Millicharged neutrino?

The electric charge is the charge from factor at zero q^2. 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 (see, for instance, **[5,6]**). A review on this topic can be found in three first papers of **[2]**.

[5] R.Foot, H.Lew, R.R.Volkas, *J. Phys.* **G 19** (1993) 361; *ibid.* 1067 [Erratum]; K.S.Babu, R.N.Mohapatra, *Phys.Rev.* **D 63** (1989) 938
[6] A. Studenikion, I.Tokarev, Nucl.Phys.**B 884** (2014) 396

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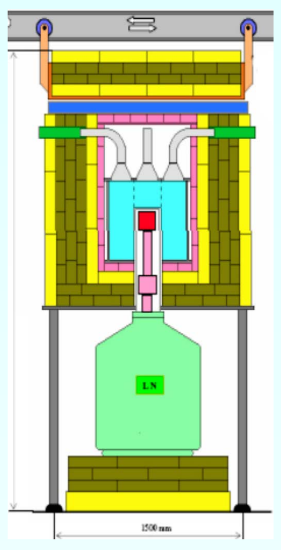
GEMMA: experimental setup, parameters and result



Germanium **E**xperiment for measurement of **M**agnetic **M**oment of **A**ntineutrino investigates the reactor antineutrino-electron scattering at the Kalinin Nuclear Power Plant (Russia). The GEMMA spectrometer includes a **HPGe** detector of **1.5 kg** installed within **NaI** active shielding. **HPGe + NaI** are surrounded with multi-layer passive shielding: electrolytic copper, borated polyethylene and lead. As a result of 4-years measurement the best world upper limit on the neutrino magnetic moments has been obtained **[7]** :

$\varphi_\nu \sim 2.7 \times 10^{13}\ \nu / cm^2 / s$
$t \sim 4$ years
$B \sim 2.5\ keV^{-1}\ kg^{-1}\ day^{-1}$
$m \sim 1.5$ kg
$T_{th} \sim 2.8$ keV

$$\mu^a_\nu \le 2.9 \times 10^{-11} \mu_B$$

[7] A.Beda et al, *Adv. High Energy Phys.* **2012**, 350150 (2012) .

Order-of-magnitude estimation of bounds on millicharge

Consider a massive neutrino with non-zero electric millicharge q_ν 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 non-zero (anomalous) magnetic moment 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:

$$\mu_\nu^q = \frac{q_\nu}{2m_\nu}\ . \qquad (3)$$

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

$$\mu_\nu = \mu_\nu^q + \mu_\nu^a\ . \qquad (4)$$

Now we consider the direct constraints on the neutrino millicharge q_ν obtained **[8]** using data on the neutrino electromagnetic cross section in the GEMMA experiment **[7]** . 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 **(4)** 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 expressions for the neutrino magnetic moment and millicharge cross sections are

$$\left(\frac{d\sigma}{dT}\right)_{\mu_\nu^a} \approx \pi\alpha^2\frac{1}{m_e^2 T}\left(\frac{\mu_\nu^a}{\mu_B}\right)^2, \quad \left(\frac{d\sigma}{dT}\right)_{q_\nu} \approx 2\pi\alpha\frac{1}{m_e T^2}q_\nu^2. \qquad (5)$$

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

$$q_\nu^2 < \frac{T}{2m_e}\left(\frac{\mu_\nu^a}{\mu_B}\right)^2 e_0^2 \qquad (6)$$

demanding that possible effect due to q_ν does not exceed one due to the neutrino magnetic moment. Thus we predict **[8]** that with the present GEMMA experiment data the neutrino millicharge can be probed on the level

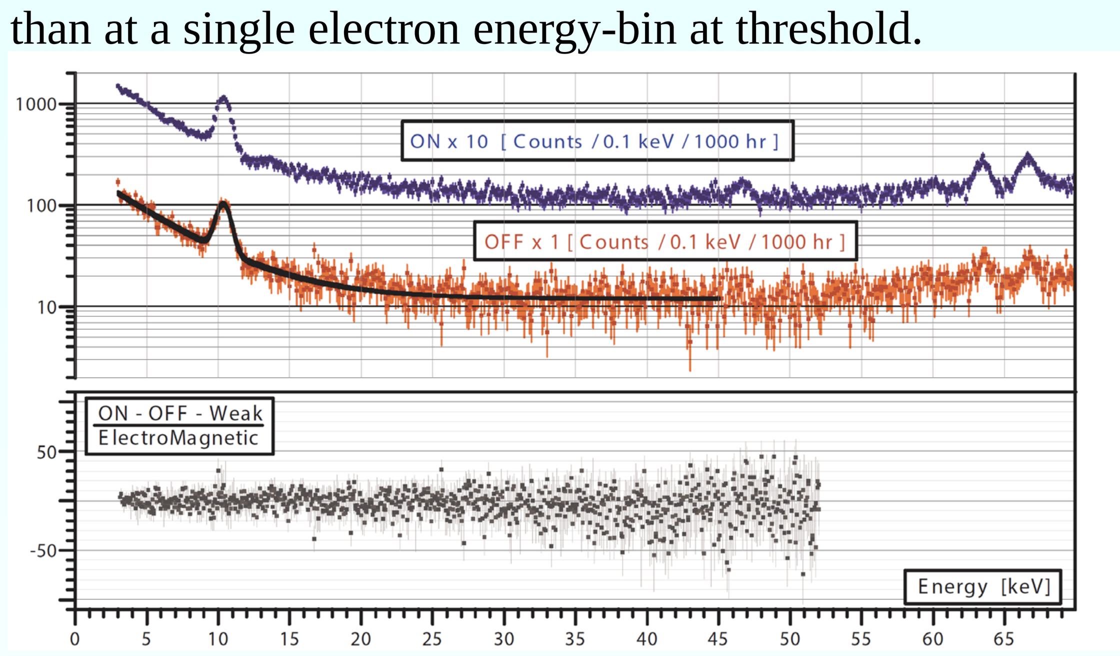
$$|\ q_\nu\ | \sim 1.5 \times 10^{-12} e_0. \qquad (7)$$

This value provides twice more stringent upper bound for q_ν than one previously obtained in **[9]** from the TEXONO reactor anineutrino experiment data **[10]**.

[8] A.Studenikin, arXiv:1302.1168, accepted for publication in *Eur.Phys.Lett.*, 2014
[9] S. Gninenko, N. Krasnikov, A. Rubbia, *Phys.Rev.* **D 75** (2007) 075014
[10] H. Li *et al.*, *Phys.Rev.Lett.* **90** (2003) 131802

New bound on millicharge from GEMMA experiment

The obtained constraint **(7)** on a neutrino millicharge 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 to 55 keV , rather than at a single electron energy-bin at threshold.



To evaluate the limit on q_ν we use the final spectra from GEMMA. The difference between S_{ON} and S_{OFF} taking into account S_{Weak} normalized by the theoretical electromagnetic spectra can be interpreted as evaluation of μ_ν and/or q_ν for each energy bin from the region of interest. The detailed procedure of data processing and obtaining the final result on μ_ν is shown in **[7]**. It includes the differential method that illustrates equal pattern for ON and OFF spectra. The likelihood method is used to obtain the upper limit for electromagnetic parameter. Applying this procedure to the millicharge cross section instead of the magnetic moment cross section (see **(5)**) we get **[8]** the preliminary result for the upper bound on q_ν

$$|\ q_\nu\ | < 2.7 \times 10^{-12} e_0\ (90\%\ C.L.). \qquad (8)$$

Thus, the limit evaluated using the statistical procedures is of the same order of magnitude as one given by **(7)** .

Future bounds on electromagnetic parameters from GEMMA

It is interesting to estimate **[8]** the range of the neutrino millicharge that can be probed in a few years with GEMMA-II experiment that is now in the final stage preparation and is expected to get data in 2015. The experimental setup is being placed under the reactor #3 where the distance from the centre of the core is **10 m**. In this way the antineutrino flux will be doubled up to **5.4×10^{13} 1/cm²/s**. Furthermore, being equipped with a special lifting mechanism the spectrometer will be moveable. The mass of the detector is increased by a factor of **4** (two detectors with a mass of **3 kg** each). To avoid the "Xe-problems" the internal part of the detector shielding will be gas tight. A special U-type low-background cryostat is used in order to improve the passive shielding and thus reduce the external background in the ROI down to ~ **0.5-1.0 (keV*kg*day)$^{-1}$**. A special care is taken to improve antimicrophonic and electric shielding. It is also planed to reduce the effective threshold from 2.8 to **1.5 keV**.

As a result, GEMMA-II will be sensitive to possible electromagnetic parameters at the level

$$\mu_\nu < 1.0 \times 10^{-11}\mu_B, \quad |\ q_\nu\ | < 9.4 \times 10^{-13} e_0. \qquad (9)$$

For GEMMA-III with new generation detectors (**T_{th}~ 350 eV**) the sensitivity will be even more improved:

$$\mu_\nu < 5.8 \times 10^{-12}\mu_B, \quad |\ q_\nu\ | < 5.5 \times 10^{-13} e_0. \qquad (10)$$

The obtained results **(7), (8)** on the millicharge from the recent GEMMA data, as well as estimations for the fututre **(9)** and **(10)**, provide more stringent constraints on q_ν than the reactor neutrino scattering constraint included by the Particle Data Group Collaboration to the **Review of Particle Physics 2012**.