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GEMMA EXPERIMENT: THREE YEARS OF THE SEARCH FOR THE NEUTRINO MAGNETIC MOMENT

A. G. Beda [a], *V. B. Brudanin* [b], *V. G. Egorov* [b,1], *D. V. Medvedev* [b], *M. V. Shirchenko* [b], *A. S. Starostin* [a]

[a]State Science Center, Institute for Theoretical and Experimental Physics, Moscow

[b]Joint Institute for Nuclear Research, Dubna

The result of the 3-year neutrino magnetic moment measurement at the Kalinin Nuclear Power Plant (KNPP) with the GEMMA spectrometer is presented. Antineutrino–electron scattering is investigated. A high-purity germanium detector of 1.5 kg placed at a distance of 13.9 m from the 3 $\mathrm{GW_{th}}$ reactor core is exposed to the antineutrino flux of $2.7 \cdot 10^{13}$ $\mathrm{cm^{-2} \cdot s^{-1}}$. The scattered electron spectra taken in $(5184 + 6798)$ and $(1853 + 1021)$ h for the reactor ON and OFF periods are compared. The upper limit for the neutrino magnetic moment $\mu_\nu < 3.2 \cdot 10^{-11} \mu_B$ at 90% CL is derived from the data processing.

В работе представлен результат трехлетних измерений магнитного момента нейтрино (ММН) с помощью спектрометра GEMMA на Калининской АЭС. Исследуется рассеяние реакторных антинейтрино (поток $\simeq 2{,}7 \cdot 10^{13}$ $\text{см}^{-2} \cdot \text{с}^{-1}$) на электронах 1,5-кг германиевого детектора, помещенного на расстоянии 13,9 м от центра активной зоны стандартного реактора тепловой мощностью 3 ГВт. По результатам сравнения спектров электронов отдачи, измеренных за $(5184 + 6798)$ и $(1853 + 1021)$ ч при работающем и заглушенном реакторе соответственно, на 90 %-м уровне достоверности получен верхний предел ММН: $\mu_\nu < 3{,}2 \cdot 10^{-11} \mu_B$.

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INTRODUCTION

The Minimally Extended Standard Model predicts a very small magnetic moment for the massive neutrino ($\mu_\nu \sim 10^{-20} \mu_B$) which cannot be observed in an experiment at present. On the other hand, there are a number of extensions of the theory beyond the Minimal Standard Model where the *Majorana* neutrino magnetic moment (NMM) could be at the level of $10^{-(10-12)} \mu_B$ irrespective of the neutrino mass [1–5]. At the same time, from general considerations [6, 7] it follows that the *Dirac* NMM could not exceed $10^{-14} \mu_B$. Therefore, observation of an NMM value higher than $10^{-14} \mu_B$ would be evidence for New Physics and, in addition, indicate [8–10] undoubtedly that the neutrino is a Majorana particle.

[1]E-mail: egorov@nusun.jinr.ru

It is rather important to make laboratory NMM measurements sensitive enough to reach the $\sim 10^{-11}\mu_B$ region. The Savanna River experiment by Reines' group could be considered as the beginning of such measurements. Over a period of thirty years sensitivity of reactor experiments increased by a factor of three only — from $(2-4)\cdot 10^{-10}\mu_B$ [11, 12] to $(6-7)\cdot 10^{-11}\mu_B$ [13,14]. Similar limits were obtained for solar neutrinos [15,16], but due to the MSW effect (as well as matter-enhanced oscillations in the Sun) their flavor composition changes, and therefore the solar NMM results could differ from the reactor ones. In this paper, the results of the 3-year NMM measurement by the collaboration of ITEP (Moscow) and JINR (Dubna) are presented. The measurements are carried out with the GEMMA spectrometer [14, 17, 18] at the 3 $\mathrm{GW_{th}}$ reactor of the Kalinin Nuclear Power Plant (KNPP).

1. EXPERIMENTAL APPROACH

A laboratory measurement of the NMM is based on its contribution to the ν–e scattering. For nonzero NMM the ν–e differential cross section is given [12] by a sum of the *weak* interaction cross section ($d\sigma_W/dT$) and the *electromagnetic* one ($d\sigma_{\mathrm{EM}}/dT$):

$$\frac{d\sigma_W}{dT} = \frac{G_F^2 m_e}{2\pi}\left[\left(1-\frac{T}{E_\nu}\right)^2\left(1+2\sin^2\theta_W\right)^2 + 4\sin^2\theta_W - \right.$$
$$\left. - 2(1+2\sin^2\theta_W)\sin^2\theta_W\frac{m_e T}{E_\nu^2}\right], \quad (1)$$

$$\frac{d\sigma_{\mathrm{EM}}}{dT} = \pi r_0^2\left(\frac{\mu_\nu}{\mu_B}\right)^2\left(\frac{1}{T}-\frac{1}{E_\nu}\right), \quad (2)$$

where E_ν is the incident neutrino energy; T is the electron recoil energy; θ_W is the Weinberg angle, and r_0 is the electron radius ($\pi r_0^2 = 2.495\cdot 10^{-25}$ cm^2).

Figure 1 shows differential cross sections (1) and (2) averaged over the typical antineutrino reactor spectrum vs. the electron recoil energy. One can see that at low recoil energy ($T \ll E_\nu$) the value of $d\sigma_W/dT$ becomes almost constant, while $d\sigma_{\mathrm{EM}}/dT$ increases as

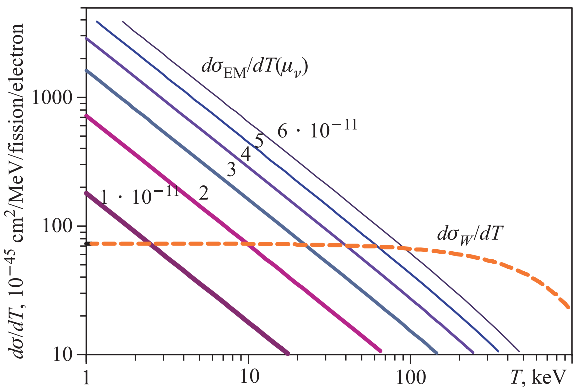

Fig. 1. Weak (W) and electromagnetic (EM) cross sections calculated for several NMM values

T^{-1}, so that the lowering of the detector threshold leads to a considerable increase in the NMM effect with respect to the weak unremovable contribution.

To realize this useful feature in our GEMMA spectrometer [14], we use a 1.5 kg HPGe detector with the energy threshold as low as 3.0 keV. To be sure that there is no efficiency cut at this energy, the «hard» trigger threshold was twice lower (1.5 keV).

Background is suppressed in several steps. First, the detector is placed inside a cup-like NaI crystal with 14 cm thick walls surrounded by 5 cm of electrolytic copper and 15 cm of lead. This active and passive shielding reduces external γ background in the ROI to the level of $\sim$ 2 counts/keV/kg/day. Being located just under reactor No. 2 of the KNPP (at a distance of 13.9 m from the reactor core, which corresponds to the antineutrino flux of $2.7 \cdot 10^{13}$ cm$^{-2} \cdot$ s^{-1}), detector is well shielded against the hadronic component of cosmic rays by the reactor body and technologic equipment (overburden $\simeq$ 70 m w.e.). The muon component is also reduced by a factor of $\sim$ 10 at $\pm 20°$ with respect to the vertical and $\sim$ 3 at 70–80°, but a part of residual muons are captured in massive shielding, and thus produce neutrons which scatter elastically in Ge and give rise to a low-energy background. To suppress it, the spectrometer is covered with additional plastic scintillator plates which produce relatively long μ-veto signals. Special care is taken to reduce nonphysical low-amplitude circuit noise (afterpulses, radio frequency interference, microphonism, etc.). In particular, the detector signal is processed by three parallel independent electronic channels with different shaping time, which allows performing a primitive Fourier analysis [19] à posteriori, and thus discriminating artefact signals (Fig. 2).

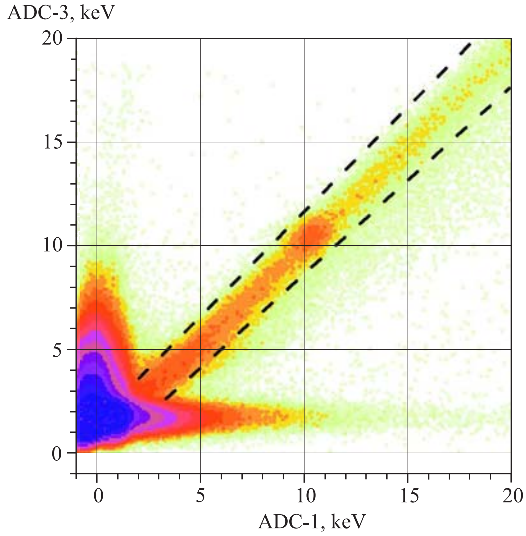

Fig. 2. Example of the primitive Fourier analysis done with two different shaping times: ADC-1 operates with 2 μs pulses, and ADC-3 operates with 12 μs pulses. (Color intensity scale is logarithmic)

2. DATA TAKING AND PROCESSING

In order to get a recoil electron spectrum, we use a differential method comparing the spectra measured at the reactor operation (ON) and shut down (OFF) periods. In our previous work we considered Phase-I (13 months' measurement from 08.2005 to 09.2006, including 5184 and 1853 h of the reactor ON and OFF periods, respectively). Today we can add Phase-II — 19 months from 09.2006 to 05.2008. Unfortunately, for some organizational and technical reasons, there were several long interrupts in the measurement. After preliminary selection, 6798 ON-hours and 1021 OFF-hours of live time were found to be available for analysis.

During the measurements, the signals of the HPGe detector, anticompton NaI shielding and outer anticosmic plastic counters, as well as dead-time information, are collected on an event-by-event basis. Detection efficiency just above the threshold is checked with a pulser. The neutrino flux monitoring in the ON period is carried on via the reactor thermal power measured with accuracy of 0.7%.

The collected data are processed in several steps. First, we reject those files which correspond to the periods of liquid nitrogen filling and any mechanical or electrical work at the detector site, as they could produce a noise. Second, we analyze energy spectra produced for each hour in order to check stability of γ background. If any visible excess of 81 keV (^{133}Xe), 250 keV (^{135}Xe) or 1294 keV (^{41}Ar) γ line occurs, the files are removed. Third, the level of nonphysical low-amplitude noise is checked second by second, and those seconds which contain more than 5 events with $E > 2$ keV are rejected. Fourth, we reject those events which are separated by a time interval shorter than 80 ms or equal to $(n\,20.0 \pm 0.1)$ ms (in such a way we suppress the noise caused by mechanical vibrations and 50 Hz power-line frequency).

Then, we build three plots similar to that shown in Fig. 2 and select only those events which fall (within the energy resolution) into diagonals, thus rejecting low- and high-frequency noise. As a result, we obtain energy spectra for the ON and OFF periods which must be normalized by the corresponding active time. Since the described selection of events is complicated, it is difficult to count active time in a proper way. To avoid possible errors caused by this procedure, both the ON and OFF spectra are normalized by the intensity of the background γ lines which are definitely known in time. These are the 1173 and 1333 keV-lines of ^{60}Co, the 1461 keV-line of ^{40}K and 238 keV-line of ^{212}Pb. The above radiation originates from the pollution of the internal parts of the spectrometer, and therefore must be independent of the reactor operation.

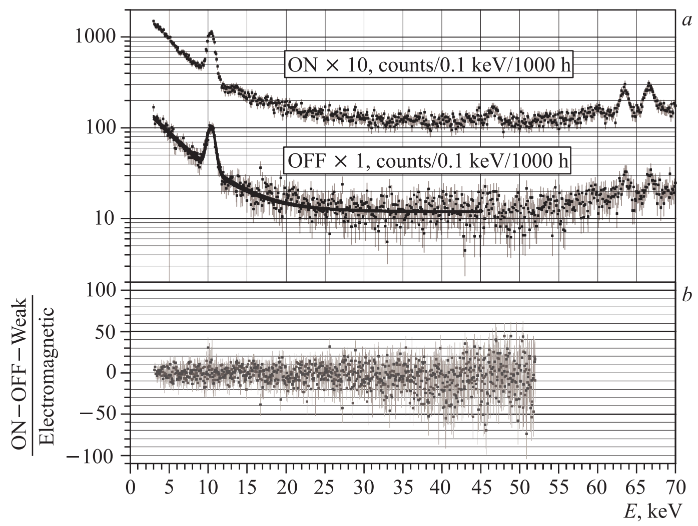

Fig. 3. Fragments of the experimental ON and OFF spectra (*a*) and their difference normalized by the electromagnetic cross section (*b*)

To extract the μ_ν value from the normalized ON and OFF spectra, we use two procedures. One of them was described in detail in our previous work [14]. It consists in the channel-by-channel comparison of the spectra (taking into account the weak contribution) and then averaging of the extracted X_i values over the ROI. Here i is the 0.1 keV-channel number, and X stands for an NMM squared in terms of 10^{-10} Bohr magnetons:

$$X \equiv \left(\frac{\mu_\nu}{10^{-10}\mu_B}\right)^2. \tag{3}$$

The above procedure is perfectly reliable and does not depend on the background structure. Unfortunately, the ON and OFF periods are not equal from the point of view of statistics (compare error bars in Fig. 3). A usual OFF period is much shorter, and therefore the final sensitivity is limited by the background uncertainties. On the other hand, today, after three years of data taking, we know the ROI background structure with more confidence. It gives us the right to introduce additional information in our analysis, namely, to state that our background is *a smooth curve*.

To implement this idea, we fit the background in the ROI from 2.9 to 45 keV with a parametrized smooth function (an example of such a fit with a sum of Gaussian, exponential and linear functions is shown in Fig. 3; other functions produce slightly different results, the systematic error includes their spread). Then, we compare the ON spectrum channel by channel with the obtained curve (to be more precise, with a narrow corridor of the width given by the fitting uncertainty). Applying this advanced procedure to the total statistics of Phases I+II, we get the following NMM limit:

$$\mu_\nu < 3.2 \cdot 10^{-11}\mu_B \quad (90\%\ \mathrm{CL}). \tag{4}$$

CONCLUSION

The experimental NMM search with the GEMMA spectrometer has been going on at the Kalinin Nuclear Power Plant (Russia) since 2005. The HPGe detector of 1.5 kg placed 13.9 m under the core of the 3 $\mathrm{GW_{th}}$ water-moderated reactor is exposed to the antineutrino flux of $2.7 \cdot 10^{13}$ $\mathrm{cm^{-2} \cdot s^{-1}}$. As a result of the 3-year measurement (about 13 000 ON-hours and 3000 OFF-hours of live time), the upper limit of $3.2 \cdot 10^{-11}\mu_B$ at 90% CL was found for the NMM.

At present, the data taking is in progress, but analysis of the data indicates that the sensitivity limit of the setup is almost reached. To improve it, we prepare significant upgrading of the spectrometer (GEMMA-2). Within the framework of this project we plan to use the antineutrino flux of $\sim 5.4 \cdot 10^{13}$ $\mathrm{cm^{-2} \cdot s^{-1}}$, increase the mass of the germanium detector by a factor of four and decrease the level of the background. These measures will provide the possibility of achieving the NMM limit at the level of $1.5 \cdot 10^{-11}\mu_B$.

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REFERENCES

1. *Voloshin M. B., Vysotsky M. I., Okun L. B.* // JETP. 1986. V. 64. P. 446.
2. *Fukugita M., Yanagida T.* // Phys. Rev. Lett. 1987. V. 58. P. 1807.
3. *Pakvasa S., Valle J. W. F.* Neutrino Properties before and after KamLAND. hep-ph/0301061.
4. *Gorchtein M. et al.* Model Independent Naturalness Bounds on Magnetic Moments of Majorana Neutrinos // Proc. of AIP Conf. 2007. V. 903. P. 287–290; hep-ph/0610388.
5. *Bell N. F. et al.* Model Independent Bounds on Magnetic Moments of Majorana Neutrinos // Phys. Lett. B. 2006. V. 642. P. 377; hep-ph/0606248.
6. *Bell N. F. et al.* How Magnetic is the Dirac Neutrino? // Phys. Rev. Lett. 2005. V. 95. P. 151802; hep-ph/0504134.
7. *Bell N. F. et al.* Magnetic Moments of Dirac Neutrinos // Proc. of AIP Conf. 2006. V. 842. P. 874–876; hep-ph/0601005.
8. *Kayser B.* Neutrino Properties // Proc. of the «Neutrino 08», Christchurch, New Zealand, May 25–31, 2008.
9. *Giunti C., Studenikin A.* Neutrino Electromagnetic Properties. hep-ph/0812.3646.
10. *Studenikin A.* Neutrino Magnetic Moment: A Window to New Physics // Nucl. Phys. Proc. Suppl. 2009. V. 188. P. 220; hep-ph/0812.4716.
11. *Reines F., Gurr H. S., Sobel H. W.* // Phys. Rev. Lett. 1976. V. 37. P. 315.
12. *Vogel P., Engel J.* // Phys. Rev. D. 1989. V. 39. P. 3378.
13. *Wong T. H. et al. (TEXONO Collab.)* // Phys. Rev. D. 2007. V. 75. P. 012001; hep-ex/0605006.
14. *Beda A. G. et al.* // Phys. At. Nucl. 2007. V. 70. P. 1873; hep-ex/0705.4576.
15. *Liu D. W. et al. (Super-Kamiokande Collab.)* // Intern. J. Mod. Phys. A. 2005. V. 20. P. 3110; hep-ex/0402015.
16. *Arpesella C. et al. (Borexino Collab.)* // Phys. Rev. Lett. 2008. V. 101. P. 091302; astro-ph/0805.3843.
17. *Beda A. G. et al.* // Phys. At. Nucl. 1998. V. 61. P. 66.
18. *Beda A. G. et al.* // Phys. At. Nucl. 2004. V. 67. P. 1948; hep-ex/9706004.
19. *Garcia E. et al.* Dark Matter Searches with a Germanium Detector at the Canfranc Tunnel // Nucl. Phys. Proc. Suppl. A. 1992. V. 28. P. 286–292.

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