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GEMMA EXPERIMENT: THE RESULTS OF NEUTRINO MAGNETIC MOMENT SEARCH

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The result of the neutrino magnetic moment (NMM) measurement at the Kalinin Nuclear Power Plant (KNPP) with GEMMA spectrometer is presented. The antineutrino–electron scattering is investigated. A high-purity germanium (HPGe) detector with a mass 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 recoil electron spectra taken in 18134 and 4487 h for the reactor ON and OFF periods are compared. The upper limit for the NMM $\mu_\nu < 2.9 \cdot 10^{-11} \mu_B$ at 90% C.L. is derived from the data processing.

Представлен результат измерения магнитного момента нейтрино (ММН) с помощью спектрометра GEMMA на Калининской АЭС. Исследуется рассеяние реакторных антинейтрино (поток $2{,}7 \cdot 10^{13}$ $\mathrm{см^{-2} \cdot с^{-1}}$) 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 энергетических спектров, измеренных за 18134 и 4487 ч при работающем и заглушенном реакторе соответственно, на 90 %-м уровне достоверности получен верхний предел на ММН: $\mu_\nu < 2{,}9 \cdot 10^{-11} \mu_B$.

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INTRODUCTION

The Minimally Extended Standard Model (MSM) predicts a very small magnetic moment value for the massive neutrino ($\mu_\nu \sim 10^{-19} \mu_B$) that cannot be observed in experiment at present. However, there are a number of theory extensions beyond the MSM where NMM could be at the level of $10^{-(10-12)} \mu_B$ [1–5] for Majorana neutrino. At the same time, it follows from general considerations [6, 7] that the Dirac NMM cannot exceed $10^{-14} \mu_B$. Therefore, the observation of NMM value higher than $10^{-14} \mu_B$ would be an evidence of New Physics and indicate undoubtedly [8–10] that neutrino is a Majorana particle. Furthermore, according to [11], new lepton-number-violating physics responsible for the generation of NMM arises at the scale Λ which is well below the see-saw scale. For example, for $\mu_\nu = 1.0 \cdot 10^{-11} \mu_B$ and the neutrino mass $m_\nu = 0.3$ eV we can find that $\Lambda \leqslant 100$ TeV.

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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 can be considered as the beginning of such measurements. Over a period of thirty years the sensitivity of reactor experiments has been improved by only a factor of three: from $(2-4)\cdot 10^{-10}\mu_B$ [12, 13] to $(6-7)\cdot 10^{-11}\mu_B$ [14, 15]. Similar limits were obtained for solar neutrinos [16, 17], but due to the MSW effect their flavor composition changes and therefore the solar NMM results could differ from the reactor ones. In this paper the result of NMM measurement by the collaboration of ITEP (Moscow) and JINR (Dubna) is presented. The measurements are carried out with the GEMMA spectrometer [15, 18, 19] at the 3 $\mathrm{GW_{th}}$ reactor of the KNPP.

1. EXPERIMENTAL APPROACH

A laboratory measurement of the NMM is based on its contribution to the $\nu - e$ scattering. For nonzero NMM the $\nu - e$ differential cross section is [8] a sum of weak interaction cross section ($d\sigma_W/dT$) and electromagnetic one ($d\sigma_{\mathrm{EM}}/dT$):

$$\frac{d\sigma_W}{dT} = G_F^2\left(\frac{m_e}{2\pi}\right)\left[4x^4 + (1+2x^2)^2\left(1-\frac{T}{E}\right)^2 - 2x^2(1+x^2)\frac{m_eT}{E^2}\right], \qquad (1)$$

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

where E is the incident neutrino energy; T is the electron recoil energy; $x^2 = \sin^2\theta_W = 0.232$ is a Weinberg parameter; and r_0 is a classical electron radius ($\pi r_0^2 = 2.495\cdot 10^{-25}$ cm^2). Since in the ultrarelativistic limit the neutrino magnetic moment interaction changes the neutrino helicity and the Standard Model weak interaction conserves the neutrino helicity, the two contributions add incoherently in the cross section. The small interference term due to neutrino masses has been derived in [20].

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 ($T \ll E_\nu$)

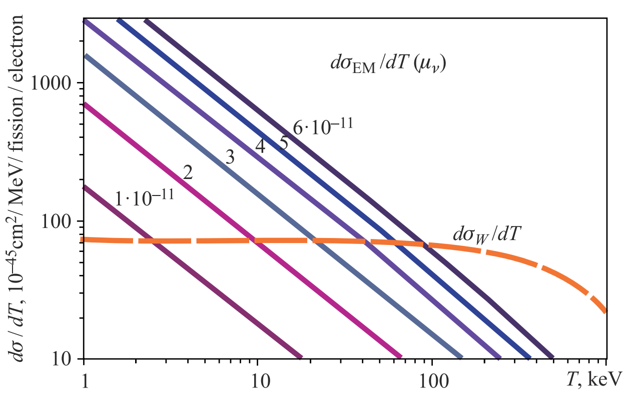

Fig. 1. Weak (W) and electromagnetic (EM) cross sections calculated for several NMM values in terms of μ_B

the value of $d\sigma_W/dT$ becomes almost constant, while $d\sigma_{\rm EM}/dT$ increases as T^{-1}. It becomes evident that the lower the detector threshold is, the more considerable increase in the NMM effect with respect to the weak unremovable contribution we can obtain.

To realize this useful feature in our GEMMA spectrometer [15], we use a 1.5 kg HPGe detector with the energy threshold as low as 2.8 keV to measure the electron recoil energy spectrum. To be sure that there is no efficiency cut at this energy, the «hard» trigger threshold is set twice lower (1.5 keV).

Various methods are implemented for the background suppression. The detector is placed inside a cup-shaped NaI crystal with 14-cm-thick walls and surrounded by 5 cm of electrolytic copper and 15 cm of lead. This active and passive shielding reduces the external γ-background in the ROI[1] to the level of ~ 2 counts/keV/kg/day. Being located just under reactor No. 2 of KNPP (at a distance of 13.9 m from the reactor core center), the detector is well shielded against the hadronic component of cosmic rays by the reactor body and technologic equipment (overburden ~ 70 m w.e.). The muon component is reduced by a factor of 10 at $\pm 20^\circ$ with respect to vertical line and 3 at 70–80°. Nevertheless, a part of residual muons is captured in the massive shielding and produce neutrons that scatter elastically in Ge detector and raise the low energy background. To suppress this effect, the spectrometer is covered with additional plastic scintillator plates which produce relatively long μ-veto signals. In order to reduce nonphysical low-amplitude circuit noise (afterpulses, radio frequency interference, microphonism, etc.), the detector signal is processed by three parallel independent electronic channels with different shaping time. This allows us to apply a primitive Fourier analysis [21] and thus discriminate the artefact signals.

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. Our experiment is divided into 3 phases. For Phase-I we have 5184 and 1853 h for the reactor ON and OFF periods, respectively. 6798 ON-hours and 1021 OFF-hours of live time statistics have been found to be available for analysis in Phase-II. Today we can add Phase-III results. They contain 6152 ON-hours and 1613 OFF-hours of live time statistics.

During the measurement the signals of the HPGe detector, anti-Compton NaI shielding and outer anticosmic plastic counters as well as dead time information are collected on the event-by-event basis. The detection efficiency just above the threshold is checked with a pulser [22]. The neutrino flux during the ON period is estimated via the reactor thermal power measured with an accuracy of 0.7%.

The detailed procedure of data processing is described in our previous work [22]. As a result, we obtain energy spectra S for the ON and OFF periods which must be normalized by the corresponding active times $T_{\rm ON}$ and $T_{\rm OFF}$ and then compared to each other, taking into account the additional neutrino-dependent term:

$$\frac{S_{\rm ON}}{T_{\rm ON}} = \frac{S_{\rm OFF}}{T_{\rm OFF}} + m_d \Phi_\nu (W + X \times {\rm EM}). \tag{3}$$

[1] The Region Of Interest (ROI) in our analysis includes two fragments from 2.8 to 9.4 and from 11.2 to 55 keV, i.e., the low-energy part of the continuous spectrum without peaks which could depend on the reactor operation.

The last term includes the fiducial detector mass m_d and the antineutrino flux Φ_ν (known with an accuracy of 1.7 and 3.5%, respectively) multiplied by the sum of two neutrino contributions: the weak one (W) which can be calculated easily using formula (1) and is completely negligible in our case, and the electromagnetic one (EM) which is proportional to the squared NMM value:

$$X \equiv \left(\frac{\mu_\nu}{10^{-11}\mu_B}\right)^2. \tag{4}$$

The exposition times of ON and OFF periods are not equal. A usual OFF period is much shorter and therefore the final sensitivity is limited by the background uncertainties. However, today, after four years of data taking, we know the ROI background structure with good confidence (280 kg · day of OFF statistics). 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 conventional idea, we fit the background OFF spectrum in the ROI from 2.8 to 55 keV with a parametrized smooth function (e.g., a sum of Gaussian, exponential and linear functions). We can also use splines for this procedure. All these fits produce slightly different results and their spread is taken into account in the final systematic error.

Figure 2 illustrates good background knowledge. Furthermore, its bottom part shows that there is no visible deviation of X value (4) from zero within statistical errors. This demonstrates that our way of data processing is adequate and does not bring in an additional systematic error.

To extract the NMM value, we compare ON spectrum with the obtained curve channel by channel (to be more precise, with a narrow corridor with the width given by the fitting uncertainty). Applying this procedure to the total statistics of Phases I + II + III, we get the final distribution for X (Fig. 3). After a conventional renormalization recommended by the

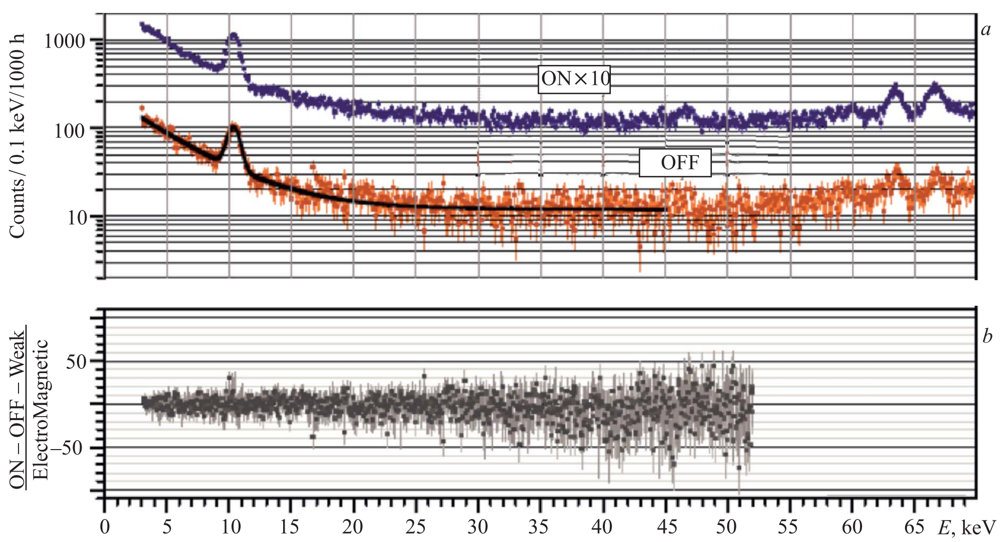

Fig. 2. Fragments of the experimental ON and OFF spectra (*a*) and their difference normalized by the electromagnetic cross section (*b*)

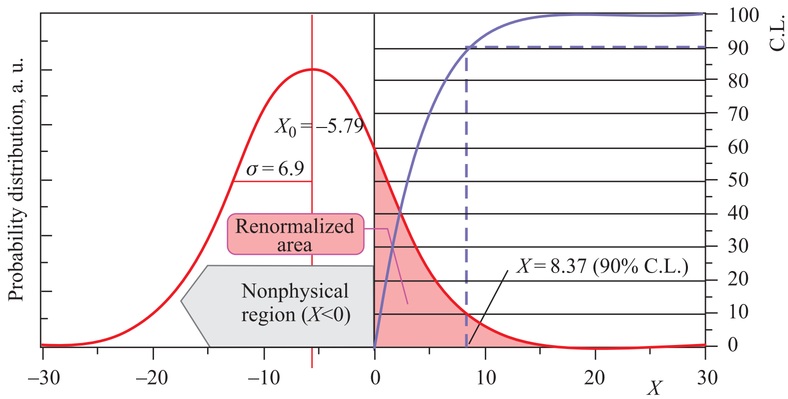

Fig. 3. Final probability distribution of X

Particle Data Group [23] and described in our previous work [15], we extract the upper limit for the X parameter and thus get the following NMM limit:

$$\mu_\nu < 2.9 \cdot 10^{-11} \mu_B \quad (90\% \text{ C.L.}). \tag{5}$$

There are two kinds of possible systematic errors in the procedure of X-value extraction from experimental data. The first one arises from the uncertainties in knowledge of the neutrino energy spectrum and initial intensity as well as its distortions caused by possible short-baseline neutrino oscillations [24]. It includes also the uncertainty of the reactor thermal power, detector fiducial volume and effective measurement time. Each of these terms enters the final result as *a factor* so that a sum of their relative errors gives a small rise only to the X-distribution width ($\sim 10\%$) but not to the central value. That is why it is not very important for the case of upper limit estimation. The second source of systematic error originates from the background estimation. As was mentioned, the idea of the experiment is to compare low energy background measured for the reactor ON and OFF periods *ceteris paribus*. Nonequivalence of the conditions could either shift the mean value to the unphysical (negative) region or mimic the nonzero NMM value. It could be caused by the incorrect normalization of the measurement times $T_{\rm ON}/T_{\rm OFF}$ as well as by the presence of any unrecorded background component correlated with the reactor operation. The absence of the above effects is demonstrated in Fig. 3. One can see the deviation of central value X_0 from zero to be comparable with the dispersion σ. That proves the validity of our assumptions and the propriety of the chosen method for estimation of the upper limit on X value.

3. FUTURE PLANS

At the present time we are preparing an experiment GEMMA-II. The experimental setup is being placed under reactor No. 3, where the distance from the centre of the core is 10 m. In this way we double the antineutrino flux up to $5.4 \cdot 10^{13}$ cm$^{-2} \cdot$ s^{-1}. The γ-background conditions in the new room are much better (by an order of magnitude), the climate conditions are more stable. Furthermore, being equipped with a special lifting mechanism, the spectrometer will be moveable. It gives us an opportunity to vary on-line the antineutrino flux significantly and thus suppress the main systematic errors caused by the possible long-term instability and uncertainties of background knowledge. 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 $\sim 0.5{-}1.0$ (keV · kg · day)$^{-1}$. A special care is taken to improve antimicrophonic and electric shielding. We also plan to reduce the effective threshold from 2.8 to 1.5 keV. The neutrino flux monitoring will be available by means of special detector (project DANSS, to be published). As a result of all the improvements, we will be able to suppress the systematic errors and expect the experimental sensitivity to be at the level of $1 \cdot 10^{-11}\mu_B$, and thus to reach the region of astrophysical interest.

CONCLUSION

The experimental NMM search with GEMMA spectrometer has been going on at KNNP (Russia) since 2005. The HPGe detector of 1.5 kg placed 13.9 m under the core of the 3 GW$_{\rm th}$ water moderated reactor has been exposed to the antineutrino flux of $2.7 \cdot 10^{13}$ cm$^{-2} \cdot$ s^{-1}. As a result of the measurement (about 18000 ON-hours and 4500 OFF-hours of live time), the world best upper limit of $2.9 \cdot 10^{-11}\mu_B$ at 90% C.L. was set for the NMM.

The analysis of data indicates that the sensitivity limit of the setup is almost reached. To improve it, we prepare significant upgrading of the spectrometer (GEMMA-II). Within the framework of this project, we plan to use the antineutrino flux of $5.4 \cdot 10^{13}$ 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 us the possibility of achieving the NMM limit at the level of $1 \cdot 10^{-11}\mu_B$.

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