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Experiment GEMMA: Search for the Neutrino Magnetic Moment*

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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 centre of the 3 GW_{th} reactor core is used in the spectrometer. The antineutrino flux is 2.7×10^{13} $\bar{\nu}_e$/cm^2/s. The differential method is used to extract ν-e electromagnetic scattering events. The scattered electron spectra taken in 5184+6798 and 1853+1021 hours for the reactor *ON* and *OFF* periods are compared. The upper limit for the neutrino magnetic moment μ_ν was found to be $3.2\times10^{-11}\mu_B$ at 90% CL.

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The Minimally Extended Standard Model predicts a very small magnetic moment for the massive neutrino ($\mu_\nu \sim 10^{-19}\mu_B$) which cannot be observed in an experiment at present. On the other hand, there is a number of extensions of the theory beyond the SM where the *Majorana* neutrino magnetic moment (NMM) could be at the level of $10^{-(10...12)}$ μ_B irrespective of the neutrino mass, whereas the *Dirac* NMM could not exceed $10^{-14}\mu_B$ (see, e.g, [1] and references therein). Therefore, observation of an NMM value higher than 10^{-14} μ_B would be evidence for New Physics and, in addition, indicate undoubtedly that the neutrino is a Majorana particle. That is why it is rather important to make laboratory NMM measurements sensitive enough to reach the $\sim 10^{-11}\mu_B$ region. However, the sensitivity of reactor experiments only increased by a factor of three since the Savanna River experiment by Reines' group: from $(2\ldots4)\times10^{-10}\mu_B$ [2] to $(6\ldots7)\times10^{-11}\mu_B$ [3, 4]. Similar limits were obtained for solar neutrinos [5, 6], but due to oscillations at long distance (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.

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 [2] by a sum of the *weak* interaction cross section ($d\sigma_W/dT$) and the *electromagnetic* cross section ($d\sigma_{EM}/dT$). At a low recoil electron energy ($T \ll E_\nu$) the value of $d\sigma_W/dT$ becomes almost constant, while $d\sigma_{EM}/dT$ behaves as 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.[1]

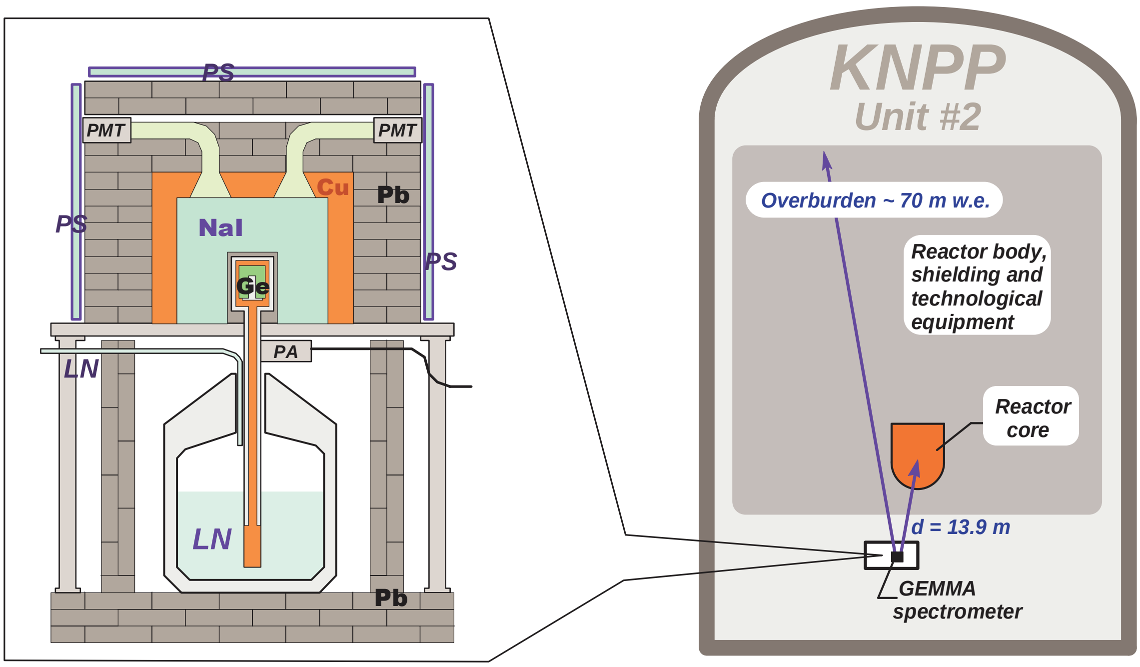

Figure 1: Ge detector inside the active (NaI, PS) and passive (Cu, Pb) shielding.

To realize this useful feature in our GEMMA spectrometer [4], we use a 1.5 kg HPGe detector with an energy threshold as low as 3 keV. The background is suppressed in several steps. First, the

[1] According to H. T. Wong et al. [7], the NMM effect could be significantly enhanced by atomic ionization, but the magnitude of such enhancement is questionable [8].

detector is placed inside a cup-like NaI crystal with 14 cm thick walls surrounded with 5 cm of electrolytic copper and 15 cm of lead (Fig. 1). Active and passive shielding reduces the external γ-background in the ROI to a level of ~ 2 counts/keV/kg/day. Being located just under reactor #2 of the KNPP (at a distance of 13.9 m from the reactor core, which corresponds to an antineutrino flux of 2.7×10^{13} $\bar{\nu}_e/\mathrm{cm}^2/\mathrm{s}$), the detector is well shielded against the hadronic component of cosmic rays by the reactor body and technological equipment (overburden$\simeq$70 m w.e.). To suppress low-energy background caused by elastic scattering of secondary neutrons (produced by cosmic muons in the massive Pb+Cu shielding), the spectrometer is covered with additional plastic scintillator plates (PS) which generate relatively long μ-veto signals.

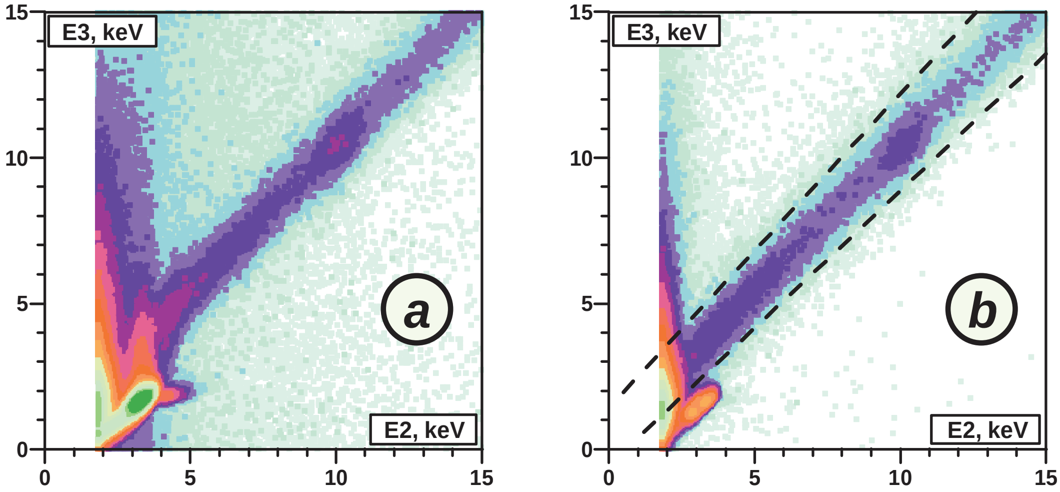

Figure 2: Example of the Fourier analysis made with different shaping-times: ADC-2 and ADC-3 operate with 4 μs and 12 μs pulses, respectively. Plot (a) is made *before* and (b) – *after* the "audio-frequency" rejection; it is seen that most of the rejected events are non-diagonal. (The color intensity scale is logarithmic.)

Special care is taken to reduce non-physical low-amplitude circuit noise (afterpulses, radio frequency interference, microphonism, etc.). Thus, for example, we reject those events which are separated by a time interval shorter than 80 ms or equal to $(n \cdot 20.0 \pm 0.1)$ ms. With this "audio-frequency" rejection we suppress the noise caused by mechanical vibrations ("ringing") and the 50 Hz power-line frequency. In addition, the detector signal is processed by three parallel independent electronic channels with different shaping time (2, 4 and 12 μs), which allows a primitive Fourier analysis (Fig. 2) to be performed à posteriori, so artefact signals are discriminated.

In order to get a recoil electron spectrum, we use a differential method comparing the spectra measured during the reactor operation (ON) and shutdown (OFF) periods, the last one being considered as a background. In our previous work [4] we presented Phase-I (13 months' measurement including 5184 and 1853 hours 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 interruptions in the measurement. After the preliminary selection, 6798 ON-hours and 1021 OFF-hours of active time were found to be available for analysis.

Fitting the background OFF spectrum in the ROI from 2.9 keV to 55 keV with a parametrized smooth function (Fig. 3) and comparing the ON spectrum channel by channel with the obtained background curve, we extract their normalized difference $X \equiv \frac{\mathrm{ON-OFF-Weak}}{\mathrm{Electromagnetic}}$ which actually represents the NMM value squared (in terms of $10^{-11}\mu_B$). Averaging over the total ROI and adding the data of the Phase-I, we get at the 90%CL the following upper limit: $\mu_\nu \leq 3.2 \times 10^{-11}\mu_B$, which could be an order of magnitude lower if the Atomic Ionization Enhancement [7] really exists (in this case our analysis gives the limit as low as $\mu_\nu \leq 0.5 \times 10^{-11}\mu_B$).

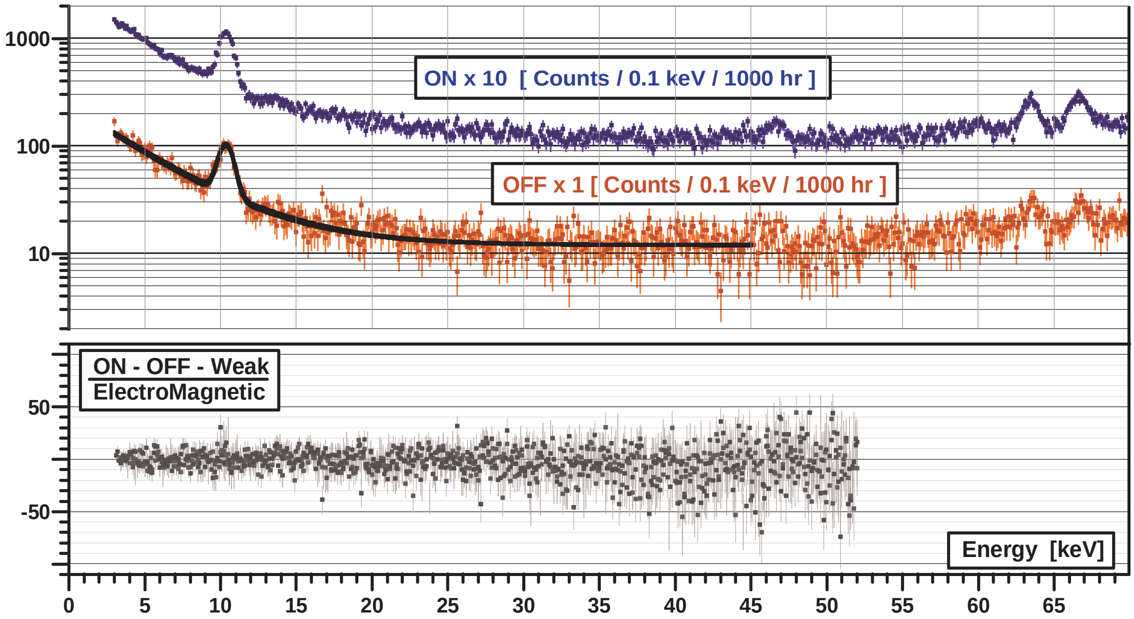

Figure 3: Fragments of the experimental ON and OFF spectra measured in Phase-II, as well as their difference normalized by the electromagnetic cross section. (Only a part of the available statistics is presented.)

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