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Limiting the effective magnetic moment of solar neutrinos with the Borexino detector

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Abstract. Borexino has provided an updated upper limit on the effective neutrino magnetic moment of solar neutrinos $\mu_{\rm eff} < 2.8 \times 10^{-11}\,\mu_B$ at 90% C.L. This result represents nearly a factor of two improvement with respect to the previous result based on 192 days of the Phase-I data. The current analysis has been performed using 1291.5 days exposure of the Phase-II data, characterized by a further improved level of radio-purity of liquid scintillator. Another key ingredient of the new analysis, lowering the threshold from 260 to 186 keV, was possible thanks to a better understanding of the detector-response function at low energies. The global spectral fit was preformed up to 2970 keV energy, using constraints on the sum of the solar neutrino fluxes implied by the radiochemical gallium experiments. From the limit for the effective neutrino magnetic moment, new limits for the magnetic moments of the neutrino flavour states were derived.

1. Borexino and solar neutrinos

Borexino is a large-volume liquid-scintillator detector located at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy. It is shielded with 3800 m water-equivalent against cosmic radiation. The 278 ton of the ultra-pure pseudocumene (PC)-based liquid scintillator is contained in a thin nylon vessel of 4.25 m radius. An array of 2212 inner photomultipliers (PMTs) is used to detect the scintillation light. The amount of detected light is a measure of the amount of energy deposited by an interacting particle, while the vertex position is reconstructed from the the hit-time distribution. The scintillator, having 1.5 g/l of PPO as a fluor, has in the current Phase-II significantly reduced radioactive contaminants with respect to the Phase-I: ^{238}U $< 9.4 \times 10^{-20}$ g/g (95% C.L.), ^{232}Th $< 5.7 \times 10^{-19}$ g/g (95% C.L.), ^{85}Kr of few counts per day (cpd)/100 ton, reduced by a factor of nearly 5, and ^{210}Bi below 20 cpd/100 ton, reduced by more than a factor of 2. The scintillator volume is then shielded

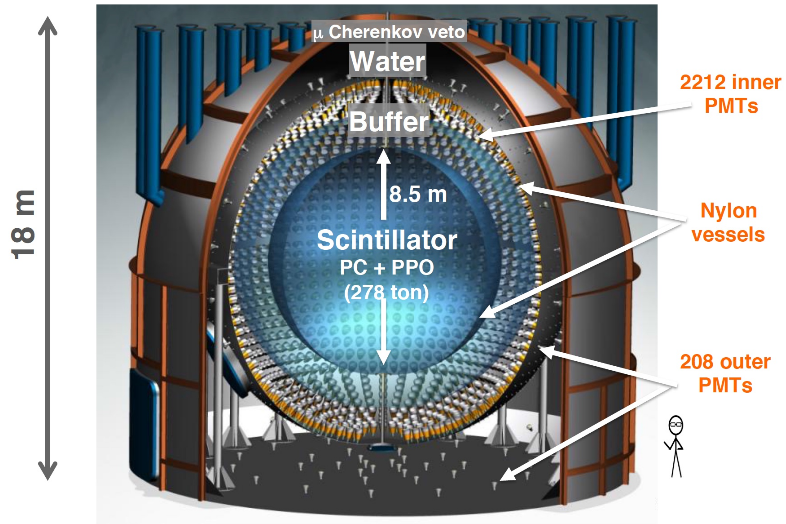

Figure 1. Schematic view of the Borexino detector.

by 2.6 m of the buffer liquid (PC + 2.0 g/l of the DMP quencher) contained in the 6.85 m radius stainless steel sphere (SSS). The buffer region is divided in two sections by 5.5 m radius outer nylon vessel, serving as a barrier against radon possibly leaking towards the scintillator. The SSS serves also as a base, on which are mounted both the inner-PMTs, as well as additional 208 outer-PMTs, viewing the Cherenkov light produced by cosmic muons passing the outermost water shield. This ultra-pure water is hold in a tank of 9 m base radius and 16.9 m height. The schematic view of the Borexino detector is shown in Fig. 1.

Borexino is measuring solar neutrinos via elastic scattering off electrons, sensitive to all neutrino flavours and having a typical cross section of about $10^{-44}\,\mathrm{cm}^2$ at 1-2 MeV of energies. The analysis is performed in a wall-less fiducial volume (FV), in which the events are selected via a software cut. The energy spectrum of all events passing the selection criteria (muon veto, FV and noise-cuts), is then fit with the spectra of all signal (solar neutrinos) and background (radioactive contaminants, cosmogenic background) components. With this real-time technique and thanks to an unprecedentedly low radioactive background, Borexino has provided the 5% measurement of ^{7}Be solar neutrinos [1], the first observation of the *pep* solar neutrinos [2], the first spectroscopic observation of *pp* solar neutrinos [3], the observation of ^{8}B solar neutrinos with 3 MeV threshold, as well as the best available limit on CNO neutrinos [2]. Updated results on the *pp*, ^{7}Be, and *pep* measurements, as well as on the CNO limit were presented on the TAUP 2017 conference [5]. For the first time, the analysis was performed on an extended energy interval from 186 to 2970 keV and all results have been obtained by a simultaneous multi-variate fit (energy spectra, radial and pulse-shape distributions). Borexino is currently continuing its data acquisition. In spring 2018, a ^{144}Ce/^{144}Pr antineutrino generator will be placed below the Borexino detector, in order to search for short-baseline neutrino oscillations (SOX project) [6] and to test the hypothesis of the existence of $\sim 1\,\mathrm{eV}^2$ sterile neutrino.

2. Neutrino Magnetic Moment

Experimental observation of neutrino oscillations has proven the existence of non-zero neutrino mass. Consequently, the Standard Model needed to be extended and in the so called minimal extension, the neutrino magnetic moment μ_ν is proportional to neutrino mass m_ν:

$$\mu_\nu = \frac{3 m_e G_\mathrm{F}}{4\pi^2\sqrt{2}} m_\nu \mu_\mathrm{B} \approx 3.2 \times 10^{-19} \left(\frac{m_\nu}{1\mathrm{eV}}\right) \mu_B, \tag{1}$$

where μ_B is Bohr magneton, G_F is the Fermi coupling constant, and m_e electron mass. Following this equation and considering the current limits on the neutrino mass, the upper limit on the neutrino magnetic moment is $\mu_\nu < 10^{-18}\mu_B$, 7 to 8 orders of magnitude below the current experimental limits on μ_ν. However, there exist more general models, that predict the μ_ν to have much larger values, reaching the current experimental limits. Neutrino mixing means that the coupling of the neutrino mass eigenstates i and j to an electromagnetic field is characterized by a 3×3 matrix of the magnetic (and electric) dipole moments μ_{ij}. The experimental limits on the neutrino magnetic moment are not obtained on single mass eigenstates. In case of bounds obtained by studying

Experiment	Neutrino source	$\times 10^{-11}\mu_{\rm B}$ @ 90% C.L.
GEMMA [7]	reactor $\bar{\nu}_e$	$\mu_{\bar{\nu}_e} < 2.9$
TEXONO [8]	reactor $\bar{\nu}_e$	$\mu_{\bar{\nu}_e} < 7.4$
SuperK [9]	solar ^{8}B-$\nu > 5\,$MeV	$\mu_{\rm eff} < 36$
	+ all solar + KamLAND	$\mu_{\rm eff} < 11$
Borexino [10]	solar ^{7}Be-ν	$\mu_{\rm eff} < 5.4$
Borexino [11], this work	solar ^{7}Be- and *pp*-ν	$\mu_{\rm eff} < 2.8$

Table 1. An overview of the current experimental limits on the neutrino magnetic moment from the measurement of solar neutrinos and reactor antineutrinos.

(ν, e) elastic-scattering of solar neutrinos, reaching the Earth as a mixture of different flavours, we speak about an effective magnetic moment $\mu_{\rm eff}$, while for reactor antineutrinos we speak about $\mu_{\bar{\nu}_e}$. The current laboratory bounds on μ_ν obtained by measurement of solar neutrinos and reactor anti-neutrinos are summarised in Table 1. The most stringent limits at the level of $\sim 10^{-12}$ $\mu_{\rm B}$ [12, 13], coming from the astrophysical observations, are model dependent.

3. New Borexino analysis and results

In case of non-zero neutrino magnetic moment, the total cross-section of neutrino scattering off electrons would acquire an additional electromagnetic term. This single-photon exchange term changes the helicity of the final neutrino state, does not interfere with the amplitude of the weak-interaction term, and it is proportional to the square of the effective magnetic moment $\mu_{\rm eff}$:

$$\frac{d\sigma_{\rm EM}}{dT_e}(T_e, E_\nu) = \pi r_0^2 \mu_{\rm eff}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu}\right), \tag{2}$$

where $\mu_{\rm eff}$ is measured in $\mu_{\rm B}$ units and depends on the components of the neutrino moments matrix μ_{ij}, T_e is electron recoil energy, and $r_0 = 2.818 \times 10^{-13}$ cm is the classical electron radius. For $T_e << E_\nu$, the total scattering cross section is proportional to $1/T_e$ and thus the spectrum of the scattered electron is influenced mostly at low energies. The comparison of the energy spectra of electrons scattered off *pp* and ^{7}Be solar neutrinos for the case of $\mu_{\rm eff} = 0$ and $\mu_{\rm eff} < 5.0 \times 10^{-11}$ $\mu_{\rm B}$ is shown in left part of Fig. 2. The major sensitivity to the neutrino magnetic moment comes from the strong change of the shape of ^{7}Be spectrum. In case of *pp* neutrinos, the change of the shape is almost equivalent to the change of the normalisation: an independent constraint on the *pp* neutrino flux is thus of help. This was achieved by applying the results from radiochemical solar-neutrino experiments, which are independent of the electromagnetic properties of neutrinos, as a constraint to the sum of the neutrino fluxes detected in Borexino.

The updated Borexino result on the $\mu_{\rm eff}$ limit was obtained on the Phase-2 data in the FV defined such, that the reconstructed radius of an event from the detector's center $R < 3.021$ m and the vertical coordinate $|z| < 1.67$ m. The cuts reduce the live-time to 1270.6 days and the total FV exposure corresponds to 263.7 ton$\times$year. The model function fitted to the data included background components of ^{14}C, ^{85}Kr, and ^{210}Bi β^--decay shapes, the β^+ spectrum of the cosmogenic ^{11}C, the mono-energetic α peak from ^{210}Po decays, γ-rays from external background sources, and the electron-recoil spectra from ^{7}Be, *pp*, *pep*, and the CNO cycle solar neutrinos. Other backgrounds and solar-neutrino components have a negligible impact on the total spectrum. The analytical model used to describe the data is an improved version of the one described in [14] with the goal of enlarging the fitting energy range. The model function has in total 15 free parameters: the light yield, defining the energy scale, two parameters related to the energy resolution, the position and width of the ^{210}Po α-peak, the starting point of the ^{11}C β^+-spectrum, the background rates, namely ^{14}C (constrained to the value determined by analyzing an independent sample of ^{14}C events selected with low threshold), ^{85}Kr, ^{210}Bi, ^{11}C, ^{210}Po peak, and external backgrounds (responses from the ^{208}Tl and ^{214}Bi γ-rays modelled with MC), and the *pp* and ^{7}Be interaction rates represent the solar neutrino parameters. The other solar neutrino components were kept fixed according to the Standard Solar Model (SSM).

The likelihood profile as a function of $\mu_{\rm eff}$ is obtained from the fit with the addition of the electromagnetic component of the (ν, e) total cross section, as defined in Eq. 2, for ^{7}Be and *pp*-neutrinos, keeping $\mu_{\rm eff}$ fixed at each point. The electromagnetic contribution from all other solar neutrino fluxes is negligible and is not considered in the fit. Right part of Fig. 2 shows the spectral fit of the Borexino Phase-II data with the neutrino effective moment fixed at $\mu_{\rm eff} = 2.8 \times 10^{-11}$ $\mu_{\rm B}$.

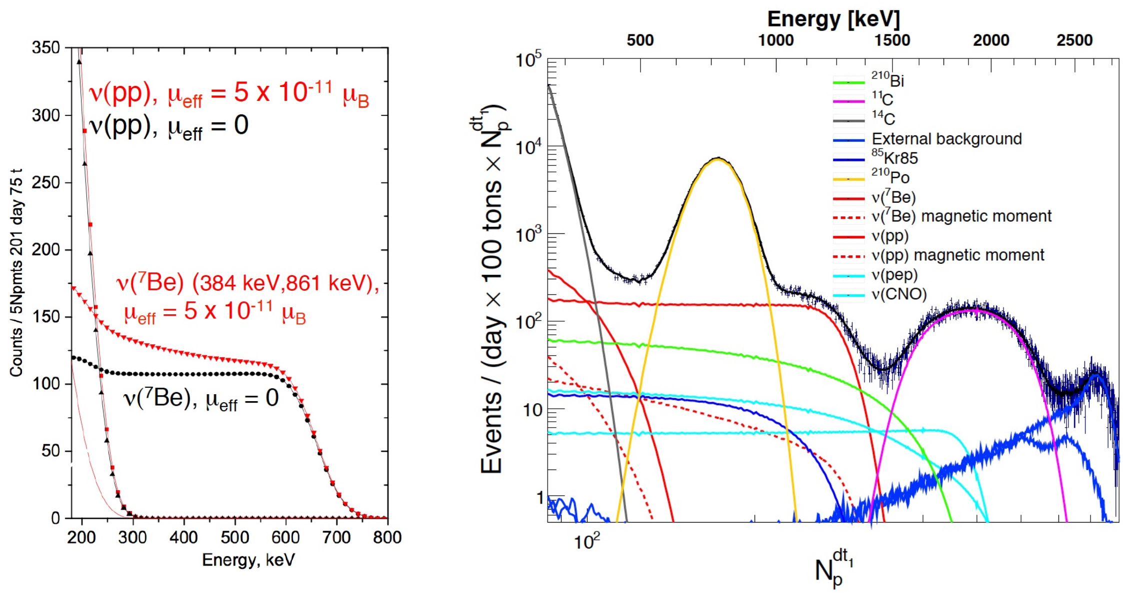

Figure 2. **(Left)** Comparison of the energy spectra of electrons scattered off *pp* and ^{7}Be solar neutrinos. The black and red points represent the case of the effective neutrino magnetic moment $\mu_{\rm eff} = 0$ and $< 5.0 \times 10^{-11}\,\mu_{\rm B}$, respectively. The red continuous line without data points represents the pure electromagnetic contribution to the total (ν, e) cross section for *pp* solar neutrinos for $\mu_{\rm eff} < 5.0 \times 10^{-11}\,\mu_{\rm B}$. **(Right)** Spectral fit of the Borexino Phase-II data with the neutrino effective moment fixed at $\mu_{\rm eff} = 2.8\times10^{-11}\,\mu_{\rm B}$ (note the scale is double logarithmic to underline the contributions at lower energies).

The radiochemical constraints mentioned above are based on the results from [15]. The measured neutrino signal in gallium experiments expressed in Solar Neutrino Units (SNU) is:

$$R = \sum_i R_i^{Ga} = \sum_i \Phi_i \int_{E_{th}}^{\infty} s_i^{\odot}(E) P_{ee}(E) \sigma(E) dE = \sum_i \Phi_i < \sigma_i^{\odot} >= 66.1 \pm 3.1 \text{ SNU}, \tag{3}$$

where R is the total neutrino rate, R_i is the contribution of the i-$^{\rm th}$ solar neutrino flux to the total rate, Φ_i is the neutrino flux from i-$^{\rm th}$ reaction, $s_i^{\odot}(E)$ is the shape of the corresponding neutrino spectrum in the Sun, $P_{ee}(E)$ is the electron-neutrino survival probability for neutrinos with energy E, and $\sigma(E)$ is the total cross-section of the neutrino interaction with Ga, which has a threshold of $E_{th} = 233\,$keV.

If applied to Borexino, the radiochemical constraint takes the form:

$$\sum_i \frac{R_i^{Brx}}{R_i^{SSM}} R_i^{Ga} = (66.1 \pm 3.1 \pm \delta_R \pm \delta_{FV}) \text{ SNU}, \tag{4}$$

where the expected gallium rates R_i^{Ga} are estimated using new survival probabilities of P_{ee} based on values from [16] (therefore giving a new estimate for $< \sigma_i^{\odot} >$), $\frac{R_i^{Brx}}{R_i^{SSM}}$ is the ratio of the corresponding Borexino-measured rate to its SSM prediction within the MSW/LMA oscillation scenario. We used the same SSM predictions for Borexino and the gallium experiments to avoid rescaling the gallium expected rates. The $\delta_R \simeq 4\%$ is the error related to the theoretical prediction of the rates in the gallium experiments, while $\delta_{FV} \simeq 1\%$ is the uncertainty of the Borexino FV selection.

Applying the radiochemical constraint of Eq. 4 to the fit as an additional penalty term, the analysis of the likelihood profile gives a limit of $\mu_{\rm eff} < 2.6 \cdot 10^{-11}\mu_{\rm B}$ at 90% C.L. Accounting for the systematic uncertainties, dominated by the choice of energy estimator and the approach used for the ^{14}C pile-up modelling, the limit on the effective neutrino magnetic moment becomes $\mu_{\rm eff} < 2.8{\cdot}10^{-11}\,\mu_{\rm B}$ at 90% C.L. The corresponding likelihood profile is shown in Fig. 3. We note, that without radiochemical constraint and without the full systematic error, the limit is weaker $\mu_{\rm eff} < 4.0 \cdot 10^{-11}\mu_{\rm B}$ at 90% C.L.

Assuming the LMA-MSW solution, the effective magnetic moment can be decomposed in the base of flavour eigenstates:

$$\mu_{\rm eff}^2 = P^{3\nu}\mu_e^2 + (1 - P^{3\nu})(\cos^2\theta_{23} \cdot \mu_\mu^2 + \sin^2\theta_{23} \cdot \mu_\tau^2), \tag{5}$$

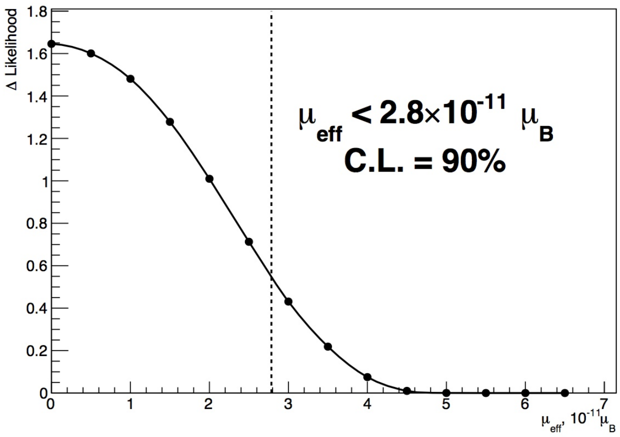

Figure 3. Resulting weighted likelihood profile used to estimate the limit on the effective neutrino magnetic moment $\mu_{\rm eff}$. The profile does not follow the Gaussian distribution as it is flatter initially and goes to zero faster than the normal distribution. The upper limit of $2.8{\times}10^{-11}\mu_{\rm B}$ corresponds to 90% of the total area under the curve. Note that unphysical values of $\mu_{\rm eff} < 0$ are not considered.

where $P^{3\nu} = \sin^4\theta_{13} + \cos^4\theta_{13}P^{2\nu}$ is the ν_e survival probability, with $P^{2\nu}$ calculated in the 2-neutrino scheme, θ_{13} and θ_{23} are the corresponding mixing angles. The limits on the neutrino flavour magnetic moment can be obtained from Eq. 5, because individual contributions are positive. With $\mu_{\rm eff} < 2.8 \cdot 10^{-11}\mu_{\rm B}$ and for $\sin^2\theta_{13} = 0.0210 \pm 0.0011$ and $\sin^2\theta_{23} = 0.51 \pm 0.04$ for normal hierarchy (or $\sin^2\theta_{23} = 0.50 \pm 0.04$ for inverted hierarchy) [16] we obtain: $\mu_e < 3.9 \cdot 10^{-11}\mu_{\rm B}$, $\mu_\mu < 5.8 \cdot 10^{-11}\mu_{\rm B}$, and $\mu_\tau < 5.8 \cdot 10^{-11}\mu_{\rm B}$, all at 90% C.L. Because the mass hierarchy is still unknown, the values above were calculated for the choice of hierarchy providing more conservative limit.

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