New constraints on magnetic moments of solar neutrinos in Borexino

A. Vishneva

JINR, Russia

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Neutrino magnetic moment in the Standard Model

Massive neutrino has a non-zero magnetic moment

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

K. Fujikawa and R. Shrock, Phys. Rev. Lett. **45**, *963 (1980).*

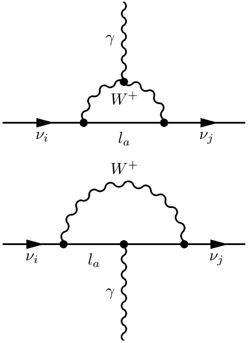
$\nu_i \to \nu_j \gamma$ interaction at one-loop level:

- changes neutrino helicity
- can change neutrino flavor

Magnetic moments in mass eigenstate basis:

- dipole moments μ_{11}, μ_{22}, μ_{33}
- transition moments μ_{12}, μ_{23}, μ_{31}
  ($\mu_{ij} = \mu_{ji}$ if CPT is conserved)

Note: effective magnetic moment μ_ν^{eff} is observed experimentally



Observable effects

Astrophysics:

- Spin-flavor rotation caused by μ_ν was considered as a possible solution of the solar neutrino problem (still might be a sub-dominant process)
- Can provide an additional mechanism of star cooling: $\mu_\nu < 3.0 \times 10^{-12}\ \mu_{\rm B}$ at 3σ level from observations of red giants

  [First considered: G.G. Raffelt, Phys. Rev. Lett. **64**, *p. 2856 (1990)]*

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Particle physics:

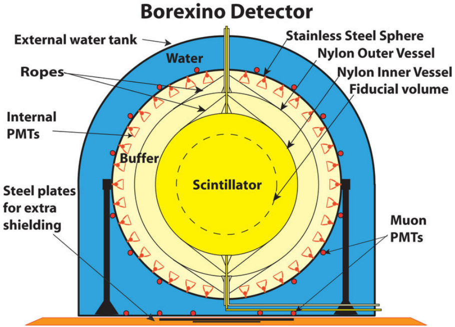
- μ_ν contributes to $\nu - e$ elastic scattering
- does not interfere with weak interaction contribution: $\sigma_{\text{tot}} = \sigma_{\text{weak}} + \sigma_{\text{EM}}$
- cross-section $\frac{\mathrm{d}\sigma_{\rm EM}(T_e,E_\nu)}{\mathrm{d}T_e} \propto \mu_{\rm eff}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$
- possible to study with scintillation detectors

Borexino detector for μ_ν studies

Main goal: real-time solar neutrino detection in sub-MeV region

Detection technique: $\nu - e$ elastic scattering

Scintillator: pseudocumene + PPO (1.5 g/l)



Energy threshold on recoil electrons: ~ 200 keV

Mass: 278 t (71.3 t fiducial)

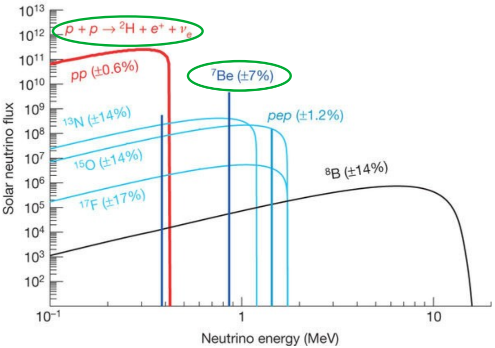
Location: Laboratori Nazionali del Gran Sasso (Italy)

Abundance of ^{238}U and ^{232}Th: $< 10^{-19}$ g/g (the most radiopure experiment ever!)

Energy resolution @ 1 MeV: $\sim 5\%$

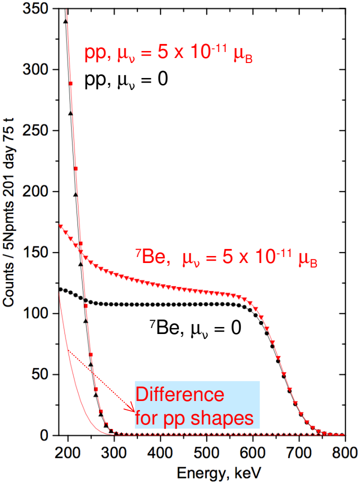
Magnetic moment of solar neutrinos

Neutrino spectra

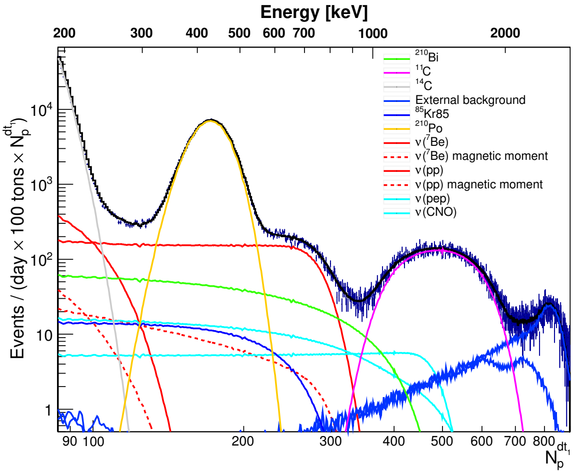


$$\frac{d\sigma_{EM}(T_e, E_\nu)}{d T_e} = \pi r_0^2 \mu_{eff}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu} \right) \Rightarrow$$

Electron recoil spectra



Electron recoil spectrum (1291.5 days of Phase-II data set)



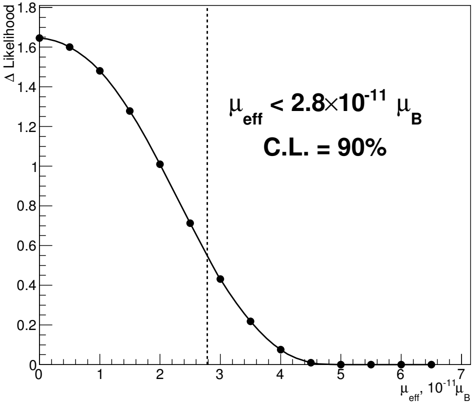
Energy estimator: number of PMTs triggered within 230 ns (`npmts_dt1`) or 400 ns (`npmts_dt2`)
Variables are normalized to 2000 working PMTs

Result for the effective solar neutrino magnetic moment

Likelihood profile
(systematics included)

Sources of systematic errors:

- choice of energy estimator (`npmts_dt1`/`npmts_dt2`)
- two approaches of pile-up description (dark noise convolution/synthetic spectral component)
- SSM constraints with high/low metallicity of the Sun



Results for mass and flavor bases

For initially electron neutrino:

Dirac: non-diagonal elements are vanishing due to GIM mechanism

$$\mu_{\text{eff}}^2 = P_{e1}\mu_{11}^2 + P_{e2}\mu_{22}^2 + P_{e3}\mu_{33}^2$$

Majorana: diagonal elements are zero under CPT conservation

$$\mu_{\text{eff}}^2 = P_{e1}(\mu_{12}^2 + \mu_{13}^2) + P_{e2}(\mu_{21}^2 + \mu_{23}^2) + P_{e3}(\mu_{31}^2 + \mu_{32}^2)$$

Flavors:

$$\mu_{\text{eff}}^2 = P_{ee}^{3\nu}\mu_{\nu_e}^2 + \left(1 - P_{ee}^{3\nu}\right)\left(\cos^2\theta_{23}\mu_{\nu_\mu}^2 + \sin^2\theta_{23}\mu_{\nu_\tau}^2\right)$$

$$\left|\mu_{11}^{\text{D}}\right| < 3.4; \quad \left|\mu_{22}^{\text{D}}\right| < 5.1; \quad \left|\mu_{33}^{\text{D}}\right| < 18.7;$$

$$\left|\mu_{12}^{\text{M}}\right| < 2.8; \quad \left|\mu_{13}^{\text{M}}\right| < 3.4; \quad \left|\mu_{23}^{\text{M}}\right| < 5.0;$$

$$\left|\mu_{\nu_e}\right| < 3.9; \quad \left|\mu_{\nu_\mu}\right| < 5.8; \quad \left|\mu_{\nu_\tau}\right| < 5.8.$$

in $10^{-11}\mu_{\text{B}}$ (90% C.L.)

Comparison with other experiments

ν_e

GEMMA:

$\mu_{\nu_e} < 2.9 \times 10^{-11} \mu_B$ (90% C.L.)

A. G. Beda et al., Phys. Part. Nucl. Lett. **10**, *139 (2013).*

This analysis:

$\mu_{\nu_e} < 3.9 \times 10^{-11} \mu_B$ (90% C.L.)

ν_τ

DONUT:

$\mu_{\nu_\tau} < 3.9 \times 10^{-7} \mu_B$ (90% C.L.)

R. Schwienhorst et al. Phys. Lett. B **513**, *23 (2001).*

This analysis:

$\mu_{\nu_\tau} < 5.8 \times 10^{-11} \mu_B$ (90% C.L.)

ν_μ

LSND:

$\mu_{\nu_\mu} < 6.8 \times 10^{-10} \mu_B$ (90% C.L.)

L. B. Auerbach et al. Phys. Rev. D **63**, *112001 (2001).*

This analysis:

$\mu_{\nu_\mu} < 5.8 \times 10^{-11} \mu_B$ (90% C.L.)

ν_{eff} (solar)

Super-Kamiokande:

$\mu_\nu^{eff} < 1.1 \times 10^{-10} \mu_B$ (90% C.L.)

D. W. Liu et al. Phys. Rev. Lett. **93**, *021802 (2004).*

This analysis:

$\mu_\nu^{eff} < 2.8 \times 10^{-11} \mu_B$ (90% C.L.)

Summary

New limit on the effective magnetic moment of solar neutrinos from 1291.5 days of Borexino data

$$\mu_\nu^{\mathit{eff}} < 2.8 \times 10^{-11} \mu_\mathrm{B} \text{ (90\% C. L.)}$$

Details: M. Agostini et al. Phys. Rev. D **96***, no. 9, 091103 (2017)* backup slides

Analytical fit approach: energy conversion

Energy → npe

$$\overline{N_{pe}} = N^0_{pe} + Y * E * \left(Q_\beta(E, k_B) + fCher * N^{Ch}_{pe}\right)$$

- N^0_{pe}: pedestal due to random noise (usually fixed at 0)
- Y: light yield (free parameter)
- $Q_\beta = \frac{1}{E}\int_0^E \frac{dE}{1+k_B\frac{dE}{dx}}$ — quenching factor (free for ^{210}Po and ^{11}C)
- k_B: Birk's coefficient (fixed by calibrations)
- $fCher * N^{Ch}_{pe}(E)$: contribution of Cherenkov light. The shape is fixed by calculations.
- $fCher$: scaling factor (free parameter)

npe → npmts

$$\overline{N_{pmts}} = N_{live}\left(1 - exp\left[-\frac{N_{pe}}{N_{live}}\right]\left(1 + pt\frac{N_{pe}}{N_{live}}\right)\right)\left(1 - gc * \frac{N_{pe}}{N_{live}}\right)$$

- N_{live}: average number of live PMTs (2000 for normalized variable)
- gc: geometric correction (fixed from Monte-Carlo studies)
- $pt = 0.12$: part of the single electron response under the threshold. Fixed from measurements (for the data fit).

Analytical fit approach: Resolution for normalized NPMTs variable

Variance

$$
\begin{aligned}
\sigma^2_{pmts} &= fEq\left[1 - p_1\left(1 + v_1\right)\right]\overline{N_{pmts}} \\
&+ 10^{-6}\frac{v_T}{fEq} * \overline{N_{pmts}}^3 \\
&+ 10^{-2} fEq * v_N * \overline{N_{pmts}} \\
&+ 10^{-4} v_q * \left(\frac{(1 - p_1)\log(1 - p_1)}{p_1}\right)^2 \overline{N_{pmts}}^2
\end{aligned}
$$

- $p_1 = \frac{N_{pe}}{N\_live}$
- $fEq = \frac{2000}{<N\_live>}$: equalization factor
- $v_1 = 0.16$: account for the variance of the PMT triggering probability for events uniformly distributed in the detector volume (fixed from calculations)
- v_N: intrinsic resolution of the scintillator — only for β's (free parameter)
- v_T, v_q: account for non-uniformity of light collection
  - v_T: free parameter, **can be different for α's and β's** (energy dependence from MC studies)
  - $v_q = 7$ (for β's): (energy dependence from calculations)

Independent constraint on the total solar neutrino flux

Neutrinos are captured in gallium experiments via charged current and thus not sensitive to neutrino electromagnetic properties:

$$^{71}Ga + \nu_e \to ^{71} Ge + e^-$$

Constraint of the total solar neutrino flux:

$$R^{Ga} = 66.1 \pm 3.1 \text{ SNU}$$

[J. N. Abdurashitov et al., Phys. Rev. C **80***, 015807 (2009)]*

$+$ additional uncertainties:

- $\delta_R \sim 4\%$: theoretical uncertainty (SSM+neutrino oscillations)
- $\delta_{FV} \sim 1\%$: fiducial mass uncertainty

added as a pull-term to the likelihood function:

$$\Delta\mathcal{L} = \frac{\left[\sum_i R_i^{Ga} \frac{R_i^{BX}}{R_i^{SSM}} - R^{Ga}\right]^2}{\sigma^2}$$