Limits on neutrino magnetic moments from the spectral analysis of the Borexino Phase-II data

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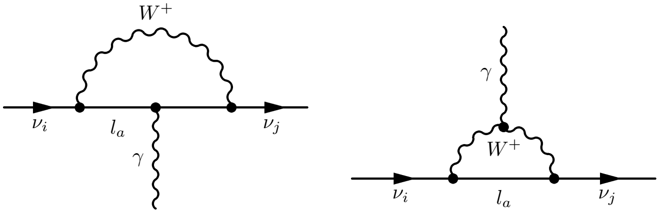
5th international solar neutrino conference

June 14, 2018

Outline

Neutrino magnetic moment in the Standard Model

- occurs at one-loop level (for massive neutrinos only)



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

- proportional to the neutrino mass

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

- changes neutrino helicity (and possibly flavor)

Magnetic moments in the mass eigenstates 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)

Dirac neutrinos

- all μ_{ij} can be non-zero
- non-diagonal elements are suppressed due to the GIM mechanism

Majorana neutrinos

- $\mu_{ii} = 0$ under the CPT-conservation
- only transition moments are non-vanishing

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- Effective magnetic moment μ^{eff} is a mixture of mass (flavor) eigenstates which 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: $\mu_\nu < 3.0 \times 10^{-12}\ \mu_\mathrm{B}$ 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 $\frac{\mathrm{d}\sigma_{\mathrm{EM}}(T_e,E_\nu)}{\mathrm{d}T_e} \propto \mu_{\mathrm{eff}}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$
- possible to study with scintillation detectors

Borexino detector

Location Laboratori Nazionali del Gran Sasso (Italy)

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

Detection technique $\nu - e$ elastic scattering, inverse β decay (for anti-neutrinos)

Energy threshold on recoil electrons ~ 200 keV

Scintillator pseudocumene + PPO (1.5 g/l)

Mass 278 t (71.3 t fiducial)

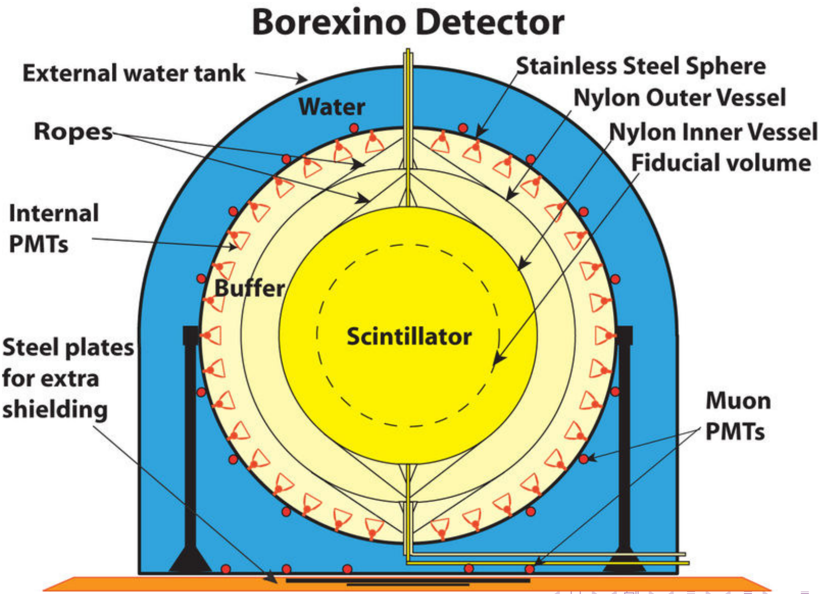
Number of PMTs nominally 2212

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

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

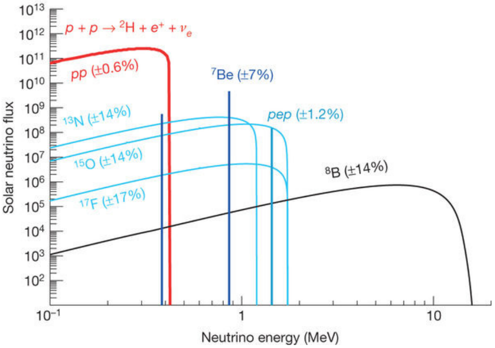
Spatial resolution @ 1 MeV ~ 10 cm

Borexino scheme



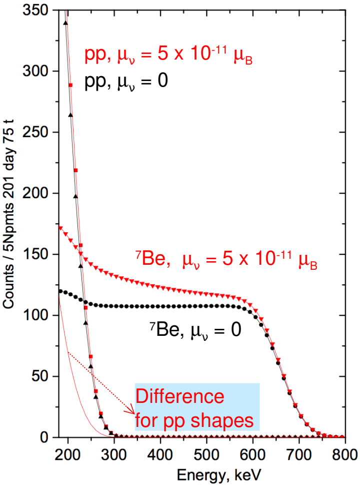
Magnetic moment of solar neutrinos

Neutrino spectra

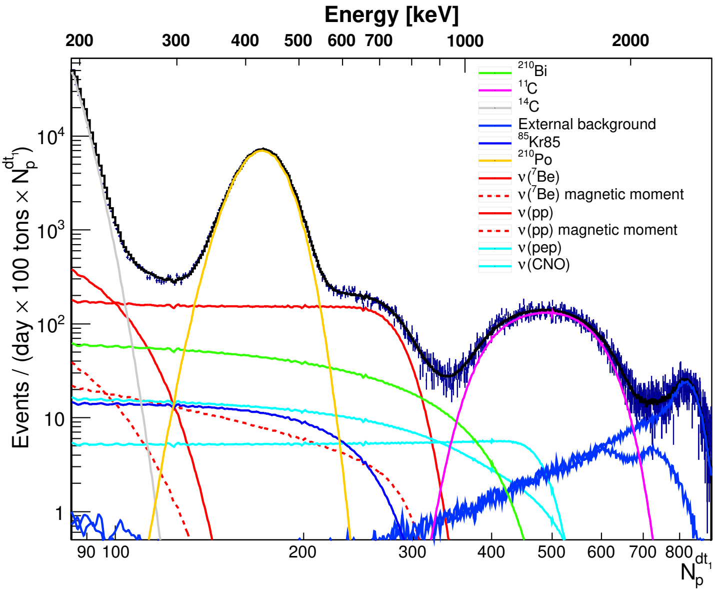


$$\frac{d\sigma_{EM}(T_e, E_\nu)}{d T_e} = \pi r_0^2 \mu_{eff}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu} \right) \Rightarrow$$

Electron recoil spectra



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



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:

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

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:

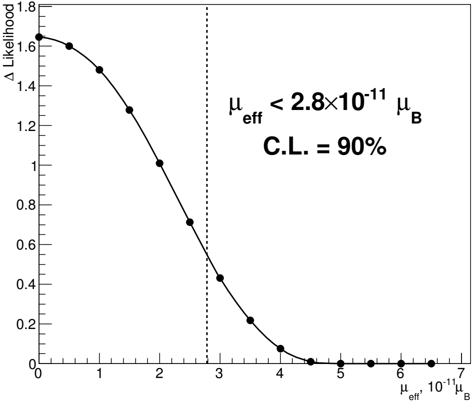
$$\Delta\mathcal{L} = \frac{\left[\sum_i R_i^{Ga} \frac{R_i^{BX}}{R_i^{SSM}} - R^{Ga}\right]^2}{\sigma^2}$$

Result for the effective solar neutrino magnetic moment

Likelihood profile
(systematics included)

Sources of systematics:

- choice of energy estimator (number of triggered PMTs within 230 or 400 ns)
- two approaches of pile-up description
- SSM constraints with high/low metallicity of the Sun



Results for mass and flavor bases

For initially electron neutrino:

Dirac:

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

Majorana:

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

Flavors:

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

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

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

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

$$|\mu_e| < 3.9; \quad |\mu_\mu| < 5.8; \quad |\mu_\tau| < 5.8.$$

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

Comparison with other experiments

ν_e

GEMMA:

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

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

This analysis:

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

ν_τ

DONUT:

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

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

This analysis:

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

ν_μ

LSND:

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

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

This analysis:

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

ν_{eff} (solar)

Super-Kamiokande:

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

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

This analysis:

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

Thank you!