Effective neutrino magnetic moment limit from Borexino data

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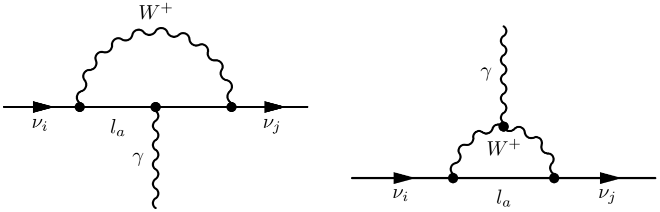
Outline

Neutrino magnetic moment in 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)
- "confusing 11-year modulation" of solar neutrino flux in Super-Kamiokande data
- 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
  [G.G. Raffelt, Astrophysical Journal, 365, p.559 (1990)]

Neutrino magnetic moment in the Standard Model

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



- proportional to the neutrino mass

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

- changes neutrino helicity (and possibly flavor)

Magnetic moments of mass eigenstates

- 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 Glashow–Iliopulos–Maiani mechanism

Majorana neutrinos

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

- Effective magnetic moment μ^{eff} is a mixture of mass (flavor) eigenstates which is observed experimentally

How to measure the neutrino magnetic moment?

- μ_ν contributes to $\nu - e$ elastic scattering
- does not interfere with weak interaction contribution (total cross-section is the sum of two)
- cross-section $\frac{\mathrm{d}\sigma_{\mathrm{EM}}(T_e,E_\nu)}{\mathrm{d}T_e} \propto \mu_{\mathrm{eff}}^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu}\right) \Rightarrow$ low threshold is needed

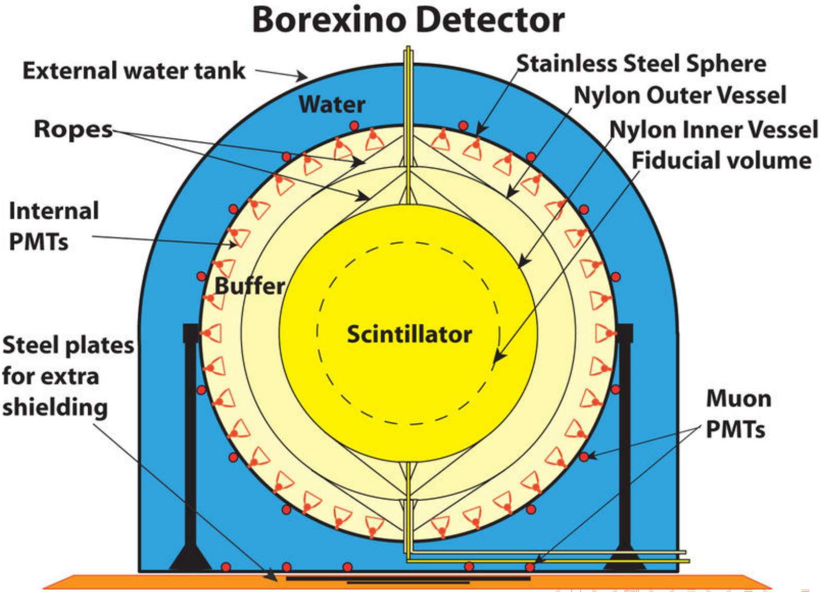
JINR participates in:

- GEMMA (KNPP, Russia): μ_{ν_e}, reactor
- BOREXINO (LNGS, Italy): μ_ν^{eff}, solar

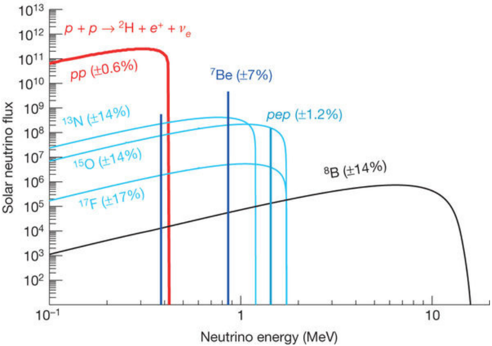
Borexino detector

- **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

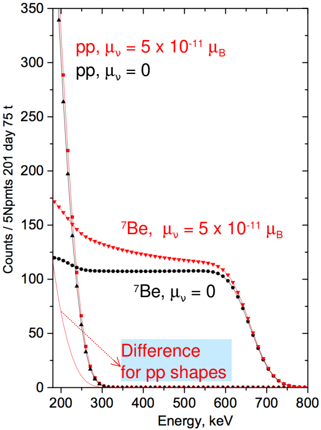
Borexino scheme



Magnetic moment of solar neutrinos

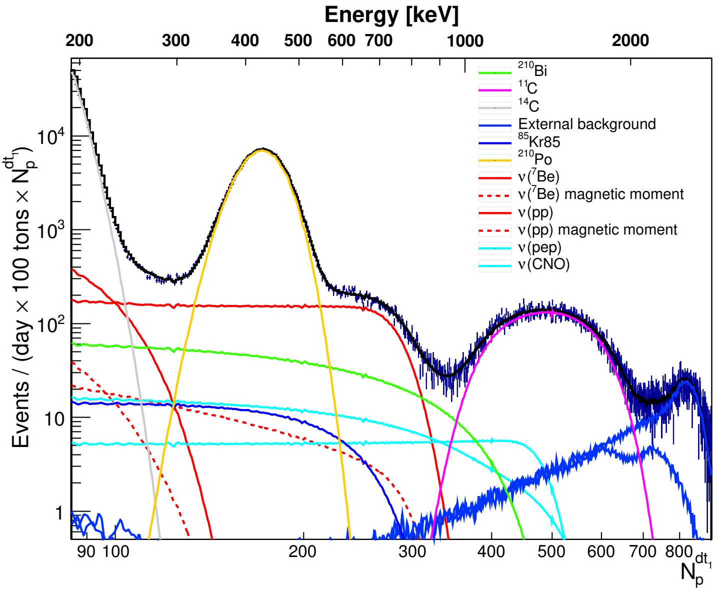


Electron recoil spectrum



only pp and ^{7}Be neutrinos are considered due to the largest fluxes at low energies

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



Independent constraint on the solar neutrino fluxes

Neutrinos are captured in gallium experiments via charged current:

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

Thus, they are not sensitive to neutrino electromagnetic properties and their data can be used in order to constrain the rate of $\nu - e$ weak interaction:

$$\sum_{solar\ \nu} R_{Ga} \frac{R_{BX}^{weak}}{R_{exp}} \frac{P_{ee}^{new}}{P_{ee}^{old}} = 66.1 \pm 3.1 \pm \delta_R \pm \delta_{FV},$$

δ_R is the uncertainty of single rates estimation
δ_{FV} is the fiducial mass uncertainty

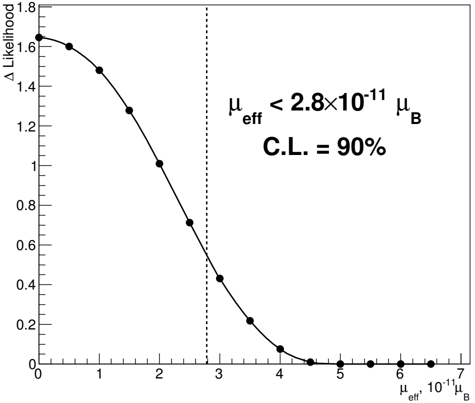
added as a pull-term in the likelihood function

Result for the effective solar neutrino magnetic moment (including systematic uncertainties)

Varying fit conditions:

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

Likelihood profile for each fit configuration is obtained by fitting the spectrum with μ_ν fixed at a certain value. The total profile is a weighted sum of the individual ones.



Results for mass and flavor eigenstates

For initially electron neutrino:

Dirac:

$$\mu^2_{\mathrm{eff}} = P_{e1}\mu^2_{11} + P_{e2}\mu^2_{22} + P_{e3}\mu^2_{33}$$

Majorana:

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

Flavors:

$$\mu^2_{\mathrm{eff}} = P^{3\nu}_{ee}\mu^2_e + \left(1 - P^{3\nu}_{ee}\right)\left(\cos^2\theta_{23}\mu^2_\mu + \sin^2\theta_{23}\mu^2_\tau\right)$$

$$\left|\mu^{\mathrm{D}}_{11}\right| < 3.4; \quad \left|\mu^{\mathrm{D}}_{22}\right| < 5.1; \quad \left|\mu^{\mathrm{D}}_{33}\right| < 18.7;$$

$$\left|\mu^{\mathrm{M}}_{12}\right| < 2.8; \quad \left|\mu^{\mathrm{M}}_{13}\right| < 3.4; \quad \left|\mu^{\mathrm{M}}_{23}\right| < 5.0;$$

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

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

Comparison with other experiments

μ_{ν_e}

GEMMA:

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

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

This analysis:

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

μ_{ν_τ}

DONUT:

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

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

This analysis:

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

μ_{ν_μ}

LSND:

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

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

This analysis:

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

μ_ν^{eff} (solar)

Super-Kamiokande:

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

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

This analysis:

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

Conclusions

- Using the Phase-II data of Borexino experiment the effective magnetic moment of solar neutrinos has been limited

Effective magnetic moment of solar neutrinos

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

- Limits on neutrino magnetic moments of mass and flavor eigenstates are also calculated

See for more details:
M. Agostini *et al.* Phys. Rev. D **96**, no. 9, 091103 (2017)