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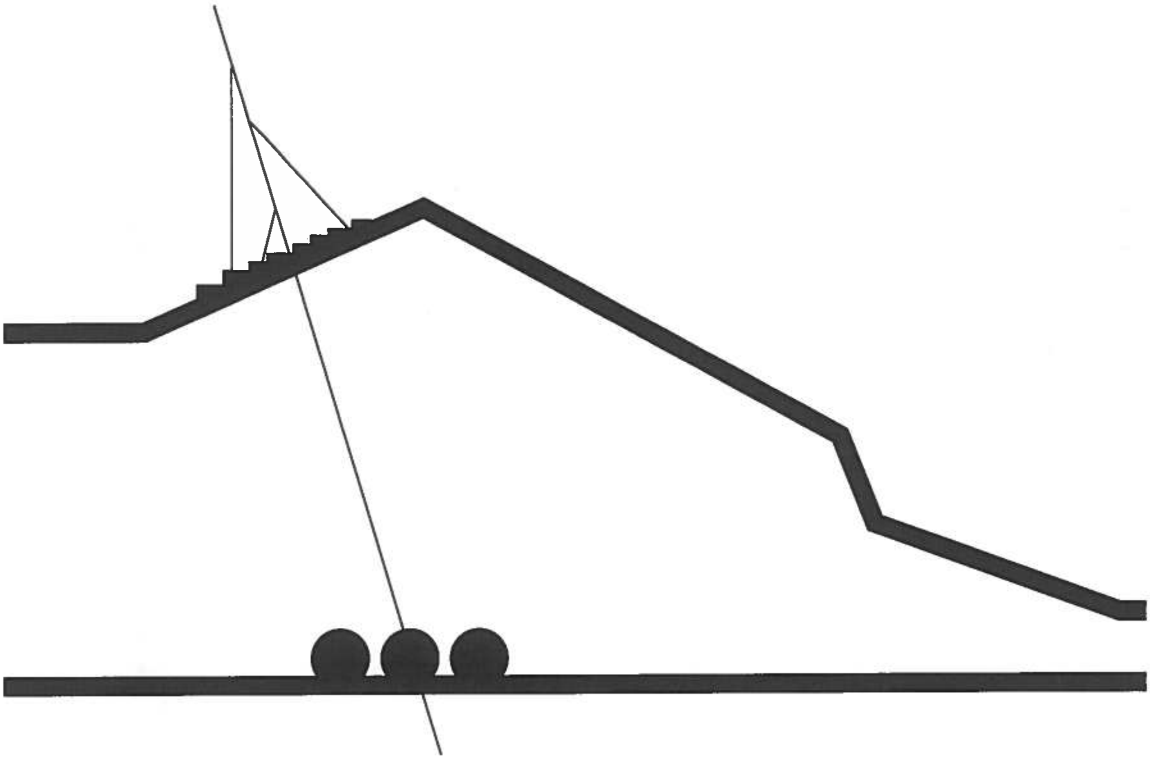

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The ^{51}Cr and ^{90}Sr sources in BOREXINO as tool for neutrino magnetic moment searches

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Abstract

The expected number of events in BOREXINO for $\nu_e(\overline{\nu}_e)e^-$ scattering using both a ^{51}Cr neutrino source and a ^{90}Sr-^{90}Y antineutrino source with an activity of $\sim$2 MCi are presented. The background solar ν rates ("source-off") are estimated for different scenarios. Then, we evaluate the possibility of BOREXINO to detect a small neutrino magnetic moment by means of the above mentioned sources. Sensitivity to $0.5 \div 0.6 \cdot 10^{-10}\mu_B$ (90% C.L.) can be reached using the ^{51}Cr source in less than 100 days of data taking in the signal region $T \in [0.25, 0.7]$ MeV, where T = recoil energy, while a sensitivity to $0.3 \cdot 10^{-10}\mu_B$ (90% C.L.) can be reached using the ^{90}Sr antineutrino source in the signal region $T \in [0.25, 1.0]$ MeV.

1 Introduction

In this paper we quantify the effect of a radioactive (anti)neutrino source to be used in BOREXINO both for calibration purpose and to search for a possible neutrino magnetic moment, as proposed in [1]. During calibration experiment, solar neutrinos are background for the measure. We evaluate this background calculating the solar neutrino flux in the Standard Solar Model (SSM) case and for two representative cases in which neutrino oscillation mechanism is active. We assume the source activity equal to the first ^{51}Cr GALLEX source (1.69±0.01 MCi) [2] and then we evaluate the sensitivity of BOREXINO in searching for deviation of the differential $\nu_e(\overline{\nu}_e)e^-$ cross section, signal for a neutrino magnetic moment.

The plan of the paper is as follows. We start by evaluating the solar neutrino rates in BOREXINO both for the SSM scenario and for the Mikheyev-Smirnov-Wolfenstein (MSW) oscillations one in Sec. 2. In Sec. 3 and 4 the rates induced in the detector respectively for the ^{51}Cr and the ^{90}Sr-^{90}Y sources are calculated. In Sec. 5 we show how a neutrino magnetic moment modifies the $\nu - e$ cross section. In Sec. 6 the implications of a nonvanishing neutrino magnetic moment for the calibration experiments are discussed. In Sec. 7 we evaluate the effective sensitivity of BOREXINO to neutrino magnetic moment using neutrino sources. Finally, in Sec. 9 we draw our conclusions.

2 The solar neutrino rates

In this section we evaluate the differential spectra for the main solar neutrino sources. Here we assume that neutrino has only standard properties. The differential cross section of the scattering process $\nu_{e,x} + e \to \nu_{e,x} + e$ (where $x = \mu, \tau$) versus the recoil kinetic energy T in the Standard Model, at first perturbative order, is [3]:

$$\frac{d\sigma_{e,x}}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(C_V + C_A)^2 + (C_V - C_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + \left(C_V^2 - C_A^2\right)\frac{m_e T}{E_\nu^2}\right] , \qquad (1)$$

where E_ν is the incident neutrino energy, $\frac{G_F^2 m_e}{2\pi} \simeq 43.05 \cdot 10^{-46}$ cm^2/MeV, $C_V = \pm\frac{1}{2} + 2\sin^2\theta_W$ (θ_W is the Weimberg angle) and $C_A = \pm\frac{1}{2}$ and the sign + (−) is used when the incident neutrino is a ν_e (ν_μ, ν_τ). We adopt $\sin^2\theta_W \simeq 0.2315$ [4]. Equation (1) is modified with the prescriptions in [5] when the one-loop radiative corrections are considered.

We also consider the finite detector energy resolution due to the photon statistics by defining a *smeared* cross section obtained by a convolution of the differential cross section in Eq. (1) with a gaussian function resolution:

$$\frac{d\widehat{\sigma}_{e,x}}{dT}(E_\nu, T) = \int_0^{T_{\max}} dT' \, \frac{d\sigma_{e,x}}{dT'}(E_\nu, T')\frac{1}{\sqrt{2\pi}\sigma_{T'}}\exp\left[-\frac{1}{2}\left(\frac{T - T'}{\sigma_{T'}}\right)^2\right] , \qquad (2)$$

where $\sigma_{T'} = \sqrt{T'/N_{pe}}$ (N_{pe} is the number of photoelectrons/MeV), T' is the *true* electron kinetic energy, T is the *measured* recoil kinetic energy and $T_{\max} = 2E_\nu^2/(m_e c^2 + 2E_\nu)$.

The photoelectron detection efficiency measured in the prototype of BOREXINO, the Counting Test Facility (C.T.F.), correspondes to 300/MeV [6]. However, a better value for BOREXINO, coming from MonteCarlo simulations, could be 430/MeV [11]. Hereafter we adopt this photoelectron detection efficiency.

We now evaluate the differential spectra (in unit of SNU/MeV) for each of the relevant solar neutrino sources by folding the smeared differential cross section in (2) with the energy spectrum of each source:

$$S_i(T) = \Phi_i \int dE_\nu \, \lambda_i(E_\nu) \frac{d\widehat{\sigma}_e}{dT}(E_\nu, T) \, , \tag{3}$$

where $i \in \{\text{pp}, {}^{13}\text{N}, {}^{15}\text{O}, {}^{8}\text{B}, {}^{7}\text{Be}(0.38), {}^{7}\text{Be}(0.86), \text{pep}\}$, Φ_i and λ_i are, respectively, the flux on Earth and the spectrum for the source i. The solar neutrino spectra and fluxes are taken from [7] according to the Helium and Metal diffusion model. For monoenergetic sources [i.e., ${}^{7}\text{Be}(0.38)$, ${}^{7}\text{Be}(0.86)$, pep] the spectrum is simply given by $\lambda_i(E_\nu) = \delta(E_\nu - E_i)$ where δ is the Dirac delta function and $E_i = 0.38, 0.86, 1.44$ MeV respectively. Fig. 1 shows the differential rates in SNU/MeV for the SSM scenario (in this figures are not included the radiative corrections for the cross section). For the sake of completeness, the total electron differential spectrum without the effect of the energy resolution is also shown in Fig. 1.

In Tabs. 1, 2, and 3 the $\nu_e e^-$ rates in Solar Neutrino Unit (1 SNU= 10^{-36} neutrino interactions per second and per target electron) for different scenarios and energy intervals of the recoil energy are reported. The total rate for the source i-th in a given window $T_1 < T < T_2$ is obtained simply integrating the spectrum $S_i(T)$ between T_1 and T_2. The rates for the SSM are calculated without and with the effect of the one-loop radiative correction to the differential cross section [5]. As can be seen, the differences among the two cases are of the order of $\sim 3\%$ and then cannot be neglected for a high precision experiment like BOREXINO. MSW-SMA and MSW-LMA stand for MSW conversion using two representative values for the oscillation parameters corresponding to the the Small Mixing Angle solution ($\Delta m^2 = 5.21 \cdot 10^{-6}$ eV^2, $\sin 2\theta = 8.06 \cdot 10^{-3}$) and the Large Mixing Angle solution ($\Delta m^2 = 1.45 \cdot 10^{-5}$ eV^2, $\sin 2\theta = 0.64$), respectively [8]. In presence of oscillations the Eq. 3 modifies as follows:

$$S_i(T) = \Phi_i \int dE_\nu \, \lambda_i(E_\nu) \left[\frac{d\widehat{\sigma}_e}{dT}(E_\nu, T) P(E_\nu, i) + \frac{d\widehat{\sigma}_x}{dT}(E_\nu, T) \left(1 - P(E_\nu, i)\right) \right] \, . \tag{4}$$

The conversion probability $P(E_\nu, i) = P(\nu_e \to \nu_e)$ is calculated following the prescriptions in [9] and smeared on the production zone of the i-*th* source inside the Sun. For simplicity, the Earth matter effect has not been included in the calculation of $P(\nu_e \to \nu_e)$. In the MSW rates reported, the radiative corrections for the scattering cross section are included. [1]

In Tab. 4 the $\nu_e e^-$ rates in Solar Neutrino Unit for different photoelectron detection efficiencies in the interval $T \in [0.25, 1.0]$ MeV are reported. The case with the efficiency of 10^4/MeV can be an approximation of the ideal detector energy resolution.

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[1] Hereafter we mark with the symbol (*) those calculations were radiative corrections in the cross

ν source	SSM	SSM (*)	MSW-SMA (*)	MSW-LMA (*)
pp	0.22	0.22	0.19	0.19
^{13}N	1.35	1.31	0.30	0.73
^{15}O	1.73	1.68	0.36	0.84
^{8}B	0.03	0.03	0.01	0.01
^{7}Be(0.38)	0.01	0.01	0.01	0.01
^{7}Be(0.86)	16.15	15.69	3.53	8.66
pep	0.59	0.57	0.12	0.26
total	20.08	19.51	4.52	10.66

Table 1: *Rates in SNU in the interval* $T \in [0.25, 0.7]$ *MeV for solar* ν*-e scattering.*

ν source	SSM	SSM (*)	MSW-SMA (*)	MSW-LMA (*)
pp	0.22	0.22	0.19	0.16
^{13}N	1.45	1.40	0.32	0.78
^{15}O	1.99	1.93	0.42	0.96
^{8}B	0.04	0.04	0.01	0.01
^{7}Be(0.38)	0.01	0.01	0.01	0.01
^{7}Be(0.86)	16.29	15.83	3.56	8.73
pep	0.71	0.69	0.14	0.32
total	20.71	20.12	4.65	10.96

Table 2: *Rates in SNU in the interval* $T \in [0.25, 0.8]$ *MeV for solar* ν*-e scattering.*

ν source	SSM	SSM (*)	MSW-SMA (*)	MSW-LMA (*)
pp	0.22	0.22	0.19	0.16
^{13}N	1.49	1.45	0.33	0.80
^{15}O	2.36	2.30	0.49	1.12
^{8}B	0.05	0.05	0.02	0.02
^{7}Be(0.38)	0.01	0.01	0.01	0.01
^{7}Be(0.86)	16.29	15.83	3.56	8.73
pep	0.95	0.93	0.19	0.42
total	21.39	20.78	4.79	11.26

Table 3: *Rates in SNU in the interval* $T \in [0.25, 1.0]$ *MeV for solar* ν*-e scattering.*

3 The ^{51}Cr source contribution

In this section we evaluate the contribution of an external pointlike monoenergetic ^{51}Cr source [E_ν = 0.751 MeV (9%), 0.746 MeV (81%), 0.431 MeV (1%), 0.426 MeV (9%)]

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section are included.

photoelectrons/MeV	SSM (*)	MSW-SMA (*)	MSW-LMA (*)
300	20.83	4.85	11.31
430	20.78	4.79	11.26
10^4	20.64	4.63	11.15

Table 4: *Rates in SNU in the interval* $T \in [0.25, 1.0]$ *MeV for solar* ν-e *scattering and different photoelectron detection efficiencies.*

with an initial activity equal to $(62.5 \pm 0.4) \cdot 10^{15}$ decay/s, similar to those used for the calibration of the GALLEX experiment [2], for a 100 tons Fiducial Volume (FV) of scintillator for the BOREXINO detector. The half-time for the ^{51}Cr decay is 27.7 d. The activity of the GALLEX source corresponds to 1.69 ± 0.01 MCi. The source is placed $D = 8.25$ m away from the vessel center underneath the BOREXINO water tank. The number of target electrons is $N_e = 3.3 \cdot 10^{31}$ electrons in the FV ($R = 3$ m radius). The differential spectrum, taking into account the "geometrical factor" (i.e., the average on the detection volume), is [1]:

$$\frac{dN}{dT} = \frac{3N_e}{2h^3}\Phi_0 \left[h - \frac{1-h^2}{2}\ln\left(\frac{1+h}{1-h}\right)\right]\frac{d\hat{\sigma}}{dT}\,, \tag{5}$$

where $h = R/D$, R being the FV radius and D the source distance from the vessel center, Φ_0 is the source flux at the vessel center. The spectrum, dN/dT, in SNU/MeV is shown in Fig. 2 by considering, for simplicity, the source activity constant and equal to the initial one.

Now we give a more realistic evaluation for the differential spectra by considering the time-dependence of the source activity. If Δt is the measurement time and t_0 the time necessary to transport the source in the underground laboratory, the number of decays in Δt can be written as:

$$N_\Delta = \frac{A(0)}{\lambda} \cdot e^{-\lambda t_0} \cdot \left(1 - e^{-\lambda \Delta t}\right)\,, \tag{6}$$

where $A(0)$ is the initial activity and λ is the decay constant. For example, we take $t_0 = 5$ days and $\Delta t = 30$ days. The corresponding spectra are shown in Fig. 3. We set the analysis window in the measured electron kinetic energy to $T \in [0.25, 0.7]$ MeV, the lower limit being determined by the ^{14}C decay background and the upper limit is $3\sigma_{T'_{\rm max}}$ above the Compton edge ($T'_{\rm max} = 0.56$ MeV) for the electrons scattered by ^{51}Cr neutrinos. In Tab. 5 the number of events in the BOREXINO FV for the ^{51}Cr source and for different data taking periods are reported.

For completeness, in appendix A we report the same calculations of this section but when the source is placed at the vessel center.

data taking period (days)	number of events (*)
$\Delta t = 30$	889
$\Delta t = 60$	1309
$\Delta t = 100$	1547

Table 5: *Possible scenarios using the* ^{51}Cr *source. Each data taking period starts 5 days after the source activation. The energy interval is* $T \in [0.25, 0.7]$ *MeV.*

4 The ^{90}Sr source contribution

In this section we consider a ^{90}Sr-^{90}Y source of anti-neutrinos as calibration source. We assume the same source activity of the the ^{51}Cr source considered in the previous section. At the equilibrium this system has an half-time of about 28 yr (the Sr half-life) and emits 2 $\overline{\nu}_e$ for any Sr decay. The differential energy spectrum of the anti-neutrino for each decay has the following form:

$$\lambda\left(E_{\overline{\nu}}\right) = A\left(Q + m_e - E_{\overline{\nu}}\right) E_{\overline{\nu}}^2 \sqrt{\left(Q + m_e - E_{\overline{\nu}}\right)^2 - m_e^2}\,\frac{x}{1 - e^{-x}}\,, \tag{7}$$

where A is a normalization factor, Q is the β-endpoint energy, m_e the electron mass and

$$x = 2\pi Z\alpha \frac{Q + m_e - E_{\overline{\nu}}}{\sqrt{\left(Q + m_e - E_{\overline{\nu}}\right)^2 - m_e^2}}\,, \tag{8}$$

Z being the atomic number and $\alpha = 1/137$. In our case we have $Q_{^{90}\mathrm{Sr}} = 0.546$ MeV and $Q_{^{90}\mathrm{Y}} = 2.27$ MeV. The spectrum of anti-neutrinos produced from this source is shown in Fig. 4.

The differential cross section for the process $\overline{\nu}_{e,x} + e \to \overline{\nu}_{e,x} + e$ is given by the same expression in Eq. (1) but with the substitution $C_A \to -C_A$. The rate (in unit of SNU/MeV) in presence of the source antineutrinos in the case of a constant source activity and equal to the initial one is shown in Fig. 5 with the total standard solar differential rate. For simplicity we do not show the spectra for a chosen data taking period as we did for the Cr source in Fig. 3. Anyway,in the same conditions as in Fig. 3, the conversion factor to obtain the spectra in unit of events/MeV/1ton/30d from SNU/MeV is 0.8542. Moreover, in Tab. 6 the number of events in the BOREXINO FV for the ^{90}Sr source in the window $T \in [0.25, 1]$ MeV and for different data taking periods are reported.

5 Neutrino magnetic moment contribution to the $\nu - e$ cross section

The presence of an electromagnetic dipole and/or a transition moment implies that neutrinos couple to the electromagnetic field. This cause an additional interaction with the scattered electron via a photon exchange. Supposing a vanishing neutrino charge radius

data taking period (days)	number of events (*)
$\Delta t = 30$	1407
$\Delta t = 60$	2811
$\Delta t = 100$	4678

Table 6: *Possible scenarios using the* ^{90}Sr *source. Each data taking period starts 5 days after the source activation. The energy interval is* $T \in [0.25, 1.0]$ *MeV.*

($\langle r^2 \rangle = 0$) the $\nu - e$ scattering cross section for a non-zero magnetic moment, μ_ν, simply reads [3]:

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(C_V + C_A)^2 + (C_V - C_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + \left(C_A^2 - C_V^2\right)\frac{m_e T}{E_\nu^2}\right] +$$

$$+\frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right) , \tag{9}$$

where α is the fine-structure constant and μ_ν is measured in Bohr magnetons (μ_B). Numerically:

$$\frac{\pi\alpha^2\mu_\nu^2}{m_e^2} \simeq 24.94 \cdot \left(\frac{\mu_\nu}{10^{-10}\mu_B}\right)^2 \cdot 10^{-46}\,\mathrm{cm}^2 \, . \tag{10}$$

The net effect of a neutrino magnetic moment is to enhance the $\nu - e$ cross section. An increase of observed scattering events respect to the those calculated by the standard formula (1) can be a signal of neutrino magnetic moment interaction. Moreover, the additional term in (9) modifies the scattered electron energy spectrum in a peculiar way. The study of the spectral distortion with respect to the standard case can provide an additional piece of information about the neutrino magnetic moment interaction that would affect the $\nu - e$ cross section. In the next section we evaluate the effect of a nonvanishing magnetic moment on the number of observed events in a calibration experiment using ^{90}Sr and ^{51}Cr source.

6 The ^{51}Cr and ^{90}Sr sources and the neutrino magnetic moment

In Fig. 6 are shown the differential spectra (in unit of SNU/MeV) for a ^{51}Cr source for a vanishing neutrino magnetic moment and for $\mu_\nu = 0.5 \cdot 10^{-10}\mu_B$. In Tabs. 7 we evaluate the difference between the number of events reported in Tab. 5 and the number of events calculated for three representative values of μ_ν and different data taking periods.

In Fig. 7 are shown the differential spectra (in unit of SNU/MeV) for a the ^{90}Sr source and for a data taking of 30 days, as discussed in the previous section, in the cases of a vanishing magnetic moment and $\mu_\nu = 0.5 \cdot 10^{-10}\mu_B$. The strong distortion of the spectra when $T \to 0$ can be noticed. In Tab. 8 we evaluate the difference between the numbers

data taking period (days)	$\mu_\nu = 0.4 \cdot 10^{-10}\mu_B$	$\mu_\nu = 0.5 \cdot 10^{-10}\mu_B$	$\mu_\nu = 0.6 \cdot 10^{-10}\mu_B$
$\Delta t = 30$	57	89	128
$\Delta t = 60$	84	130	188
$\Delta t = 100$	98	153	221

Table 7: *Differences between the number of events calculated with and without (Tab. 5) the magnetic moment contribution to the cross section for the* ^{51}Cr *source in BOREXINO. The differences are calculated for three representative values of the magnetic moment. Each data taking period starts 5 days after the source activation. The energy interval is* $T \in [0.25, 0.7]$ *MeV.*

reported in Tab. 6 and the number of events calculated for three representative values of μ_ν and different data taking. In particular, the value of $\mu_\nu = 0.3 \cdot 10^{-10}\mu_B$ is the best value that the MUNU collaboration claims to estimate [10].

data taking period (days)	$\mu_\nu = 0.2 \cdot 10^{-10}\mu_B$	$\mu_\nu = 0.3 \cdot 10^{-10}\mu_B$	$\mu_\nu = 0.4 \cdot 10^{-10}\mu_B$
$\Delta t = 30$	50	113	201
$\Delta t = 60$	100	226	401
$\Delta t = 100$	167	376	668

Table 8: *Differences between the number of events calculated with and without (Tab. 6) the magnetic moment contribution to the cross section for the* ^{90}Sr *source in BOREXINO. The differences are calculated for three representative values of the magnetic moment. Each data taking period starts 5 days after the source activation. The energy interval is* $T \in [0.25, 1.0]$ *MeV.*

7 Borexino sensitivity to neutrino magnetic moment

In Sec. 6 we have shown that a neutrino magnetic moment $\mu_\nu \sim$ few$\cdot 10^{-11}\mu_B$ can enhance substantially the event rate in the calibration experiment. Unfortunately, two kind of background annoy the measure: one is the internal background due to radioactive impurities lying into the scintillator, and the second is the solar neutrino flux. Both this backgrounds can be experimentally evaluated when the sources are off and then subtracted, but they can contribute with their statistical fluctuations to the uncertainties in the calculation of μ_ν.

The solar neutrino rate has been calculated in Sec. 1 with different scenarios of oscillations and energy window. Notice that a neutrino magnetic moment could give rise to $\nu_L \to \nu_R$ transitions (in the case of Dirac neutrinos) or $\nu_e \to \overline{\nu}_\mu$ transitions (in the case of Majorana neutrinos) due to neutrino magnetic interactions with the strong solar magnetic field. In both cases, the rates calculated in Sec. 1 could be affected by neutrino magnetic moment itself. However, at a first approximation, we not account for this effect since we want give only an estimation of the solar neutrino background with and without oscillations. At this level, we consider only the effect of the neutrino magnetic moment in the $\nu - e$ cross section. For completness in Fig. 8 we report the solar neutrino spectra for two representative μ_ν values together to the standard spectra.

To quantify the sensitivity of BOREXINO to the small μ_ν contribution to the total $\nu - e^-$ scattering cross-section, we compare the "source-on" to the "source-off" total number of events detected for different time windows considering the solar neutrino signal and the internal BOREXINO radioactivity as a constant background to the number of events induced by the source. In the signal region $T \in [0.25, 0.7]$ MeV the radioactivity background [11] in the BOREXINO FV is ~16 events/d, when ^{238}U, ^{232}Th~ 10^{-16} g/g and K$_{nat}$~ 10^{-14} g/g. Therefore, assuming that BOREXINO detects N total events in one year of "source-off" data taking, the number of events in a time window of Δt days is fN, where $f = \Delta t/365$. The corresponding one standard deviation error is $\sqrt{(1+f)fN}$, taking into account both the error due to statistical fluctuations and the one due to the finite time acquisition of the background. Notice that the solar neutrino flux change in one year by a factor of ±3.34% from its average value due to the "$1/R^2$" effect. [2] The solar neutrino flux should be corrected by this factor depending on the period of the year in which the calibration experiment is performed. Since we do not know when the experiment will be done, we assume here a constant solar neutrino rate equal to the annual average. In this case, the ^{51}Cr standard "source-on" scenario at 90% C.L., using the SSM neutrino flux or the MSW-LMA and MSW-SMA as in Tab. 1 is shown in Tab. 9.

data taking period (days)	SSM (*)	MSW-LMA (*)	MSW-SMA (*)
$\Delta t = 30$	3038 ± 94	2281 ± 81	1756 ± 71
$\Delta t = 60$	5607 ± 132	4092 ± 112	3126 ± 95
$\Delta t = 100$	8710 ± 171	6186 ± 141	4436 ± 120

Table 9: *Possible standard "source-on" scenario in the ^{51}Cr signal region including the radioactivity background. The errors are only statistical and at 90%C.L.*

For the ^{90}Sr source signal region an even pessimistic (because of the higher ^{40}K contamination considered) background of 37.7 events/d can be considered [11] (^{238}U, ^{232}Th~ 10^{-16} g/g and K$_{nat}$~ 10^{-13} g/g). The corresponding "source-on" scenario in analogy to the ^{51}Cr case is shown in Tab. 10.

Using these data and the previous results (Tabs. 5, 6), it turns out that a sensitivity at 90% C.L. to $0.5 \div 0.6 \cdot 10^{-10} \mu_B$ can be reached in BOREXINO with a GALLEX-like ^{51}Cr neutrino source depending on Solar Neutrino scenario. The sensitivity can be lowered to $0.3 \cdot 10^{-10} \mu_B$ using a ~2 MCi ^{90}Sr-^{90}Y antineutrino source.

Finally, to give a more general description of the BOREXINO sensitivity to μ_ν, we report in Fig. 9 and in Fig. 10 the difference in the number of counts due to a nonvanishing μ_ν versus the "source-on" data taking time experiment for the Cr and Sr source,

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[2] In the case of vacuum oscillations this factor could be greater. For simplicity here we do not consider this effect.

data taking period (days)	SSM (*)	MSW-LMA (*)	MSW-SMA (*)
$\Delta t = 30$	4316 ± 110	3501 ± 100	2948 ± 92
$\Delta t = 60$	8628 ± 161	6999 ± 145	5893 ± 132
$\Delta t = 100$	14373 ± 214	11658 ± 191	9814 ± 174

Table 10: *Possible standard "source-on" scenario in the ^{90}Sr signal region including the radioactivity background. The errors are only statistical and at 90%C.L.*

respectively. In the same figures the background fluctuation for different scenarios is also shown.

Fig. 10 shows the possibility to reach a sensitivity to $0.2 \cdot 10^{-10}\mu_B$ in BOREXINO using the Sr source for a data taking time longer than 200 days. Of course for such a long experiment a detailed analysis of the solar neutrinos background, which takes into account the $1/R^2$ effect, is needed.

8 Conclusions

In this paper we have studied the possibility of a neutrino magnetic moment search through the study of the event rate and the spectrum in the BOREXINO detector of neutrinos produced from an external artificial source. In particular, we have studied two neutrino sources, i.e. the ^{51}Cr (monoenergetic neutrinos) and the ^{90}Sr (antineutrinos with continuum spectra). The solar neutrino background has been evaluated in different scenarios with and without neutrino oscillations. Taking into account also the internal background, a sensitivity to $\mu_\nu = 0.5 \div 0.6 \cdot 10^{-10}\mu_B$ (90% C.L.) can be reached using the ^{51}Cr source. This sensitivity can be increased to $0.3 \cdot 10^{-10}\mu_B$ (90% C.L.) by using the ^{90}Sr antineutrino source and even to $0.2 \cdot 10^{-10}\mu_B$ in a "long range" experiment. Furthermore, more information can be obtained analyzing the shape of the scattered electron spectrum that can be substantially modified at low energies.

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Appendix A: Locating the source at the center of the detector

In this appendix we estimate the rates with and without a possible neutrino magnetic moment when the source is placed in the vessel center. In this way, the source neutrino counting rate (and hence, the sensitivity) would be enormously increased, although the technical problems that arise when one attempts to place a radioactive source in the vessel are enormous. For simplicity, we consider only the ^{51}Cr source with the same activity as in Sec. 3. When the source is placed in the vessel center, the Eq. (5) simply reads:

$$\frac{dN}{dT} = 3N_e\Phi(R)\frac{d\hat{\sigma}}{dT} , \tag{11}$$

where $\Phi(R)$ is the source neutrino flux at distance R from the center (where $R = 3$ m is FV radius). The results of calculation are reported in Tab. 11. As can be seen, we have an increase in the signal of about a factor 20 greater than the one calculated with the source placed outside the vessel, as in Sec. 3.

data taking period (days)	$\mu_\nu = 0$	$\mu_\nu = 0.3 \cdot 10^{-10} \mu_B$
$\Delta t = 30$	19620	20322
$\Delta t = 60$	28883	29916
$\Delta t = 100$	34122	35342

Table 11: *Possible scenarios using the ^{51}Cr source located at the vessel center. Each data taking periods starts 5 days after the source activation. The energy interval is* $T \in [0.25, 0.7]$ *MeV.*

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