Prospects for Detecting a Neutrino Magnetic Moment with a Tritium Source and Beta-beams

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We compare the prospects for detecting a neutrino magnetic moment by the measurement of neutrinos from a tritium source, reactors and low-energy beta-beams. In all cases the neutrinos or antineutrinos are detected by scattering of electrons. We find that a large (20 MCurie) tritium source could improve the limit on the neutrino magnetic moment significantly, down to the level of a few $\times 10^{-12}$ in units of Bohr magnetons μ_B while low-energy beta-beams with sufficiently rapid production of ions could improve the limits to the level of a few $\times 10^{-11} \mu_B$. The latter would require ion production at the rate of at least 10^{15} s^{-1}.

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1 Introduction

Physicists have long speculated on the existence of a neutrino magnetic moment. Since recent evidence for neutrino oscillations provides indirect evidence for a neutrino mass, this suggests that neutrinos have small magnetic moment, although the size will depend on the nature of the neutrino mass, Dirac or Majorana. In the case of a Dirac mass, standard model interactions give the neutrino a magnetic moment of $3 \times 10^{-19}(m_\nu/\text{eV})$ in units of Bohr magnetons, μ_B, although beyond the Standard Model interactions could give the neutrino a larger magnetic moment. A positive measurement of the neutrino magnetic moment would therefore provide valuable information for understanding the neutrino mass mechanism.

At present, limits on the neutrino magnetic moment come both from direct measurements and indirect considerations. The most recent experiments using reactor neutrinos set the present upper limit of $\mu_\nu < 1.0 \times 10^{-10} \mu_B$ at 90% C.L. by the MUNU collaboration at the Bugey reactor [1] and $\mu_\nu < 1.3 \times 10^{-10} \mu_B$ at 90% C.L. by the TEXONO collaboration at the Kuo-Sheng reactor [2]. Previous measurements set similar upper limits. From the pioneering experiment at Savannah River [3] and the following experiments at the Kurtchatov and Rovno reactors, the limits $\mu_\nu < 2 - 4 \times 10^{-10} \mu_B$ [4], $\mu_\nu < 2.4 \times 10^{-10} \mu_B$ at 90% C.L. [5], $\mu_\nu < 1.9 \times 10^{-10} \mu_B$ at 95% C.L. [6] have been derived respectively. From solar neutrino-electron scattering at SuperKamiokande a limit of $< 1.5 \times 10^{-10} \mu_B$ at 90% C.L. has been obtained [7]. From astrophysical and cosmological considerations, namely Big Bang nucleosynthesis, star lifetime and cooling and supernova explosions [8], one infers upper limits in the range $10^{-11} - 10^{-12} \mu_B$. The exact values for these limits are model dependent. Since neutrinos mix, and different flavors will contribute in different cases, the reactor, solar and astrophysical limits cannot be compared directly. However, for experiments which make use of terrestrial neutrinos and have a short baseline relative to the energy of the neutrinos, those originally produced as ν_e ($\bar{\nu}_e$) will have had little opportunity to change flavor. Whether the baseline (L) is long or short depends on the energy of the neutrinos. For mixing associated with the solar neutrino solution, there will be little transformation as long as $(L/\mathrm{m}) \ll 25(E/\mathrm{keV})$, and for transformation governed by the third mixing angle and mass squared difference, the baseline is short as long as $(L/\mathrm{m}) \ll 0.4(E/\mathrm{keV})$. In the latter situation the transformation will not be large even if the baseline is long, because the mixing angle is small and, for this reason, as yet unknown.

Since the neutrino magnetic moment interaction operates in the mass eigenstate basis, an incoming electron neutrino will scatter via a photon into at least three possible final states. For Dirac neutrinos, we can write, $\mu_e^2 = \sum_i |U_{ie}|^2 \mu_i^2$, where μ_i are the magnetic moments in the mass eigenstate basis, and $|U_{ie}|^2$ are entries in the Maki-Nakagawa-Sakata (MNS) matrix. However, if the magnetic moment were not diagonal the above equation should be expanded to include transition moments. Similarly in the case of a Majorana neutrino, one needs to take into account a sum over all transition moments. In all cases we consider here however, the measurement is of the scattering of an electron neutrino or antineutrino into any type of neutrino by way of the magnetic moment, so we can compare the case of reactor neutrinos, a tritium source and beta-beams directly without the need to decompose a neutrino magnetic moment into its possible components in the mass basis.

The scenario with a tritium source that we consider is a 200 MCurie, 20 kg source which is used in conjunction with a large Time Projection Chamber (TPC) detector. This has just been proposed as a way to explore many neutrino properties [9] one of which is the neutrino magnetic moment. This idea

in principle is very attractive because of the low threshold of the detector and the large number of neutrinos from the source.

"Beta-beams" is a novel method to produce neutrino beams which consists in boosting radioactive nuclei, that decay through beta-decay, to obtain an intense, collimated and pure neutrino beam [10]. The use of this new concept to have a beta-beam facility for low-energy neutrinos has been proposed by Volpe [11] and has the important benefit that the neutrino spectra will be well understood. Interest in this method is fairly recent and studies of the feasibility of such beams are planned [12].

In this letter we investigate the potential for setting new limits on the neutrino magnetic moment using a tritium source or a low-energy beta-beam. We use the specific example of a TPC detector to observe neutrino-electron scattering. We compare the sensitivities which could be obtained by these methods with what can be achieved with reactor neutrinos.

2   Calculations and Results

Each of the sources we consider emits a neutrino flux which peaks at different energies. For the tritium source and the low-energy beta-beams, the neutrino flux is just that of a standard beta decay spectrum from a nucleus at rest. To calculate the spectrum, we use a Fermi function to approximate the final state Coulomb interaction. Tritium is a low energy source, since the maximum energy of the antineutrinos it produces is 18.6 keV. The ions typically considered for the beta-beams, such as ^{6}He, a β_- emitter and ^{18}Ne, a β_+ emitter, have Q-values of a few MeV, although other ions with smaller Q-values may be considered in the future. In table 1 we give the fluxes for these two beta-beam emitters. Reactor antineutrinos have a different spectrum since they are produced by many pathways in the course of the fissioning of the nuclei. The understanding of the exact nature of the reactor flux at low energies is therefore less certain than in the case of the beta decay of a single isotope, but the spectrum peaks at around 1-2 MeV. We use the antineutrino fluxes as given by [4].

In all cases considered the neutrinos are detected through recoil electrons from neutrino-electron scattering. The weak and electromagnetic cross section as a function of recoil energy T and neutrino energy E_ν is given by [4]

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

$$+ \frac{\pi \alpha^2 \mu_\nu^2}{m_e^2} \frac{1 - T/E_\nu}{T}$$

where $g_V = 2\sin^2\theta_W + 1/2$, θ_W is the Weinberg angle, $g_A = 1/2$ (-1/2) for ν_e ($\bar{\nu}_e$), m_e is the electron mass and G_F is the Fermi coupling constant. Following Eq. (1) we consider scattering of neutrino on free electrons. The effect of atomic binding is discussed in [13]. These cross sections have to be averaged by the neutrino flux from the relevant source :

$$\langle \frac{d\sigma}{dT} \rangle = \frac{\int \frac{dN_\nu}{dE_\nu} \frac{d\sigma(E_\nu)}{dT} dE_\nu}{\int \frac{dN_\nu}{dE_\nu} dE_\nu} \tag{2}$$

where dN_ν/dE_ν is the number of neutrinos per unit energy emitted by the neutrino source. Note that the electron recoil energy is restricted to the values :

$$T \lesssim \frac{2E_\nu^2}{2E_\nu + m_e} \tag{3}$$

At lower electron recoil energies the flux-averaged weak cross section becomes constant while the part proportional to the magnetic moment diverges. Experimentally one searches for the contribution from the magnetic moment by looking for an excess of counts at low electron recoil energy. The lack of such an observation has produced the current limit on the magnetic moment e.g. [1,2,6]. In tables 2 and 3 we give flux-averaged electron-neutrino cross sections (Eq.2) as a function of recoil energy.

In order to consider the number of counts as a function of electron recoil energy we take the specific example of a TPC detector as in Ref.[9]. For both the beta-beams and the tritium source, the geometry is the same 4π configuration where the source is located at the center. The radius of the detector is 10 meters and contains 20 tons of Xenon. In the comparison with the reactor experiments we consider a detector located 18 m from the source and having 1 m^3 volume as used in the MUNU experiment [1], although we take Xenon as the detection medium.

3   Toward New limits on the Magnetic Moment: Tritium and Beta-Beams

Here we compare the sensitivities of the recoil electron spectrum to a non-zero magnetic moment for the three different neutrino sources. In Figs. 1-3 we show the electron scattering rates as a function of electron recoil energy for cases
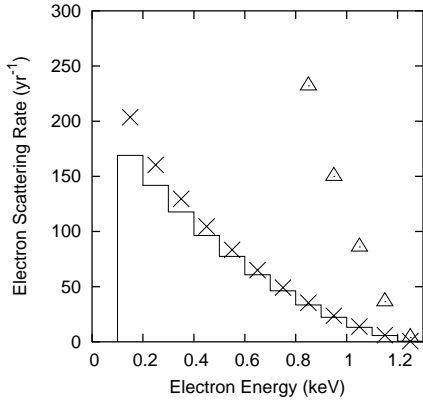
Fig. 1. TRITIUM SOURCE: Number of neutrino-electron scattering events from a 20 MCurie Tritium source in a 4π TPC detector of 10m in radius. The crosses give the number of scatterings if the neutrino has a magnetic moment of $\mu_\nu = 10^{-12}\mu_B$, while the triangles present the number of counts if $\mu_\nu = 10^{-11}\mu_B$. The histogram shows the expected number of events for a vanishing neutrino magnetic moment.
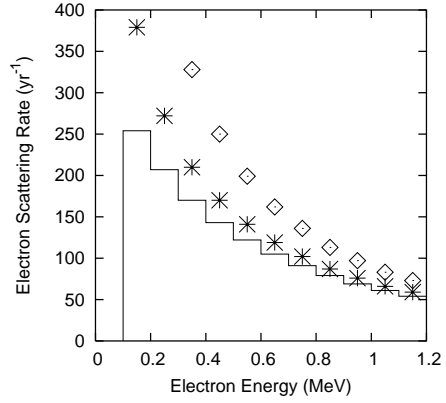
Fig. 2. REACTOR: Number of neutrino-electron scattering events from a 2750MW reactor in a detector of $1m^3$ volume at distance of 18m. The diamonds show the number of scatterings if the neutrino has a magnetic moment of $\mu_\nu = 10^{-10}\mu_B$, while the stars show the number of counts if the neutrino has a magnetic moment of $\mu_\nu = 5 \times 10^{-11}\mu_B$. The histogram shows the expected number of events for a vanishing neutrino magnetic moment.

with and without a neutrino magnetic moment. The event rate is obtained by combining the flux-averaged cross sections with both the number of electrons in the detector and the number of neutrinos per unit time and area in the detector. A 100 % efficiency has been assumed in all cases.

Figure 1 shows the electron rate for the tritium source. The detector is sensitive to an electron energy above 100 eV and the maximum electron energy from this source is 1.26 keV. We find about 900 events/year in the absence of a neutrino magnetic moment. For a magnetic moment of $10^{-11}\mu_B$, this number is increased to ten thousand events per year. Since the cross section is diverging, most of these events occur at the lower energies, where the points are so large that they are not shown on the figure. As can be seen from the figure the limit $\mu_\nu = 10^{-11}\mu_B$ is clearly distinguishable while $\mu_\nu = 10^{-12}\mu_B$, which would produce about one hundred events in this energy range, seems more challenging. From this, one expects a sensitivity of a few $\times 10^{-12}\mu_B$ to be achievable, with the exact value to be determined by detailed detector simulations. Fig 1 clearly shows that the use of a 200 MCurie tritium source, which has a well understood spectrum coupled with a low threshold detector, e.g.[9], can be extremely attractive from the point of view of setting limits on the neutrino magnetic moment.
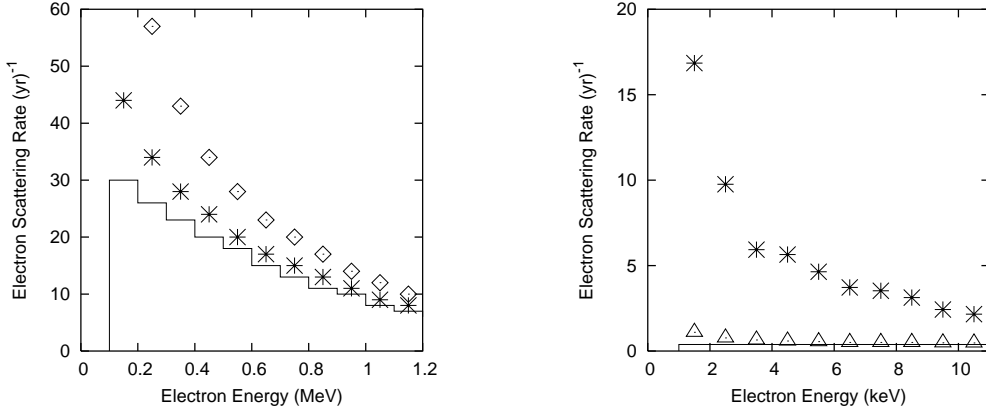
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Fig. 3. BETA-BEAMS: Number of neutrino-electron scattering events from a Helium-6 ion source produced at the rate 10^{15} per second, and a 4π detector of 10 m in radius. The diamonds show the number of scatterings if the neutrino has a magnetic moment of $\mu_\nu = 10^{-10}\mu_B$, the stars present the number of events if $\mu_\nu = 5 \times 10^{-11}\mu_B$, and the triangles give the number of events if the neutrino has a magnetic moment of $\mu_\nu = 10^{-11}\mu_B$. The histogram shows the expected number of events for a vanishing neutrino magnetic moment.

Scattering rates for neutrinos produced by reactors are shown in Figure 2. For the purposes of this figure, we assume a 2750 MW reactor, like the Bugey reactor, and a fuel composition of 55.6% ^{235}U, 32.6% ^{239}Pu, 7.1% ^{238}U and 4.7% ^{241}Pu. For these values the number of neutrinos produced is about $4 \times 10^{20}\nu$/s and as stated before, we assume that the detector is located about 18 meters away from the source. Since the reactor neutrino flux peaks at 1-2 MeV there are significant electron recoil events in the tenths of MeV range. Between 0.1 MeV and 1.2 MeV, there would be about 400 events in three months with this detector and this number would increase to 500 with a neutrino magnetic moment of $5 \times 10^{-11}\mu_B$. Therefore, if the electron recoil is measured in this range, it is in principle sensitive to a magnetic moment of $5 \times 10^{-11}\mu_B$ or even smaller. In order to reach this it is crucial to understand the low energy part of the neutrino spectrum [14]. In fact, there are several sources of uncertainty, like for example β-decays, which are not well known, either of the fission products or induced by neutrons absorbed by the materials. A detailed discussion of the influence of such uncertainty on the μ_ν sensitivity, for different energy ranges of the electron recoil energy, is presented in [14]. The knowledge of the low energy spectra is a limiting factor in the MUNU experiment [1] which quotes a limit based on data taken above 900 keV.

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Let us now consider the case of a beta-beam source. Similarly to the case of a static tritium source, an advantage of the beta-beams is that the neutrino fluxes can be very accurately calculated. Figure 3 shows the electron-neutrino scattering events in the range of 0.1 MeV to 1 MeV and 1 keV to 10 keV respectively. (In Figure 3b we have rounded to the nearest integer number of counts). The shape of the flux-averaged cross sections is very similar to the reactor case as reflected in the event rates shown in the figures. As can be seen, by measuring electron recoils in the keV range with a beta-beam source one could, with a sufficiently strong source, have a very clear signature for a neutrino magnetic moment of $5 \times 10^{-11} \mu_B$. These figures are for Helium-6 ions, however, similar results can be obtained using neutrinos from ^{18}Ne. The results shown are obtained for an intensity of 10^{15} ν/s (i.e. 10^{15} ions/s). If there is no magnetic moment, this intensity will produce about 170 events in the 0.1 MeV to 1 MeV range per year and 3 events in the 1 keV to 10 keV range per year. These numbers increase to 210 and 55 respectively in the case of a magnetic moment of $5 \times 10^{-11} \mu_B$.

Although the first feasibility study shows that an intensity of a few $\times 10^{13}$ ions/s can be reached for ^{6}He [15], higher intensities such as 10^{15} ions/s may be obtained for specific ions and/or designs [16]. An intensity at least that high is needed to improve the present limit on the neutrino magnetic moment.

4   Conclusions

We have discussed different routes for obtaining improved limits on the neutrino magnetic moment. The best scenarios for improving the limits, or indeed for detecting a neutrino magnetic moment, will involve three main aspects. One needs to understand well the spectrum of the neutrino source, to be able to measure electron recoil at as low energy as possible, and to have an intense neutrino flux.

The main advantage of a large tritium source when combined with a low threshold detector such as a large TPC detector, is that the neutrino flux is well known and many counts can be obtained at low recoil energy. Such a configuration is very attractive since one can obtain sensitivities to the neutrino magnetic moment of a few $\times 10^{-12} \mu_B$.

Reactor neutrinos have provided the best terrestrial limits on the neutrino magnetic moment to date $\mu_\nu \lesssim 10^{-10} \mu_B$. Reactor experiments have the advantage that there is an intense source that can be utilized. In order to improve the current limits using reactor neutrinos, one needs to be able to measure and understand well the electron recoil spectrum below an MeV, for which it is necessary to understand the low energy component of the neutrino flux.

Beta-beams provide a new and as yet unexplored possibility for measuring a neutrino magnetic moment. As in the case of the tritium source, the knowledge of the spectrum of neutrinos is very good. The limiting feature of this scenario is the intensity of the neutrino fluxes. One needs at least 10^{15} ions/s in order to improve the current limit and reach a few $\times 10^{-11} \mu_B$. For higher fluxes, one obtains better limits. For a low energy application such as this, it would be extremely helpful to evaluate ways to attain high production rates for beta-beam ions.

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$E_{\bar{\nu}}$ (MeV)	$\frac{dN_\nu}{dE_\nu}$
0.35	0.04
0.70	0.14
1.1	0.27
1.4	0.36
1.75	0.40
2.1	0.41
2.5	0.37
2.8	0.28
3.2	0.14
3.5	0.02

E_{ν} (MeV)	$\frac{dN_\nu}{dE_\nu}$
0.34	0.02
0.68	0.06
1.0	0.11
1.4	0.16
1.7	0.18
2.1	0.19
2.4	0.17
2.7	0.13
3.1	0.07
3.4	0.01

Table 1

The left table shows the spectrum of antineutrinos (MeV^{-1} s^{-1}) from ^{6}He and the right table shows the spectrum of neutrinos (MeV^{-1} s^{-1}) from ^{18}Ne from the decay to the ground state of ^{18}F (92% branch).

T recoil (MeV)	WEAK	MAGNETIC $\times (\mu_\nu/10^{-10})^2$
3.5×10^{-4}	10.1	7090.
7.0×10^{-4}	10.1	3540.
1.0×10^{-3}	10.1	2360.
5.3×10^{-3}	10.1	471.
1.0×10^{-2}	10.0	243.
5.0×10^{-2}	9.5	48.
1.0×10^{-1}	8.9	23.
5.0×10^{-1}	5.2	3.4
1.0	2.5	1.0
3.1	6.0×10^{-3}	7.2×10^{-4}

Table 2

Flux-averaged cross sections, $\langle d\sigma/dT \rangle$ in units of (10^{-45} cm^{2}MeV^{-1}) as a function of electron recoil for electron scattering of ^{6}He antineutrinos. The column labeled WEAK was calculated with the term in Eq.(2) which is proportional to G_F^2, while the column labeled MAGNETIC was calculated with the term in Eq.(2) which is proportional to μ_ν^2.

T recoil (MeV)	WEAK	MAGNETIC $\times (\mu_\nu/10^{-10})^2$
3.4×10^{-4}	10.1	7260.
6.8×10^{-4}	10.1	3630.
1.0×10^{-3}	10.1	2420.
5.1×10^{-3}	10.1	483.
1.0×10^{-2}	10.1	240.
5.0×10^{-2}	10.0	48.
1.0×10^{-1}	9.9	23.
5.0×10^{-1}	8.9	3.4
1.	7.3	1.0
3.1	2.5×10^{-2}	1.8×10^{-4}

Table 3

As in Table 2, flux-averaged cross sections (10^{-45} cm^{2}MeV^{-1}) as a function of electron recoil for electron scattering of ^{18}Ne neutrinos are shown.