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Neutrino oscillation and magnetic moment from $\nu - e^-$ elastic scattering

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Abstract. We discuss how the measurement of the $\bar{\nu}_e - e^-$ elastic cross section at reactor energies can be used to extract new information on the neutrino oscillation parameters. We also consider the magnetic moment contribution and show how both effects tend to cancel each other when the total cross section is measured. To achieve the separation of each of the effects, experiments capable of measuring angular and energy distributions with respect to the outgoing electron become necessary. The sensitivity of these kind of experiments to magnetic moments, masses and mixings is discussed. We also discuss the possibility of measuring the magnetic moment of τ neutrinos via $\bar{\nu}_e \leftrightarrow \bar{\nu}_\tau$ oscillation.

1 Introduction

Neutrino-electron elastic scattering is the most elementary purely weak scattering process. It involves very well known particles (e^-) and neutrinos and thus it is a clean probe for the study of neutrino properties [1]. Nevertheless, the smallness of the cross section seems a serious drawback to obtain precision measurements. At accelerators, there exist measurements of the weak couplings reaching a 5% precision in the determination of $sin^2\theta_W$ [2]. In reactor experiments such statistics has been far from reach until now.

The interest of the elastic process $\bar{\nu}_e - e^-$ at reactors has been concealed to setting bounds for the electromagnetic properties of neutrinos [3–5]. Elastic $\nu - e$ scattering at reactors provide the most stringent bounds in laboratory for neutrino magnetic moment ($\mu_{\bar{\nu}_e} < 2.4\,10^{-10}\mu_B$ [3]). Since the magnetic moment term goes as $1/Q^2$ (being Q the transferred momentum) low energies enhance the relative contribution of the electromagnetic term. Elastic $\nu - e$ scattering at reactors is the most appropriate process to measure magnetic moments because electrons are the lightest massive leptons and low energies are available.

To improve present bounds several strategies should be considered: first, decreasing the detection threshold for electrons; second, improving the statistics; third, improving the subtraction of background. New reactor experiments will lower down the threshold; besides, the statistics will be also considerably improved. The MUNU experiment will reach kinetic energies (T) around $0.1 - 0.5$ MeV [6,7] and the statistics will be good enough to measure $sin^2\theta_W$ with a 5% uncertainty. Besides, the experiment will be measure at some extent angles and energies of outgoing electrons and then the background will be better under control. The MUNU collaboration expects to set a bound as low as $2 - 3 \times 10^{-11}\mu_B$.

The fact that the experiment is sensitive both to the angle and energy of recoil electrons leads to new experimental possibilities. As was discussed in [8] the cancellation of the weak cross section $d\sigma^{\bar{\nu}_e}/dT$ for a neutrino energy $E_\nu = m_e/4sin^2\theta_W$ and forward electrons gives rise to an appearance-like experiment. The study of neutrino oscillations is available by measuring events around the *dynamical zero* [9].

In this work we will also consider $\bar{\nu}_e - e^-$ elastic scattering as a disappearance experiment. Oscillation decreases the number of detected events when total cross section measurements are considered [10]. Contrary, the magnetic moment interaction tends to increase the number of events. Then, each of the effects can not be measured neglecting the other one: they could even cancel each other.

On the other hand any non-standard interaction would increase the number of events for $T \sim 0.3 MeV$ and forward electrons, where the dynamical zero takes place. By measuring events around this region, one could set bounds on any of the effects considered; however, such a goal is only possible in case the experiment is sensitive to angles and energies of recoil electrons.

In other words, future calorimetric experiments to bound μ_ν could need to be complemented with better bounds on oscillation while MUNU-like experiments, able to measure distributions, can disentangle both effects by themselves. We will estimate the sensitivity of the MUNU

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experiment when both effects are considered; we will show that they can be separated due to their different angle and T dependence. The estimated bounds extracted for Δm^2 will be quite close to present bounds from charged current detection. Also, considering $\bar{\nu}_e \leftrightarrow \bar{\nu}_\tau$ oscillation, we will see how the experiment is sensitive to combinations of ν_τ magnetic moment and mixings not excluded by experiments so far.

2 Cross sections for $\bar{\nu}_e - e^-$; oscillation and magnetic moment

Let us consider the modulation of differential cross sections for $\nu - e^-$ due to neutrino oscillation. First, let us briefly describe the standard model cross sections for $\bar{\nu} - e^-$ elastic scattering and the strength of the interaction depending on the neutrino flavor and kinematical configuration.

2.1 Standard model cross sections and the dynamical zero

The standard model cross section for $\bar{\nu}_i - e^-$ elastic scattering can be written

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

where

$$g_L = \begin{cases} -1 + 2sin^2\theta_W & \text{for } \bar{\nu}_\mu, \bar{\nu}_\tau \\ 1 + 2sin^2\theta_W & \text{for } \bar{\nu}_e \end{cases} ;\ g_R = 2sin^2\theta_W$$

and for neutrinos one should replace $g_R \leftrightarrow g_L$. The recoil angle of electrons (θ) is related to T (kinetic energy) and the neutrino energy (E_ν) through

$$cos\theta = \frac{T}{\sqrt{T^2 + 2m_e T}}\left(1 + \frac{m_e}{E_\nu}\right) \quad (2)$$

Taking $\theta = 0$ (forward electrons) one can write

$$\left(\frac{d\sigma_{\bar{\nu}}}{dT}\right)_{\text{back}} = \frac{G_F^2 m_e}{2\pi}\left[g_R - g_L \frac{m_e}{2E_\nu + m_e}\right]^2 \quad (3)$$

which, for electron antineutrinos, vanishes when

$$E_\nu = \frac{g_l - g_R}{2g_R} = \frac{m_e}{4sin^2\theta_W}$$

This kind of non-kinematical cancellation, which we called *dynamical zero*, was shown to take place only for $\theta = 0$, $E_\nu = m_e/4sin^2\theta_W$ ($T \simeq 2m_e/3$) and only for electron antineutrinos [9].

Due to the existence of the dynamical zero, one can choose T and θ such that $d\sigma^{\bar{\nu}_e}/dT << d\sigma^{\bar{\nu}_{\mu,\tau}}/dT$. To be sensitive to this kind of effect the experiment should measure the angle and energy of recoil electrons; in other words, the experiment should measure the distribution:

$$\frac{d^2N}{dTd(cos\theta)} = k\Theta_{p.s.}f(T,\theta)\frac{d\sigma(T,\theta)}{dT}\frac{m_e pT}{(pcos\theta - T)^2} \quad (4)$$

with k a normalization, $\Theta_{p.s}$ a Heaviside function giving the limits of phase space, $f(T,\theta) \equiv dn/dE_\nu$ the neutrino energy spectrum as a function of T and θ ($E_\nu = E_\nu(T,\theta)$); the last factor accounts for $dE_\nu/d(cos(\theta))$ and $p = \sqrt{T^2 + 2m_e T}$.

On the other hand, since $g_L^{\bar{\nu}_e} > g_L^{\bar{\nu}_{\mu,\tau}}$ one can also find regions where $d\sigma^{\bar{\nu}_e}/dT > d\sigma^{\bar{\nu}_{\mu,\tau}}/dT$. In particular, when total cross sections (averaged over the spectrum) are considered we get a factor 2–3.

$$N^{\bar{\nu}_e} \sim (2-3)N^{\bar{\nu}_\mu} ;$$
$$N^i = \int_{T_{th}}^{Tmax} dT \int_0^1 d(cos\theta)\frac{d^2N^i}{dTd(cos\theta)} \quad (5)$$

2.2 Oscillation and magnetic moment

The cross section for $\bar{\nu}_e - e^-$ including the magnetic moment term reads

$$\frac{d\sigma}{dT} = \frac{d\sigma_W^{\bar{\nu}_e}}{dT} + \frac{\pi\alpha}{m_e^2}\left(\frac{\mu_\nu}{\mu_B}\right)^2\frac{1 - T/E_\nu}{T} \quad (6)$$

and the magnetic moment contribution ads incoherently to the weak term; the interference would be proportional to neutrino mass and then negligible. The magnetic moment term would always increase the number of detected events.

Let us now consider the modulation of the cross section due to neutrino oscillation. The cross section when $\bar{\nu}_e \leftrightarrow \bar{\nu}_X$ ($X = \mu, \tau$) oscillation takes place within the distance x from the reactor to the detector reads [8]

$$\frac{d\sigma}{dT}(x, E_\nu, T) = \frac{d\sigma^{\bar{\nu}_e}}{dT} + \sum_i P_{\bar{\nu}_e \to \bar{\nu}_i}(x)\left(\frac{d\sigma^{\bar{\nu}_\mu}}{dT} - \frac{d\sigma^{\bar{\nu}_e}}{dT}\right) \quad (7)$$

where we have used that $\sum_i P_{\bar{\nu}_e \to \bar{\nu}_i} = 1$ (we don't consider oscillation to sterile neutrinos) and $d\sigma_{\bar{\nu}_\mu} = d\sigma_{\bar{\nu}_\tau}$ in the Standard Model.

Considering mixing of two generations ($\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$) we will have

$$\sum_i P_{\bar{\nu}_e \to \bar{\nu}_i}(x) = sin^2(2\phi)sin^2\left(\frac{\Delta m^2 x}{4E_\nu}\right) \quad (8)$$

where, as usual, Δm^2 is the difference of the squared masses and ϕ the mixing angle.

Since the cross section for $\bar{\nu}_e$ are smaller or larger that that for $\bar{\nu}_\mu$ depending on the values of T and θ, an increase or a decrease in the number of events is possible. In other words, appearance and disappearance regimes are available.

In kinematical regions around the dynamical zero ($T \sim 0.3MeV$ and small θ) $d\sigma^{\bar{\nu}_e} << d\sigma^{\bar{\nu}_\mu}$ and then

$$\frac{d\sigma}{dT}(x, E_\nu, T) > \frac{d\sigma^{\bar{\nu}_e}}{dT} \tag{9}$$

while far away for such regions $d\sigma^{\bar{\nu}_e} > d\sigma^{\bar{\nu}_\mu}$ and

$$\frac{d\sigma}{dT}(x, E_\nu, T) < \frac{d\sigma^{\bar{\nu}_e}}{dT} \tag{10}$$

In particular, since total cross sections are larger for $\bar{\nu}_e$ than for $\bar{\nu}_\mu$, the number of events for all angles (in a given interval of T), would be smaller than expected without oscillation. This means that calorimetric experiments on $\bar{\nu}_e - e^-$ scattering can be considered as disappearance experiments [10].

As advanced, one should take care of the fact that, in the disappearance regime, oscillation and magnetic moment act in the opposite direction.

In the following section we will estimate the sensibility of the MUNU experiment to μ_ν and oscillation in both regimes. Disappearance and appearance regions will be fairly sensitive to oscillations when the magnetic moment term is not considered. The appearance regime has the advantage that the contribution of $d\sigma^{\bar{\nu}_e}$ in (7) can be switched off; we could say that the $\bar{\nu}_e$ background is eliminated. The disadvantage will be the small statistics. On the other hand, in the disappearance regime one always has a term proportional to the transition probability and a (larger) background term; the advantage is now the higher statistics.

3 Estimated bounds on μ_ν and the oscillation parameters

In this section, we will estimate bounds on μ_ν and the oscillation parameters. Our reference will be the MUNU proposal which is the first reactor experiment sensitive both to angles θ and energies T. Let us recall that such performance is needed to look for appearance oscillation effects.

3.1 Estimating the bounds

We will consider the toy model for the neutrino spectrum from [5]. We normalize (4) taking k such that integrating the distribution in the interval $0.5 < T < 2.0MeV$ for all angles we get the expected number of pure $\bar{\nu}_e - e^-$ events in one year [6]. We will not consider the experimental background. We will only take into account the statistical error for a one year measurement, and later, also the uncertainty in the measurement of θ.

Our estimations correspond to an ideal MUNU experiment (no systematics, no background); they will guide us in the way one should handle both oscillation and magnetic moment. Later, we will compare with a more realistic approach [7].

Table 1. 1σ estimated bounds for Δm^2 at large mixing, $sin^2(2\phi) \equiv s^2_{2\phi}$ for large Δm^2 and μ_ν. Oscillation and magnetic moment are considered separately

$0.1 < T < 2.0$ MeV	Δm^2	$s^2_{2\phi}$	μ_ν	% stat.
$\theta < 0.3\,rad$	$1.3\,10^{-2}$	0.21	$3.1\,10^{-11}$	9.0%
total × Sect.	$1.0\,10^{-2}$	0.04	$1.3\,10^{-11}$	1.3%
$0.1 < T < 0.5$ MeV	Δm^2	$s^2_{2\phi}$	μ_ν	% stat.
$\theta < 0.3\,rad$	$8.1\,10^{-3}$	0.35	2.810^{-11}	60%
total × Sect.	$9.3\,10^{-3}$	0.05	1.210^{-11}	1.7%

Let us then consider the observable:

$$R(\theta) = \frac{N_o(\theta)}{N^e_W(\theta)} \tag{11}$$

where N_o is the number of events in one year for electron angles lower than θ when oscillation (or magnetic moment interaction) occurs; N^e_W is the corresponding standard model prediction. Regarding oscillations, when θ is small and the T-window is located around $T \simeq 2m_e/3$ then $R > 1$ (appearance) while $R < 1$ when we integrate $\forall\theta$ (disappearance); the magnetic moment term alone will always cause R to be $R > 1$.

A would-be exclusion plot (1σ) can be obtained by setting $|R-1| < \sqrt{N_o}/N^e_W \equiv F$, where F accounts for the precision in the measurement of R.

We fix the kinematical variables as follows:

– We will consider the experiment will reach a detection threshold $T_{th} = 0.1MeV$ which seems to be at hand [7].

– We take two different windows in T: $0.1 < T < 2.0$ (total expected range for MUNU) and $0.1 < T < 0.5$, which is a narrower region around the dynamical zero.

– We also consider two options for θ in (11): integrating for all available θ and only for $\theta < 0.3\,rad$; for the second choice $R > 1$ while $R < 1$ in the first one. The particular value $0.3\,rad$ seems to be optimal to see appearance effects, as we will later show.

– Finally, the distance x between reactor and detector is $x = 20m$ (similar to the actual distance for the MUNU experiment).

Considering magnetic moment and oscillation separately, the estimated bounds (1σ) are collected in Table 1.

Recently, estimated bounds based on a detailed knowledge of the detector have been obtained [7]; these bounds are obtained considering each of the effects separately. Our estimated bounds for an ideal MUNU experiment (no systematic error and no background) are very similar to theirs. For $0.1 < T < 2.0MeV$ and *measuring total cross sections* (disappearance regime), they get $\mu_\nu = 2.210^{-11}\mu_B$ and $\Delta m^2 < 1.210^{-2}eV^2$ for large $sin^2(2\phi)$. For a realistic experiment, including systematic error and background events the bounds for one year measurement are estimated to be $\mu_\nu = 2.810^{-11}\mu_B$ and $\Delta m^2 < 1.610^{-2}$ eV^2. The estimated bound for oscillations is above present limits (lower than $10^{-2}eV$) [11]; still, they are interesting being in the range of values compatible with Kamiokande experiment on atmospheric neutrinos.

At this point, let us recall that MUNU was originally an experiment to measure neutrino magnetic moments; the possibility of measuring neutrino oscillation was suggested later [8]. In spite of this fact, bounds quite close to current ones will be established. It is then worthwhile to analyze the possibility of bounding both μ_ν and oscillation by a same elastic scattering experiment. Besides, in the last section of this paper, we will show a possibility of observing new physics even at MUNU.

Let us then go back to our estimated bounds, corresponding to an ideal MUNU experiment. Our concern will be to consider the joint effect of magnetic moment and oscillation and to study how to distinguish both contributions.

3.2 Dependence of the bounds on the kinematical configuration. Cancellation of μ_ν and oscillation

We will now study the estimated bounds to explain their dependence on the different kinematical configurations considered. We will be mainly concerned in the way one effect modifies the measurement of the other one.

Our estimated bounds for neutrino magnetic moment say that, neglecting oscillations, the best bounds are obtained considering the total number of events. The study of the dynamical zero seems not very useful since the important thing is to get as high statistics as possible. Of course, as T_{th} is set lower, the bounds will be also improved.

About neutrino oscillation parameters, the same applies when bounding the mixing angle and the important thing is again to get as high statistics as possible. However, similar bounds on Δm^2 for large mixing are obtained in both regimes ($\theta < 0.3\,rad$ and $\forall\theta$). Besides, when we consider a narrower window in T ($0.1 < T < 0.5\,MeV$) the estimated bound for low Δm^2 becomes better than that extracted from a larger T-window.

The sensitivity to low Δm^2 is explained considering that

$$\langle P\rangle \simeq k(\Delta m^2)^2 sin^2 2\phi \qquad (12)$$

with $k = \left\langle (x/4E_\nu)^2\right\rangle$. Higher values of E_ν enter in the integration for all angles compared to integration for $\theta < 0.3\,rad$. Also, as T is lower, lower E_ν's enter.

Therefore, the measurement of events around the dynamical zero can be interesting to bound Δm^2; the estimated bound is, in fact, smaller than present day bounds when $\theta < 0.3\,rad$ and $0.1 < T < 0.5 MeV$. Notice, besides, that the statistical error is large and one can expect it to be dominant over systematic errors (around 5% [7]).

Let us consider now the simultaneous measurement of μ_ν and Δm^2. Qualitatively, the crucial point is that magnetic moment and neutrino oscillation subtract each other when we integrate over all angles. In fact, for the values in the table corresponding to total cross section measurements, both effects would cancel completely. Since the estimated bounds for the oscillation parameters are quite close to present bounds, total cross sections hardly can give a clean information. Contrary to this fact, any nonstandard effect would increase the number of detected events for forward ($\theta < 0.3\,rad$, for instance) electrons and $T \sim 0.3 MeV$; if the experiment is precise enough any departure from the standard model would then be noticed.

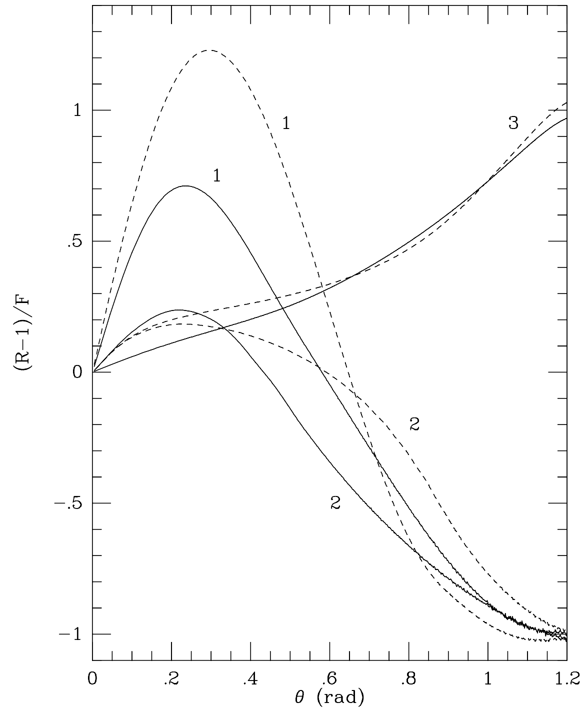

Fig. 1. σ-deviation of the observable $R(\theta)$ from 1 for $0.1 < T < 0.5\,MeV$ (*dashed*) and $0.1 < T < 2.0$ (*solid*). $\Delta m^2 = 10^{-2}eV^2$ and $sin^2 2\phi = 1$ for curves **1**; $\Delta m^2 = 1eV^2$ and $sin^2 2\phi = 0.04$ for **2**; $\mu_\nu = 1.3\,10^{-11}\mu_B$ for **3**

These facts are illustrated in Fig. 1. The σ-deviation of R with respect to 1, both for oscillation and magnetic moment, is plotted as a function of the angle of integration. Recall that $R(\theta)$ is the ratio of observed versus expected events for angles lower than θ. Oscillation and magnetic moment are taken into account separately and the parameters are fixed to the bounds in the second row of Table 1. Notice how R is sensitive to oscillation integrating for all angles and also for $\theta \sim 0.3\,rad$. The sensitivity to magnetic moment is always better integrating over all angles; unfortunately, the deviation of R from 1 for oscillation and magnetic moment cancel each other in this case.

4 Disentangling the magnetic moment effect from oscillation

In this section we will see that, due to the different shape of the magnetic moment and oscillation effects, a reactor experiment able to measure distributions ((5)) can disentangle both effects and set independent bounds on each of them.

The magnetic moment term would always increase the number of detected events. On the other hand, the oscillation effect increases the number of events for forward electrons and acts in the opposite direction for large θ and integrating $\forall\theta$. Therefore, magnetic moment will show up like an overall normalization effect while oscillation will be related to the (normalized) shape of the distributions. Due to their different dependence on T and θ these effects can be disentangled.

We will show how such separation is possible considering, as an illustration, the following observable:

$$\mathcal{O}_o(\theta_0) = \frac{N_o(\theta < \theta_0)}{N_o(\theta > \theta_0)} \bigg/ \frac{N_W(\theta < \theta_0)}{N_W(\theta > \theta_0)} \qquad (13)$$

where, given a window in T, $N(\theta < \theta_0)$ is the number of observed events (N_o) or expected events from the S.M. predictions (N_W) for angles lower than θ_0; $N(\theta > \theta_0)$ is the corresponding number of events for angles larger than θ_0.

Considering an observable such like $\mathcal{O}_o$ has several benefits: first, we can take advantage of both the appearance ($N(\theta < \theta_0)$) and disappearance regimes ($N(\theta > \theta_0)$); second, since we are integrating in the same window of T both for $\theta < \theta_0$ and $\theta > \theta_0$ similar neutrino energies appear, thus canceling neutrino spectrum uncertainties partially and total flux uncertainty completely; and third, the observable will enable the separation of the oscillation effect from magnetic moment due to their different angular dependence.

Figure 2 shows the sigma deviation of $\mathcal{O}_{osc}$ from 1 for different selection of T-windows and oscillation parameters. In the same figure, we also plot the σ-deviation of the observable for electromagnetic interaction taking $\mu_\nu = 2.3\,10^{-11}\mu_B$. Only the statistical error and the propagation of the uncertainty in θ is considered (taking $\varepsilon(\theta) = 0.05\,rad$ [6]); we sum in quadrature both uncertainties.

From Fig. 2 one sees that for $\theta_0 \sim 0.3\,rad$ the observable shows its maximum sensitivity to oscillations; for such angles, one is fairly sensitive to low Δm^2 when $0.1 < T < 0.5 MeV$. To set a bound for $sin^2(2\phi)$ it is better, as discussed previously, to choose $0.1 < T < 2.0 MeV$. The observable $\mathcal{O}$ is not very sensitive to μ_ν for $\theta_0 = 0.3\,rad$.

On the other hand, for $\theta_0 \sim 1$ the observable is sensitive to magnetic moment and much less sensitive to oscillations. As the T-window is larger, with a same threshold T_{th}, the best bounds are obtained.

Then, we see that there are two regions (small and large θ_0) and each of them is mainly sensitive to one of the effects considered. Notice also the dependence of the effects on the selection of $T - window$. Magnetic moments and $sin^2(2\phi)$ for large Δm^2 are better measured when larger T-windows are considered since one needs in this case as high statistics as possible. For large $sin^2 2\phi$ and small Δm^2 it is more convenient to chose a narrower window around the dynamical zero (in our case $0.1 < T < 0.5 MeV$). Then, this is a tunable experiment which can prospect different regions of parameter space by choosing different angles and recoil energies.

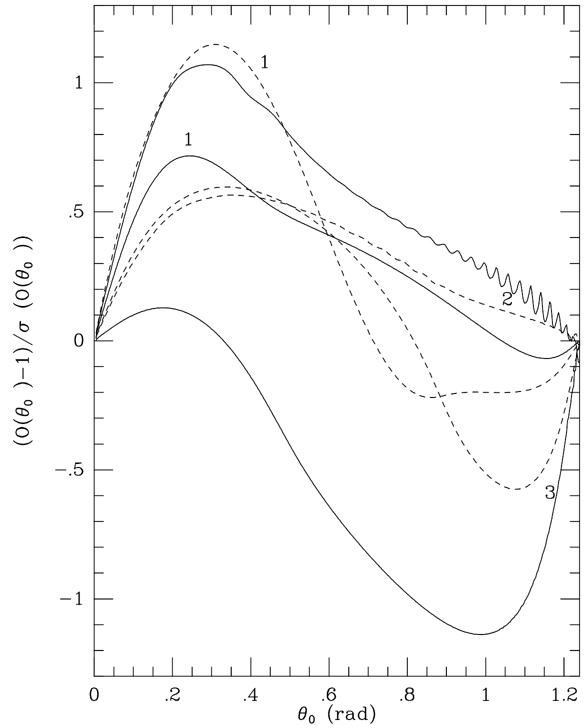

Fig. 2. Sigma-deviation of the observable $\mathcal{O}_o(\theta_0)$ from 1 for $0.1 < T < 0.5\,MeV$ (*dashed*) and $0.1 < T < 2.0\,MeV$ (*solid*). $\Delta m^2 = 10^{-2} eV^2$ and $sin^2 2\phi = 1$ for curves **1**; $\Delta m^2 = 1 eV^2$ and $sin^2 2\phi = 0.15$ for **2**; $\mu_\nu = 2.3\,10^{-11}\mu_B$ for **3**

5 $\bar{\nu}_\tau$ electromagnetic properties from $\bar{\nu}_e - e^-$ elastic scattering

Finally, it is interesting to note that, in case oscillations take place, any extra interaction of the new flavors originated from oscillations, could affect the value of the elastic cross section. Consider, for instance, that $\bar{\nu}_e$ oscillate to $\bar{\nu}_\tau$ and that the tau neutrino has a large magnetic moment (the best lab. bound is $4\,10^{-6}\mu_B$ [12]). To simplify the analysis, let us consider that the magnetic moment cross section for the tau neutrino is much larger than the weak cross sections (which is granted for $\mu_\nu > 10^{-9}\mu_B$) and that τ-neutrino mass effects are negligible in the cross section; then, we would expect an excess to respect to the standard model prediction and one can write

$$\frac{d\sigma}{dT} \simeq \frac{d\sigma^{\bar{\nu}_e}}{dT} + \mu^2 P(x) \frac{\pi\alpha^2}{m_e^2} \frac{1 - T/E_\nu}{T} \ ;\ \mu = \mu_{\bar{\nu}_\tau}/\mu_B \quad (14)$$

where the terms $P(x)d\sigma^{\bar{\nu}_e}$ and $P(x)d\sigma^{\bar{\nu}_\tau}$ have been neglected. Then one gets the following 1σ bounds from the observable $\mathcal{O}$:

- $\chi^2 sin^2(2\phi) < 0.1$ at large Δm^2 for $0.1 < T < 2.0\,MeV$ and $\theta_0 \sim 1\,rad$; total error $\sim 5\%$.
- $\chi^2 sin^2(2\phi)(\Delta m^2)^2 < 2\,10^{-5}(eV^4)$ at large $sin^2(2\phi)$ for $0.1 < T < 0.5\,MeV$, $\theta_0 \sim 0.4\,rad$; total error $\sim 20\%$.

where $\chi = \mu_{\bar{\nu}_\tau}/10^{-10}\mu_B$.

This kind of bounds would explore combinations of values of $sin^2(2\phi)$, Δm^2 and χ which are not excluded yet; or, in other words, the elastic measurement of the neutrino-electron cross section is sensitive to non standard neutrino physics in still admissible scenarios.

6 Conclusions

Present reactor experiments (MUNU) on $\bar{\nu}_e - e^-$ elastic scattering are sensitive to unexplored values of neutrino magnetic moment. Also, they are sensitive to neutrino oscillation. By measuring the total cross section one can not set bounds on μ_ν neglecting oscillation since both effects tend to cancel. Experiments able to measure energy and angle of recoil electrons are needed; only then one can safely separate both effects and set independent bounds on each of them. Furthermore, the elastic neutrino-electron cross section is sensitive to non-standard neutrino interactions induced by oscillation, as is the case of magnetic moment interaction of $\bar{\nu}_\tau$ ($\bar{\nu}_\mu$), for still available values of the parameters. Therefore, this process promises a better understanding of neutrino dynamics.

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References

1. K. Winter, Lepton-Photon Symp. (1995) 569;
   G.G. Raffelt, Blois 1992, Proceedings, Particle Astrophysics 99-110
2. P. Vilain et al., Phys. Lett **B335** (1994) 246
3. G.S. Vidyakin et al., JETP Lett. **49** (1989) 740; JETP Lett. **55** (1992) 206
4. D.A. Krakauer et al., Phys. Lett. **B252** (1990) 177;
   P. Vilain et al., Phys. Lett. **B345** (1995) 115
5. J. Bernabéu et al., Nucl. Phys. **B246** (1994) 434
6. C. Broggini et al., LNGS-92/47 (MUNU proposal)
7. Romuald Bon Nguyen, PhD Thesis. Université Joseph Fourier; Grenoble, France, October 1997
8. J. Segura et al., Phys. Lett. **B335** (1994) 93
9. J. Segura et al., Phys. Rev. **D49** (1994) 1633
10. W.J. Marciano, Phys. Rev. **D36** (1987) 2859;
    S.P. Rosen, B. Kayser, Phys. Rev. **D23** (1981) 669;
    L.A. Ahrens et al., Phys. Rev. **D31** (1985) 2732;
    B. Halls, B.H.J. McKellar, Phys. Rev. **D24** (1981) 1785
11. B. Achkar et al., Nucl. Phys. **B434** (1995) 503;
    G. Zacek et al., Phys. Rev. **D34** (1986) 2621;
    G.S. Vidyakin et al., JETP Lett. **59** (1984) 364
12. H. Grotch, R. Robinet, Z. Phys. **C39** (1988) 563;
    T.M. Gould, I.Z. Rothstein, Phys. Lett. **B333** (1994) 545