Searching for Neutrino Dipole Moments

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We propose a new approach using a laser in the near detector hall, and looking for an effect in the Minos far detector.

Introduction

Dirac neutrinos can have electric and magnetic dipole moments. In the SM,

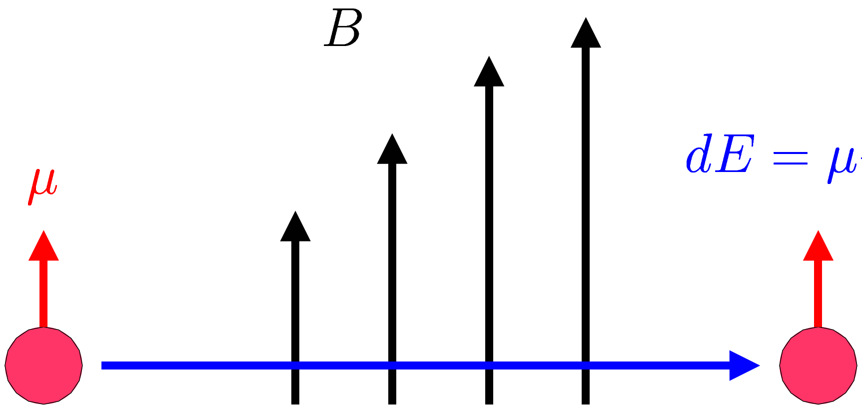
$$\mu_\nu \approx 3 \times 10^{-19} \mu_B \left(\frac{m_\nu}{1\mathrm{eV}} \right)$$

Current searches look for enhanced $\nu - e$ scattering at low T.
Current limits on μ_ν: (we're focusing on MDM)
ν_e: $1.5 \times 10^{-10} \mu_B$ Equal parts ν_1 and ν_2
ν_μ: $7.4 \times 10^{-10} \mu_B$ Equal parts ν_1, ν_2, and ν_3
ν_τ: $3.9 \times 10^{-7}\ \mu_B$ Equal parts ν_2 and ν_3

These limits can be improved. Neganov *et. al.* propose a search with a Tritium source and low background detector, with sensitivity to $3 \times 10^{-12} \mu_B$. However, progress is difficult:

$$\sigma \propto (\mu_\nu)^2$$

New concept



$$dE = \mu \frac{\partial B}{\partial x} dx$$

A transverse field gradient accelerates dipoles

A Dirac neutrino can be expressed in terms of transverse components:

$$|\rightarrow\rangle = |\uparrow\rangle + |\downarrow\rangle$$

After traversing a field gradient, this becomes

$$|\rightarrow\rangle = e^{-i(E+dE)t}|\uparrow\rangle + e^{-i(E-dE)t}|\downarrow\rangle$$

When $2(dE)t = \pi$, this evolves into the sterile state:

$$|\leftarrow\rangle = |\uparrow\rangle - |\downarrow\rangle$$

$\Rightarrow$ We have a quantum effect much different from classical precession:
The effect continues en-route to a far detector.
This results in a disappearance signal.

$$N_{\text{sterile}} = N \sin^2(dE\, L)$$

Note: Disappearance is independant of E.

For comparison:

- $1\, \mu_B T \approx 6 \times 10^{-5}$ eV
- $\dfrac{\Delta M^2}{2E} \approx 2 \times 10^{-12}$ eV

If the mass eigenstates have different magnetic moments, flavor oscillations can also be dramatically modified (derivation in progress).

Use of a laser to accelerate neutrinos

Since $\gamma \approx 10^{10}$ a neutrino can surf along a laser beam, staying in phase
A laser beam contains large transverse fields:

$$B = B_0(kx - \omega t)$$

with gradients:

$$\frac{\partial B}{\partial x} = kB_0(kx - \omega t)$$

For a "surf" distance l, the disappearance signal becomes:

$$N_{\text{sterile}} = \frac{N}{2}\sin^2(\mu k B_0 l L)$$

Where we lose a factor of two since not all neutrinos see the maximum gradient.

Alignment

To realize this effect, the neutrino and laser have to be aligned so that the neutrino stays in phase, experiencing a constant sign of the gradient.

The neutrinos headed for the far detector have a very well defined direction. For Minos, $\approx 10^{-5}$ rad.

The laser should be aligned well enough that the neutrino stays in phase by 1/2 wavelength:

$$\theta < \sqrt{\frac{\lambda}{l}}$$

For the parameter choices we will make, an off-axis detector would be far enough off-alignment for the effect to disappear if the laser is aimed at Minos.

Application to Minos initial running

Time structure: 5 batches, 84 bunches/batch, 1.6 μsec/batch
$\Rightarrow$ not easy to obtain high energy density
More work needed to investigate laser options

for now, assume

- 1000 Joule pulse overlapping with 1 batch/spill
- 1m diameter, 1.6 μsec pulse length. $E = (1/2\mu_0)B_0^2 V$
- Nd:Glass laser with $\lambda = 1\mu$m.
- 30 m surf distance in near-detector hall

- $\mu k B_0 l L = 1$ for $\mu_\nu = 2 \times 10^{-14} \mu_B$
- Alignment $\theta < 0.2$ mrad
  (proton beam alignment spec is 0.7 mrad).
  (NuMI physicists know the direction to 0.015 mrad).

Application to future Minos running

There are many possibilities to improve the sensitivity after the initial running. Many of these are compatible with the general program of near-detector physics:

- Run in the HE configuration $\Rightarrow$ more statistics
  Sensitivity to $\mu k B_0 l L = 0.1$
- Use a higher frequency laser
- Upgrade the laser intensity
- Add a new beam dump to the decay tunnel, and dedicate the last 300m to "surf distance."

Sensitivities to $10^{-17}\mu_B$ may be possible, if alignment and other challenges can be met.

Conclusions

Need more work on

- Theory
- Laser technologies

But, looks promising!

A small-scale experiment (adjunct to Minos) can extend current limits and pioneer the technique during initial NuMI running.
Orders of magnitude improvement may be possible in future runs.