Searching for the
Neutrino Magnetic Moment

John Krane
Iowa State University
NuFACT'00

Traditional:

- ν e cross section

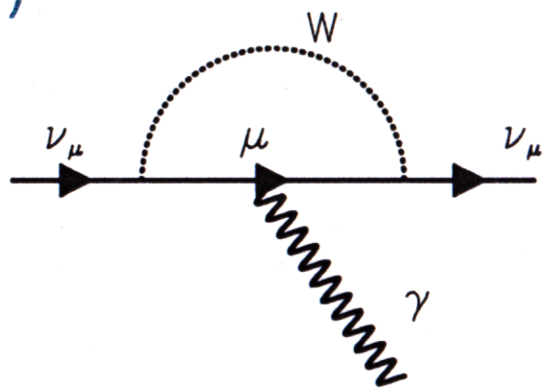
Non-Traditional:

- Čerenkov Radiation
- Transition Radiation
- Time-varying Fields
  - Stimulated Emission
  - → Phase rotation

Origin of the Magnetic Moment

- Actually, the "effective moment"

$$\mu_{eff} = (\mu^2+d^2)^{1/2}$$



- also R-parity violating SUSY
- limited to $<10^{-10}\ \mu_B$
  but SM expects more than 10^9 smaller yet
- If neutrinos are massive, then to first order, SM says μ linearly dependent on neutrino mass

c.f.: Lee and Shrock, PRD 16 1444 (1977)
or
Marciano and Sanda, Phys Lett 67B 303 (1977)

Traditional Method: measure the ν e cross section

c.f.: Miranda, Segura, Semikoz, and Valle,

hep-ph/9906328

- Traditional approach followed by NuMu, HELLAZ, etc.

SM: $$\frac{d\sigma^{W}}{dT} = \frac{2m_e G_F^2}{\pi}\left\{ g_L^2 + g_R^2 (1 - \frac{T}{E_\nu})^2 - \frac{m_e}{E_\nu} g_R g_L \frac{T}{E_\nu} \right\}$$

$$g_L = 1 \pm \sin^2\theta_W \text{ for } \binom{\text{electrons}}{\text{muons}}$$

$$g_R = \sin^2\theta_W$$

$$T = \text{electron recoil E}$$

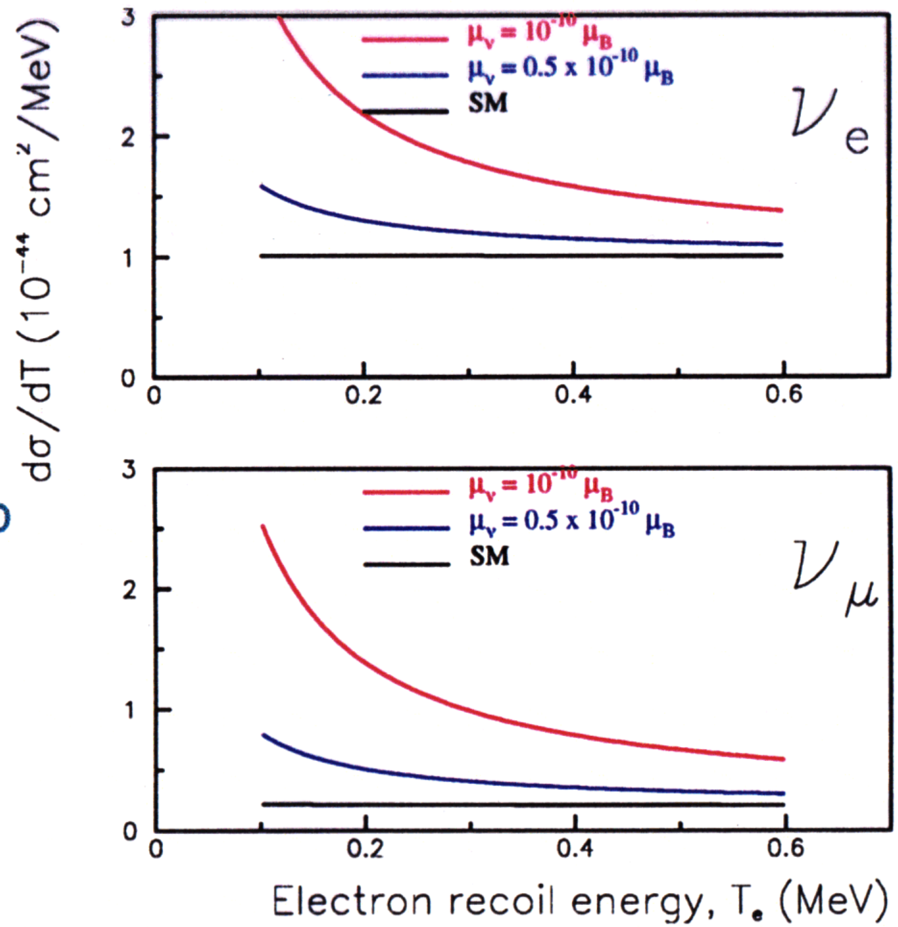
EM: $$\frac{d\sigma^{mm}}{dT} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)$$

For a NuFACT, there is no sig. E-dependence or charge-dependence.

Calculation of ν e cross section

$$\frac{d\sigma^{mm}}{dT} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right)$$

To make a point, these plots were made with 10 MeV neutrinos; use 10 GeV and you won't see a difference.



- High neutrino E does not help
- Quadratic dependence on mag moment
- Need a dedicated detector… yet can't do much better than others

Non-Traditional Methods

Because a NuFACT would give us unprecedented intensity and energy

- The usual limitations might vanish
- Otherwise infinitesimal rates might become significant

Čerenkov Radiation

- Consider a 1 km long water tank…

c.f. Grimus and Neufeld, Phys Lett B315 129 (1993)

$$\frac{dR}{d\omega} = \frac{\alpha\mu_{eff}^2}{4m_e^2}\left(\frac{n-1}{n}\right)^2 \omega^2$$

- With ultrarelativistic ν's, no E-dependence
- Quadratic in μ
- Numerical calculation for 2E20 ν's per year: 0.00033 photons per year…

Transition Radiation

W = total TR energy

E = neutrino energy

d = foil thickness

ω = photon frq

ω_p = plasma frq

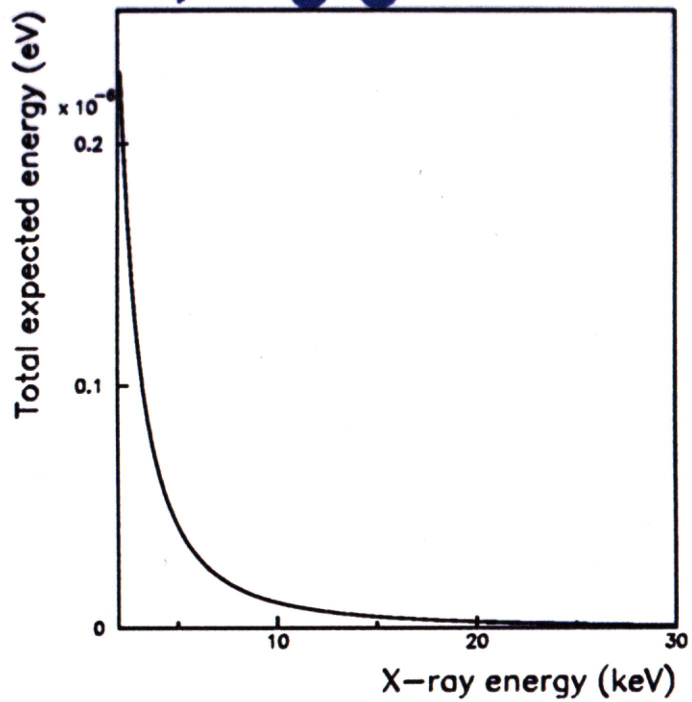
- From solar neutrino calculations
  c.f. Grimus and Neufeld hep-ph 9410245

$$\frac{dW}{d\omega} \approx \frac{\mu_{eff}^2 d}{4\pi^2} \omega^2 \frac{E-\omega}{E} \left(\frac{\omega_p}{\omega}\right)^4 \times \frac{\pi}{2}$$

- Still quadratic in μ…
- Numerically integrating over ω (for 2E20, 1E6 foils): 4.5E-8 keV collected per year (X-rays are keV)

TR: Small Adjustments, big gains?

$$\frac{dW}{d\omega} = \frac{\mu_{eff}^2 d}{4\pi^2}\omega^2 \frac{E-\omega}{E}\left(\frac{\omega_p}{\omega}\right)^4 \times \frac{\pi}{2}$$



- Lowering x-ray detection threshold from 20 keV to 5 keV gives you a factor of 100…but low efficiency in real detectors
- Increase ω_p for big gains?
- Originally I was looking at a big reactor…2 meters away
  …I still am

Resonant Cavity

for stimulated ν conversion

C.f.: Vannucci, hep-ex 9911025

- Essentially a low-energy photon target
- Stimulate (inverse-)radiative decays

$$\nu \to \gamma + \nu'$$

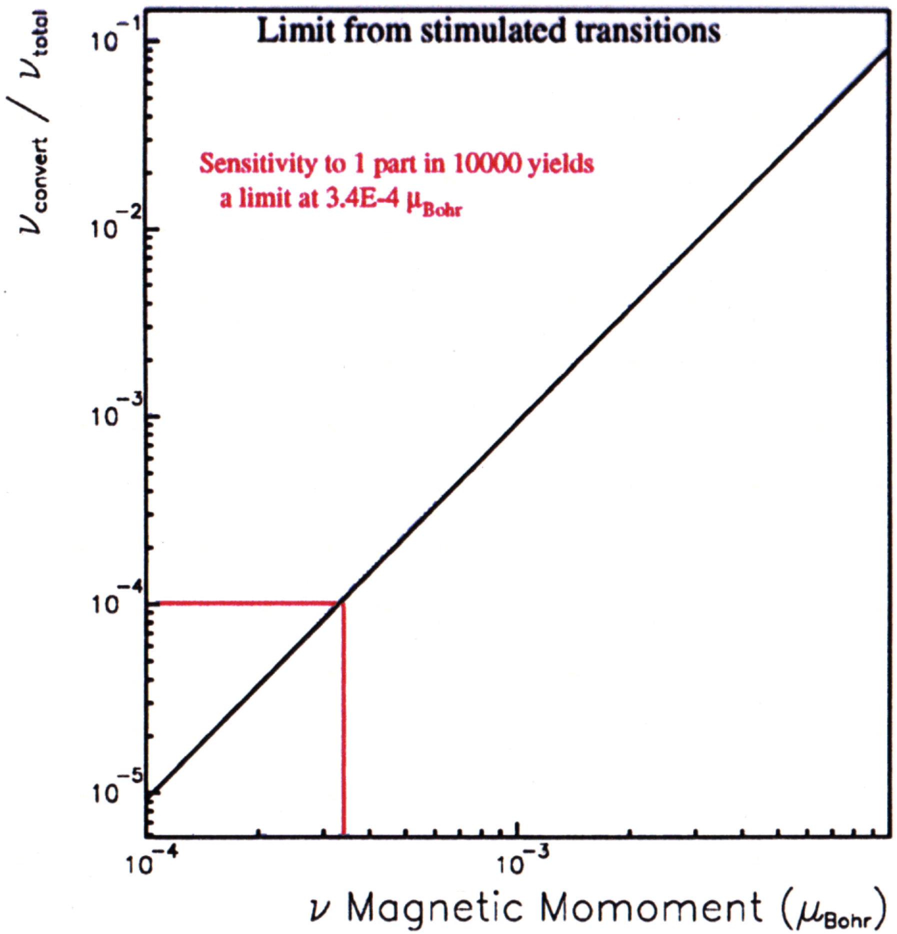
- The fraction of converted neutrinos
  ~ *quality*power*μ^2

- No E-dependence as long as transition energy is much smaller

ResCav: No real limits for mm

- To get to a competitive limit, you need to notice a lack of 1 part in 1E17…
- The result could be framed in terms of ν lifetime if you are interested
- Limits can improve for transition moments

I assumed Q=1E9, 100 Watts



Phase Rotation

Fritz DeJongh's idea

$$V = -\mu \cdot B$$

- Decompose helicity and μ into "left and right" components
- A transverse B-field can split these states

$$|\uparrow\rangle = \frac{1}{\sqrt{2}} e^{-i(+V)t} |\leftarrow\rangle + \frac{1}{\sqrt{2}} e^{-i(-V)t} |\rightarrow\rangle$$

- While in the field, the ν rotates from active to sterile and back (Dirac case)
- How long can we keep it in the B-field?

How Many Phase Rotations?

- Good news: depends on the product of B, t, and μ

1000 km

Not μ^2!

$$\sin^2(\mu \cdot B\, t) = \sin^2\left(10^{-10}\mu_B \cdot 1\mathrm{T} \cdot 3.3\times10^{-3}\mathrm{sec}\right)$$

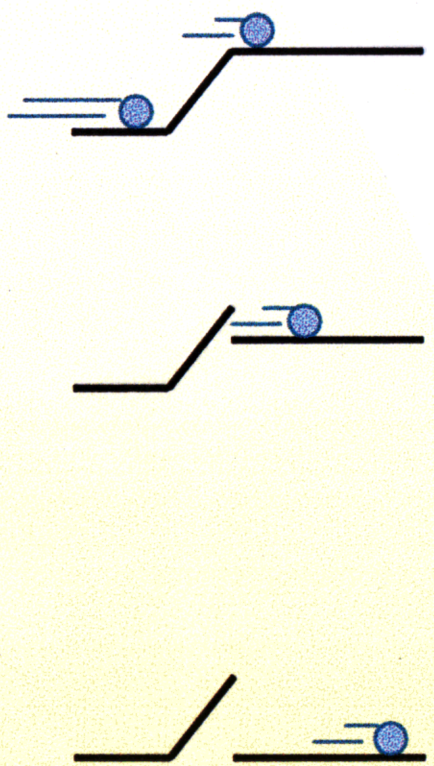
$$= \sin^2\left(10^{-10} \cdot 5.8\times10^{-11}\frac{\mathrm{MeV}}{\mathrm{T}} \cdot 1\mathrm{T} \cdot 3.3\times10^{-3}\mathrm{sec} \cdot \frac{2\pi}{6.582\times10^{-22}\mathrm{MeV}\cdot\mathrm{s}}\right)$$

$$= \sin^2(0.058\pi) = 0.03$$

About 2 degrees of rotation…

- Bad news: we can't build a 1000 km magnetic field
- There is another way to do this…

The One-way B-Gradient



Silly mechanical example

- ν enters the B field, experiences the gradient, energy states split, phase rotations begin
- B field goes to zero homogeneously in space; i.e., we turn it off (alternately, the cavity finishes its cycle)
- Because there is no spatial “return” gradient, the states never come back together and the phase rotations continue

Now you don't need a huge field region

1000 km to detector

$$\sin^2(\mu \cdot B\,t) = \sin^2\left(10^{-10}\mu_B \cdot 1\mathrm{T} \cdot 3.3\times10^{-3}\mathrm{sec}\right)$$

$$= \sin^2\left(10^{-10} \cdot 5.8\times10^{-11}\,\frac{\mathrm{MeV}}{\mathrm{T}} \cdot 1\mathrm{T} \cdot 3.3\times10^{-3}\mathrm{sec} \cdot \frac{2\pi}{6.582\times10^{-22}\,\mathrm{MeV}\cdot\mathrm{s}}\right)$$

$$= \sin^2(0.058\pi) = 0.03$$

About 2 degrees of rotation…

- A 400 MHz field needs a 0.75 m long homogeneous region
- Can put several fields in series
- Can raise B above 1 Tesla?

A Notable Reference

"Decelerating Neutral Dipolar Molecules,"
Bethlem, Berden, and Meijer, Univ. of Nijmegen, PRL 83, 1558, 23 Aug. 1999.

They changed the kinetic energy of CO molecules with electric field stages.

We propose splitting quantum states with magnetic field stages.

More info: One might also search SPIRES for (resonant) spin-flavor precession

The Phase Rotation Experiment

- Find a "host" long-baseline experiment
- Generate a time-varying B at beam source,
  run with B for half the time,
  compare event rates with and without B
- Dirac: Look for CC deficit
  Majorana: or wrong-sign, wrong flavor neutrinos

Sensitivity Speculation

(Majorana, continued)

Can we detect tau neutrino interactions?
- If so, we might get much better sensitivity
- If not, they look like NC interactions…lost

Best answer

Will we polarize the muons?
- If we chose the one polarization, then $\nu_{\mu} >> \bar{\nu}_{e}$. Now, can we tell electron neutrino interactions from NC?

Not ideal for osc phys

Differences for Majorana

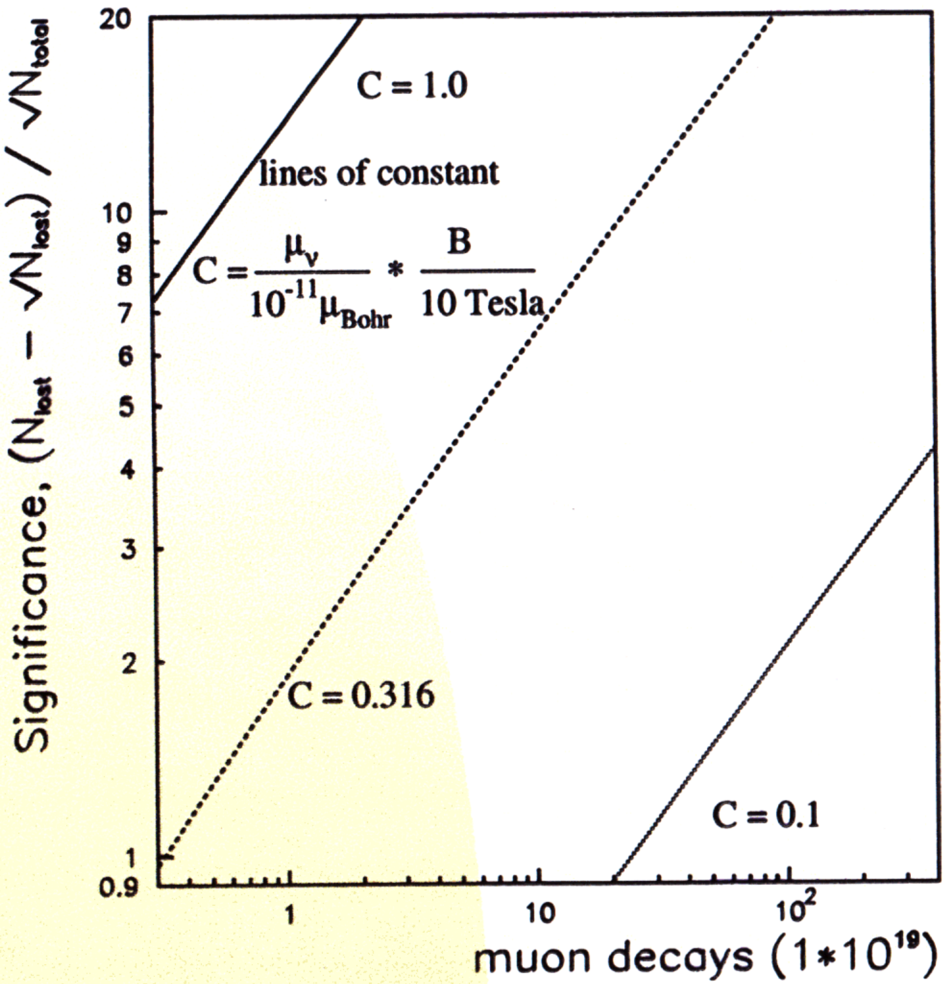
Majorana ν case, rotated ν become $\bar{\nu}$'

$\nu_\mu \to \bar{\nu}_e$ *both beam components*

and $\nu_\mu \to \bar{\nu}_\tau$ and $\bar{\nu}_e \to \nu_\tau$

This is to say, the mag. moment is a matrix w/zeros on diagonal

Sensitivity Estimate 1



Dirac ν case, where rotated ν are sterile

Assume 25% duty cycle for the B field

Compare CC cross section with and without field

Normalized to 5000 events per year (50 ktons at 2800 km, 20 GeV muons)

Final Comments

- Bunches would make the phase rotation scheme more efficient, but lack of bunches is not crippling.
- Anything that increases CC rate at far detector increases sensitivity.

Summary

- Traditional search not viable at NuFact
- Čerenkov, TR fail
- Stimulated emission only competitive for ν lifetime…interest?
- Phase Rotation is as good as your B field