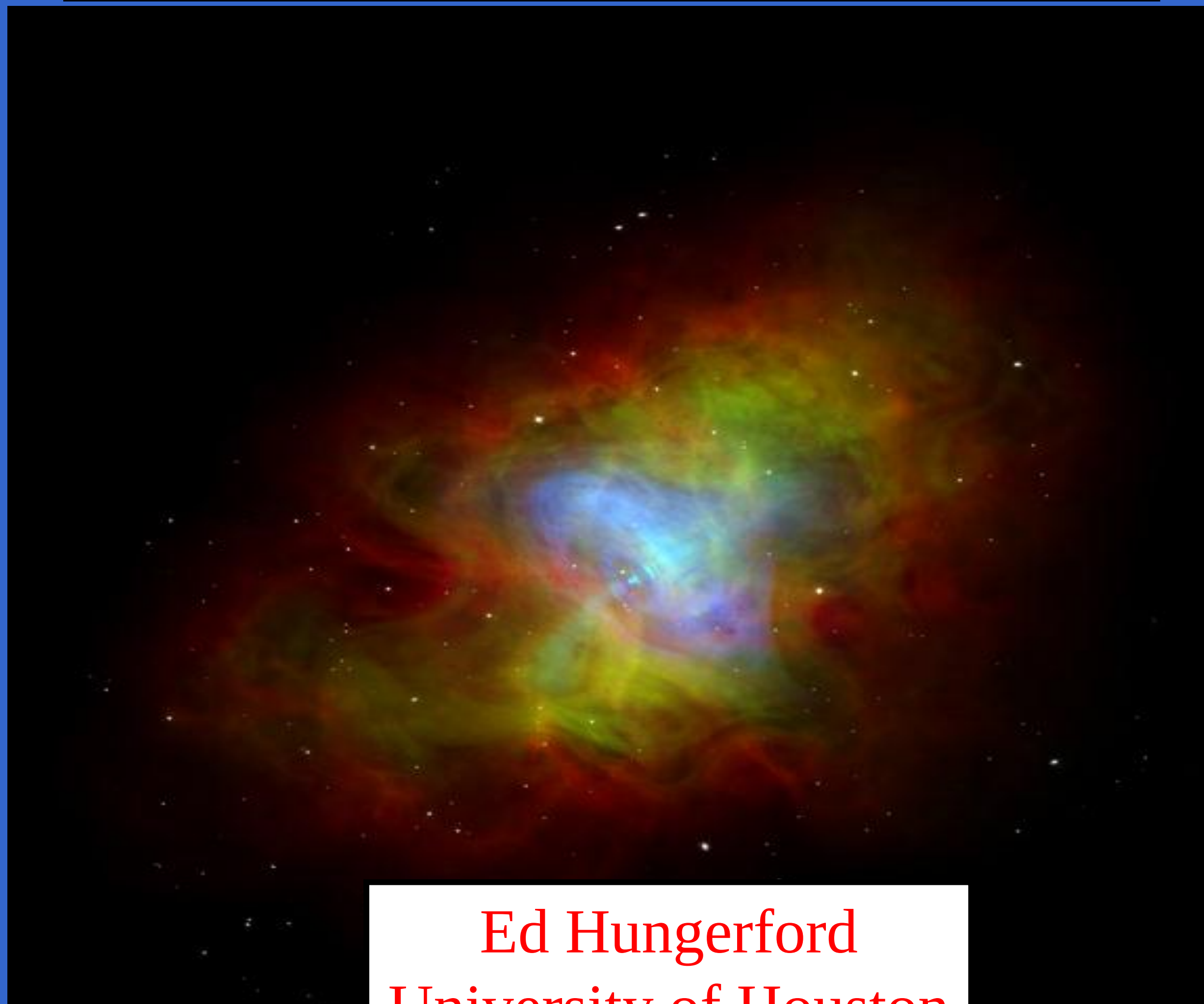
Coherent Neutrino Scattering
and
the ν Magnetic Moment



Ed Hungerford
University of Houston

Examples of experiments using neutrinos from stopping π/μ beams

1) Low-energy muon and electron neutrino scattering

   a) Neutrino-nuclear cross sections are needed for supernova simulations

   b) Calibration and design of cosmogenic Neutrino detectors

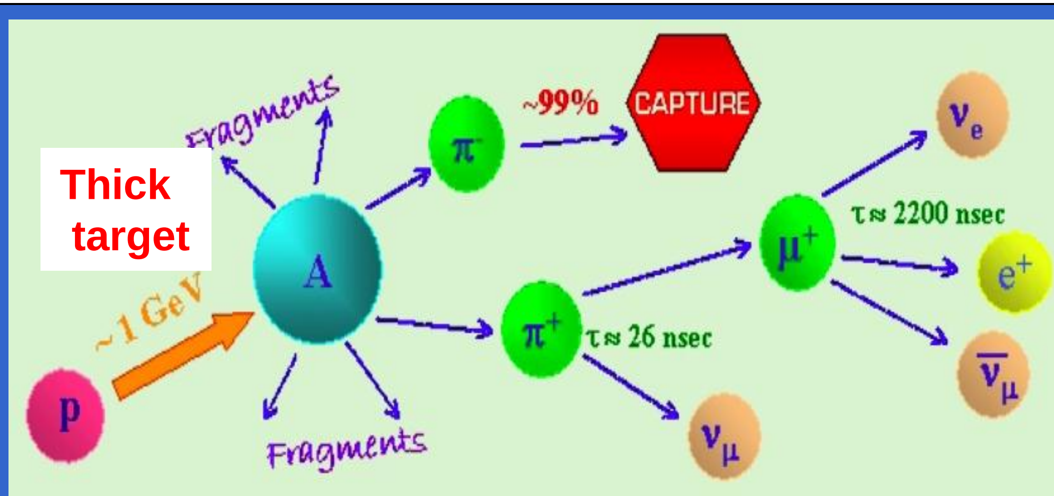
2) Fundamental Physics measurements

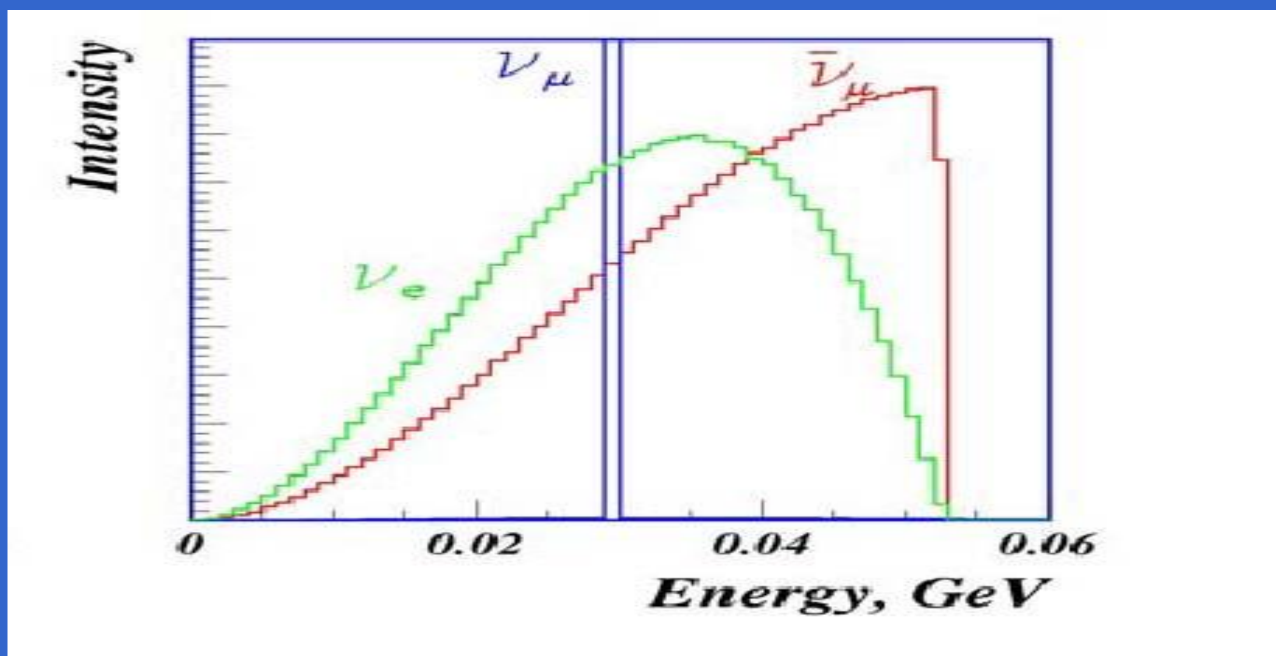
   a) Neutrino oscillations

   b) Search for non-standard neutrino interactions

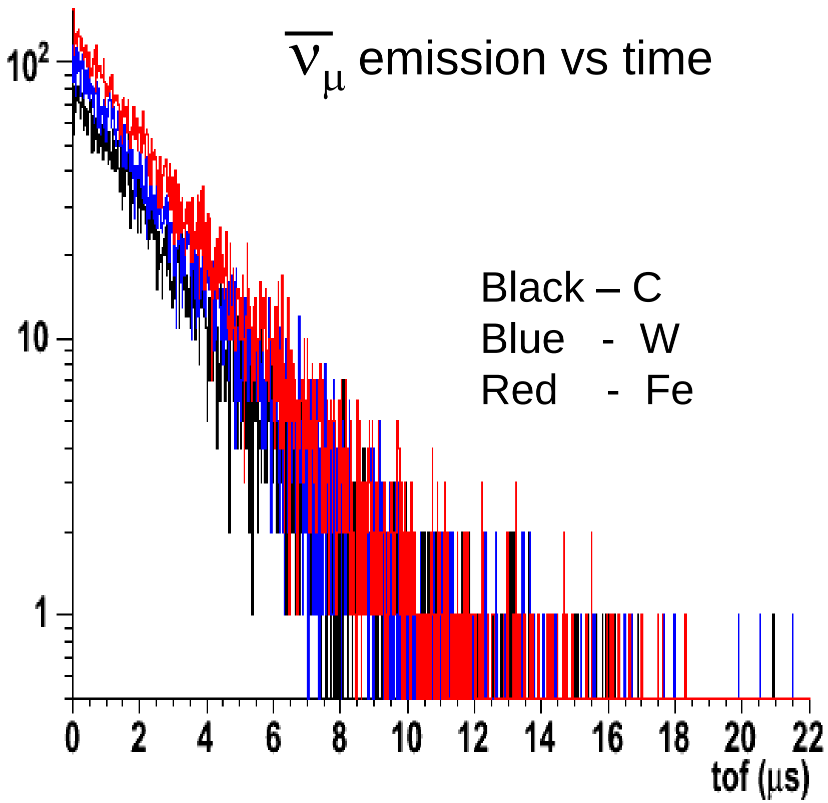
   c) Search for a non-SM neutrino magnetic moment

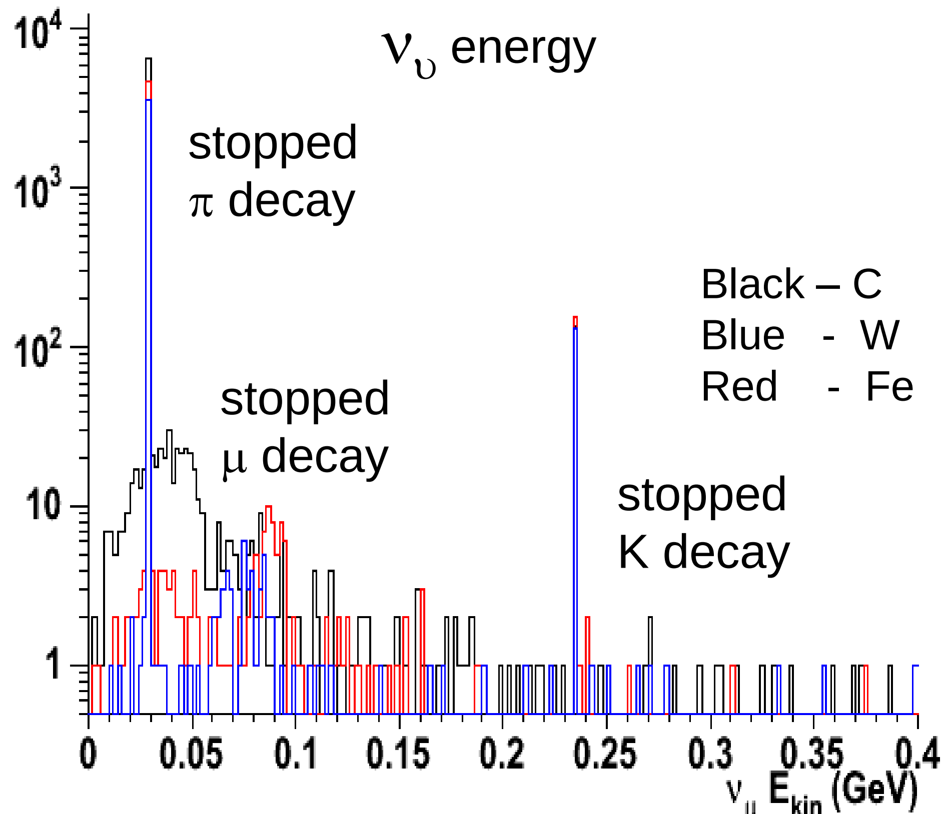
Neutrinos from stopped π/μ decays





Fluka Simulations of neutrino production from 8 GeV protons on C, Fe, and W



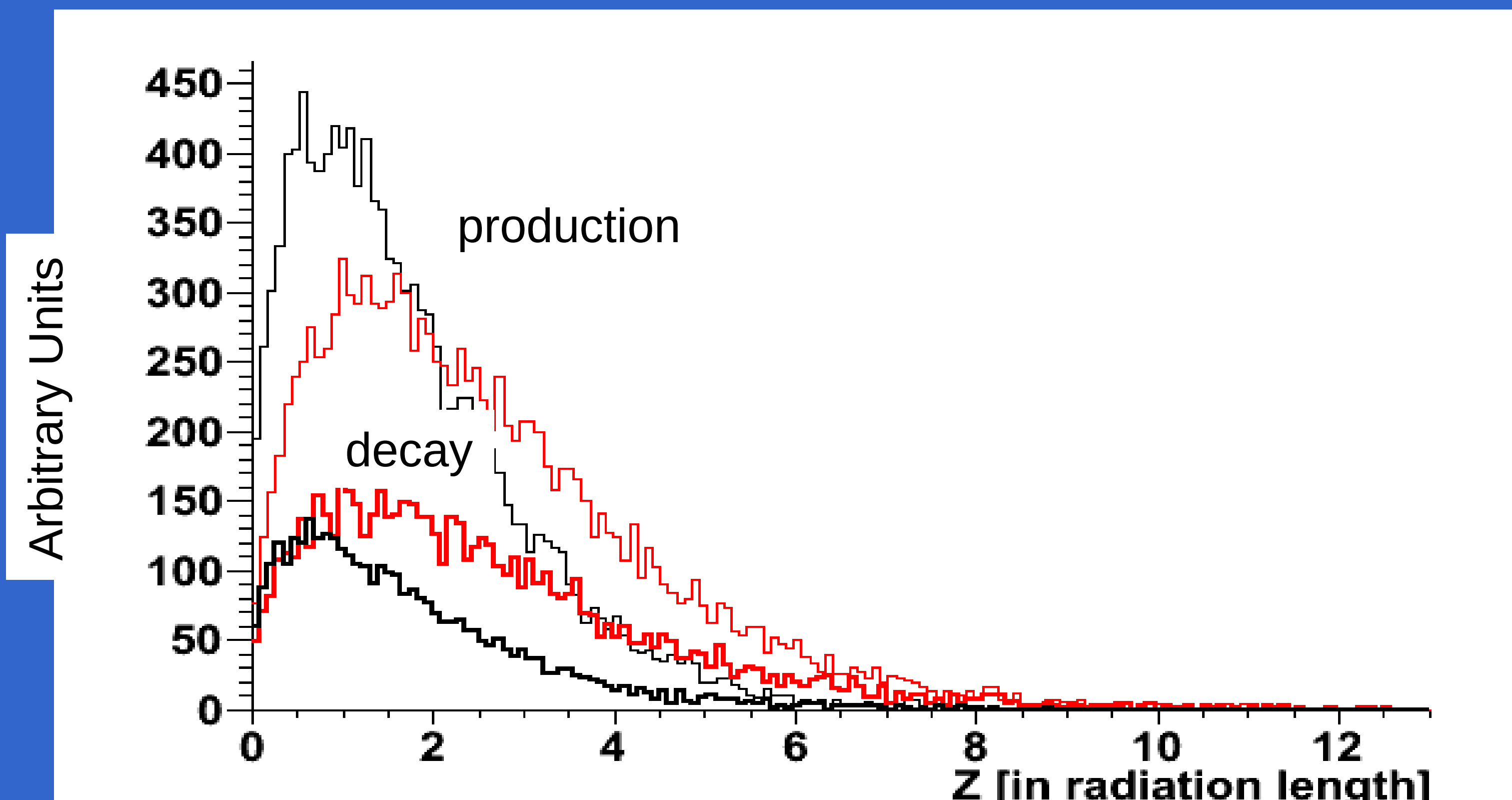


Fluka Simulations of neutrino production from

8 GeV protons on C, and W

Red – C   Black – W

Number of π produced (thin) and π decay in terms of the radiation length traveled by the beam



UHM EP

Neutrino Production Rates from a FLUKA Simulation

Neutrino production in to 4 π per incident 8 GeV proton for various targets. Thick target is a cylinder 10m x 10m thin target a cylinder with 5% interaction length

THICK				**THIN**			
Target	ν_e	ν_μ	$\bar{\nu}_\mu$	Target	ν_e	ν_μ	$\bar{\nu}_\mu$
Be	1.23	1.27	1.27	Be	0.007	0.007	0.007
C	1.29	1.33	1.33	C	0.004	0.007	0.004
Cu	0.99	1.00	1.00	Cu	0.010	0.012	0.011
W	0.74	0.751	0.750	W	0.008	0.010	0.008

Comparison of stopped pion facilities

Facility	LANSCE	ISIS	SNS
Beam energy	0.8 GeV	0.8 GeV	1.3 GeV
Beam current	1.0 mA (0.8MW)	0.2 mA (0.16MW)	1.1 mA (1.4 MW)
Coulomb delivered per year to the target	6500 (LSND)	2370 (KARMEN)	22000
Beam structure	Continuous	Two 200 nsec bunches separated by 300 nsec repetition rate - 50 Hz	380 nsec FWHM pulses at 60 Hz
Target	Various	Water cooled Tantalum	Mercury

SNS produces 0.13 neutrinos of each flavor per proton (9 x 10^{14} s^{-1})

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Differential cross section neutrino-nuclear coherent scattering

1) Coherent Scattering requires low momentum neutrinos(<50 MeV)
2) Low momentum transfer
3) Cross section almost completely dependent on the NEUTRON distribution
4) Coherence increases the rate by the square of the form factor
5) Has never been measured

$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2). \quad (1)$$

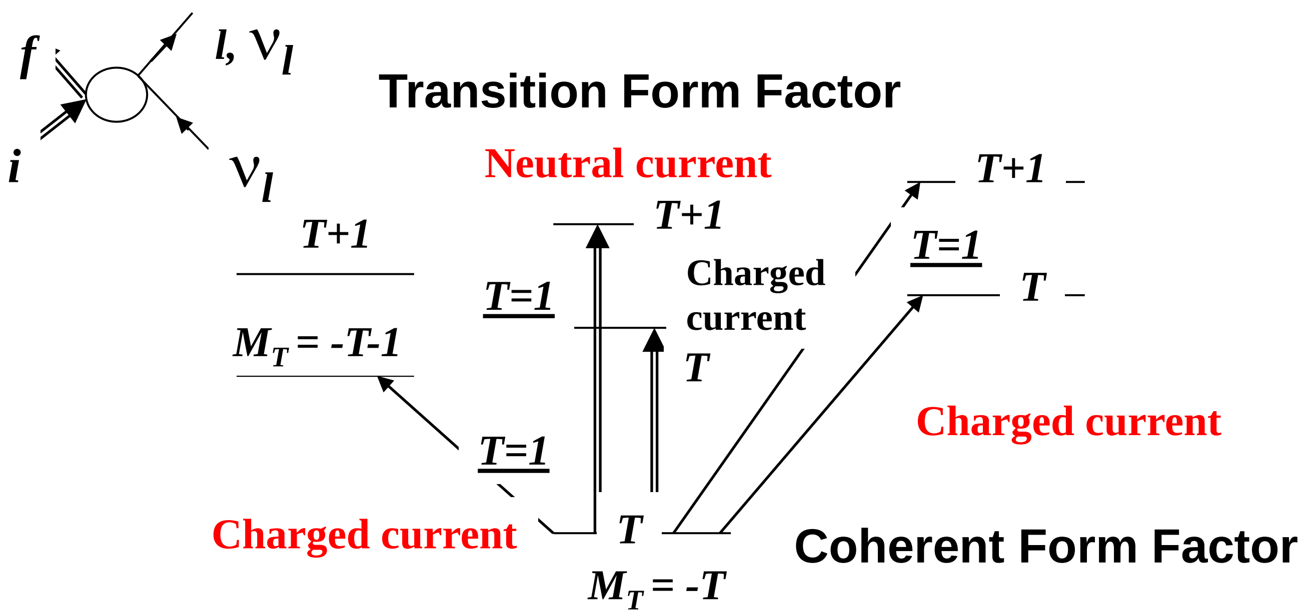
$$F(Q^2) = \frac{1}{Q_w}\left[N F_n(Q^2) - Z(1 - 4\sin^2\theta_W) F_p(Q^2)\right] \quad (7)$$

$$F_n(Q^2) \sim F(Q^2)_p = \frac{3 j_1(QR_0)}{QR_0} \exp\left[-\frac{1}{2}(Qs)^2\right],$$

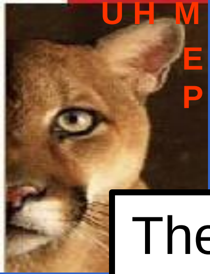
E Neutrino energy
T Recoil energy
M Nuclear mass
Q_w Weak charge
G_f Fermi constant
R_0 Nuclear radius
s Nuclear surface
Q Momentum transfer
j_1 Spherical Bessel fn

Form Factor Basics

Nuclear Form Factors



Ed Hungerford
University of Houston

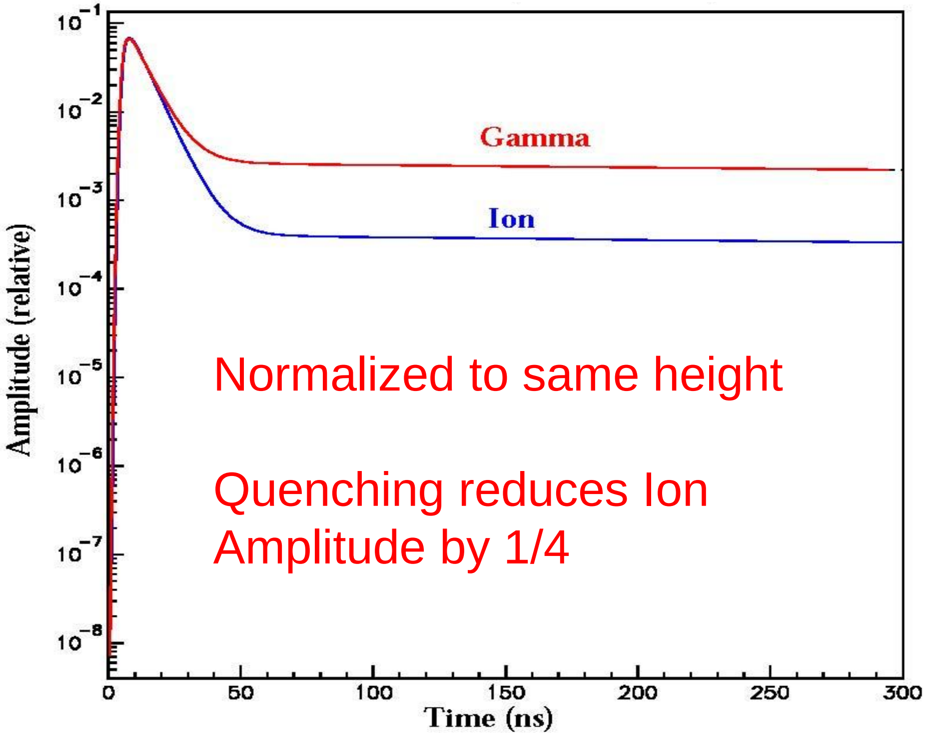


Targets should have large background suppression
Similar, but not equal to, those of DM experiments

These detectors have discrimination between electron and ion recoils on the order of 10^8. There are problems however.

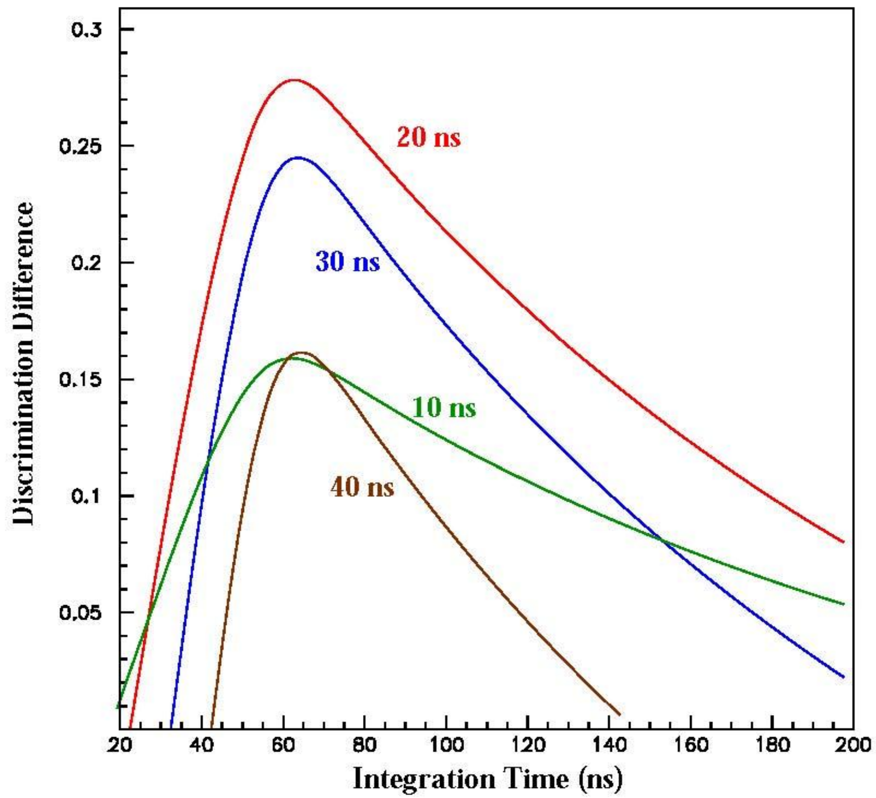
1) the detectors are slow
2) cannot preferentially reject neutron induced recoils.
3) requires complicated detector design

Scintillation in LAr



Normalized to same height

Quenching reduces Ion Amplitude by 1/4

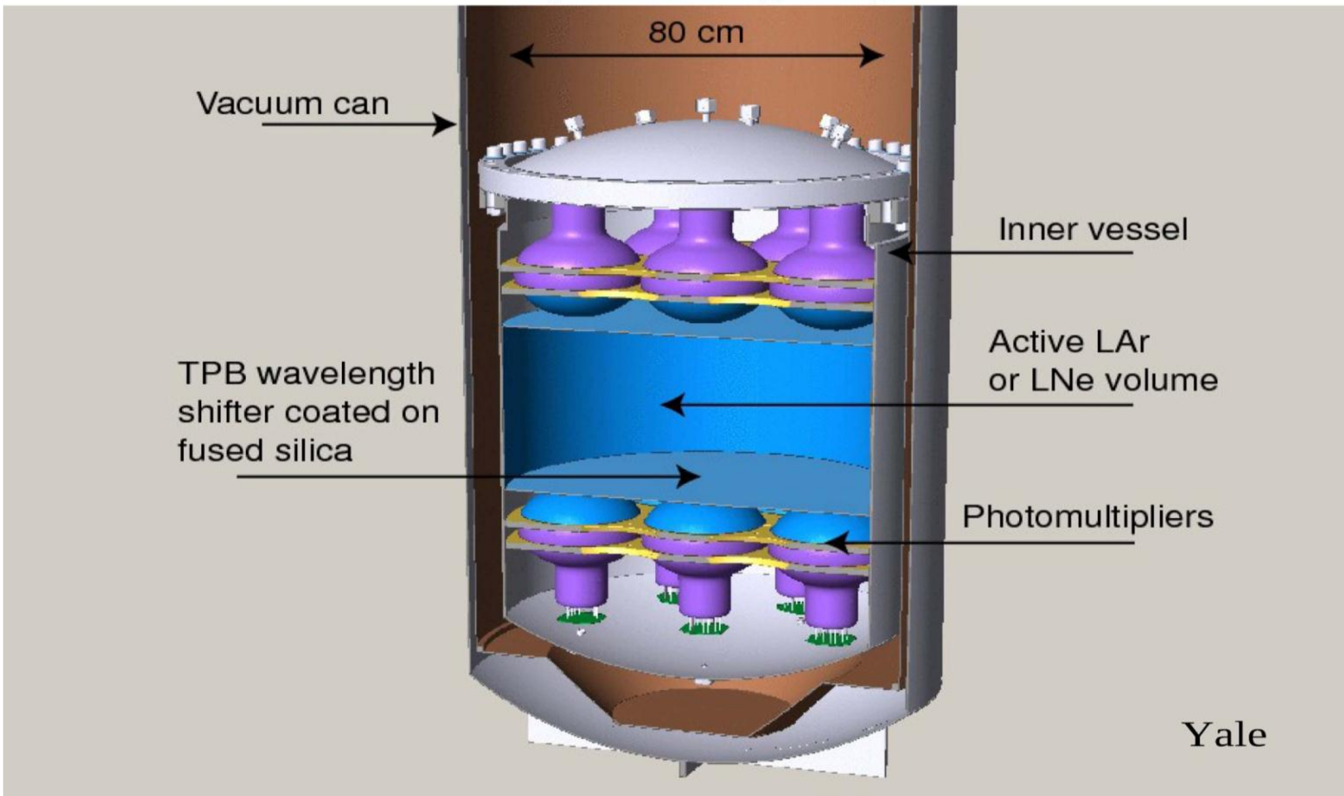


Targets of Interest for a possible experiment

Nucleus	A	Z	N	R(fm)	P (g/cm^3)	Volume x 10^{-6} cm^3 (1T)	# Nuclei x10^{-28} (1T)
Ne	20	10	10	3.26	1.20	0.83	3.0
Ar	40	18	22	4.10	1.40	0.72	1.5
Ge	74	32	42	5.04	5.32	0.19	0.81
Xe	132	54	78	6.11	3.05	0.33	0.46

Example of a LAr target design ~ 400 kg

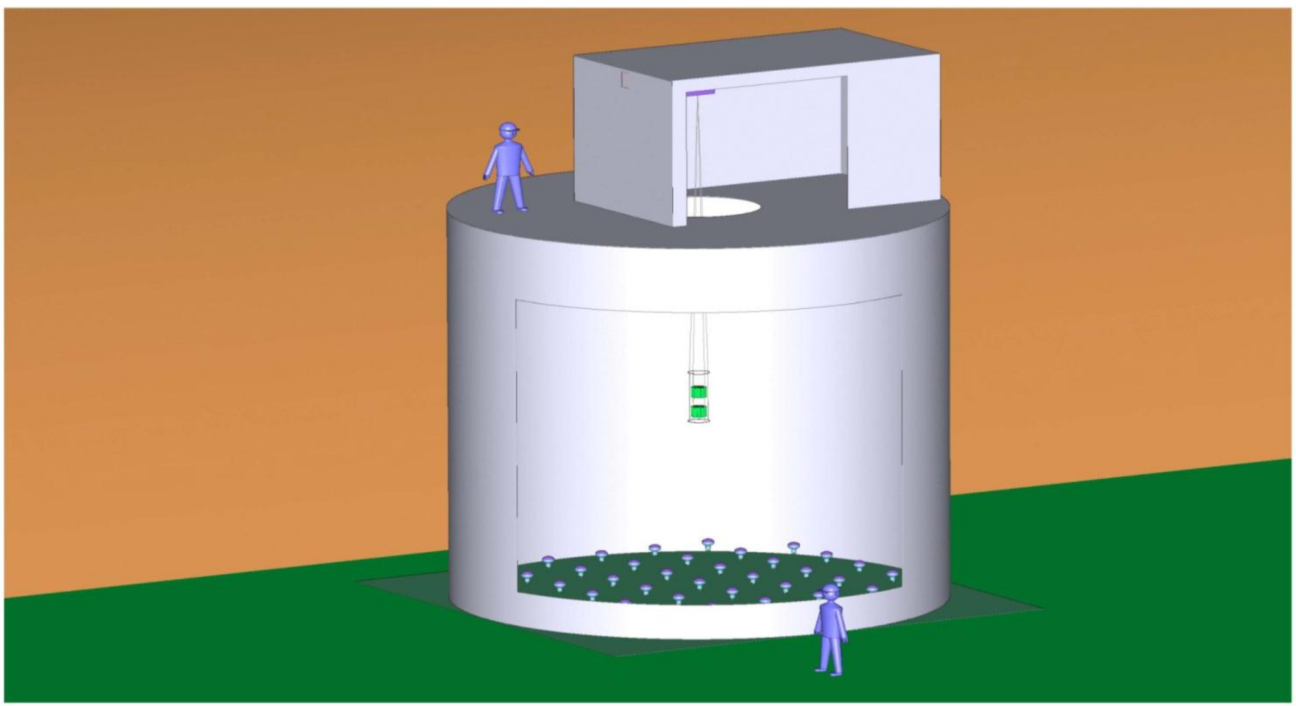
Detector concept: single phase Ar/Ne



14 Hamamatsu 20 cm 5912-02MOD PMTs

Water Shield
(7.3 m x 4.9m)

Shielding: 8 m diameter bolted steel water tank
66 cm steel (Duratek blocks, not shown)
Water tank instrumented with PMTs for cosmic veto

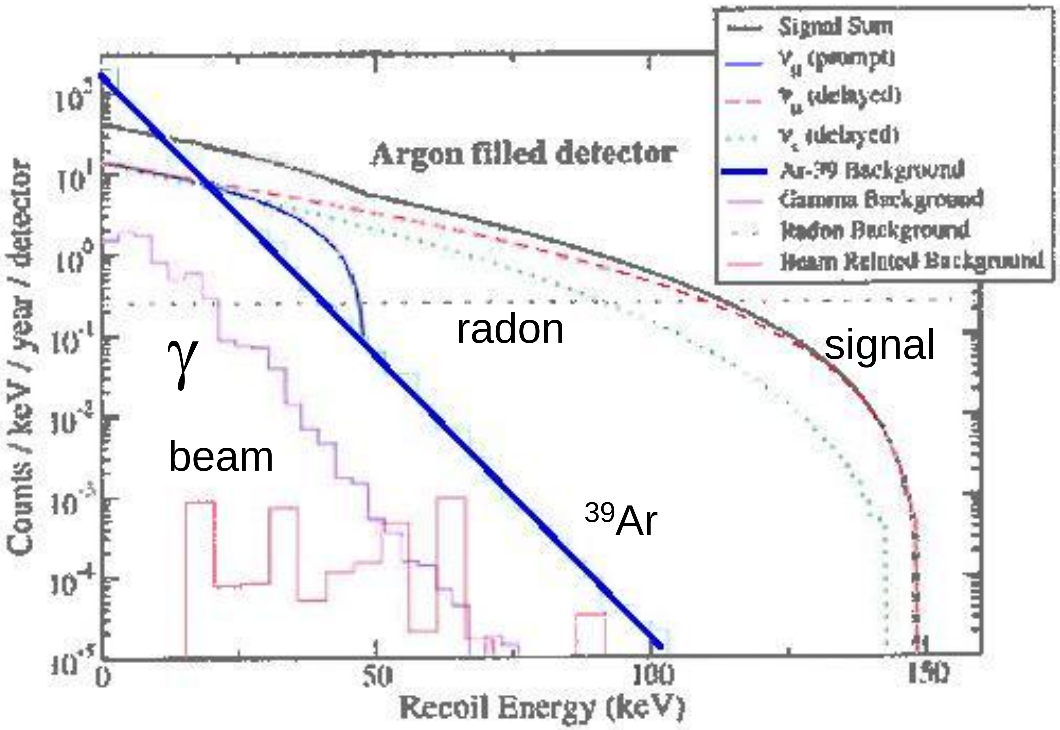


MC estimated backgrounds for coherent Ar scattering

Signal + beam-related neutron backgrounds

Expect ~500 events/year in 240 kg of Ar >20 keVr
(160 ev/yr in Ne >30 keVr)

SNS neutronics group calculation of neutron spectrum
+ Fluka sim through shielding (T. Empl, U. of Houston)
+ inner detector sim (J. Nikkel, Yale)



Magnetic moment scattering not included

Non-Standard Neutrino Interactions Parameterized by $\varepsilon_{\alpha\beta}^{qV}$

$\alpha \neq \beta$ non-universal

$\alpha = \beta$ universal

$\varepsilon_{\alpha\beta}^{qV} = \varepsilon_{\alpha\beta}^{qL} + \varepsilon_{\alpha\beta}^{qR}$

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times$$
$$\times \left\{ \left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})\right]^2 + \right.$$
$$\left. + \sum_{\alpha=\mu,\tau} \left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV})\right]^2 \right\}.$$

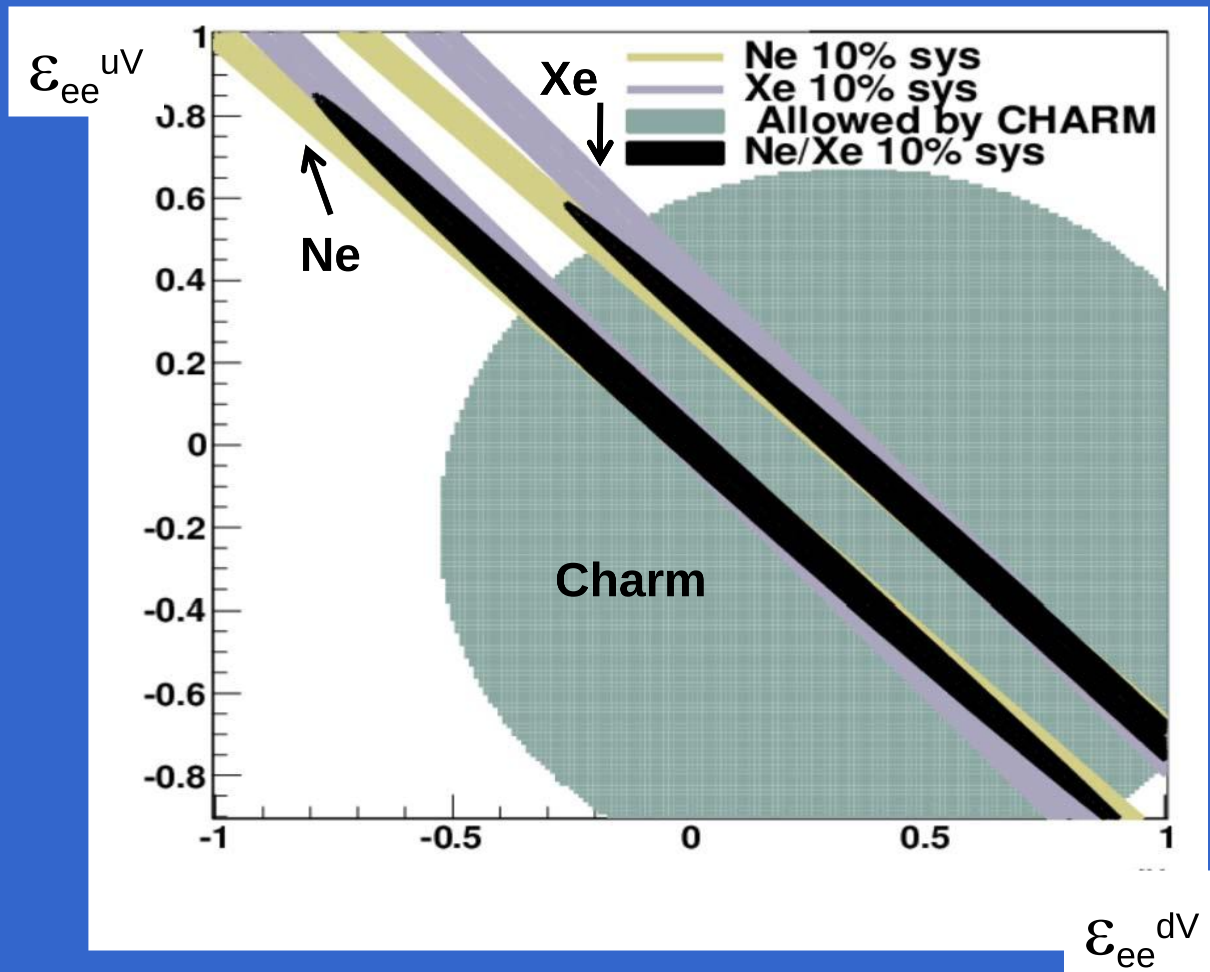
Limits on Non-standard interaction parameters

TABLE I. Constraints on NSI parameters, from **JHEP 3(03)011**

NSI parameter limit	Source
$-1 < \varepsilon^{uL}_{ee} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.4 < \varepsilon^{uR}_{ee} < 0.7$	
$-0.3 < \varepsilon^{dL}_{ee} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.6 < \varepsilon^{dR}_{ee} < 0.5$	
$\lvert\varepsilon^{uL}_{\mu\mu}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon^{uR}_{\mu\mu} < 0.003$	
$\lvert\varepsilon^{dL}_{\mu\mu}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon^{dR}_{\mu\mu} < 0.015$	
$\lvert\varepsilon^{uP}_{e\mu}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon^{dP}_{e\mu}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon^{uP}_{e\tau}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon^{dP}_{e\tau}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon^{uP}_{\mu\tau}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering
$\lvert\varepsilon^{dP}_{\mu\tau}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering

Potential limits from coherent scattering using neutrinos from the SNS

PRD 73(06)033005 PRD 73(06)113001



90 % C.L. for 100/yr each using ^{20}Ne and ^{132}Xe at the SNS

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Measurements of neutrino Electromagnetic Properties

The effective Lagrangian of the neutrino interacting with an electronagnetic fiel is;

$$\mathcal{L} = (1/2)\bar{\nu}^i \sigma_{\alpha\beta}(\mu_{ij} + \epsilon_{ij}\gamma_5)\nu^j F^{\alpha\beta}$$

In the above μ_{ij} and ϵ_{ij} are the magnetic and electric transition moments of th neutrino ($i = j$ diagonal), $\sigma_{\alpha\beta} = [\gamma_\alpha, \gamma_\beta]$ are Dirac matricies, ν_i are the neutrinos and $F^{\alpha\beta}$ is the EM field tensor. In the following;

$$\mu_{ij} \rightarrow \kappa_{ij} = (\mu_{ij} + \epsilon_{ij}\gamma_5)$$

A Dirac neutrino has diagonal moments, but a Majorana neutrino only has non diagonal moments.

The minimally extended SM has a moment;

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

As this is much smaller than any potentially measurement, an observation of non-zero moment would be an indication of physics beyond the SM.

The strongest bounds on the magnetic moment come from astro/cosmology

Model independent neutrino Electromagnetic Properties

In a general development it is difficult to decouple the value of the moment from a dependence on the neutrio mass. This results in small values of the moment for most extensions to the SM, and little difference between moments for the various Dirac neutrinos. (PL B642(06)377)

a) EM coupling to SM extensions
b) Mass generation from SM extensions

General neutrino Electromagnetic Properties
PL B642(06)377

SM value for the neutrino moment

$$\mu_\nu = \frac{3 G_F m_e m_\nu}{4 \pi^2 \sqrt{2}} \mu_B \qquad \mu_\nu \approx 3 \times 10^{-19} \left(\frac{m_\nu}{1 \text{ eV}} \right) \mu_B .$$

More Generally

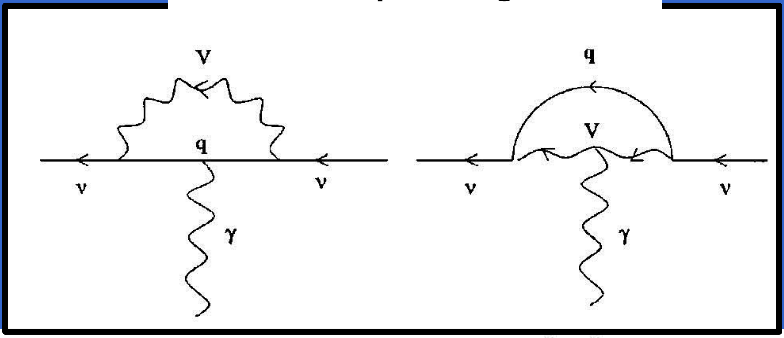
$$m_\nu \sim \frac{\alpha \Lambda^2}{16 \pi m_e} \left(\frac{\mu_\nu}{\mu_B} \right)$$

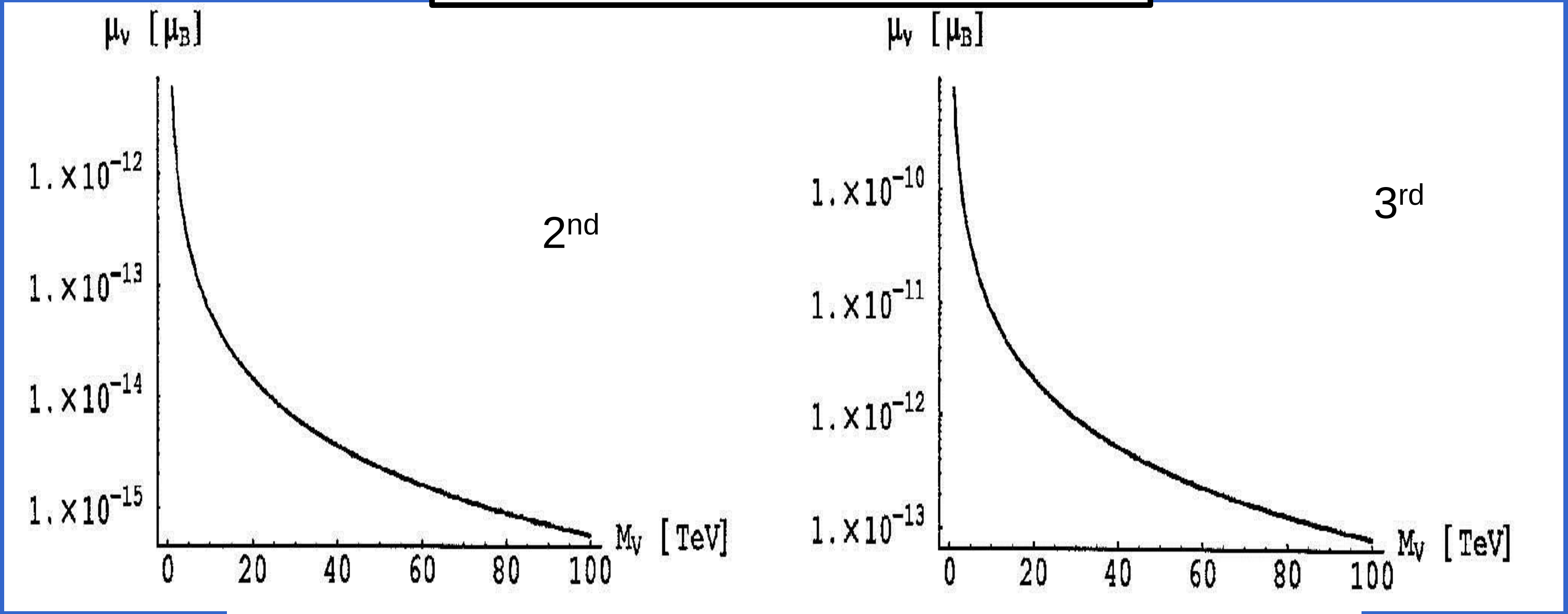
In the above Λ is an energy scale, which when taken at 1 TeV with $m_\nu = 0.3$ eV one obtains;

$$\frac{\mu_\nu}{\mu_B} \approx 10^{-15}$$

An example of a SM extension
Vector leptoquark coupling
PRD 60(99)073002

One loop diagrams



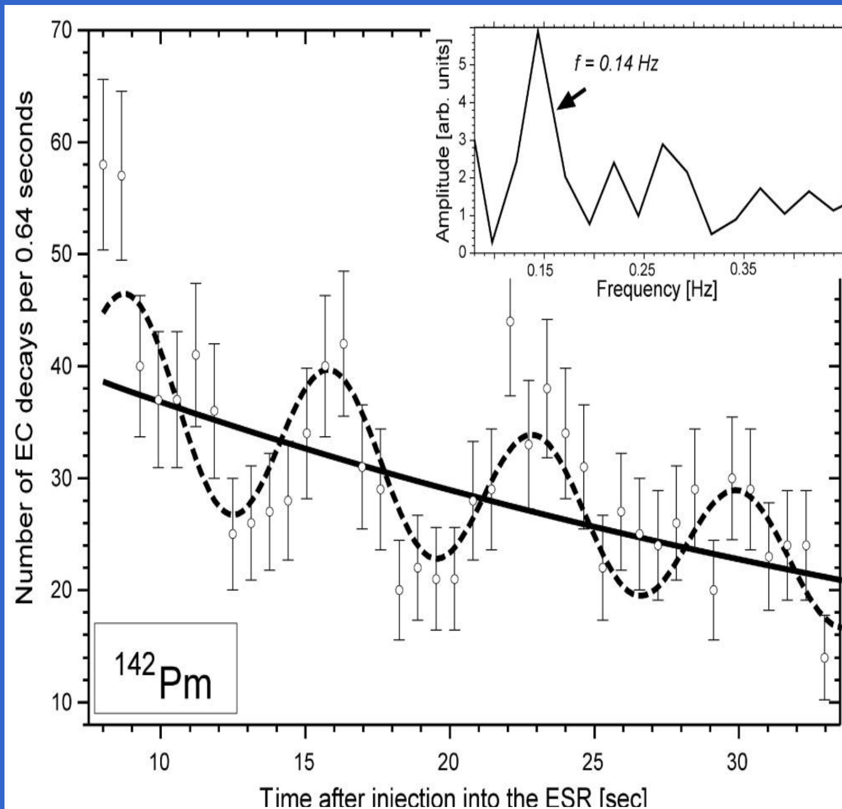


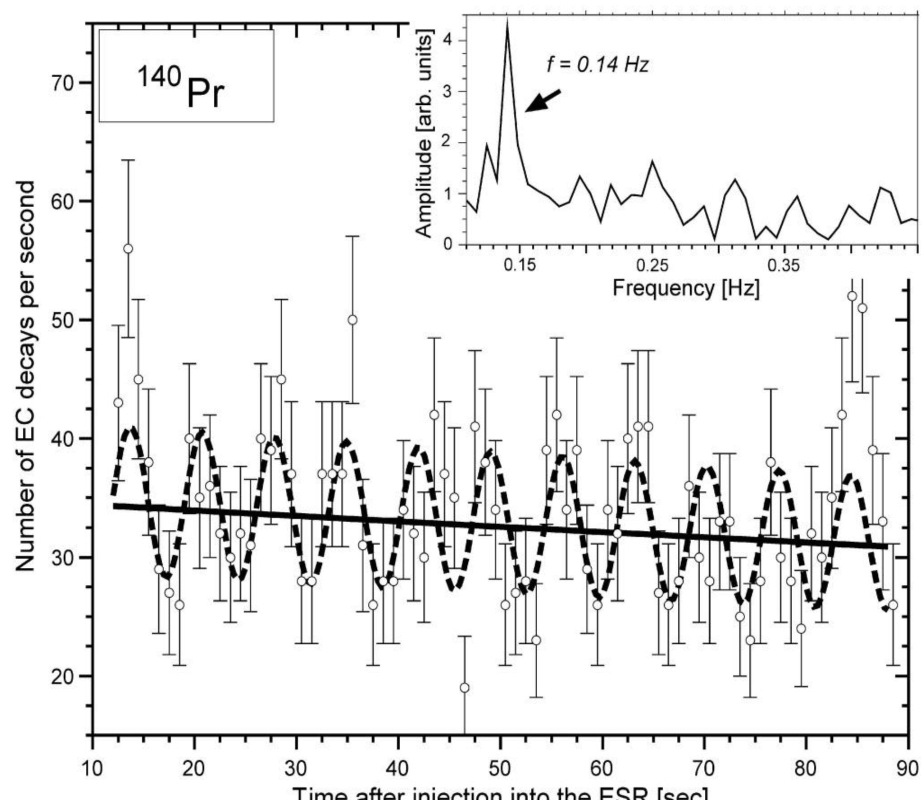
Neutrino moments for the 2nd and 3rd generations as a funcfion of the leptoquark mass (TeV)

The GSI anomalous oscillations
PL B 664(08)162

Time resolved EC of single H-like Praseodymium, ^{140}Pr, and Promethium, ^{142}Pm Ions observed in the ESR storage-cooler ring at GSI.

$$^{140}\mathrm{Pr} \longrightarrow {}^{140}\mathrm{Ce} + \nu \ \ (\mathrm{EC})$$





Time after injection **Time after injection**

Experimental Summary

- Decay rate of the two-body EC branch is periodically modulated with $\lambda_{EC}(t) = \lambda_{EC}\,(1 + a_{EC}\cos(\omega t + \Phi))$
- The period of modulation $T = 2\pi/\omega$ is about 6s (^{122}I) and 7s (^{140}Pr and ^{142}Pm)
- The period T scales with the atomic number A like $T \cong A/20$ in s
- The amplitude of modulation a_{EC} is about equal for all decays with the value $a_{EC} \sim 0.21$
- The phase Φ of the modulation is ~ $-\pi/2$, so $\lambda_{EC}(t) \sim \sin(\omega t)$
- The β^+ branch of ^{142}Pm shows no modulation with $a_{EC} = 0.03(3)$

The GSI anomaly Interpretation
NP A 842(10)102

No evidence for this oscillation observed in decays of neutral atoms in a solid. Atoms traversed different orbits in the fields so field harmonics could not be involved. Capture is allowed Gamow-Teller $1^+ \rightarrow 0^+$and hyperfine structure involves a sterile 3/2 and a ground ½ state but could not produce this behavior. The measured capture decay rate found consistent with known results.

The observation was interpreted as due to mixing of the neutrino final states. However, many subsequent authors pointed out that the transition probability is summed in-coherently over the neutrino final states since the neutrino was not directly observed (see a summary in NP A 842(10)102).

The GSI anomaly Interpretation

Thus the oscillation must have its origin in either a characteristic of H_like ions or the EM field in the ESR. The analysis in NP A 842(10)102 assumes;

1) Left handed ν_e emitted
2) Neutrinos are Dirac
3) Only ν_e / ν_μ coupling
4) All have the same magnetic moment μ
5) 1-d kinematics

The B field of the ESR covers only 35% of the total ring and it takes on the order of 1 sec to cool the injected and decayed nuclei. The emitted neutrino undergoes spin precession in the ESR field and then has two indistinguishable paths once produced (either in or out of field) so the transition amplitudes are entangled. This is precisely the same are the 2-slit experiment. The resulting oscillations have the correct time structure if the magnetic moment is a factor of

6 lower that the Borexino limit $\approx \mu = 0.9 \times 10^{-11}\ \mu_B$.

Measured Limits due to cosmological and astro-physical constraints PRD 76(07)053007

Plasmon decay PRL 81(98)4020

$\gamma \rightarrow \bar{\nu} + \nu$ **< 0.02 x 10^{-10}**

Supernova spin-flip PRD 59(99)111901

< 0.01-0.04 x 10^{-10}

Spectral shape PRL 93(04)021802

Super K < 1.1 x 10^{-10}

Spin flavor precession PRL 93(04)051304

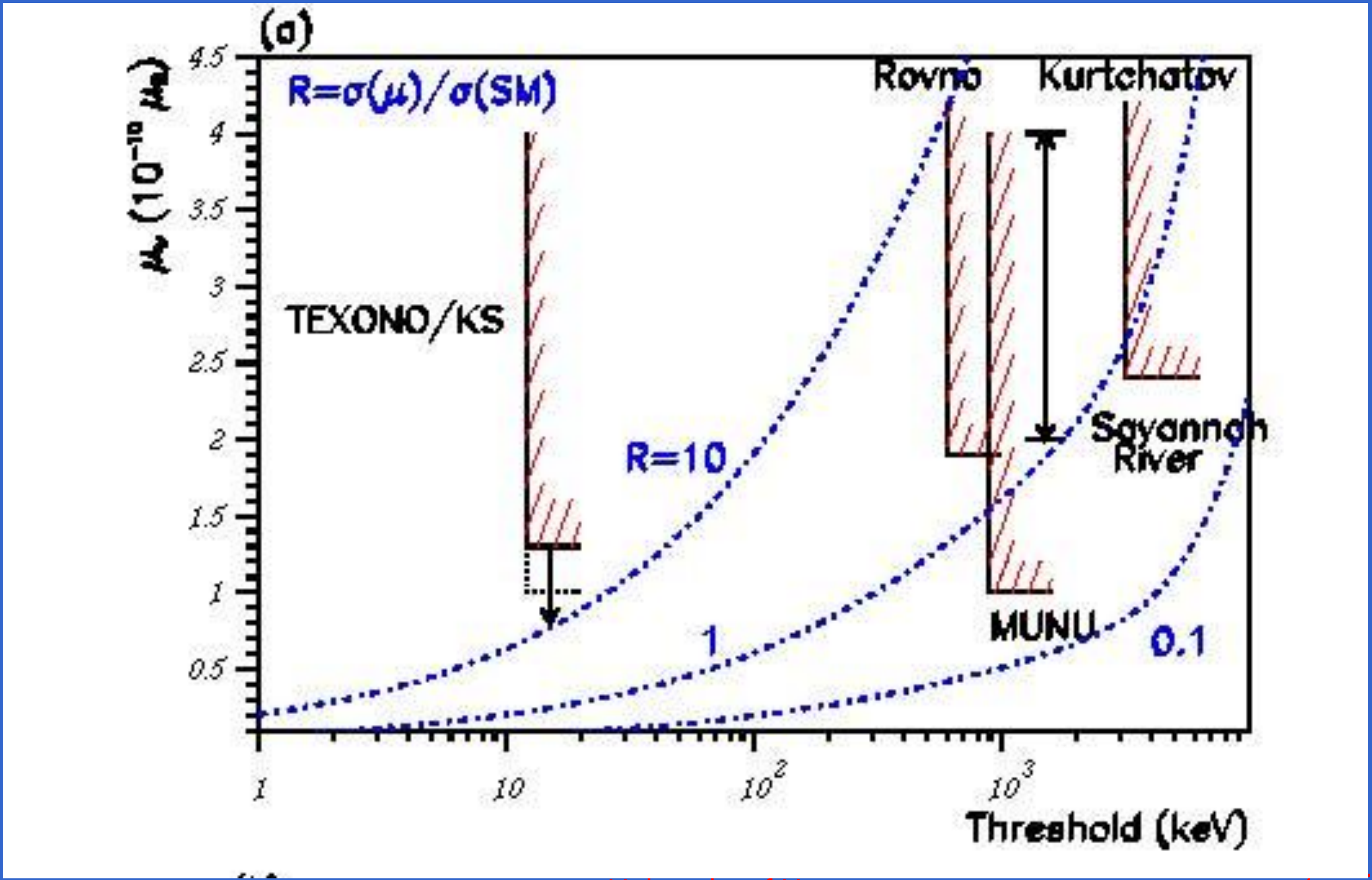
Kamland < 10^{-10} – 10^{-12}

Solar neutrino scattering PRL 101(08)091302

Borexino < 5.8 x 10^{-11} T > 250 kev

Measured Limits from nuclear decay neutrino–electron scattering

J phys Conf 120(08)052026



UHM EP

Coherent Scattering due the magnetic moment

Coherent scattering due to the magnetic moment depends on

1) 1/T (T the recoil energy)
2) Z^2
3) Form Factor $F^2(q^2)$
4) $(\mu_\nu / \mu_B)^2$

$$\frac{d\sigma}{dT} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{\mu_\nu}{\mu_B}\right)^2 \left[\frac{1 - T/E_\nu}{T}\right] Z^2 . F^2(\mathrm{Q})$$

This is in addition to coherent EW scattering from the nucleus

$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2). \qquad (1)$$

Integrated events
10-150 keV nuclear recoil

$(\# \text{ Events - } N_t^{-1} \text{- cm}^{-2} \text{- s}^{-1}) \times 10^{36}$

Target	ν_e	ν_μ	Elec. Moment	Muon Moment	Total
Ne	28	11	2.3	0.94	39
Ar	190	77	6.4	2.6	270
Xe	1200	472	25	10	1600

50-100 events/yr-T at the SNS

Summary

1. Further study of coherent neutrino-nuclear scattering might be worthwhile;
2. But any such experiments require the development of an intense flux (competitive) of low energy neutrinos
3. Reduction in non-standard neutrino interactions with quarks by an order of magnitude for some of the parameter extensions can be easily realized
4. Pushing a measurement of the dipole moment to present limits (~ few x10^{-11}) will be difficult (if for no other reason than the dependence on μ_ν^2)
5. A brief study of ν production from stopped μ's due to 8 GeV protons was presented, but off axis neutrino beams might have comparable or better yields.
6. The beam must be pulsed at rates of a few muon lifetimes to reduced background
7. Background (for sufficient neutrino flux) will limit the sensitivity of the experiments and must be carefully investigated.