Low Energy Neutrino Physics at the Kuo-Sheng Reactor Laboratory

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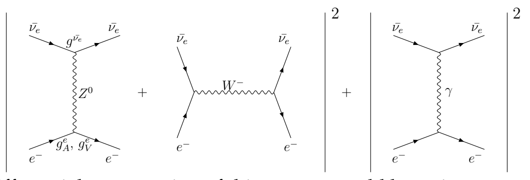
1 Introduction

1.1 TEXONO collaboration

- TEXONO established in 1996.
- First big collaboration between China and Taiwan.
- Magnetic moment results published.
- Period II → CsI detector data.
- Next → νN scattering with ULE-HPGe detector.

1.2 $\bar{\nu}_e e^- \to \bar{\nu}_X e^-$ Scattering

The searches for neutrino magnetic moments are performed by studying the recoil electron spectrum of $\bar{\nu}_e e^- \to \bar{\nu}_X e^-$ scattering. Both both diagonal and transition moments are allowed.



The differential cross-section of this process could be written as a sum of a standard model term and a magnetic moment term [3],

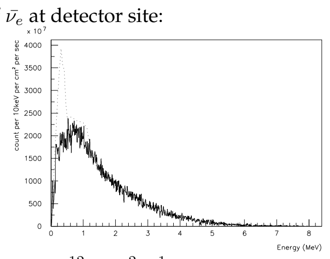
$$(\frac{d\sigma}{dT})_{\rm SM} = \frac{{G_F}^2 m_e}{2\pi}[(g_V - g_A)^2 + (g_V + g_A)^2(1-\frac{T}{E_\nu})^2 + (g_A^2 - g_V^2)\frac{m_e T}{E_\nu^2}],$$

$$(\frac{d\sigma}{dT})_{\rm MM} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}(\frac{1}{T}-\frac{1}{E_\nu}),$$

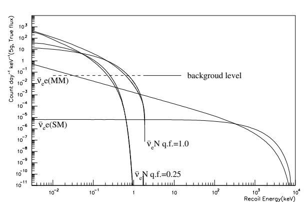
with T is the energy of recoil electron, μ_ν is the neutrino magnetic moment in units of μ_B.
When $T \to 0$, $(\frac{d\sigma}{dT})_{\rm SM} \to constant$, while $(\frac{d\sigma}{dT})_{\rm MM} \to 1/T$.
In very low recoil energy, magnetic moment term will dominated over standard model term.
The value of μ_{eff}^2 we are interested in is $\sim 10^{-10}\mu_B$, which is consistent with solar data(before KamLand results), and could be reached by present day laboratory experiment.

1.3 $\bar{\nu}_e$ Spectrum and Recoil Energy Spectrum

The spectrum of $\bar{\nu}_e$ at detector site:



with a total flux $\sim 6\times10^{12}$ cm^{-2}s^{-1}
This yield a recoil electron spectrum:



In the experiment, we focus at 10 - 100 keV range, in which magnatic moment related event rate is "decoupled" from standard model "background" at $\mu^2 \approx 10^{-10}\mu_B$.
The spectrum will compare with the reactor-on subtract reactor-off spectrum to search for neutrino magnetic moment bound.
The magnetic moment bound provide a limit on neutrino radiative decay constant in the process:

$$\nu_1 \to \nu_2\gamma.$$

The neutrino radiative decay constant is related to magnetic moment in this equation [4]:

$$\Gamma = \frac{1}{2\pi}\frac{(\Delta m^2)^3}{m^3}{\mu_\nu}^2$$

1.4 νN coherent scattering

The differential cross section of νN coherent scattering could be described by [5]:

$$(\frac{d\sigma}{dt})_{SM} = \frac{{G_F}^2 m_N}{4\pi}[Z(1-4sin^2\theta_W) - N]^2[1-\frac{M_N T_N}{2E_\nu^2}]$$

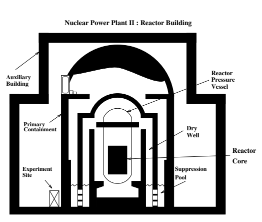
$$(\frac{d\sigma}{dt})_{MM} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}Z^2(\frac{1}{T}-\frac{1}{E_\nu})$$

The magnetic moment term enhanced by Z^2. However, due to the nuclei mass and quenching factor, the recoil energy of nuclei has a very low energy at ~ 100eV.
The figure shown rate of νN scattering with quenching factor 1.0 and 0.25 respectively, as well as $\bar{\nu}_e e^-$ scattering and background level of period I at 5 - 8 keV.

2 The Experiment

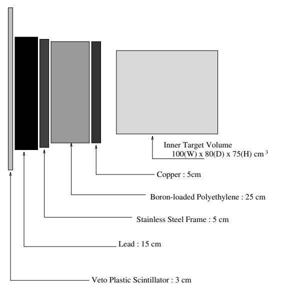
2.1 Location

The Kuo-Sheng nuclear power plant locate at the nothern shore of Taiwan, with two 2.9 GW reactor core. The detector is 28 m from first core. Diagram of experiment site and reactor core is shown in figure at right:



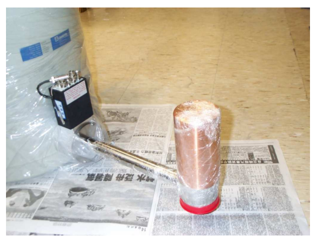
The experiment site is overburden by 10 m of concrete(30 mwe), which effectively shield hadronic component of cosmic ray.

2.2 Shielding

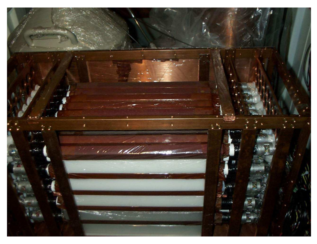


The shielding include plastic scintillator as cosmic veto, lead, steel(structure frame), boron loaded polyethelyene and copper.

2.3 Period I Configuration

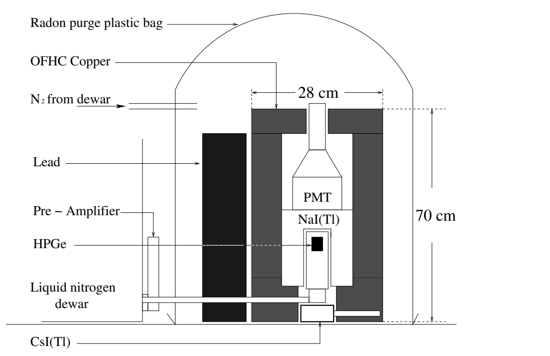


HPGe detector(1 kg)



CsI detector (186 kg, Period II)

In the period I(June 2001 - April 2002) experiment, the main detector is a 1 kg HPGe detector, along with a 46 kg CsI array detector, which is upgraded to 186 kg in period II.



The HPGe detector is surrounded by a NaI detector and a CsI detector at bottom as anti-Compton detector, and copper as passive shielding. The whole volume is flushed with nitrogen.

3 Data and Event Selections

3.1 Data

Period I data:

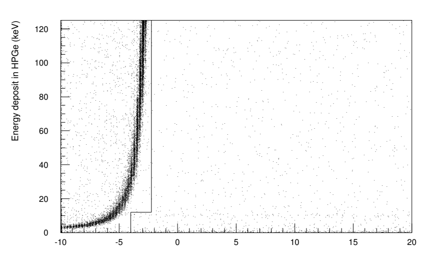
- 4712 hours of reactor-on, 1250 hours of reactor-off data.
- Detector mass 1.06 kg.
- Energy resolution of 0.4 keV(RMS) at 10 keV.
- Detector threshold 5 keV.
- Background at 12 - 60 keV is at O(1 cpd), comparable to underground Dark Matter experiment.

An efficiencied normalization accurated to 0.2% is achieved by:

- DAQ book keeping(hardware status, deadtime).
- Monitoring of random trigger events.
- Stability of ^{40}K peaks.
- Monitoring of 10 keV Ga X-rays peak(decaying with time).

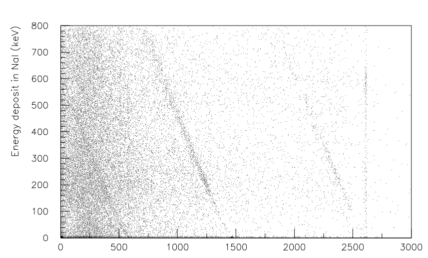
3.2 Event Selections

Arrival time of signal on veto scintillator vs. Energy deposit in HPGe:



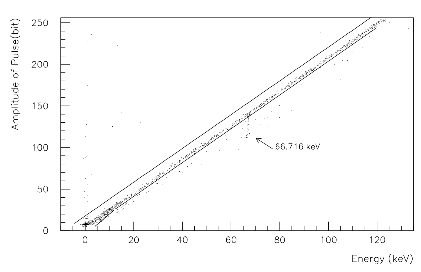
only events uniformly distributed at right had been seleted.

Energy deposit in NaI vs. Energy deposit in HPGe:



events without deposit energy in NaI detector had been selected.

Pulse shape discrimination: Pulse height vs. Energy:



select those events with proper pulse height to pulse area(energy) ratio, also shown in the plot is 66.712 keV double pulses events.

3.3 Efficiency & Uncertainties

The event selections give us a total suppression factor of 5% with effeciency 94%.
The uncertainties is came, mainly, from uncertainties of reactor $\bar{\nu}_e$ spectrum, which give us a final systematic error of $<0.4\times10^{-20}\mu_B^2$.
The sources of effeciency and uncertainties is summarized as follow:

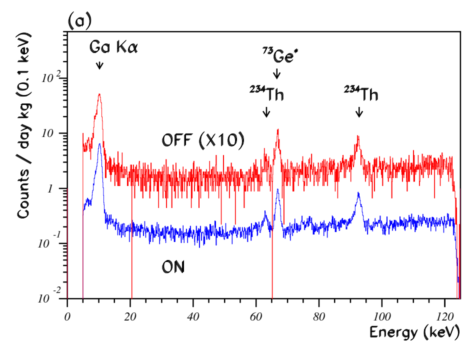
Event selection	Suppression	Efficiency
Raw data	1.0	1.0
Anti-Compton (AC)	0.06	0.99
Cosmic-ray veto(CRV)	0.96	0.95
Pulse shape analysis	0.86	1.0
Combined efficiency	0.05	0.94

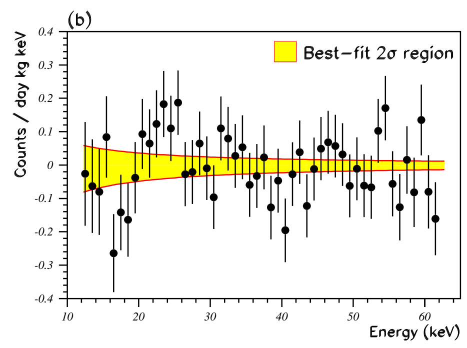
Sources	Uncertainties	$\sigma(\kappa_e^2)10^{-20}\mu_B^2$
DAQ live time ON/OFF	<0.2%	<0.30
Efficiencies for magnetic scattering	<0.2%	<0.01
Rates for magnetic scattering	24%	0.23
SM background subtraction	23%	0.03
Combined systematic error	···	<0.4

4 Results

4.1 Neutrino Magnetic Moment

The following figure show the reactor-on/off spectrum. The spectrum are calibrated by peaks from Ga x-rays, ^{73}Ge* and ^{234}Th,





The reactor-off spectrum is fitted with a polynomial $\phi_{OFF}(\chi^2/dof = 80/96)$, with use as an input to fit the reactor-on spectrum ϕ_{ON} with

$$\phi_{OFF} + \phi_{SM} + \kappa^2\phi_{MM}[10^{-10}\mu_B]$$

The best fit value of

$$\kappa^2 = -0.4 \pm 1.3(\text{stat.}) \pm 0.4(\text{sys.})[10^{-10}\mu_B]$$

with $\chi^2/dof = 48/49$ is obtained.
Adopting unified approach [6], yield

$$\mu_\nu < 1.3(1.0)\times10^{-10}\mu_B \qquad 90(68)\%C.L.$$

$2-\sigma$ best fit region of κ^2 is plotted in (b).

4.2 Limits from Other Experiments

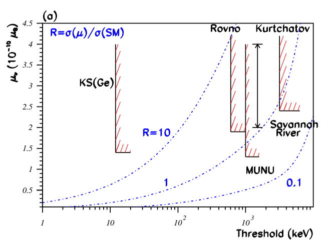
The limits quoted by PDG [6] is $\mu_\nu < 1.5\times10^{-10}\mu_B$, from the $\nu_e e^-$ scattering of SuperK data.
Limits from other reactor $\bar{\nu}_e e^-$ scattering experiment [6]:

- Savannah River(plastic scintillator), $\mu_\nu \approx 2-4\times10^{-10}\mu_B$
- Kurtchatoc(fluorocarbon scintillator), $\mu_\nu < 2.4\times10^{-10}\mu_B$
- Rovno(Si(Li)), $\mu_\nu < 1.9\times10^{-10}\mu_B$
- MUNU(CF^4), threshold ~ 1 MeV.

These reactor $\bar{\nu}_e e^-$ scattering experiment limits is around $1-2\times10^{-10}\mu_B$.
Astrophysics bound is more stringent, at $10^{-12}\mu_B$ order [6], however those limits is depends on stellar model and interaction model between neutrino and stellar objects.

4.3 Sensitivity

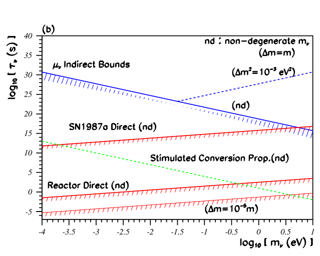
Our limits slightly better than previous $\bar{\nu}_e e^-$ scattering experiment. The most important thing is that our experiment sitting at a very low threshold, at which magnetic moment contribution is decoupled from standard model "background", and thus the uncertainties of expected $\bar{\nu}_e e^-$ scattering rate play a less significant role.



Derive from the bound on neutrino magnetic moment, the bound on neutrino radiative decay is

$$\tau_\nu {m_\nu}^3 > 2.8\times10^{18}\text{eV}^3\text{s}$$

which is more stringent than direct search.



5 νN coherent scattering and ULE-HPGe detector

5.1 ULE-HPGe Calibration Data: Threshold

With ULE-HPGe, measurement of νN coherent scattering is possible. Figure at right show ^{55}Fe spectrum with Ti as back-scattering source on a 5 g ULE-HPGe detector with Threshold ~ 60 eV .

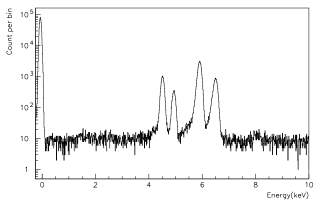
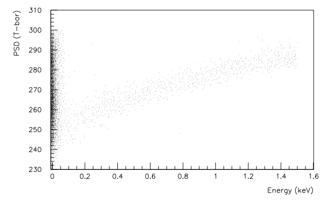


Figure at right show that noise and signal have different PSD, the noise edge is at ~ 60 eV.



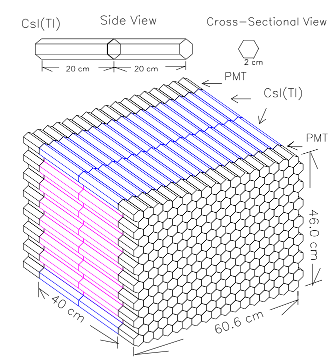
However, with such a small detector, integral count rate of νN scattering events is $\sim$0.05 counts per days. A larger detector is needed.

6 CsI: Period II

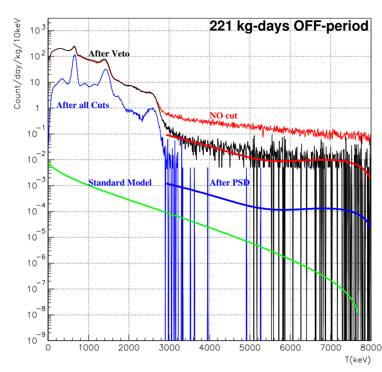
The purpose of the CsI detector is to study electro-weak parameter, g_V, g_A, $\sin^2(\theta_W)$, at MeV range [7] [8].

The period II CsI array detector consist 93×2 kg CsI crystals with PMT readout at both end, as shown in figure at right:

- The energy resolution is 10% at 660 keV.
- Position resolution is 2 cm at 660 keV.
- Calibration by ^{137}Cs, ^{40}K and ^{208}Tl.



6.1 Background spectrum of Period II CsI



After events selections and reactor-on/off subtration, the residual event rate is close to expected $\bar{\nu}_e e^-$ scattering rate at above 3 MeV.
The event selections include:

- Cosmic veto cut → one order suppression factor.
- Single crystal event and PSD → two order suppression factor.
- Reactor-on subtract reactor-off → one order suppression factor.

Goal: $\sigma(\bar{\nu}_e e^-)$ accurate to 20%.

7 Summary

Period I HPGe:

- μ_ν analysis : results published

Period II: HPGe

- addtional 1400/790 hours reactor-ON/OFF data
  → background and analysis improvement.

Period II: CsI(Tl)

- Measure electro-weak parameter at MeV range with $\sigma(\bar{\nu}_e e^-)$.
- Data analysing.

Period III and ULE-HPGe:

- continue with HPGe and CsI(Tl) configuration at period II.
- explore potentials on $\bar{\nu}_e N$ coherent scattering with ULE-HPGe.
- study quenching factor and pulse shape with neutron beam experiment.
- study on-site ULE-HPGe background.

References

[1] Home Page http://hepmail.phys.sinica.edu.tw/˜texono, also hep-ex/0307001.
[2] H. B. Li, et al., TEXONO Coll., Phys. Rev. Lett. 90, 131802 (2003).
[3] P. Vogel and J. Engel, Phys. Rev. D **38**, 3378(1989).
[4] G. G. Raffelt, Phys. Rev. D **39**, 2066(1989).
[5] A. C. Dodd, et al., Phys. Lett. **B 266** 434(1991).
[6] See the respective sections in *Review of Particle Physics*, Phys. Rev. D **66** (2002).
[7] H. B. Li, et al., Nucl. Instrum. Methods A **459** 93(2001).
[8] Y. Liu, et al., Nucl. Instrum. Methods A **482** 125(2002).