Low Energy Reactor Neutrino Physics with Germanium Detectors + ……

- Physics & Experiments & Requirements
- Crisis / Challenges / Opportunities
- Wish (Wishful Thinking) List from Users
- TEXONO@KSNL New Results [arXiv: 1303.0925]

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Sino-German Germanium Workshop
Tuebingen, April 2013
Tuebingen: stage of the most famous absence from a meeting in History of Physics
 Appears in 1st page of every neutrino physics text book
⇒ Introduction of the idea of neutrinos to science by Pauli, 1930.
Kuo Sheng Reactor Neutrino Laboratory (KSNL)
TEXONO Collaboration (since 1997) [Taiwan, China, India, Turkey]

Kuo-Sheng Nuclear Power Station: Reactor Building

28 m from core#1 @ 2.9 GW
~30 mwe overburden
Baseline Hardware Design

**p- PCGe**

- p+ (500g – 1 kg)
- n+ (~1mm Li diffused)

**n- PCGe**

- p+ (~0.5 μm Boron implanted)
- n+ (500 g)

**4x5g ULEGe**

- Proprietary Implanted Contact
- Passivated Surface
- N+ (Li-diffused) Contact

**Plastic Bag For Radon Purging**

- Liquid Nitrogen Dewar
- OFHC Copper
- HPGe
- Pre-Amplifier
- NaI(Tl)
- PMT

**Dimensions**

- 75 cm height
- 28 cm width

**Protection**

- Lead: 15 cm
- Stainless Steel Frame: 5 cm
- Boron-loaded Polyethylene: 25 cm
- OFHC Copper: 5 cm

**Moveable Trolley**
Current Research Theme:
“sub-keV” Ge Detectors

Physics Goals for $O[100 \text{ eV threshold}] \oplus 1 \text{ kg mass} \oplus 1 \text{ cpkkd} \text{ detector}:

- $\nu N$ coherent scattering, potential applications to reactor monitoring
- Low-mass WIMP searches
- Neutrino magnetic moments
- Open & Explore new detector window & detection channel & physics parameter space
**Neutrino Properties & Interactions at Reactor**

- **Quality**
- **Detector requirements**
- **Mass**

### Coherent Scattering

- **νN Coherent Scattering**
  - sub-keV O(kg) Ge
  - Dark Matter Searches (PRDRC-09)
  - DM@CJPL
  - .. more twists & turns (the “Beyonds”)?

### Observable Spectra with Reactor Neutrino “Beam”

- Threshold ~ 100 eV

### Detector requirements

- 1 counts / kg-keV-day

### Observable Spectra

- 1 kg HPGe
- 200 kg CsI(Tl)

### SM & NSI/BSM νe Scattering

- (2 ⊗ PRD10, PRD12)
- 200 kg CsI(Tl)

### Magnetic Moments

- (PRL03, PRD05, PRD07)
- 1 kg HPGe
Reactor Neutrino @ KSNL: Summary

1 kg ULB-HPGe

200 kg CsI(Tl)

FIG. 14 (color online). Summary of the results in the searches of neutrino magnetic moments with reactor neutrinos. Both the limits and the detection thresholds of the various experiments are shown.

\[ R_{SM} = R^{CC} + R^{NC} + \eta \times R^I \]

\[ \sin^2 \theta_W \]
Neutrino-Nucleus Coherent Scattering:

- **Standard Model allowed and predicted processes:**
  - $\nu + A \rightarrow \nu + A$

- **Diagram:**
  - Neutral current process (same for all $\nu$-flavor)
  - $\sigma \propto N^2 \quad @ \quad E_\nu < 50 \text{ MeV}$
    - $\Rightarrow$ “Coherent” [probe “sees” the whole nucleus]
  - sensitive probe for BSM ; interest in reactor monitoring
  - important process in stellar collapse & supernova explosion
  - analogous interaction used in dark matter detection
  - Ge at KSNL @ QF~0.2 : cut-off ~ 300 eV ;
    - Rate ~10 kg$^{-1}$ day$^{-1}$ @ threshold~100 eV

- **Techniques:**
  - Ionization: Ge, Si
  - Bolometer: TeO$_2$, Ge, CaWO$_4$, ...
  - Scintillation: NaI(Tl), LXe, CaF$_2$(Eu), ...
Wishes & Challenges

- > keV: $O(1 \text{ cpkkd})$ achieved
- Sub-keV Bkg goal: $O(10 \text{ cpkkd}) \rightarrow O(1 \text{ cpkkd})$
- How? Understand background and detector response; radiopure materials
- Novel Ideas?? Nuclear Vs Electron recoil differentiation??

- 20 g target: 200-eV physics threshold achieved
- Kg-target Threshold goal: $\sim 500 \text{ eV} \rightarrow 100 \text{ eV}$
- How? Sub noise-edge analysis; electronics JFET R&D
- Novel Ideas?? Signal Amplification??
PSD Selection to Suppress Electronic Noise

E.g. 1 $\Rightarrow$ correlations in two readout of different gains & shaping times

- look for specific +ve pulse fluctuations at specific & known timing

$6 \mu s$  
$12 \mu s$

![Signal](image1.png)

![Noise](image2.png)
Phys-Vs-Noise Selection Efficiency

Nal-AC & Ge Coincidence Events

ACV-Tagged 200-400 eV

50% @ 320 eV

E.g. 2 ⇒ correlations between Max. Amp. & Energy

Background Events
ACT Events

PSD cut
self-trigger
random-trigger

Counts per Bin

Before PSD
After PSD

Efficiency

Trigger:
Pulser
Background
PSD

0 50 100 150 200 250 300 350 385
Time of Nal

Nal Timing(50ns)

Counts per Bin

Before PSD
After PSD

Efficiency

Trigger:
Pulser
Background
PSD

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
Energy(keV)

Counts per Bin

Before PSD
After PSD

Efficiency

Trigger:
Pulser
Background
PSD

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
Energy(keV)
Exciting (Worrying) Development:
CDMS Experiment exploiting “phonon amplification at high drift voltage”

Luke Phonons:


Luke’s† experimental observations

Energy of phonons ~ V_{bias}

Noise is roughly constant up to some break down potential


Luke, P.N.\(^a\), Beeman, J.\(^a\), Goulding, F.S.\(^b\), Labov, S.E.\(^b\), Silver, E.H.\(^b\)

Calorimetric Ionization detector


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Abstract

A new mode of operation for ionization detectors is described. The amount of ionization produced in a detector is determined by measuring the amount of heat generated during the carrier collection process. Very high detection sensitivities, including single carrier detection, may be achieved at cryogenic temperatures. Results from an experimental device operated at T = 0.3 K are presented. © 1990.
Public Conference Statements by CDMS

Noise is very well behaved

We could reach a threshold of 0.085 keVee!

- Single Excitation Sensitivity Should Be Possible
  - The performance of the new iZIP detectors deployed in SuperCDMS Soudan has already proven to be excellent. We expect initial science results in 2013 for light mass WIMPs.
- Exciting possibilities for much lower phonon thresholds and substantial improvements in charge thresholds with HEMTs.

ALSO [arXiv:1206.2644, PRL12]: LiqXe techniques may have achieved single-electron sensitivities or O(10 eV) threshold.
Wish (Wishful Thinking) from Physicist Users:

*Climb Every Mountain ........*

- Innovations to do nuclear/electron differentiation, even down to 10-keVee ??
- Innovations to do electron-hole amplifications ??

Germanium Detector with Internal Amplification for Investigation of Rare Processes


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Abstract

Device of new type is suggested - germanium detector with internal amplification. Such detector having effective threshold about 10 eV opens up fresh opportunity for investigation of dark matter, measurement of neutrino magnet moment, of neutrino coherent scattering at nuclei and for study of solar neutrino problem. Construction of germanium detector with internal amplification and perspectives of its use are described.
Configurations:

※ 39.5 kg-days of data @ KSNL
※ Baseline design with NaI(Tl) AC & active CR vetos
※ PPCGe, 840 g fiducial mass
※ Analysis above electronic noise edge of 500-eV

Basic (Previously Used) Selection Criteria:

※ Physics Vs Electronics Noise (PN):
  ▶ pedestal tails, microphonics, preamp-reset induced ..... 
  ▶ Via pulse shape analysis & timing 
  ▶ WIMP-eff ~ survival of doubly-tagged ACT+CRT events

※ Anti-Compton vetos (ACV): NaI(Tl) anti-coincidence 
  ▶ WIMP-eff ~ survival of random trigger (RT) events

※ Cosmic-Ray vetos (CRV):
  ▶ WIMP-eff ~ survival of RT
  ▶ CR-rejection eff: survival of reference samples with NaI(Tl)>20 MeV
"Calibration" ≡ measure energy-dependent signal-retaining ($\varepsilon_{BS}$) & background-suppressing ($\lambda_{BS}$) efficiencies, such that [B,S=real; B’S’=measured]

$$\begin{align*}
B' &= \varepsilon_{BS} \cdot B + (1 - \lambda_{BS}) \cdot S \\
S' &= (1 - \varepsilon_{BS}) \cdot B + \lambda_{BS} \cdot S
\end{align*}$$

Approach: Identify at least two calibration data where (B,S) are known & (B’,S’) measured ⊕ solve coupled equation for ($\varepsilon_{BS}$, $\lambda_{BS}$) ⇒ correct physics (B’S’) to get (B,S)

Valid scheme should produce physics rates insensitive to location
Three complementary [different depth distributions] calibration data:

- Very Surface-rich low-energy $\gamma$ ($^{241}$Am, 60 keV); B=simulation
- Surface-rich high-energy $\gamma$ ($^{137}$Cs, 660 keV); B=simulation
- Bulk-rich cosmic-induced high energy neutrons by ACV+CRT tagging; B=same tag from NPCGe
"Candidate Events" = ACV+CRV+B

- ACV+CRV+B' + (ε_{BS}, λ_{BS}) correction
- insensitive to exact BS-cut location
- Subtract flat γ background & L-X-ray
  - residual spectrum for placing WIMP constraints
  - ∃ not-yet-accounted-for sub-keV events
Interesting windows on neutrino and dark matter experiments are opened up with detectors having sub-keV sensitivities.

Ge as ionization detectors has been and is a leading technology; competitive results achieved.

Formidable (potentially game-changing) challenges arising from bolometric Ge and liquid xenon techniques.

In addition to incremental improvements, the users would love (need) to have quantum leaps through innovative techniques to maintain competitive edges.

[☠️.... for brainstorming in this meeting]