Low Energy Neutrino & Dark Matter Physics with sub-keV Germanium Detectors

- Overview (Collaboration; Program; History)
- Facilities: KSNL & CJPL
- Detector & Physics Highlights
- Dark Matter Results

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TEXONO-CDEX Collaboration

TEXONO: Taiwan EXperiment On Neutrino [since 1997]:
- Neutrino Physics at Kuo-Sheng Reactor Neutrino Laboratory (KSNL)
  - Taiwan (AS, INER, KSNPS)
  - India (BHU)
  - Turkey (METU, DEU)

CDEX: China Dark Matter EXperiment [birth 2009]:
- Dark Matter Searches at China Jin-Ping Underground Laboratory (CJPL)
  - China (THU, CIAE, NKU, SCU, YLJHD)

Research Program: Low Energy Neutrino and Dark Matter Physics
TEXONO Collaboration
[ July 2013 @ Taipei ]

CDEX Collaboration
[ Dec 2012 @ Beijing ]
• 28 m from core#1 @ 2.9 GW
• Shallow site: ~30 mwe overburden
• ~10 m below ground level
Configuration: Modest yet Unique

Flexible Design: Allows different detectors config. for different physics

Front View (cosmic vetos, shieldings, control room ....)

Inner Target Volume

Shielding (Sept 2000)
KSNL : Detectors Schematics

ULB-HPGe [1 kg]

Csl(Tl) [200 kg]

Sub-keV Ge Detectors (20-900 g)

Data Acquisition with FADC
Readout & FPGA Capabilities

Multi-Disks Array [~300 Tb]
Neutrino Properties & Interactions at Reactor

**Detector requirements**

- **Threshold ~ 100 eV**
- Observable Spectra with Reactor Neutrino “Beam”
  - Magnetic Moments
    - $\nu-e$ Scattering
      - $[PRD03,PRD05,PRD07]$ (SM & NSI/BSM)
      - $\Rightarrow 200$ kg CsI(Tl)
    - $\Rightarrow 1$ kg HPGe
- Neutrino Milli-charge [$PRD14$]
  - $\Rightarrow$ sub-keV O(kg) ULEGe / PCGe
- $\nu N$ Coherent Scattering
  - $\Rightarrow$ sub-keV O(kg) ULEGe / PCGe
  - Dark Matter Searches @ KSNL [$PRD09,PRL13,AP14$]
  - CDEX Program@CJPL [$PRD13,PRD14,PRD14$]
CsI(Tl) 200 kg: Probe Electroweak Physics [PRD10]

\[ R = [1.08 \pm 0.21 \text{ (stat)} \pm 0.16 \text{ (sys)}] \times R_{SM} \]

\[ \sin^2 \theta_W = 0.251 \pm 0.031 \text{ (stat)} \pm 0.024 \text{ (sys)} \]

Verify SM Destructive Interference

Constraints on Various Beyond SM Effects [PRD10;PRD12]
Neutrino Electromagnetic Properties: Magnetic Moments

Search of $\mu_\nu$ at low energy with Reactor $\nu_e$ scattering

⇒ high signal rate & robustness:
- $\mu_\nu >>$SM [ decouple irreducible bkg $\oplus$ unknown sources ]
- $T << E_\nu \Rightarrow d\sigma/dT$ depends on total $\phi_\nu$ flux but NOT spectral shape [ flux well known: $\sim 6$ fission-$\nu \oplus \sim 1.2 238U$ capture-$\nu$ per fission ]

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

$\mu_\nu(\nu_e) < 7.2 \times 10^{-11} \mu_B$ [PRL03, PRL07]

...... Same approach continuing in GEMMA (Kalinin, Russia)

$\mu_\nu(\nu_e) < 2.9 \times 10^{-11} \mu_B$ [2013]
NEW (!) : Neutrino “Milli-charge” [+Chen, Liu, Chi; PRD14]

Neutrino Electromagnetic Form Factors

\[ \Gamma_{\text{em}}^\mu \equiv F_1 \cdot \gamma^\mu + F_2 \cdot \sigma^{\mu\nu} \cdot q_\nu, \]

\[ F_1 = \delta_Q \cdot e_0 + \frac{1}{6} \cdot q^2 \cdot \langle r^2 \rangle, \]

\[ F_2 = (-i) \cdot \frac{\mu_{\nu}}{2 \cdot m_e}, \]

Atomic Ionization Differential Cross-Section with full atomic physics many-body “MCRRPA” calculation [PL13]

Cross-section enhanced at low energy transfer (“minimum ionizing”)

Smoking-gun signatures for positive signals: peaks at known K/L binding energy at known ratios [different from cosmic-activation electron-capture background]

Present Bound: \( \delta_Q < 10^{-12} \)

Future Sensitivity Goal (100 eVee threshold): \( \delta_Q \sim 10^{-14} \)
Current Research Theme: “sub-keV” Ge Detectors

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

- $\nu N$ coherent scattering
- Low-mass WIMP searches
- Improve sensitivities on neutrino electromagnetic properties
- Implications on reactor operation monitoring
- Open new detector window & detection channel available for surprises
Neutrino-Nucleus Coherent Scattering:

Standard Model allowed and predicted processes:

\[ \nu + A \rightarrow \nu + A \]

- Neutral current process (same for all \( \nu \)-flavor)
- \( \sigma \propto N^2 \) @ \( E_\nu < 50 \text{ MeV} \)
  \( \Rightarrow \) “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 \( \sim 10 \text{ kg}^{-1} \text{ day}^{-1} \) @ threshold~100 eV

Ionization:
Ge, Si

Bolometer:
TeO\(_2\), Ge, CaWO\(_4\), ...

Scintillation:
NaI(Tl), LXe, CaF\(_2\)(Eu), ...
\[ \sigma_{\text{tot}} = \frac{G_F^2 E_\nu^2}{4\pi} \left[ Z(1 - 4\sin^2 \theta_W) - N \right]^2 \]

### Differential

- Needs Background < 10 cpkkd,
- Target \( \rightarrow \) 1 cpk kd

### Integral

- Needs Threshold < 200 eV\text{ee},
- Target \( \rightarrow \) 100 eV\text{ee}
Baseline Hardware Design

**p- PCGe**

- 500g – 1 kg

**n- PCGe**

- 500g

**p^+ (~0.5 μm Boron implanted)**

**n^+ (~1mm Li diffused)**

**4x5g ULEGe**

**Baseline Hardware Design**

- Plastic Bag For Radon Purging
- N\textsubscript{2} from dewar
- OFHC Copper
- Liquid Nitrogen Dewar
- HPGe
- Pre-Amplifier
- PMT
- Na\textsubscript{1}(Tl)

**40 cm**

**Stainless Steel Frame**: 5cm

**Boron-loaded Polyethylene**: 25cm

**Lead brick**:

**Lead**: 15cm

**Novable trolley**
TEXONO @ KSNL (2007): 220 eV threshold with 20g ULEGe; Opened window for “Light WIMPs” searches [PRD09]

2010—2013: claimed evidence of GeV WIMPs from terrestrial experiments and astrophysics data [strength diminished by now]

Hints for light dark matter

On the Earth …

- Several intriguing direct detection signals
- But severe tension with null results

… and in the skies

- An tentative $\gamma$ ray excess from the Galactic Center
  Hooper Goodenough 0912.2998, 1010.2752, 1201.1303
  - Morphology ≠ point source
- Radio filaments
  Linden Hooper Yusef-Zadeh 1106.5493
- Isotropic radio background
  Hooper Belikov Jeltema Linden Profumo Slatyer 1203.3547
Sub-keV Ge Detector Techniques: Users’ R&D Items

- Quenching Factors -- nuclear recoils’ Ionization Yields
- Energy Definition & Calibration
- Trigger Efficiencies near threshold
- Bulk Vs Surface Events Selection – algorithms & efficiencies
- Physics Vs Noise Pulse-Shape Selection -- algorithms & efficiencies
Light WIMP Searches @ KSNL with Ge

Learn & Establish Techniques
Catalyze CDEX-1 @ CJPL
Produce Physics Results!

TEXONO@KSNL [PRL13,AP14] :
- 500 eV threshold
- devised schemes for B/S separation & efficiencies
- probed and excluded some light WIMP allowed regions
- Indicated: leakage of “Surface” background to “Bulk” samples can give false positive signals.
- 2400+ m rock overburden, drive-in road tunnel access
- ~6 muons/m²-month (cf sea-level 100 Hz/m²)
- 6X6X40 m cavern constructed [managed by THU & YLJHDC]
- CDEX-1 Dark Matter Program
China, others dig more and deeper underground labs

From tiny to gargantuan, experiments are in the works to exploit the shielding from cosmic rays that being deep underground offers.
CDEX-1 @ CJPL:
- Adopt KSNL Baseline Design
- Engineering Run 2011
- Physics Run June 2012
- First Results 2013

1 m thick PE House

Internal space: 8mX4.5mX4m(H)

\( \mu \)-rate ~ 6 per m\(^2\) per month
CDEX-1 @ CJPL 2014 [PRD13, PRD14]

- 1 kg pPCGe @ 475 eVee threshold
- All events quantitatively accounted for; No Residual Excesses at sub-keV
- Exclude CoGeNT-2013 excess as WIMP-induced, independent of interaction channels
Design of CDEX-10: with LAr Anti-Compton

- Ge + JFET
- PCGe in Arrays & Strings
- LiqN (LiqAr) as both cryogenics (& active anti-Compton)
- \( \sim 30-40 \text{ cm} \ 4\pi \) shielding range
- Prototype 2014
- Baseline Design for Future O(1 ton) Expt for DM+0νββ

CDEX-10 (2015+)

CDEX-(1 ton) Artist’s Conception
Ge Processing & Assembly Facility @ THU

- Growth & Processing of raw Ge crystal
- Application-specific optimized assembly
- R&D on JFETs & Preamps & ASICs

Crystal → Processing & Assembling → Detector & Cryogenics
**NEW Lab: CJPL-II**

- Four 14m*14m*130m Lab Halls
- Construction Started end 2014

**CJPL-I** (~500 m)

- 1# Auxiliary Tunnel
- Drainage Tunnel
- 2# Auxiliary Tunnel
- Traffic Tunnel
- Water Tunnel

**Four 14m*14m*130m Lab Halls**

**[30+ > CJPL-I]**

**Construction Started end 2014**

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**China supersizes its underground physics lab**

Planned expansion could pave way for “ultimate dark matter experiment”

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**Physics Today** 68(1), 23 (2015)

**China carves out larger role in underground science**

As it is doing in so many areas of science, China is racing onto the world stage of underground astroparticle physics.
Summary & Prospects

- Competitive results on light WIMPs with sub-keV Ge, even at a surface TEXONO@KSNL; further improved with underground CDEX-1 @ CJPL

- Surface leakage to Bulk samples is important to PPCGe at low energy, origin of earlier "WIMP signal".

- CJPL-2: 30+ times more space, being built

- Ge-R&D + technology acquisition $\Rightarrow$ next generation DM (+DBD) experiment @ CJPL

- KSNL: more matured to return to original goal
  - $\nu$N coherent scattering
Back Up
Technical Materials
CDEX-0 [20g prototype] @CJPL 2014 [PRD14]

12g ULEGe e @ 177 eVee Analysis Threshold

combined efficiency (%)

Energy (keVee)

177 eVee at 50% eff.

Energy (keVee)

counts (kg⁻¹ keVee⁻¹ day⁻¹)

Energy (keVee)

Projected
(10 kg-yr; 100 eV; 1 kg⁻¹ keVee⁻¹ day⁻¹)

Mₚ (GeV/c²)
QF in Ge:

- Data available down to sub-keV measurable energy
- TRIM Software: better match to data over extended energy
PCGe → Reset Preamp

SA: Shaping time 0.5 µs to fit in one frame; Typical operation in 6-12 µs
Energy Definition:
- Area of Shaping Amplifier Output with Optimized Integration Range
- Linear in Area (Q), not in Amplitude (A) Near Noise-Edge

Energy Calibration:
- Random Trigger to define Pedestals
- X-ray Sources up to 60 keV
- Internal Lines (1-12 keV) from in situ data
- Precision Pulser for low energy interpolation

PCGe
Q(RMS) ≈ 80 eV

A Vs Q

Trigger Efficiency

Pulser Direct Measurement
Derivation from In Situ Q-A

Discriminator Threshold
Trigger Rates:

- Agreed with expectations
- A universal curve valid to all detectors with discriminator threshold in “Noise RMS” unit.
- Saturation at low threshold due to “Gate Width”
- Physics events start dominating at high threshold (background dependence)

\[ R \sim \frac{1}{4\pi} \exp \left( -\frac{d^2}{2\sigma^2} \right) \]
Valid scheme should produce physics rates insensitive to location

- n+ "inactive layer" is not totally dead; signals finite but slower rise time
- ACV+CRT tag (cosmic-induced high energy neutrons) \(\Rightarrow\) no surface band
- n-type PCGe \(\Rightarrow\) no surface band

PSD for Surface Vs Bulk Events @ PCGe [AP14]
“Calibration” $\equiv$ measure energy-dependent signal-retaining ($\varepsilon_{BS}$) & background-suppressing ($\lambda_{BS}$) efficiencies, related by the coupled equations \([B,S=\text{real} ; B',S'=\text{measured}]\):

\[
B' = \varepsilon_{BS} \cdot B + (1 - \lambda_{BS}) \cdot S \\
S' = (1 - \varepsilon_{BS}) \cdot B + \lambda_{BS} \cdot S
\]

Approach: Identify **THREE(+)** calibration data \([\text{low and high energy } \gamma, \text{ cosmic-induced neutrons}]\) where \((B,S)\) are known & \((B',S')\) measured $\oplus$ solve coupled equation for \((\varepsilon_{BS}, \lambda_{BS})\)

KSNL: $^{241}\text{Am}, ^{137}\text{Cs}, \text{ cosmic-HE-n}$

CJPL: $^{241}\text{Am}, ^{57}\text{Co}, ^{137}\text{Cs}, ^{60}\text{Co}$

Bulk-Rich high-energy neutrons constrain $\varepsilon_{BS}$

Surface-Rich $\gamma$-rays constrain $\lambda_{BS}$
PSD Selection to Suppress Electronic Noise

E.g. 1 ⇒ correlations in two readout of different gains & shaping times

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

![Graphs showing PSD selection to suppress electronic noise with specific pulse fluctuations at specific timing]

- Signal
- Noise

- 6µs
- 12µs

![Graph showing ULEG with PSD cut, background events, and calibration events]
Phys-Vs-Noise Selection Efficiency

Nal-AC & Ge Coincidence Events

ACV-Tagged 200-400 eV

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

50% @ 320 eV

Trigger:
- Background Events
- ACT Events

Before PSD

After PSD

Counts per Bin

Efficiency

Energy (keV)

Nal Timing (50 ns)