PICO–LON dark matter search project

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PICO-LON Collaboration

- Tokushima University
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- Osaka University
- Osaka Sangyo University
  - R.Hazama
- Kavli IPMU Tokyo University (WPI)
  - A.Kozlov, Y.Takemoto
- Tohoku University
  - K.Inoue, H.Ikeda, Y.Teraoka
- I.S.C. Lab.
  - K.Imagawa, K.Yasuda
PICO-LON for WIMPs search

- Pure
- Inorganic
- Crystal
- Observatory for Low-background
- Neutr(al)ino

- High selectivity
- Background reduction
- Sensitive to
  - Elastic scattering (SI+SD)
  - Inelastic scattering (SD)
- Study the interaction type of WIMPs
Outline of PICO-LON project

- **Search for dark matter by 250 kg NaI(Tl)**
  - Test the annual modulation signal (DAMA/LIBRA)
  - Detection of dark matter candidates
  - 42 modules of 5 inch $\phi \times 5$ inch NaI(Tl)
  - Simple detector design

- **Present status**
  - Performance test of single module
  - Purification of NaI powder
  - Low BG measurement by single module
  - Material selection
## NaI(Tl) purification

<table>
<thead>
<tr>
<th></th>
<th>DAMA</th>
<th>DM-Ice</th>
<th>Ingot 23 (2013)</th>
<th>Goal of PICO-LON</th>
</tr>
</thead>
<tbody>
<tr>
<td>natK (ppb)</td>
<td>&lt;20</td>
<td>660</td>
<td>Not yet (&lt;100)</td>
<td>&lt;20</td>
</tr>
<tr>
<td>232Th (ppt)</td>
<td>0.5-0.7</td>
<td>2.5</td>
<td>3.3 ± 2.0</td>
<td>&lt;4</td>
</tr>
<tr>
<td>238U (ppt)</td>
<td>0.7-10</td>
<td>1.4</td>
<td>5.4 ± 0.9</td>
<td>&lt;10</td>
</tr>
<tr>
<td>210Pb (μBq/kg)</td>
<td>5-30</td>
<td>1470</td>
<td>58 ± 26</td>
<td>&lt; 5</td>
</tr>
</tbody>
</table>

- **U-chain**: 1ppt = 12.3μBq/kg
- **Th-chain**: 1ppt = 4.0μBq/kg
- **210Pb**: 1ppt = 2.5kBq/kg

Purification of NaI powder

- Purification of NaI powder
  - Selection of cation exchange resin
  - Cation exchange resin for Pb reduction
  - Optimization of purification condition

- Low BG measurement
  - Selection of surrounding materials
  - Measurement in Kamioka Underground Laboratory
Alpha ray intensity $^{210}\text{Pb}$ was removed!

Double-Gate PSD is applied

\[
\text{Gate Ratio} = \frac{Q_{\text{tail, 1us}}}{Q_{\text{1.2us}}}
\]

\[Q (\text{total Q}) \]

\[Q_{0.2us} \quad Q_{\text{tail, 1us}} \quad Q_{1.2us}\]

\[\alpha \text{ is faster for NaI}\]

\[\alpha \text{ background rate is consistent to Ingot23. A reduction method is under investigation.}\]

**Rate [uBg/kg]**

<table>
<thead>
<tr>
<th></th>
<th>Ingot23</th>
<th>Ingot26</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{226}\text{Ra ($^{234}\text{U, 230Th}$)}$</td>
<td>$105 \pm 17$</td>
<td>$118 \pm 13$</td>
</tr>
<tr>
<td>$^{222}\text{Rn ($^{210}\text{Po, 228Th}$)}$</td>
<td>$108 \pm 17$</td>
<td>$115 \pm 9$</td>
</tr>
<tr>
<td>$^{218}\text{Po ($^{212}\text{Bi, 222Rn}$)}$</td>
<td>$100 \pm 14$</td>
<td>$95 \pm 8$</td>
</tr>
</tbody>
</table>

(arXiv:1407.3542)
**Shielding**
- 2700 m.w.e rock
  - Cosmic ray, 10^{-5}
- 5 cm + B-PE
  - Neutrons
- 18 cm + High purity Pb
  - External γ
- 5 cm + OFC (8 yr. UG)
  - γ from Pb

**Rn purge**
- G1 GN2 2 l/min in the most inner region
Low BG data and Calibration data

① Scaled so that $^{40}$K $\gamma \Rightarrow 1460$ keV

② Same scale reproduces $^{133}$Ba X rays (31, 53, 81 keV)

③ At least we see down to 7 keV and the rate is $\sim 20$ cpd/kg

~25.2 days x 1.2 kg exposure

Calib. ($^{133}$Ba & $^{40}$K)

④ 200 ns Integ. TFA & wf. $> 100$ ns $\Rightarrow \sim 1$ keV Th.

Preliminary result.
Monte Carlo simulation for low BG measurement

For each, 6 chains are simulated.

- **U1**: $^{238}\text{U} - ^{226}\text{Ra}$
- **U2**: $^{226}\text{Ra} - ^{210}\text{Pb}$
- **U3**: $^{210}\text{Pb} - ^{206}\text{Pb}$
- **Th1**: $^{232}\text{Th} - ^{228}\text{Th}$
- **Th2**: $^{228}\text{Th} - ^{208}\text{Pb}$
- **K**: $^{40}\text{K}$

**Known Rate**

**PMT (Ge)**
- **K**: $819 \pm 38$ mBq
- **U2–3**: $23.7 \pm 2.8$ mBq
- **Th2**: $22.8 \pm 4.8$ mBq

**Rock (NaI)**
- **K**: $1.56$ ppm
- **U2–3**: $3.13$ ppm
- **Th2**: $5.69$ ppm
## Impurities in NaI(Tl) detector

<table>
<thead>
<tr>
<th></th>
<th>Best Fit ($\mu$Bq/kg)</th>
<th>NaI K=0 ($\mu$Bq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI U2($^{226}$Ra)</td>
<td>57.8 ± 3.5</td>
<td>56.8 ± 3.4</td>
</tr>
<tr>
<td>NaI U3($^{210}$Pb)</td>
<td>29.4 ± 6.6</td>
<td>27.9 ± 6.5</td>
</tr>
<tr>
<td>NaI Th2($^{228}$Th)</td>
<td>1.46 ± 1.85</td>
<td>1.52 ± 1.72</td>
</tr>
<tr>
<td>NaI K</td>
<td>(1.10 ± 0.03) × 10$^5$</td>
<td>0</td>
</tr>
<tr>
<td>Cu case K</td>
<td>(5.19 ± 0.97) × 10$^5$</td>
<td>(0.2 ± 10.7) × 10$^3$</td>
</tr>
<tr>
<td>Rubber K</td>
<td>0 ± 731</td>
<td>(2.14 ± 0.86) × 10$^5$</td>
</tr>
<tr>
<td>Cover K</td>
<td>5.19 × 10$^5$</td>
<td>2.14 × 10$^5$</td>
</tr>
<tr>
<td>PMT K</td>
<td>6.42 × 10$^5$</td>
<td>(1.78 ± 0.043) × 10$^6$</td>
</tr>
</tbody>
</table>

No significant signal from NaI(Tl) measured by Ge
Summary

• Reduction of RI impurities in NaI has been achieved
  • To the same level as DAMA/LIBRA
• Low BG test has been performed
  • \(~20\ \text{day/keV/kg} \ @ \ 7\ \text{keV}_\text{ee}\)
  • This background rate is mainly due to PMT and Spacer
  • Refurbished NaI(Tl) is now in Kamioka

• Future
  • Further purification of NaI powder
  • Material selection (In collaboration with XMASS)
  • 5 inch\(\phi\) × 5 inch NaI(Tl) (PICO-LON module) in 2016
  • 250 kg NaI(Tl) : 42 modules of PICO-LON
Expected sensitivity (Elastic, 250 kg*yr)

\[ 2.1 \text{ day/kg/keV} \quad \text{Eth}=1\text{keV} \]
Back up slides
TFA Installation & Energy Threshold

[Diagram of TFA installation and energy threshold system]

- **NaI(Tl)**
- **R6091**
- **MoGURA**
- **FPGA**
- **DAC**
- **NIM**
- **TFA**
- **Discri.**
- **Gate GEN**
- **HV +2kV**
- **WAVEFORM**
- **Dig HIT**
- **Ana HIT**
- **TRG**
Gamma Fit

**40K & 208TI**

\[ \frac{\sigma}{\sqrt{\mu}} = 3.6\% / \sqrt{\text{MeV}} \]

\[ \text{FWHM} / \mu = 6.9\% \]

- **40K -- Gaussian + Linear --**
  - \[ \chi^2/\text{ndf} = 3.2/65 \]
  - \[ \text{Prob} = 100.0\% \]
  - \[ N = 1769.2 \pm 145.3 \]
  - \[ \mu = 1471.5 \pm 3.2 \]
  - \[ \sigma = 43.3 \pm 3.4 \]
  - \[ \text{Int} = 18.7 \pm 3.8 \]
  - \[ \text{Grad} = 0.0099 \pm 0.0025 \]
  - \[ R = 353.8 \pm 29.1 \]

- **208TI -- Gaussian + Linear --**
  - \[ \chi^2/\text{ndf} = 2.6/75 \]
  - \[ \text{Prob} = 100.0\% \]
  - \[ N = 142.4 \pm 66.2 \]
  - \[ \mu = 2716.3 \pm 18.2 \]
  - \[ \sigma = 58.3 \pm 22.7 \]
  - \[ \text{Int} = 0.8 \pm 2.4 \]
  - \[ \text{Grad} = 0.00016 \pm 0.00082 \]
  - \[ R = 28.5 \pm 13.2 \]
Original NaI scintillation light in L-Gain

Larger Tail Events

Smaller Tail Events
Decay constant of NaI scintillation light

NaI Scintillation Light Decay Trend

τ Long : 282.0 ± 0.1 ns
χ²/Ndf : 216513 / 234340 (100 %)
: 648 waveforms

τ Short : 211.8 ± 0.0 ns
χ²/Ndf : 919259 / 828436 (0 %)
: 2291 waveforms
Low energy threshold (Noise reduction)

- Fast PMT dark noise was rejected by Timing filter AMP.
- Pulse shape discrimination $\rightarrow$ Rejects pile-up events
• 1 keV Energy threshold has been established
Ingot 23 results (26 days live time)

![Graph showing counts of alpha particle energies for isotopes including 226Ra, 222Rn, 218Po, 216Po, and 214Po.](image-url)