Highly radio-pure NaI(Tl) for PICOLON
dark matter search experiment

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Pure Inorganic Crystal Observatory for Low Background Neutr(al)ino

Dark Matter Search with highly radio-pure NaI(Tl)
- Test the annual modulation signal (DAMA/LIBRA)
- Detection of dark matter candidates
- Simple & Scalable detector design

- 3” φx3”, 4” φx3” crystal for RI reduction study
- 5” φx5” crystal for realistic DM measurement
- 5” φx5” x9 modules for test DAMA
- 5” φx5” x42 modules inside KamLAND for further DM search

Today’s topic
PICOLON / KamLAND-PICO Collaborators

Pure Inorganic Crystal Observatory for Low Background Neutr(al)ino

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PICOLON NaI(Tl) History

3” φ x 3” (I23) (TAUP2013)
3” φ x 3” (I26) (TAUP2015)
4” φ x 3” (I37) (TAUP2017)
5” φ x 5” (I53) (TAUP?)

- Pure crucible w/ Pt coating
- Pb reduction resin
  + Ra reduction resin
  + N₂ bubbling on purification
  + OFC housing
- Rehousing after shock absorber was main RI source
  + K reduction resin
  + x4 purification
  - Rehousing after bubble was found inside grease
  + x1 long and large amount resin purification
  + Multiple filtering
  + Optimized drying
  - On crystallization

Many operation, parameters have been kept optimizing.
4” φ x 3” NaI(Tl) : Measurement Setup

- **cosmic μ**: 10^-5
- **+5cm OFC**
- **1000m**: High Purity Old Lead
- **85cm**: Radon-free air w/ HEPA in room.
- **60cm**: GN₂ flow inside Pb.
- **45cm Pb below copper shield**
- **R11065-20 Low RI 3” PMT**
- **+15cm**

KamLAND MoGURA
- 1GSPS
- 4us waveform
- 0.1mV-10V
- Ana/Digi discri.
- ORTEC TFA 474 reduce PMT noise
4” φ x 3” NaI(Tl) : Signal Characteristics

- 2.7mV ~1 keV DM target (0.6keV)
- 3.8mV keV DM target (3.8keV)
- 24mV $^{210}$Pb $\gamma$ (45.6keV)
- 950mV $\alpha$ BG (2.3MeV) tagged by “tailQ” ratio
- 55mV $\beta \alpha$($^{212}$BiPo) (5.1MeV) tagged by “tailQ ratio”
- 4.0mV VME Noise removed by inverse height
- 1800mV Main BG : Dark (?) (2.8keV) removed by signal width
- 10mV BG : Dark (?) (1.3keV) removed by signal width
**4” φ x 3” NaI(Tl) : Calibration (Problem)**

Very poor energy resolution: ~30% FWHM for $^{133}$Ba $\gamma$

$^{60}$Co $\gamma$ (1.17, 1.33MeV) cannot be separated even reduced HV ⇒ Crystal Problem

BG seems to show almost no $^{40}$K $\gamma$ at first glance w/ significant BG suppression, turned out to show serious energy resolution, energy quenching problem
4” $\phi \times 3”$ NaI(Tl) : Low Energy Resolution

ICP-MS meas. Agilent 7700

<table>
<thead>
<tr>
<th></th>
<th>$^{205}\text{Tl}/^{23}\text{Na}$ ratio</th>
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</thead>
<tbody>
<tr>
<td>4” Over Top</td>
<td>0.0875</td>
</tr>
<tr>
<td>4” Side Top</td>
<td>0.0347</td>
</tr>
<tr>
<td>4” Side Bottom</td>
<td>0.0260</td>
</tr>
<tr>
<td>3”</td>
<td>0.0524</td>
</tr>
</tbody>
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- false temp. control introduced steep Tl concentration gradient.
- Energy-Position dependence caused low energy resolution, caused energy non linearity.
- effect is significant @ DM energy.
- next NaI will have 0.05-0.07 ratio, with already refurbished temp control.
$4'' \phi \times 3''$ NaI(Tl) : BG Spectrum (2.27kg x 16.7d)

>99.9% data @ < 5keV, < 200ns

Events Width > 200ns are discussed later

BG : 3.4 ± 0.1DRU

~ : 4.0 ± 0.1DRU @ 5keV

α separation

By E impossible

used to be possible w/ 3'' $\phi$
4” φ x 3” NaI(Tl) : Radio Impurities

<table>
<thead>
<tr>
<th></th>
<th>DAMA</th>
<th>DM-Ice</th>
<th>3”φx3”</th>
<th>4”φx3”</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>natK (ppb)</td>
<td>&lt;20</td>
<td>660</td>
<td>2630</td>
<td>120*</td>
<td>&lt;20</td>
</tr>
<tr>
<td>232Th (ppt)</td>
<td>0.5-0.7</td>
<td>2.5</td>
<td>0.4 ± 0.5</td>
<td>~1.2</td>
<td>&lt;4</td>
</tr>
<tr>
<td>238U (ppt)</td>
<td>0.7-10</td>
<td>1.4</td>
<td>4.7 ± 0.3</td>
<td>~1.1</td>
<td>&lt;10</td>
</tr>
<tr>
<td>210Pb (uBq/kg)</td>
<td>5-30</td>
<td>1470</td>
<td>29.4 ± 6.6</td>
<td>~2300</td>
<td>&lt;5</td>
</tr>
</tbody>
</table>

(1ppt : 238U 12.3uBq/kg, 232Th 4.0uBq/kg, 210Pb 2.5kBq/kg
natK 1ppb = 40K 31uBq/kg) (* eval from MC)
4” φ x 3” NaI(Tl) : Monte Carlo Simulation

Nal(Tl) detector : Bulk/Surface NaI(Tl), reflector, optical window, grease,

Motivation : origin of $^{40}$K, $^{210}$Pb for next crystal.
Energy spectrum requires $^{40}$K @ 50um+ deep or uniform distribution.

Crystal polisher cannot enter such deep. (by HORIBA)

Polisher could be the cause only when 10-20g remains on the surface (Ge; 465-885mBq/kg)

Uniform $^{40}$K. ⇒ 3.8mBq/kg (120ppb)

Energy spectrum requires $^{210}$Pb @ 100um+ deep or uniform distribution.

Crystal polisher or radon-air during assembly cannot enter such deep and with large amount

Uniform $^{210}$Pb. ⇒ 2.3 mBq/kg

Preparing high sensitive ICP-MS
If we recover $^{210}$Pb rate as in previous 3” $\phi$ crystal; 30uBq/kg, BG will be reduced to 1.5 DRU.

$^{40}$K detection with external LS detector is under study.
Preparation for 5” $\phi \times 5”$

New large crucible.
Special coating on inner surface.
Crystallization on process till Jul. 28.
Housing will be finished end of Aug.
Housing material will be acrylic, and under RI evaluation.

New ultra-low RI 4” PMTs.
Body is under Ge evaluation.
RI check for voltage divider components are also on going.

x500 20x10x5 cm old Lead.
Surface was washed by Nitric acid, pure water, ethanol.

600kg fresh 4N OFC.
Exposed on ground only 1 month during production.
Will be cleaned as well
Summary & Prospects

- Radio activity reduction has almost reached the goal.
  - $^{238}\text{U}/^{232}\text{Th} : \sim 1\text{ppb} : \sim \text{DAMA}$
  - $^{210}\text{Pb}$ increased $0.030 \Rightarrow 2.3\text{mBq/kg}$, (cause: not enough resin)
  - $^{40}\text{K}$ still a bit high ($\sim \text{natK} 130\text{ppb}$), (cause: not enough resin)

- 4”$\varnothing$ x 3” NaI(Tl)
  - Low resolution due to small Tl rate,
  - 3.4 DRU has been accomplished: ~ world top level.
  - 1.5 DRU is feasible with next crystal.

- Future
  - 5”$\varnothing$ x 5” NaI(Tl) is under crystallization.
  - Material RI assessment is still on going.
  - Measurement will be done within a couple of month.
  - $\Rightarrow 5”\varnothing$ x 5” x 42 module experiment!