Status of direct Dark Matter search experiment at KamLAND

The University of Tokyo
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The Kamioka underground laboratory

- XMASS
- CANDLES
- LAB-1(IPMU)
- LAB-2
- LAB-3
- LAB-A
- LAB-B
- Pure-water
- Clean room
- Top Mt.Ikeno
- DM NaI(Tl)
- KamLAND
- Super-K
- CLIO
- To entrance
- 100 m
The Dark Matter project collaborators

- **Gas-type detectors**: Baksan Neutrino Observatory, Institute for Nuclear Research, Russian Academy of Science
- **NaI(Tl) Dark Matter detectors**: I.S.C. Laboratory, Tokushima U., Osaka U., Osaka Sangyo U., Tohoku U.

D. Chernyak (Tokyo U.)

Y. Takemoto (Osaka U.)
Two clean rooms (A, B) for the DM research.

Conditions at the clean rooms:

**Room A:** 70m³/min ULPA air filters. Air quality: **100-300 particles/m³ (<0.3µm)**

**Room B:** 70m³/min HEPA air filters. Air quality: **2000 particles/m³**

- 17kWatt AVR unit (100V, 115V)
- Boiled off Nitrogen supply line
- Radon-less air supply: (5-10m³ per hour) creates a positive air pressure relative to neighbour rooms.

The Kamioka mine 1000m rock overburden
Test setup for the NaI(Tl) DM detectors

The HPGe detector

The ion-pulse ionization chamber

A new setup for NaI(Tl) DM detectors

The $^6$LiF/ZnS thermal neutron detector

The NaI(Tl) radon detector

The fast neutron detector

All important parameters:

- $(T, P, \text{humidity})$ of inner and mine air, flow of a fresh air;
- flow of nitrogen to detectors;
- the Radon activity in the inner and mine air of the Cavity;
- the neutron flux is being monitored and recorded.
The HPGe detector

- **Movable weight**
- **Sealant**
- **Springs**

5cm-thick Cu, 25cm-thick Pb (3 types of lead bricks)

- **Top of HPGe detector**

- **Cryostat window** (Al thickness 0.8 mm)
- **Window electrode** (Ge dead layer 0.48 mm)

- **Aluminum endcap**
- **Ge crystal** Ø73.4 × 61.7 mm
- **Copper holder**
- **Inner electrode** (Ge dead layer 0.3 μm)
- **Outer electrode** (Ge dead layer 0.48 mm)
- **Core hole** Ø46.5 × 7.5 mm

- **260cm³ Ge crystal**
- All home-made design
- Inside of the clean tent
- Air flow via ULPA filters
- 5.5L/min of N₂ via MFC
- Cu/Pb 15y underground
Natural Lutetium contains 2.599% of $^{176}$Lu emitting $\gamma$-rays: 401 keV, 306.8 keV, 201.8 keV, 88.3 keV as well as 64.0 keV and 55.1 keV X-rays. We used 99.9% pure Lu$_2$O$_3$.

Natural Lanthanum contains 0.08881% of $^{138}$La emitting $\gamma$-rays: 0.789 MeV, 1.435 MeV and 36.4 keV X-ray. We used 99.99% pure La$_2$O$_3$.

Marinelli beakers (0.7, 1.2L) are used for loose and liquid samples.

For every sample a realistic GEANT4 model is prepared to calculate the $\gamma$-ray detection efficiency.

We made extended sources with a small admixture of Lu and La to verify correctness of the detector GEANT4 model based on the information provided by Canberra Corp.
Online database for measured samples

### Sample’s Summary

- **Provider:** A. Kozlov
- **Experiment:** KamLAND2
- **Material:** Activated carbon (powder)
- **Chemical formula:** C
- **Dimensions:** Fully-filled L-size container
- **Mass:** 491 g
- **Density:** 0.4 g/cm³
- **Date of assembling:** 26/07/2017
- **Data live time:** 72349.90 s

### GEANT4 model’s geometry

![GEANT4 model's geometry](G4_ID_069)

### Table with GEANT4 γ-ray det. efficiency

<table>
<thead>
<tr>
<th>ID</th>
<th>Provider</th>
<th>Experiment</th>
<th>Material</th>
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<th>Data live time</th>
</tr>
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<td>69</td>
<td>A. Kozlov</td>
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### RI Summary

![RI Summary](ID_069)

### Photo of the sample

![Photo of the sample](Image_0x130 to 719x372)

[Measured spectra (Click to magnify)](measured_spectra)
The $^6\text{LiF}/\text{ZnS}$ thermal neutron detector

- **①** The $^6\text{LiF}/\text{ZnS}$ scintillator
- **②** A light reflector
- **③** An aluminium box

A very bright scintillator: 95000 photons/MeV

$^6\text{Li} + n \rightarrow \alpha + t + 4.78\text{MeV} (941\text{b at } 0.025\text{eV})$

The detector is a thin sheet consisting of fine particles ($\sim \mu\text{m}$) of $^6\text{LiF}$ and $\text{ZnS:Ag}$ dispersed in a colourless binder (95% of $^6\text{Li}$). Features: insensitive to $\gamma$-rays, $12.2 \pm 0.1$ mBq of natural $\alpha$-emitters (before PSD cut)
The $^6$LiF/ZnS thermal neutron detector

$\alpha$-particle

$\alpha$-background

$\alpha$-particle background

PSD = $\sum \frac{L.G. - S.G.}{L.G.}$

Before PSD cut
Neutrons + $\alpha$-particles

After PSD cut
Neutrons + $\alpha$-particles

$^{214}$Am/$^9$Be source

The thermal neutron flux at KamLAND: $(6.43 \pm 0.50) \times 10^{-6}$ n cm$^{-2}$ s$^{-1}$
Recipe of the scintillator loaded with a **water solution of LiBr** was developed by H. Watanabe and Y. Shirahata (Tohoku U.)

Liquid scintillator (LS) loaded with nat. Lithium (7.6% of $^6\text{Li}$)
LS composition: 820cc of **pseudocumene** + **PPO** (5.4g/L) **Surfactant** (TritonX-100) 180cc, LiBr·H$_2$O + H$_2$O 37g/L (the 140/50 mass ratio).

Photo-sensors: **4 Hamamatsu 5” R1250 PMTs** (low K-40)  
DAQ: **CAEN DT5720** (4ch, 12bit, 250MS/s)  
Shielding: **10cm of lead** to reduce the γ-ray background  
**Pulse-shape discrimination** works for both prompt and delayed signals. A **94% γ-ray rejection** for a 90% eff. cut on the delayed signal was achieved.
The ion-pulse ionization chamber

Energy resolution: 1.6-2.0% (FWHM)

CSP self-discharge ($e^{-t/\tau}$)

Allows direct detection of $\alpha$-particles from the $^{222}\text{Rn}$ decay in the air.
The ion-pulse ionization chamber

- **DAQ software**
- **LabVIEW pump, valves controls**
- **Dry pump**
- **Solenoid valve**
- **air IN**
- **air OUT**
- **CAEN HV, preamp. power**
- **100MHz Digitizer**
- **Digital I/O**
- **SPDT relays**
- **P.G. DAQ**
- **P.G.**
- **Multi-layer acoustic shielding**
- **Silicone bars**
- **Anti-vibration frame**

**Components:**
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The NaI(Tl) radon detector

NaI(Tl) crystal + H3178 PMT directly connected to the DT5730 CAEN w-f digitizer (14-bit, 500 MS/s) is used to measure radon activity in the Cavity outside of the clean rooms. The ion-pulsed ionization chamber is difficult to use at that location due to a high radon activity (>1Bq/L) and relative humidity >94%.

Bottom layer: **15cm-thick lead**
Walls: **10cm-thick double layer lead**
Inner layer: a high purity Pb ($^{210}$Pb $\sim$ 20Bq/kg)
Volume of the air inside shielding: **9.7L**
The **609keV $\gamma$-ray** detection efficiency: **0.196%**
(calculated using the GEANT4 model)
Purification techniques:
- **re-crystallization** from an ultrapure water solution
- Use of sorbents “tuned” to certain elements (e.g. Pb)

Steps used to minimize Radon daughters activity in NaI:
- Use of **specially produced NaI powder** in accordance with procedures developed by Horiba Corporation;
- NaI is handled in clean rooms and a **glove box flushed with a pure nitrogen**;
- Minimized exposure to air between purification steps;
- Use of **continuous nitrogen purge** during all stages of purification and drying process.

Radio-purity control techniques at Kamioka:
- HPGe measurements
- Direct measurements using the low background shielding
The NaI(Tl) ingot production (Step 1)

Vacuum oven

Graphite crucible

A NaI(Tl) ingot

Crucible:
- Material – a coated, polished, purified at a high temperature vacuum oven graphite
- A new feature: a specially shaped bottom part – no need to use a seed to start crystal growth
- After cooling down NaI(Tl) crystals are detached from the graphite crucible easily due to a factor 10 difference in the thermal expansion coefficients.

Ingot aging
The NaI(Tl) ingot production (Step 2)

- Machine cutting
- Samples for Tl test
- Abrasion
- Humidity control
- E. resolution test
- Final encapsulation
Test setup for the NaI(Tl) DM detectors

- **12ch boards** ⇒ scalable system
- **0.1mV-10V** (PHML gain channels) covers range from **1keV DM pulses** to **several MeV α-particles**
- **1ns, 5ns** sampling FADC
- Up to **10μs** waveform
- Analog/Digital discrimination
The **R13444X** 4-inch Hamamatsu PMT

The **R13444X**: a metal (42% Ni, 57%Fe) body, a bialkali photocathode, optical window made of a synthetic silica. The spectral response we had chosen: 200-650nm. **QE@420nm** equal to **34.9%** and **33.38%** (ZK7879, ZK7880 units).

**40K** (assuming it is in the 5N Al sealant): 55-14mBq, 24-7mBq at 90% CL

**60Co** (assuming it is in the metal body): 7-1mBq, 7-4mBq at 90% CL
We used a >99.99% pure copper from **Mitsubishi Materials** specially melted for us. 2 tons of freshly manufactured (**1.5 month or less old**) electroformed copper sheets were used to avoid $^{60}$Co. After melting copper was cut into shielding bricks: ($50\text{mm} \times 100\text{mm} \times 200\text{mm}$).

Cu bricks were cleaned in 4-steps: ($H_2SO_4+H_2O_2; C_6H_8O_7; H_2O; H_2O$) to remove $^{210}$Pb and other impurities; 18.2MΩ ultra-pure water was used.
Background for latest NaI(Tl) detectors

Ingot 71
ZK7880
# Radio-purity of the NaI(Tl) crystals

<table>
<thead>
<tr>
<th>NaI(Tl)/Isotope</th>
<th>$^{238}\text{U}$, ppt</th>
<th>$^{232}\text{Th}$, ppt</th>
<th>$^{40}\text{K}$, ppb</th>
<th>$^{210}\text{Pb}$, mBq</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingot 71†</td>
<td>9.7 ± 0.8</td>
<td>1.7 ± 0.2</td>
<td>&lt;20</td>
<td>1.5</td>
</tr>
<tr>
<td>Ingot 73‡</td>
<td>3.6 ± 0.6</td>
<td>1.8 ± 0.7</td>
<td>&lt;30</td>
<td>1.3</td>
</tr>
<tr>
<td>DAMA det.</td>
<td>0.7 - 10</td>
<td>0.7 - 10</td>
<td>20</td>
<td>0.024</td>
</tr>
</tbody>
</table>

† Purified by a 2-times re-crystallization from the water solution
‡ Purified by a 3-times re-crystallization from the water solution

Still need: to find a stage where $^{222}\text{Rn}$ contaminates the NaI material. Probably, need to make a closed system for NaI powder handling.
Summary

• We created **underground clean-room laboratory** for the DM research at the Kamioka mine.

• Our commercial partner constructed a new **laboratory for production of the ultra-low background NaI(Tl) crystals** in Japan.

• We managed to produce NaI(Tl) crystals with the radio-purity level similar to that achieved by the DAMA/LIBRA collaboration.

• We built several **supplementary detectors** to monitor most possible sources of the periodic background at the Kamioka mine.

• In April 2019, we received **JSPS funding** for construction of a large NaI(Tl) DM detector.
Backup slides
A hypothetical Dark Matter (DM) signal

\[ R = S_0 + S_m \cos \left( \frac{2\pi (t-t_0)}{1 \text{yr}} \right) \]

- Signal is caused by Dark Matter particles scattering off detector nuclei.
- Energy of the expected signal in the detector is in the range of 0-100keV, which is natural radioactivity dominant.
- Fortunately, the Earth motion around the Sun creates annual modulation of the measured energy spectrum (maximum is near June 2\textsuperscript{nd}).
The DAMA/LIBRA-phase2 result

The DAMA/LIBRA-phase2 data favours presence of modulated DM signal with proper features at $9.5\sigma$ C.L. Averaged background rate is $\sim 1$ ev/keV/kg/day. The modulation effect is just few per cent.