The Dark Matter Search at KamLAND

The University of Tokyo
Alexandre Kozlov

4th International conference on particle physics and astrophysics, Moscow
24 October 2018
A hypothetical Dark Matter (DM) signal

The way how DM interacts with the SM matter, its mass & density near the Sun are unknown.

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

- 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, Earth motion around the Sun creates **annual modulation** of the measured energy spectrum (maximum is near June 2\text{nd}).
The DAMA/LIBRA-phase2 result

The DAMA/LIBRA-phase2 favours the presence of a 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.
We consider two possible explanations:
- The **Dark Matter signal**.
- **background variations** caused by seasonal effects (e.g. neutron flux intensity and energy spectrum dependence on the water content in rocks, etc).

What we can do:
1) Repeat an **“identical” experiment** at other locations.
2) **Reduce the background** below 1 ev/keV/kg/day.
3) Monitor possible **sources of background** (neutron, radon).
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.
From 2012, I develop **two clean rooms (A, B)** for an **ultra-low background research**.

**Current 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
Research infrastructure at the Kamioka mine

- Test setup for the NaI(Tl) DM detectors
- The HPGGe detector
- The NaI(Tl) radon detector
- The fast neutron detector
- The NaI(Tl) radon detector
- The 6LiF/ZnS thermal neutron detector
- The ion-pulse ionization chamber
- The HPGe detector

All important parameters:
- (T, P, 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 are being monitored and recorded.
The HPGe detector

- Movable weight
- Sealant
- Springs

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

- 320 cm³ Ge crystal
- All home-made design
- Inside of the clean tent
- Air flow via ULPA filters
- 5.5 L/min of N₂ via MFC
- Cu/Pb 15y underground

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
The HPGe detector calibration

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

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

Natural Lutetium contains 2.599% of $^{176}$Lu emitting γ-rays: 401keV, 306.8keV, 201.8keV, 88.3keV as well as 64.0keV and 55.1keV X-rays. We used 99.9% pure Lu$_2$O$_3$

For every sample a realistic GEANT4 model is prepared to calculate the γ-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.
The ion-pulse ionization chamber

*Used for a direct detection of $\alpha$-particles from the $^{222}$Rn decay in the Room A air.*

- **Laboratory VIEW pump, valves controls**
- **Air IN**
- **Air pump**
- **Solenoid valve**
- **Air OUT**
- **CAEN HV, preamp. power**
- **SOLEDT relays**
- **Digital I/O**
- **100MHz Digitizer**
- **P.G. DAQ**
- **Amplifier HV**
- **3.2L active volume**
- **Anode**
- **Cathode**
- **Insulators**

*Energy resolution: 2% (FWHM)*

JSPS grant: 16K05371
The thermal neutron flux: \((6.43 \pm 0.50) \times 10^{-6} \text{ n cm}^{-2} \text{ s}^{-1}\)

\[ ^6\text{Li} + n \rightarrow \alpha + t + 4.78\text{MeV} \]

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


JSPS grant: 16K05371

\( ^6\text{Li} \) gas flow

Before PSD cut
Neutrons + \(\alpha\)-particles

\(\alpha\)-background

After PSD cut
Neutrons + \(\alpha\)-particles

\(\alpha\)-particle background
The fast neutron detector

Organic liquid scintillator loaded with Lithium was developed and tested by H. Watanabe and Y. Shirahata (Tohoku U.)

Liquid scintillator (LS) loaded with nat. Lithium (7.6% of $^6$Li)

Pure LS components: pseudocumene (PC) + PPO (5g/L)

PC : Surfactant (TritonX-100) mixing 82% : 18%

Nat. LiBr · H$_2$O 37g/L

Photo-sensors: 4 Hamamatsu 5” R1250 PMTs (low K.)

DAQ: CAEN DT5720 (4ch, 12bit, 250MS/s)

Shielding: 10cm of lead to reduce accidentals

Pulse-shape discrimination works for both prompt and delayed signals. A 94% $\gamma$-ray rejection for a 90% eff. cut on the delayed signal was achieved.
The NaI(Tl) radon detector

- **2×2cm NaI(Tl) crystal + H3178 PMT** directly connected to the DT5730 w-f digitizer (14-bit, 500 MS/s) was 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%.

- **Pb shielding in the Cavity**
- **Walls**: 10cm-thick double layer lead
- **Inner layer**: a high purity Pb ($^{210}$Pb ~20Bq/kg)
- **Volume of the air inside shielding**: 9.7L
- **The 609keV $\gamma$–ray** detection efficiency: 0.196% (calculated using the GEANT4 model)

---

**Radon**

- $^{222}$Rn → $^{218}$Po (3.82 d)
- $^{218}$Po → $^{214}$Bi (3.1 min)
- $^{214}$Bi → $^{214}$Pb (26.8 min)
- $^{214}$Bi → $^{214}$Po (164.3 μs)
- $^{214}$Bi → $^{214}$Bi (19.9 min)
- $^{214}$Bi → $^{214}$Bi (1.5 s)

---

**Events accumulated in 1 day**

$^{214}$Bi (609keV $\gamma$-ray)
Purification techniques:
- re-crystallization from an ultrapure water solution
- Use of absorbers “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 the 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)

Crucible:
- Material – a coated, polished, purified (in a 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.
The NaI(Tl) ingot production (Step 2)

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

Mogura DAQ developed with Tokyo Electron Device Ltd

- **12ch** Input ⇒ scalable
- **0.1mV-10V** (PHML gain channels) covers energy range from **1keV DM pulses** to several **MeV α-particles**
- **1ns, 5ns** sampling FADC ⇒ essential for rejection of low-E short pulses (PMT noise)
- **10μs** waveform
- Analog/Digital discrimination

Bottom: >30cm of lead
Walls: 15cm of lead
Inner: 5cm of special Cu
Flushed with 3L/min of N₂

Hamamatsu metal body high QE ultra-low background PMTs: **R11065-20, R13444X**
NaI(Tl) signal characteristics

1. NaI(Tl) signal characteristics
2. Physics data
3. TFA width cut
4. PMT noise
5. Noise >99.9% of data

- \( \alpha \)-particle (2MeV)
- \( \beta \alpha(\text{BiPo}) \) (5.1MeV)
- \( \gamma \)-ray (46keV)
- \( \gamma \)-ray (0.6keV)
- \( \beta \)-particles (2MeV)

Charge, a.u.

- 3.8mV
- 2.7mV
- 24mV
- 950mV
- 1800mV
- 10mV
- (3.8keV)
- (0.6keV)
- (3.8keV)
- (46keV)

Width, ns

- 0
- 500
- 1000
- 1500
- 2000

Amplitude [ADC Value]

- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100
- 110
- 120
- 130
- 140
- 150
- 160
- 170
- 180
- 190
- 200

The PSD discrimination (ingot #71, 28days)

PSD Charge Profile

Tail Charge Ratio

Energy_Cs137 (keV)

β,γ-rays

β+α-particles

α-particles

10^2

10

1
Background (Ingot #71, 28 days)

- Thorium: $1 \pm 0.3$ ppt
- Uranium: $11 \pm 0.5$ ppt

(DAMA/LIBRA 0.7-10 ppt for U/Th).

One more NaI(Tl) crystal of a higher purity level is being produced now.

Cosmogenic background α-particles
Background at low energies is dominated by isotopes with a short half-life created in NaI by cosmic-ray muons on the surface. A cooling down period required for decay of a major part of the cosmogenic background is > 6 months.
The NaI(Tl) Dark Matter detector

- Detector options: **120kg** and **250kg+ of NaI(Tl) in a solid shielding**. Each module will be composed of a **5×5-inch NaI(Tl) crystal** in an acrylic case connected to a **3” or 4” Hamamatsu PMT** with a metal body.

- Deployment to KamLAND will be possible after the end of the KamLAND-Zen 800 experiment (3-4 years from now).

- Right now, we stock shielding materials, screen components for ultra-low background photomultipliers.

- **Copper** was specially melted using freshly manufactured (less than 1.5 month) electroformed copper to avoid \(^{60}\text{Co}\) (measured activity \(0.3\text{mBq/kg UL at 90% CL}\)).

- **Copper bricks** were cleaned in 4-steps: \((\text{H}_2\text{SO}_4+\text{H}_2\text{O}_2; \text{C}_6\text{H}_8\text{O}_7; 18.2\text{M}\Omega \text{ H}_2\text{O}; 18.2\text{M}\Omega \text{ H}_2\text{O})\) to remove \(^{210}\text{Pb}\) and other impurities.

- **Lead blocks** were cleaned in a **triple HNO_3 baths** to remove surface contamination. For the most old lead machine cutting was done before acid cleaning.
Summary

- We developed research infrastructure for the Dark Matter search experiment based on ultra-low background NaI(Tl) segmented detectors.
- Together with our partners we created a laboratory for mass production of NaI(Tl) crystals and achieved level of radio-purity of detectors used by the DAMA/LIBRA collaboration.
- Beginning of the full-scale detector construction depends on the Japanese government funding.

Thank you!
Other limits on search for a new physics

Muons, fast neutrons created by high energy cosmic rays in the Earth’s atmosphere are source of background in experiments at the Earth’s surface.

Possible solution: move underground
Sources of background other than muons

- The Radon that is present in the ground water and underground air (depends on the Uranium content in rocks);
- The neutron background produced by a spontaneous fission of heavy elements and in the \((\alpha, n)\) reactions at depth>100m;
- Radioactive impurities existing in detector components (a difference between our “new” and “old” lead is shown as an example).
Construction of an ultra-low background detector

- **High-class clean rooms** are needed for handing detector materials, detector construction & operation to avoid dust particles that contain natural (e.g. U, Th, K) and artificial unstable nuclei (e.g. $^{137}\text{Cs}$). That includes clean rooms at commercial companies that produce materials and detector components, and which we often cannot control well.

- Production of pure materials often require construction of **purification systems on-site**, as well as **cleaning of the surfaces exposed to Radon** and, thus, contaminated by $^{210}\text{Pb}$ ($T_{\frac{1}{2}} = 22.2\text{y}$) and $^{210}\text{Po}$ ($T_{\frac{1}{2}} = 138\text{d}$).

- Some materials, as Cu, are easily **activated on the surface by fast neutrons**, e.g. via the $^{63}\text{Cu} + n \rightarrow ^{60}\text{Co} + \alpha$ reaction $86.4 \pm 7.8 (\text{kg} \cdot \text{day})^{-1}$ $^{60}\text{Co}$ ($T_{\frac{1}{2}} = 5.3\text{y}$) nuclei are produced. This sets a stringent limit on the production time, storage and ways of transportation of cooper and other materials (e.g. Ge).

- All that work requires **sensitive and reliable research infrastructure** for control of materials radio-purity and background sources underground.