Search for physics beyond Standard Model using ultra-radio-pure NaI(Tl) crystals

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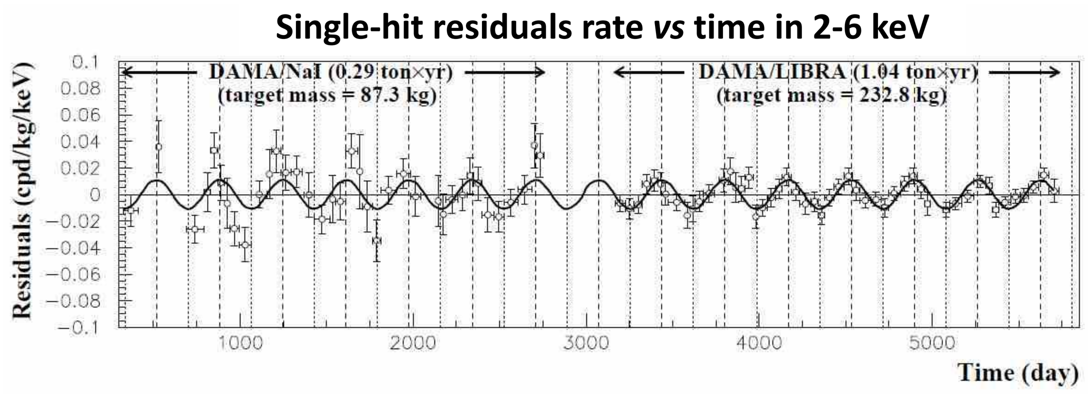
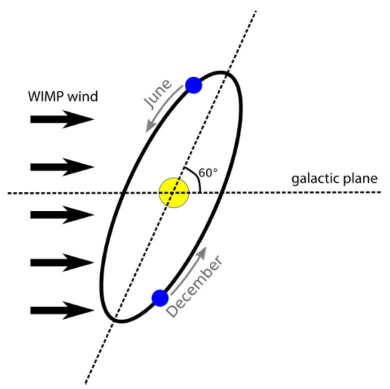
1. Dark Matter search and test of DAMA/LIBRA observations

Weakly interacting massive particles (WIMPs) are one of the most promising **dark matter candidates**. The direct detection of WIMPs is performed by measuring the recoil energy deposited by elastic and inelastic scattering between WIMPs and target nucleus. One of the most promising signal for WIMPs is the **annual modulation in energy spectrum due to Earth's motion around the Sun**.

Single-hit residuals rate *vs* time in 2-6 keV

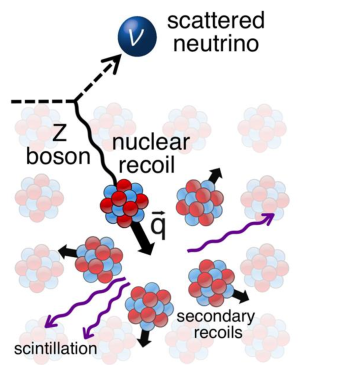




The **first possible annual modulation observation** was reported by **DAMA/LIBRA** using a **large volume and highly radiopure NaI(Tl) scintillators**. They claim to observe an annual modulating signal in event rates between 2 keV_{ee} and 6 keV_{ee}.
We aim to **test the annual modulation signal** observed by DAMA/LIBRA using **our recently developed highly radiopure NaI(Tl) crystal scintillators**. Moreover, we will try to find possible correlations between the several keV signals in NaI(Tl) detectors, the radon activity in the mine air and the neutron flux. Experiment to search for dark matter is currently in development and will be performed in Kamioka underground laboratory.

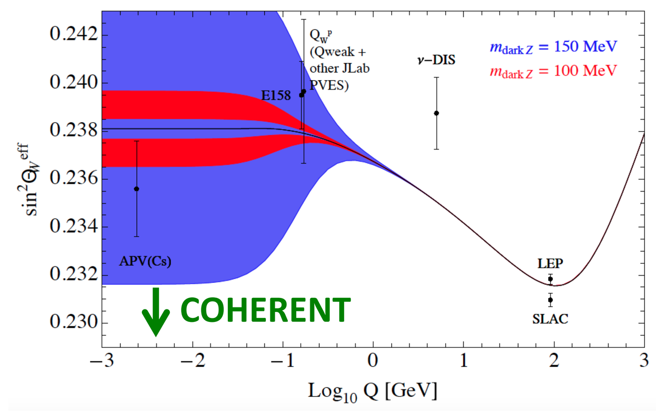
2. Precise measurement of the Weinberg angle

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) is a **fundamental process** recently observed by the COHERENT collaboration. The CEvNS cross-section can be described with the formula

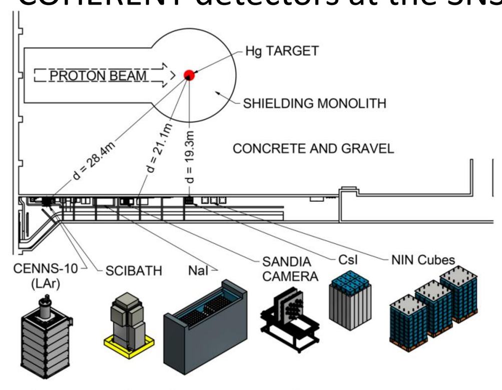


$$\sigma_{coh} \sim \frac{G_f^2 E^2}{4\pi}(Z(4\ sin^2\theta_w - 1) + N)^2$$

where G_f is the Fermi constant, E is the energy of the neutrino, ϑ_w is the Weinberg angle, Z is the number of protons and N is the numbers of neutrons in the target nucleus. Since σ_{tot} depends on Weinberg angle ϑ_w, it opens a way to measure weak mixing angle $\sin^2\vartheta_w$ using massive detectors.



COHERENT detectors at the SNS



We investigate possibility to **use our recently developed ultra-radio-pure NaI(Tl) crystals to measure Weinberg angle** at the Spallation Neutron Source (SNS) in Oak Ridge, Tennessee. The SNS provides an intense flux of neutrinos in the few tens-of-MeV range, while our **ultra-radio-pure NaI(Tl) crystals allow to observe events at low threshold** (below 1keV) and **has high light yield**.

3. Development of ultra-radio-pure NaI(Tl) crystals

The development of **highly radiopure NaI(Tl) crystal scintillator** is a **crucial point** for the experiments. We have performed many tests and R&D to **successfully develop highly radiopure NaI(Tl) scintillators**. The radioactive impurities in raw powder were removed by using **ion exchange resin**. The contamination from the crucible was prevented by selecting the **highest purity of the crucible material**. The **Bridgman method** was applied to grow the NaI(Tl) crystals.

Comparison of radioactive contamination of **NaI(Tl) crystals** for different experiments

Impurity	DAMA/LIBRA	DM-ICE	ANAIS	KIMS	Our experiment*
natK [ppb]	< 20	558	20 ~ 46	40 ~ 50	125
Th-chain [ppt]	0.5 ~ 7.5	13	0.8 ± 0.3	0.5 ± 0.3	0.3 ± 0.5
^{226}Ra [μBq/kg]	21.7 ± 1.1	900	10 ± 0.2	< 1	58 ± 4
^{210}Pb [μBq/kg]	24.2 ± 1.6	1500	600 ~ 800	470 ± 10	30 ± 7

*** Radioactive impurity levels are presented for Ø 4 × 3 inch crystal**

2013
Ø 3 × 3 inch
- Pure crucible with Pt coating
- Pb reduction resin

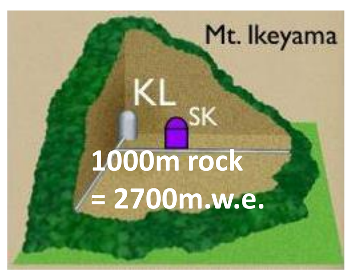
2014—2015
Ø 3 × 3 inch
- Ra reduction resin
- N_2 bubbling on purification
- OFHC copper housing
- Rehoused after shock absorber was the main source of radioimpurity

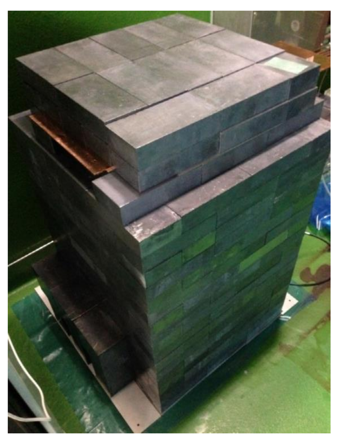
2016
Ø 4 × 3 inch
- K reduction resin
- Improved purification technique
- Rehoused after bubble was found inside grease

2017
Ø 5 × 5 inch
- High-purity graphite crucible
- Tl concentration was controlled
- Improved purification technique for Pb and K
- Optimized drying

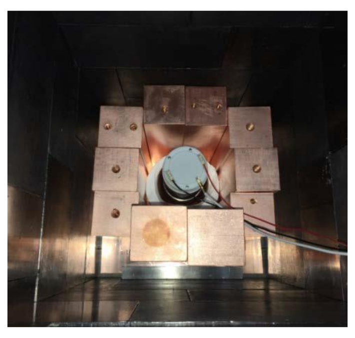
4. Experimental facility at Kamioka mine

Experimental facility for NaI(Tl) crystals is located in KamLAND area of **Kamioka underground laboratory** at the **depth of 2700m.w.e.** It consists of the several detectors located in the Class-10 clean room.

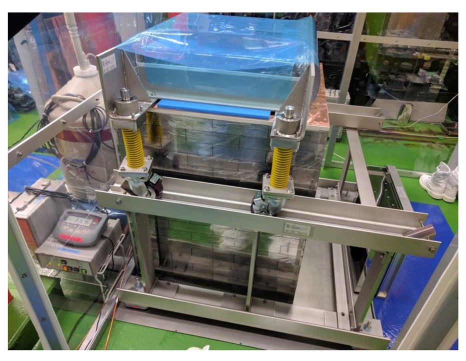


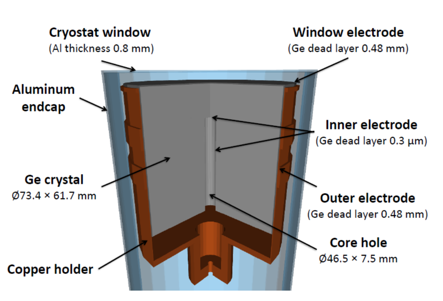


NaI(Tl) crystals were tested in the **low-background set-up**. Crystal housed in a copper holder and viewed by 3" PMT Hamamatsu R11065-20-mod2 was surrounded by a temporary shield made of **5 cm of OFHC copper** and **20 cm of high-purity old lead**. The **shielding was purged by the pure nitrogen gas** to reduce the concentration of radon

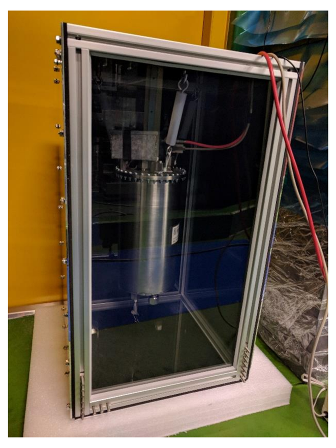


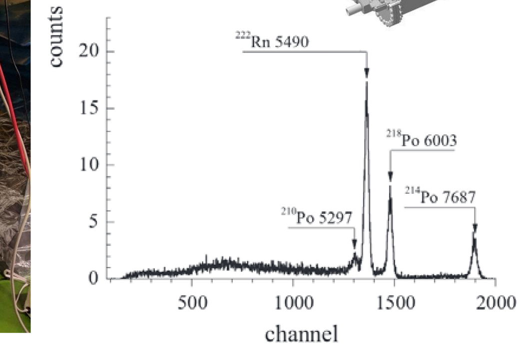
Radiopurity of the detector materials is controlled by using **Canberra GC6520 HPGe detector**

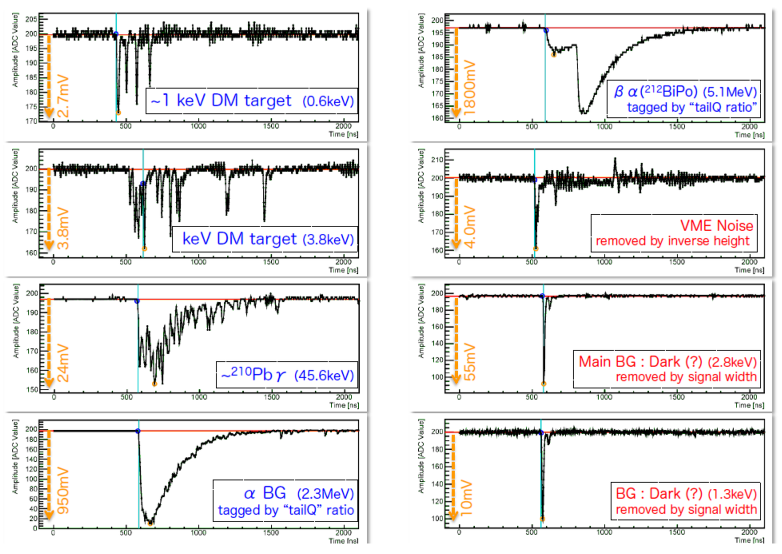


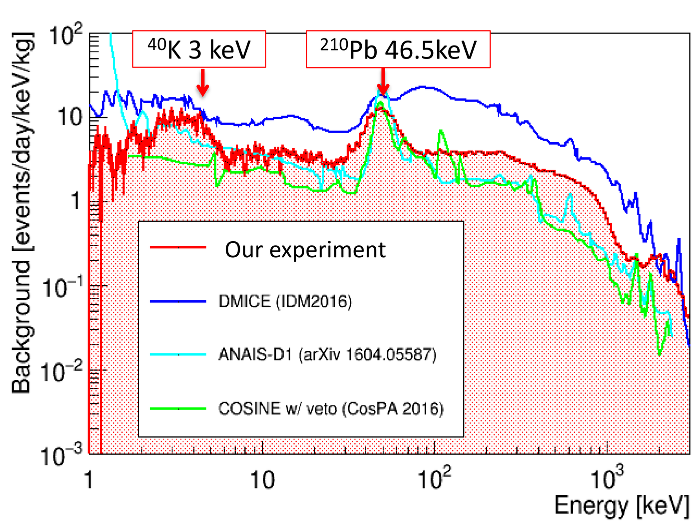


Radon activity variations in the underground air will be measured using constructed **high-resolution radon gas detector**





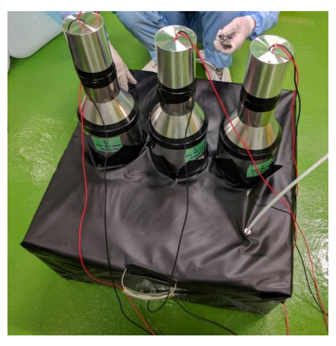


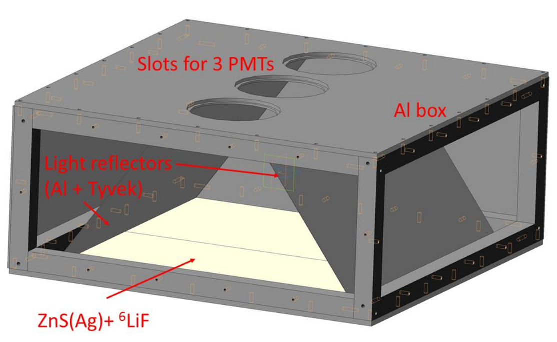


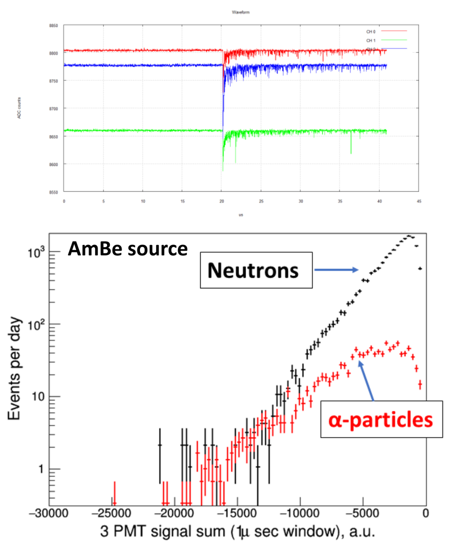
Development of **new ultra-low-background 4" PMT** is in progress

New shielding with fresh OFHC copper and cleaned lead is under construction

Seasonal variations of thermal neutron flux are measured by using **^{6}Li loaded ZnS(Ag) EJ-426 scintillator** sheets with the size of 50x50 cm



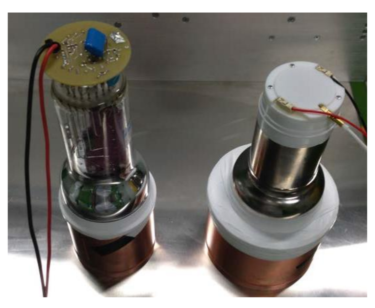


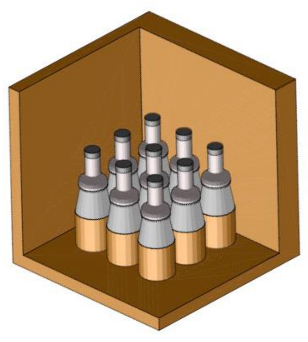


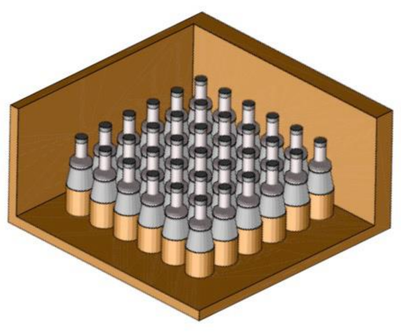
5. Future prospects on dark matter search

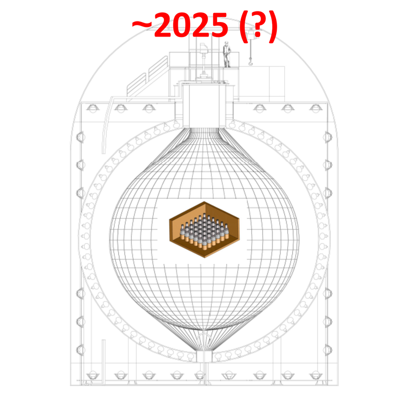
We plan to **finish all of the R&D and preparations during the next year** and to **start the experiment with 9 NaI(Tl) crystal modules in 2019**. Subsequent scaling of the detector can be done in a couple of years. Large-scale experiment using KamLAND detector can be considered in a future.

R&D	Phase I	Phase II	KamLAND with NaI(Tl) (?)
~6 kg NaI(Tl)	54 kg NaI(Tl)	250 kg NaI(Tl)	1000 kg NaI(Tl)
Now	~2019	~2021	~2025 (?)









6. Conclusions

- We have **successfully developed ultra-radiopure NaI(Tl) crystals** with radioactive contamination levels close to DAMA crystals. **New Ø 5 × 5 inch NaI(Tl) crystal was produced** recently and will be tested using **upgraded low-background set-up at Kamioka underground laboratory**
- The **experiment to search for dark matter and to test the annual modulation signal of DAMA/LIBRA is in preparation**. We plan to **start measurements with 54 kg of NaI(Tl) crystal modules in 2019**. Subsequent annual modulation test with 250 kg of NaI(Tl) crystals is expected to start in 2021
- The application of **ultra-radiopure NaI(Tl) detectors for the measurement of Weinberg angle** at the Spallation Neutron Source is under discussion. **Measurement of the CEvNS** by using ~15 kg of the developed **ultra-radiopure NaI(Tl) detectors is under consideration**

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