NEUTRINO PROGRAMS AT CUP

YEONGDUK KIM
IBS / SEJONG UNIVERSITY

2016. 8. 7.

ICHEP 2016, Chicago
1. What is dark matter?

2. Are neutrinos Majorana particles?

3. What created the asymmetry in the Universe?

4. Extreme rare phenomena in energy region $10 \text{ eV} - 100 \text{ MeV}$
Organization of CUP

Members:
- 1 Director
- 2 Group Leaders
- ~25 Research Fellows
- 6 Technicians
- 3 Administrators
- ~10 Adjunct Professors
- ~25 Adjunct Students.
YangYang (Y2L) Underground Laboratory

(Upper Dam) YangYang Pumped Storage Power Plant

Center for Underground Physics

JBS (Institute for Basic Science)

Minimum depth: 700 m / Access to the lab by car (~2km)

KIMS (Dark Matter Search)

AMoRE (Double Beta Decay Experiment)
Laboratories

Current Ground Lab.

Headquarter (2018-)

Yangyang underground laboratory (Y2L-A6 - A5)

New underground lab. (2019-)

Hall B
- Electroform Copper Room (100m²)
- 1st RRS room (50m²)
- 2nd DM exp. room (100m²)
- Control room for 2nd DM exp. (100m²)

Hall
- DBD exp. room (170m²)
- Control room of DBD exp. (100m²)
- 1st DM exp. room (100m²)
- Control room for 1st DM exp. (100m²)
- HFGe room (100m²)
- Clean room (100m²)
- for Crystal growing (100m²)

[Area]
- Hall A: 800m²
- Hall B: 1200m²
- Total: 2000m²
1. Double Beta Decay - AMoRE

8 Countries
18 Institutions
~90 Collaborators
Search for Neutrinoless double beta decay ($0\nu\beta\beta$)

- Observation of $0\nu\beta\beta$ will confirm
  - Neutrinos are Majorana particles and have Majorana masses.
  - Lepton number non-conservation.

- Observation of $0\nu\beta\beta$ will support more on
  - See-Saw model of the neutrino mass.
  - Leptogenesis to account for the baryon asymmetry of the universe.

\[
m = \frac{m_D^2}{m_N}
\]
How to confine neutrino mass with

- If discovered with a measurement of half-life, then

\[ T_{1/2}^0 \rightarrow m \]  
by  
\[ \left[ T_{1/2}^{0n} \right]^{-1} \propto m_{bb}^2 \]

Current limit is \(10^{26}\) years.

\[ \rightarrow 100 \text{ kg } ^{136}\text{Xe} \text{ has less than 3 events per year.} \]

\[ \rightarrow \text{Need extremely low backgrounds with good energy resolution.} \]
AMoRE (Advanced Molybdenum Rare-decay Experiment)

Based on Scintillating Bolometer: \((^{40}\text{Ca},X)\text{^{100}MoO}_4 + \text{MMC}\)

- Phonon detector \(\rightarrow\) High Energy Resolution
- \(Q = 3.04\ \text{MeV} \& \text{Heat vs Photon} \rightarrow\) Low Background.
- 10% natural abundance \(\rightarrow\) Reasonable Cost
### Phases of AMoRE Project

**AMoRE Pilot**

- $^{40}\text{Ca}^{100}\text{MoO}_4$
  - $\sim 1.5$ kg

**AMoRE-I**

- $^{40}\text{Ca}^{100}\text{MoO}_4$
  - $\sim 5$ kg

**AMoRE-II**

- $(^{40}\text{Ca,X})^{100}\text{MoO}_4$
  - 200 kg

<table>
<thead>
<tr>
<th>Crystal Mass (kg)</th>
<th>AMoRE-Pilot</th>
<th>AMoRE-I</th>
<th>AMoRE-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}\text{Ca}^{100}\text{MoO}_4$</td>
<td>1.5</td>
<td>5</td>
<td>200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Backgrounds (ckky)</th>
<th>AMoRE-Pilot</th>
<th>AMoRE-I</th>
<th>AMoRE-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}\text{Ca}^{100}\text{MoO}_4$</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
<td>$10^{-4}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$T_{1/2}$ (year)</th>
<th>AMoRE-Pilot</th>
<th>AMoRE-I</th>
<th>AMoRE-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}\text{Ca}^{100}\text{MoO}_4$</td>
<td>$1.0 \times 10^{24}$</td>
<td>$8.2 \times 10^{24}$</td>
<td>$8.2 \times 10^{26}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m_{bb}$ (meV)</th>
<th>AMoRE-Pilot</th>
<th>AMoRE-I</th>
<th>AMoRE-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}\text{Ca}^{100}\text{MoO}_4$</td>
<td>380-719</td>
<td>130-250</td>
<td>13-25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Schedule</th>
<th>AMoRE-Pilot</th>
<th>AMoRE-I</th>
<th>AMoRE-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}\text{Ca}^{100}\text{MoO}_4$</td>
<td>2015-2016</td>
<td>2017-2018</td>
<td>2020-2022</td>
</tr>
</tbody>
</table>
Aim at “Zero Background” experiment in the region of $0\nu\beta\beta$ signal. AMoRE will cover inverted mass hierarchy region.
Mounting detectors in pilot exp. at Y2L
Vibration noise from Pulse Tube limits
Pulse shape discrimination power & energy resolution.

Try to detach Pulse Tube and install damping system.

S35 - calibration data - 20 mK

FWHM @ 2615 keV = 16.3 keV
Simulation for AMoRE-I setup

- $^{228}\text{Th}$ backgrounds

![Diagram of decay chains]

- Major Background Sources

<table>
<thead>
<tr>
<th>Material</th>
<th>Source</th>
<th>Activity (mBq/kg)</th>
<th>Background ($10^{-3}$ckky)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMO</td>
<td>$^{226}\text{Ra}$</td>
<td>65</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>$^{228}\text{Th}$</td>
<td>50</td>
<td>0.72</td>
</tr>
<tr>
<td>Vikuiti</td>
<td>$^{214}\text{Bi}$</td>
<td>&lt;0.91</td>
<td>&lt;0.119</td>
</tr>
<tr>
<td></td>
<td>$^{208}\text{Tl}$</td>
<td>&lt;0.48</td>
<td>&lt;0.177</td>
</tr>
<tr>
<td>Copper</td>
<td>$^{228}\text{Th}$</td>
<td>&lt;0.25</td>
<td>&lt;0.25</td>
</tr>
<tr>
<td>Accidentals</td>
<td>$^{100}\text{Mo}$</td>
<td></td>
<td>0.12</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>&lt;1.6</td>
</tr>
</tbody>
</table>
Crystals for AMoRE-II – studied by KNU

There are Mo crystals excellent for AMoRE-II experiment in addition to CaMoO4.

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Energy Yield @ 10K</th>
<th>density</th>
<th>Mo Fraction</th>
<th>Exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaMoO4</td>
<td>100</td>
<td>4.34</td>
<td>0.49</td>
<td>AMoRE-1, 2(?)</td>
</tr>
<tr>
<td>ZnMoO4</td>
<td>20</td>
<td>4.37</td>
<td>0.436</td>
<td>LUMINEU</td>
</tr>
<tr>
<td>Li$_2$MoO4</td>
<td>5</td>
<td>3.03</td>
<td>0.562</td>
<td>LUMINEU, AMoRE-II(?)</td>
</tr>
<tr>
<td>PbMoO4</td>
<td>10</td>
<td>6.95</td>
<td>0.269</td>
<td>AMoRE-II(?)</td>
</tr>
<tr>
<td>Na$_2$Mo$_2$O$_7$</td>
<td>140</td>
<td>3.62</td>
<td>0.558</td>
<td>AMoRE-II(?)</td>
</tr>
</tbody>
</table>

We will decide the crystal by end of 2017.
AMoRE-II is the most massive experiment with enriched isotope having Q value > 3MeV.
Sensitivity of KIMS-LT experiment – Hyunsu Lee

Goal to have the most sensitive detector for the low-mass dark matter
2. Sterile neutrinos search – NEOS
Hints for light sterile neutrinos

All these anomalies indicate \( \sim \) eV mass right-handed sterile neutrinos.
NEOS (Neutrino Experiment for Oscillation at Short baseline)

- Possibility to search sterile neutrinos at the commercial power plant.
- Unique experiment with 3 baseline at the same time,
  -- NEOS (25m), RENO-near(~250m), RENO-far(1300m)

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Thermal Power</th>
<th>Baseline</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROSPECT</td>
<td>85 MW</td>
<td>7 - 12 (near), 15 - 19 (far) meters</td>
<td>US</td>
</tr>
<tr>
<td>Stereo</td>
<td>57 MW</td>
<td>8.9 - 11.1 meters</td>
<td>France</td>
</tr>
<tr>
<td>CHANDLER</td>
<td>60 MW</td>
<td>~ 6 meters</td>
<td>Belgium</td>
</tr>
</tbody>
</table>
Detector Constructed & Installed.

Construction and Installation at Tendon Gallery finished on Aug. 6th, 2015
Preliminary results

- First result after reactor neutrino anomaly.
- Rejected the best-fit parameter for the anomaly.
- Further analysis with Daya Bay and RENO antineutrino spectra.
Ultimate reactor neutrino spectra?

- A new ~2ton size detector with photocathode coverage > 70% at shorter baseline (~15m) can have an energy resolution better than 3% and high statistics (>10000 events/day).
- Tendon Gallery may be extended in a new reactor under consideration in Korea or China for complete burn-up measurements.
A new underground laboratory at Handuk mine

After extensive study, we finally decided to build a new underground lab at an active iron mine, Handuk.

- For 2018 Winter Olympic, construction of a high-speed train between airport to east has started.
- ~ 3 hour from Incheon airport to Handuk mine.
Two ways to access to the entrance of IBS tunnel, ramp way and vertical shaft.  
730 meter long tunnel will be constructed and lab at the end.
Concept of space in the Underground Lab

We consider the concept of water-tank (D: 10m, H: 10m) for LT detectors
For the next generation neutrino and dark matter programs, CUP is developing ultra-low background technology and infrastructure. Ultra-low background technology can be realized with a combination of low background measurement and purification with the ultra-sensitive sensor. CUP is unique to have all the technique in a center.
Ultrapure crystals – Purification & growing crystal

- The center is based on crystal detector and forming a facility for crystal growing.
- Goal: develop the technology for ultra-low background crystals for experiments.

Czochralski furnace

Kyropoulos furnace

30 kg furnace

5 kg furnace

Sublimation facility

Chemistry Lab.
Low temp sensors and detectors

Dilution refrigerators

Sputtering system: Au:Er, Au, Nb, MoGe

ICP RIE: Dry etching Nb superconducting coil

Magnetic property measurement system: Au:Er characterization
Ultra-low radioactivity measurements

- To reach the required low radioactivity in the detectors, we need to develop techniques to measure such low radioactivity in materials.

- Developed Techniques
  1. HPGe gamma-ray detectors.  
  2. ICP-MS analyzer  
  3. Alpha counter  
  4. Radon detector

  **Ra : 0.01mBq/kg level**
  **U, Th down to ppt level**
  **R>0.0001 alphas/cm²/hour**
  **Radon level down to 5mBq/m³**
In addition to Dark Matter Search program, neutrino physics programs are actively pursued at CUP. AMoRE project will cover inverted mass hierarchy region for a discovery and will lead the ton-scale 0nbb with international collaboration. NEOS gives more stringent limits to the reactor neutrino anomaly, and rejects the best-fit parameters. CUP will be the Center for the Ultra-low Background Techniques. For the planned projects, we need a new underground laboratory, which will be the basic facility for the fundamental, great physics.
If you are interested in CUP researches, join to CUP!!

Job announcement in Aug. – Sep. this year!!

http://www.ibs.re.kr
http://cupweb.ibs.re.kr
Energy absorption $\Rightarrow$ Temperature

$T - T_0 = \frac{E}{C}$

$\tau = \frac{C}{G}$

Choice of thermometers
- Thermistors (NTD Ge, doped Si)
- TES (Transition Edge Sensor)
- MMC (Metallic Magnetic Calorimeter)
- etc.
Metallic magnetic calorimeter (MMC)

Magnetic material Au:Er(10~1000ppm)
- weakly-interacting paramagnetic system
- metallic host: fast thermalization (~ 1μs)

\[ \delta E \rightarrow \delta T \rightarrow \delta M \rightarrow \delta \phi \]

\[ g = 6.8 \]
\[ \varepsilon = 1.5 \mu eV \]

5 mT \rightarrow \Delta \varepsilon = 1.5 \mu eV
1 keV \rightarrow 10^9 \text{ spin flips}

 Counts / 0.4 eV

1.6 eV FWHM for 6 keV x-rays

Am241 full spectrum
MMC with gold foil absorber with \( C \sim 0.3\text{kg CaMoO}_4 \)

0.3 keV FWHM for 60keV \( \gamma \)
1.2 keV FWHM for 5.5MeV \( \alpha \)
AMoRE-II(200kg) Shield and Cryostat

- One of conceptual plans
- Water tank for active shield (similar design and size of LUX and XMASS)
- Cryostat submerged in the pure water.
- This setup requires lots of R&Ds,
- and desperately requires wider, higher, and hopefully deeper lab space.
Radon reduction system

- Imported from Czech and installed in Aug. 2015.
- 120 m³/hour of Rn free air (50 Bq/m³ → 5mBq/m³) will be supplied.
- Important to prohibit Radon contamination during detector assembly.
- Korean company will try to develop the technique.
- Rn-free air will be supplied to the most sensitive clean room.

System Specification

<table>
<thead>
<tr>
<th>Condition Item</th>
<th>Value</th>
<th>Apparatus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet of air</td>
<td>180 m³/h</td>
<td>Compressor</td>
</tr>
<tr>
<td>Adsorption temperature</td>
<td>50 °C</td>
<td>Carbon Tower</td>
</tr>
<tr>
<td>Pressure</td>
<td>9 bar</td>
<td></td>
</tr>
<tr>
<td>Inlet condition</td>
<td>45 Bq/m³, 21 °C, 1013 mbar, RH 40%</td>
<td></td>
</tr>
<tr>
<td>Out let of Rn free air</td>
<td>5 mBq/m³</td>
<td></td>
</tr>
<tr>
<td>Reduction factor</td>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>
AMoRE schedule
## Current best results for $0\nu\beta\beta$

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Exp</th>
<th>$T_{1/2}(10^{24}\text{Y})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>ELEGANT VI</td>
<td>$&gt;0.058$</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>GERDA-I</td>
<td>$&gt;21$</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>NEMO-3</td>
<td>$&gt;0.32$</td>
</tr>
<tr>
<td>$^{96}\text{Zr}$</td>
<td>NEMO-3</td>
<td>$&gt;0.0092$</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>NEMO-3</td>
<td>$&gt;1.0$</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>Solotvina</td>
<td>$&gt;0.17$</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>CUORE</td>
<td>$&gt;2.8$</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>EXO-200,KamLAND-Zen</td>
<td>$&gt;19$</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>NEMO-3</td>
<td>$&gt;0.018$</td>
</tr>
</tbody>
</table>
## Background Simulations for AMoRE-I

<table>
<thead>
<tr>
<th></th>
<th>Concentration (mBq/kg)</th>
<th>Rate (10⁻³ counts/keV/kg/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Time</td>
</tr>
<tr>
<td>Internal CMO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pb210</td>
<td>7.3</td>
<td>42.66</td>
</tr>
<tr>
<td>U238</td>
<td>0.98</td>
<td>34.25</td>
</tr>
<tr>
<td>Ra226</td>
<td>0.065</td>
<td>516.38</td>
</tr>
<tr>
<td>Th228</td>
<td>0.050</td>
<td>698.91</td>
</tr>
<tr>
<td>Bi211</td>
<td>0.470</td>
<td>68.20</td>
</tr>
<tr>
<td>Vikuiti</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bi214</td>
<td>&lt;0.91</td>
<td>2.34E+04</td>
</tr>
<tr>
<td>Tl108</td>
<td>&lt;0.48</td>
<td>4.68E+04</td>
</tr>
<tr>
<td>CMO supporting copper frame</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ra226</td>
<td>&lt;0.16</td>
<td>8484</td>
</tr>
<tr>
<td>Th228</td>
<td>&lt;0.25</td>
<td>5684</td>
</tr>
<tr>
<td>SC lead shield</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ra226</td>
<td>1 ppt</td>
<td>9253</td>
</tr>
<tr>
<td>Th228</td>
<td>1 ppt</td>
<td>30354</td>
</tr>
<tr>
<td>Inner lead plate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ra226</td>
<td>1 ppt</td>
<td>1465.8</td>
</tr>
<tr>
<td>Th228</td>
<td>1 ppt</td>
<td>1182.8</td>
</tr>
<tr>
<td>Cu Plate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ra226</td>
<td>&lt;0.16</td>
<td>8746.0</td>
</tr>
<tr>
<td>Th228</td>
<td>&lt;0.25</td>
<td>6077.6</td>
</tr>
<tr>
<td>G10 fiberglass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ra226</td>
<td>2.16×10⁴</td>
<td>2.43E+04</td>
</tr>
<tr>
<td>Th228</td>
<td>5.03×10³</td>
<td>2.50E+04</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ra226</td>
<td>&lt;0.2</td>
<td>5.26E+06</td>
</tr>
<tr>
<td>Th228</td>
<td>&lt;0.1</td>
<td>2.55E+07</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total backgrounds < 1.34×10⁻³ cky.

Expect zero backgrounds for AMoRE-I.
Strategy for AMoRE-II

- Crystallization is very delicate technique.
- CUP is purchasing 120 kg of $^{100}$Mo powder from ECP company directly and will have all the material until 2018.
- CUP will develop purification and crystal growing techniques with a collaboration with Russian researchers and institutes.
- AMoRE-II is the largest DBD experiment fully approved, and will reach inverted mass region first!!
- If not detected at that region, then go further with ~ ton scale exp.

Crystal Experts related with AMoRE projects
- Dr. Shlagel, Institute for Inorganic Chemistry, Novosibirsk, Russia
- Dr. Galashov, Novosibirsk State University, Russia → will set up new tech in CUP
- Dr. Kornoukhov, IHEP, Moscow, Russia
- Dr. Ren, SICCAS, China
- Dr. Danevich, INR, Ukraine
- Prof. Hongjoo Kim, Kyungpook National University
- TPS company in Korea.
World-wide dark matter search status

From Lepton Photon 2015, L. Baudis
3. KIMS-LT Project

- Scintillating Crystal @ 10-20 mK
- Phonon vs Light will separate nuclear recoil signal.
- Technology developed for AMoRE experiment

Phonon collector film on bottom surface

Light detector
2 inch Ge wafer + MMC

200g CaMoO$_4$

MMC : Metallic Magnetic Calorimeter
Phonon and Photon signals

at KRISS (over-ground) lab

Nuclear recoil by neutrons?

Need to optimize the separation at low energy.
Low energy spectrum

- 8 keV X-ray from K$_{\alpha_1}$ of Cu
- 186 keV from Ra-226
- 239, 242 keV from Pb-212, Pb-214
- 511 keV annihilation line, TI-208
- Baseline
- 1.5 keV
- 8.028 keV K$_{\alpha_2}$ of Cu (51%) and 8.048 keV K$_{\beta_1}$ of Cu (100%)
- 8.905 keV K$_{\beta_1}$ of Cu (17%)

~ 1 keV energy threshold
Strategy for low-mass dark matter search

Low Mass WIMP detection

Lower Energy Threshold

Lower background

Larger detector volume

WIMP Mass (GeV)

X-section (pb)

50 kg, 0.1 dru

50 kg, 0.5 keV threshold

0.1 dru, 0.5 keV threshold

10 kg

50 kg

200 kg
CUP (Center for Underground Physics)
Energy resolution with outside source

- Pulsed Tube Cooler generates vibrational noise.
- Energy resolution $14 - 32$ keV FWHM @ $2.6$ MeV.
Running at Y2L now....

- The dilution fridge reaches 8 mK with 250kg lead attached.
- We are trying to reduce the vibrational noise.
  - High frequency noise : reasonably low.
  - Low frequency noise : should be improved. We are working on this!

![Graph showing energy vs partial meantime](image)
Purification for XMoO$_4$ crystals.

- $^{100}$MoO$_3$ powder by Russia:
  - $^{232}$Th, $^{238}$U < 1 ppb
- $^{100}$MoO$_3$ powder will be delivered until 2019.
- We will purify $^{100}$MoO$_3$ powder by sublimation + co-precipitation, or recrystallization method.
- Develop the purification techniques with 99.95% natMoO$_3$ powder (0.2 ppb of $^{232}$Th and 3.5 ppb of $^{238}$U)
- Purified powder will be measured by ICP-MS (10 ppt sensitivity for $^{232}$Th and $^{238}$U now).
- Ra reduction will be confirmed by Ba measurement.
- XMoO$_4$ crystal growing techniques are being developed.
Sterile Neutrino Search – NEOS

- Sterile neutrinos – right-handed neutrinos
- Sterile neutrinos – maybe Warm Dark Matter
- Nothing is known about the masses. Maybe very light \((m_n \ll 1\, \text{MeV})\) or very heavy \((m_n \gg 10^{10} \, \text{GeV})\)
- Sterile neutrinos may be identified since the active neutrinos can oscillate to sterile neutrinos (disappearance experiment) or again oscillate to active neutrinos (appearance experiment).

\[
\Delta m_{12}^2 = 8 \times 10^{-5} \, \text{eV}^2 \\
\Delta m_{32}^2 = 2.3 \times 10^{-3} \, \text{eV}^2 \\
m_1 = ?
\]
MC Tuning - $\gamma$ and $\beta$ sources

- $^{137}$Cs
- $^{60}$Co
- Po–Be Capture
- $^{214}$Bi
- $^{212}$Bi

1.00016 ± 0.00053

Black dots: Data
Blue line: MC
NEOS Detector

- Volume of Liquid Scintillator (LS) is ~ 1000 L
- Mixture LS: LAB based + DIN based (9:1)
- 0.5% gadolinium is loaded.

- 8” photomultiplier (PMT)
- 38 PMTs in mineral oil
- Borated polyethylene (10 cm)
- B-PE shields neutrons produced at lead.

- 10 cm lead shield for gamma
- 4π muon detector for veto (except bottom)
- Plastic scintillator
- 2” or 5” PMTs
- Mention et al., PRD 83, 073006 (2011)
## Schedule of IBS-ARF

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Infra</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBS–ARF</td>
<td>Design</td>
<td>Construction</td>
<td>Operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Bkg. Facility</td>
<td>Test Experiment</td>
<td>Operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>DM Exp.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KIMS–Nal</td>
<td>Data taking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KIMS–LT</td>
<td></td>
<td>Test Experiment</td>
<td>Data taking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>DBD Exp.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AMoRE–10</td>
<td>Data taking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AMoRE–200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Data taking</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Which isotope for experiment?

- Half-lifves depends on phase factor and matrix element.

\[
T_{1/2}^{0\nu} = G_{0\nu} \left| M_{0\nu} \right|^2 \left( \frac{m_{\beta\beta}}{m_e} \right)^2
\]

\[
m = U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3
\]

\[
T_{1/2}^{0} \rightarrow m
\]

G and M has anti-correlation.

→ Generally no single isotope is preferred.
Moore’s law for 0νββ?

$T_{1/2}^0 > 2.1 \times 10^{25}$ years

$^{76}$Ge, Gerda (0.3) 2013.9

$^{136}$Xe, EXO (0.26) 2012.7

$^{136}$Xe, KAMLAND-ZEN, 2013.2

$^{136}$Xe, KAMLAND-ZEN, 2016.5 !!!