The AMoRE (Advanced Mo-based Rare process Experiment) : Search for Neutrinoless Double Beta Decay in $^{100}$Mo

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On the behalf of AMoRE collaboration

Center for Underground Physics,
ibs (Institute for Basic Science), Korea

International Workshop on “Double Beta Decay and Underground Science”
RCNP, Osaka, Nov 8 - 10, 2016
AMoRE Collaboration

8 Countries
18 Institutions
~90 Collaborators

We are accepting collaboration.
For sizeable background case;

$$T_{1/2}^0 \text{ (exp)} = (\log 2) N_a \frac{a}{A} \sqrt{\frac{MT}{bE}}$$

For “zero” background case;
No. of background events $\sim O(1)$

$$T_{1/2}^0 \text{ (exp)} = (\log 2) N_a \frac{a}{A} \sqrt{\frac{MT}{n_{CL}}}$$

The AMoRE is aiming to zero background.
Why we use $^{100}\text{Mo}$ for $0\nu\beta\beta$ search?

- High Q-value ($\beta\beta$) of 3034.40 (12) keV.
- High natural abundance of 9.7%.
- Relatively short half life ($0\nu\beta\beta$) expected from theoretical calculation.

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<table>
<thead>
<tr>
<th>Candidate</th>
<th>Q (MeV)</th>
<th>Abund. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>4.271</td>
<td>0.19</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>2.040</td>
<td>7.8</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>2.995</td>
<td>8.7</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>3.034</td>
<td>9.7</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>2.802</td>
<td>7.5</td>
</tr>
<tr>
<td>$^{124}\text{Sn}$</td>
<td>2.228</td>
<td>5.8</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>2.533</td>
<td>34.1</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>2.479</td>
<td>8.9</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>
AMoRE Parameters

- **Crystals**: $^{40}\text{Ca}^{100}\text{MoO}_4$
  - $^{100}\text{Mo}$ enriched: > 95%
  - $^{48}\text{Ca}$ depleted: < 0.001% (N.A. of $^{48}\text{Ca}$: 0.187%)

- **Low temperature detector**: 10 – 30 mK

- **Energy resolution**: 5 keV @ 3MeV

- **The AMoRE Plan:**

<table>
<thead>
<tr>
<th></th>
<th>Pilot</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass</strong></td>
<td>1.5 kg</td>
<td>5 kg</td>
<td>200 kg</td>
</tr>
<tr>
<td><strong>Bkg [keV ·kg· year]^{-1</strong>}</td>
<td>10^{-2}</td>
<td>10^{-3}</td>
<td>10^{-4}</td>
</tr>
<tr>
<td><strong>$T_{1/2}$ Sensitivity [years]</strong></td>
<td>$\sim10^{24}$</td>
<td>2.7x10^{25}</td>
<td>1.1 x 10^{27}</td>
</tr>
<tr>
<td><strong>$&lt;m_{\beta\beta}&gt;$ Sensitivity [meV]</strong></td>
<td>300-900</td>
<td>70-140</td>
<td>12-22</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>Y2L (700 m depth)</td>
<td></td>
<td>New deeper Lab.</td>
</tr>
<tr>
<td><strong>Schedule</strong></td>
<td>2016~2017</td>
<td>2017 - 2019</td>
<td>2020 - 2025</td>
</tr>
</tbody>
</table>
Temperature dependence CaMoO$_4$ crystal

- From RT to 7K, light yield is increased by factor of 6.
  (V.B. Mikhailik et al., NIMA 583 (2007) 350)

- CMO absolute light yield:
  ~4,900 ph/MeV@Room Temp. (H.J. Kim et al., IEEE TNS 57 (2010) 1475)
  ~30,000 ph/MeV@Low Temp.

- Highest light yield among Mo contained crystals.
**100Mo enriched & 48Ca depleted materials**

- **100Mo isotope production:**
  - ECP (Electrochemical plant), Russia
  - 100MoO₃ powder:
    - **100Mo Enrichment:** ~ 95%
    - **Impurities:**
      - ICP-MS at CUP
        | U: ~ 0.2 ppb | Th: < ~0.05 ppb |
      - HPGe at Y2L
        | ²²⁶Ra: 8.3 mBq/kg | ²²⁸Ac < ~1.0 mBq/kg |

- **40Ca with depletion of 48Ca isotope production:**
  - ELEKTROCHIMPRIBOR, Lesnoy, Russia
  - 40CaCO₃ powder:
    - **48Ca < 0.001%**
    - **Impurities:** U ≤ 0.1 ppb, Th ≤ 0.1 ppb, Sr = 1 ppm, Ba = 1 ppm
      - ²²⁶Ra = 51 mBq/kg ²²⁸Ac(²²⁸Th) = 1 mBq/kg
Internal backgrounds of $^{40}\text{Ca}^{100}\text{MoO}_4$ crystals

$4\pi$ CsI(Tl) active setup with Pb shielding at Y2L

$4\pi$ gamma veto system

$\beta-\alpha$ decay in $^{238}\text{U}$ (164 $\mu$s)
$^{214}\text{Bi}$ (Q-value : 3.27-MeV) $\rightarrow$ $^{214}\text{Po}$ (Q-value : 7.83-MeV)

$\alpha-\alpha$ decay in $^{232}\text{Th}$ (145 ms)
$^{220}\text{Rn}$ (Q-value : 6.41-MeV) $\rightarrow$ $^{216}\text{Po}$ (Q-value : 6.91-MeV)

$\alpha-\alpha$ decay in $^{235}\text{U}$ (1.78 ms)
$^{219}\text{Rn}$ (Q-value : 6.23-MeV) $\rightarrow$ $^{215}\text{Po}$ (Q-value : 7.38-MeV)

<table>
<thead>
<tr>
<th></th>
<th>U-238 chain (µB/kg)</th>
<th>U-235 chain (µB/kg)</th>
<th>Th-232 chain (µB/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystals</td>
<td>Po-214</td>
<td>Po-215</td>
<td>Po-216</td>
</tr>
<tr>
<td>SS68</td>
<td>60±8</td>
<td>200±14</td>
<td>30±7</td>
</tr>
<tr>
<td>NSB29</td>
<td>200±14</td>
<td>700±26</td>
<td>80±9</td>
</tr>
<tr>
<td>S35</td>
<td>4400±66</td>
<td>1200±35</td>
<td>500±22</td>
</tr>
<tr>
<td>SB28</td>
<td>80±9</td>
<td>N/A</td>
<td>70±8</td>
</tr>
<tr>
<td>SE1</td>
<td>40±12</td>
<td>60±8</td>
<td>50±15</td>
</tr>
</tbody>
</table>

Note: 100 µBq/kg for $^{238}\text{U}$, 50 µBq/kg for $^{232}\text{Th}$ decay chain for AMoRE-I
Low temperature detectors (Calorimeters)

Energy absorption $\rightarrow$ Temperature

Choice of thermometers

- Thermistors (NTD Ge, doped Si)
- TES (Transition Edge Sensor)
- MMC (Metallic Magnetic Calorimeter)
- etc.
MMC (Metallic Magnetic Calorimeter)

Principle of operation
1. Energy absorption in CMO crystal.
3. Temperature increase (gold film).
4. Magnetization of MMC decrease.
5. SQUID pickup the change.

Advantage of MMC
- Fast rising signal: ~0.5 ms (critical to reduce $2\nu\beta\beta$ random coincidence)
- Fairly easy to attach to absorber.
- Excellent Energy resolution
MMC cryogenic technique for AMoRE (I)

Phonon and Light detectors ->

Overground measurement

Energy resolution: $< 9$ keV @2.6 MeV
MMC cryogenic technique for AMoRE (II)

- Excellent $\alpha/e$ separation: $\sim 15\sigma$
  - thanks to PSD and both Heat & Light measurements.
Yangyang underground laboratory (Y2L, South Korea)

Yangyang pumped storage Power Plant
Minimum vertical depth: 700 m
Access to the lab by car: around 2 km

Experiments
- KIMS: dark matter search experiment
- AMoRE: neutrinoless double beta decay search experiment

KIMS NaI, Ge, 4 pi

separated two main labs

AMoRE experiment at Y2L
AMoRE-Pilot detector configuration: five $^{40}\text{Ca}^{100}\text{MoO}_4$ crystals

5 crystals: 0.2kg to 0.4kg each, for a total mass of 1.5kg
Each crystal module includes a heat detector and a light detector

Operating temperatures as low as 8 mK reached using a Cryogen Free Dilution Refrigerator (CF-DR)
Shielding structure of AMoRE-pilot & AMoRE-I

- 15cm low background Pb
- 10cm ultra-low background Pb

Cryostat for AMoRE
AMoRE-Pilot run-1 measurements

- Muon band was suppressed
- S35 phonon channel was not working
- Large vibration noise

FWHM energy resolution from run-1 (S35 not available)
Energy resolution in AMoRE-Pilot run-2

Pilot run-2 (SB29 not available)

- From run-1 to run-2, the energy resolution of phonon channels have been improved by vibration reduction
- Photon channels need further improvements

<table>
<thead>
<tr>
<th>Crystals</th>
<th>Mass (kg)</th>
<th>AMoRE-Pilot run-1 (keV)</th>
<th>AMoRE-Pilot run-2 (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB28</td>
<td>0.20</td>
<td>36.8</td>
<td>25.0</td>
</tr>
<tr>
<td>S35</td>
<td>0.25</td>
<td>N/A</td>
<td>16.3</td>
</tr>
<tr>
<td>SS68</td>
<td>0.35</td>
<td>52.6</td>
<td>22.5</td>
</tr>
<tr>
<td>SE01</td>
<td>0.35</td>
<td>39.7</td>
<td>24.6</td>
</tr>
<tr>
<td>SB29</td>
<td>0.40</td>
<td>42.6</td>
<td>N/A</td>
</tr>
</tbody>
</table>
PSD in AMoRE-Pilot run-2

SE01 phonon (20 mK)

Mean time (ms)

Energy (keV)

β/γ

α

SE01 phonon (20 mK)

Rise time (ms)

Energy (keV)

β/γ

α

SE01 (20 mK)

Light/heat

Phonon pulse height (V)

β/γ

α

SE01 phonon signals (10 mK)

Counts

2615 keV γ events (208-Tl)

α events

Rise time (ms)
AMoRE-Pilot run-2: PSD as a function of temperature

- PSD vary from one crystal to another

\[
DP = \frac{X_{\beta/\gamma} - X_{\alpha}}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_{\alpha}}}
\]
Vibration from the pulse tube refrigerator (PTR)

The pulse tube refrigerator of the cryostat generates mechanical vibration which turns into heat noise and disturbs the baseline.

Comparison of vibration level between PTR on and PTR off as a function of frequency.
Mass-spring system

- Use of four phosphorus copper springs
- Room temperature test successful
Mass Spring Damper: Recent improvement

- Higher frequency region than the natural one is isolated.
- Damping is essential to reduce resonance.
Internal background simulation for AMoRE-I

- $^{208}$Tl with $\alpha$-tagging: less than $8.3 \times 10^{-4}$ DBU.
- Random coincidence of $2\nu\beta\beta$ of $^{100}$Mo: $1.2 \times 10^{-4}$ DBU.

-> Goal of 0.002 for AMoRE-I can be achieved
## Major backgrounds from radionuclides for AMoRE-II

<table>
<thead>
<tr>
<th>Background source</th>
<th>Activity [µBq/kg]</th>
<th>Bg [10^-4 cnt/keV/kg/yr]</th>
<th>Bg reduced by PSD [10^-4 cnt/keV/kg/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tl-208, internal</td>
<td>10 (232Th)</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>Tl-208, in Cu</td>
<td>16 (232Th)</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>BiPo-214, internal</td>
<td>10</td>
<td>0.11 ¹)</td>
<td>≤ 0.01</td>
</tr>
<tr>
<td>BiPo-214, in Cu</td>
<td>60</td>
<td>1.8 ¹) ²)</td>
<td>≤ 0.18</td>
</tr>
<tr>
<td>BiPo-212, internal</td>
<td>10 (232Th)</td>
<td>0.08 ¹)</td>
<td>≤ 0.01</td>
</tr>
<tr>
<td>BiPo-212, in Cu</td>
<td>16 (232Th)</td>
<td>0.36 ¹) ²)</td>
<td>≤ 0.04</td>
</tr>
<tr>
<td>Y-88, internal</td>
<td>20</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>Σ int. (w/o 2β2ν)</td>
<td></td>
<td>0.74</td>
<td>≤ 0.57</td>
</tr>
<tr>
<td>Σ Cu</td>
<td></td>
<td>2.40</td>
<td>≤ 0.44</td>
</tr>
<tr>
<td>Rand. coinc. from 2β2v decays of ¹⁰⁰Mo</td>
<td>8.7×10³ (single evts.)</td>
<td>3.1³)</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>6.2</strong></td>
<td><strong>≤ 2.2</strong></td>
</tr>
</tbody>
</table>

¹) Can be reduced x0.1 by alpha/beta PSD
²) Can be reduced by teflon coating of Cu (to remove surface alphas)?
³) Can be reduced by the leading edge separation with Δt=0.5 ms

Muon background: ~1.4×10^-4 counts/keV/kg/yr @Y2L
MoO₃ powder purifications with sublimation method.
- Results are monitored by ICP-MS and HPGe
  -> $^{226}$Ra can be reduced by ~100.
Ultra-low background crystals for AMoRE-II (II)

- Crystal growing equipment:
  1 Czochalski, 2 Kyropoulos, 1 Bridgman crystal grower

Czochalski machine

The 1st CMO crystal by us.
Summary

- AMoRE-pilot with 1.5 kg CMO are running.
- AMoRE-I with ~4.5kg of crystals in next year.
- We are performing on R&D programs for AMoRE-II.

<table>
<thead>
<tr>
<th></th>
<th>Pilot</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Crystal</td>
<td>$^{48}\text{depl}^{100}\text{CaMoO}_4$</td>
<td>$^{48}\text{depl}^{100}\text{CaMoO}_4$</td>
<td>New crystal?</td>
</tr>
<tr>
<td>Detector Mass</td>
<td>1.5 kg</td>
<td>~5 kg</td>
<td>~200 kg</td>
</tr>
<tr>
<td>Background (keV/kg/year)</td>
<td>0.01</td>
<td>0.001</td>
<td>0.0001</td>
</tr>
<tr>
<td>Sensitivity of $T_{1/2}$ (year)</td>
<td>~$10^{24}$</td>
<td>$2.7\times10^{25}$</td>
<td>$1.1\times10^{27}$</td>
</tr>
<tr>
<td>Sensitivity of $M_{\beta\beta}$ (meV)</td>
<td>&lt; 300-900</td>
<td>70-140</td>
<td>12-22</td>
</tr>
<tr>
<td>Location</td>
<td>Y2L</td>
<td>Y2L</td>
<td>Handuk mine</td>
</tr>
</tbody>
</table>
Thank you
Purification of MoO$_3$ powder: Sublimation method (I)

- MoO$_3$ has the transition from the solid to the gas phase around 700 °C.

-> Some impurities, U/Th, are still in the solid phases.
Event Rejection using $\alpha$-tagging

- **Event Rejection**
  - Events are tagged for 15 mins ($\sim 5 \times t_{1/2}$) after $\alpha$ event with 6.027 MeV (decay of $^{212}$Bi to $^{208}$Tl).
  - When events were tagged for 15 mins after $\alpha$ event with 6.027 MeV appeared, about 94.4% of $\beta$ decay event from $^{208}$Tl to $^{208}$Pb were rejected.
  - Similarly, tagging for 21 mins, 95.7% events were rejected.
  - In our recent measurement, concentration of $^{232}$Th inside the CMO crystal was < 2 $\mu$Bq/kg.
  - As long as concentration of $^{232}$Th is below 50 $\mu$Bq/kg, the background rate is lower than our goal after rejecting events.

<table>
<thead>
<tr>
<th>Concentration</th>
<th>Corrected Rate (/keV/kg/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 $\mu$Bq/kg</td>
<td>0.0015</td>
</tr>
<tr>
<td>10 $\mu$Bq/kg</td>
<td>0.0003</td>
</tr>
</tbody>
</table>
Considerable beta decays ($^{238}$U)

$^{234}$Th $Q_\beta$: 199 keV (78.0 %)

$^{234}$Pa $Q_\beta$: 2269 keV (97.6 %)

Not serious for short half life of $^{214}$Po

$^{214}$Pb $Q_\beta$: 1019 keV (11.0 %)
724 keV (40.2 %)
667 keV (45.9 %)

$^{210}$Bi $Q_\beta$: 1162 keV (100 %)

Counts/keV

Energy $E_e$ (keV)
Considerable beta decays ($^{232}$Th)

- $^{232}$Th → $^{228}$Th (1.9 Yr)
- $^{228}$Th → $^{224}$Ra (6.1 hour)
- $^{224}$Ra → $^{220}$Rn (5.7 Yr)
- $^{220}$Rn → $^{216}$Po (8.6 Yr)
- $^{216}$Po → $^{212}$Po (0.145 sec)
- $^{212}$Po → $^{212}$Bi (61 min)
- $^{212}$Bi → $^{212}$Pb (10.6 hour)
- $^{212}$Pb → $^{208}$Tl (3.1 min)

Not serious for short half life of $^{212}$Po
Considerable beta decays ($^{235}$U)

- Not serious for small Q value (44.8 keV)
  - $^{235}$U
  - $^{211}$Pb $Q_\beta$: 1367 keV (91.3 %)
  - 160 keV (6.3 %)

- $^{207}$Tl $Q_\beta$: 1418 keV (99.7 %)
Time-Amplitude analysis method

U-235 chain: \[ \text{Rn-219 (3.965 s)} \rightarrow \text{Po-215 (1.78 ms)} \]
\[ \rightarrow \text{Pb-211} \]

U-238 chain: \[ \text{Bi-214 (20 m)} \rightarrow \text{Po-214 (164 us)} \]
\[ \rightarrow \text{Pb-210} \]

Th-232 chain: \[ \text{Rn-220 (55.6 s)} \rightarrow \text{Po-216 (0.145 s)} \]
\[ \rightarrow \text{Pb-212} \]
History of CaMoO4

1) 2002 : Idea and try to grow CMO in Korea
2) 2003 : Collaboration with V.Kornokov.
3) 2004 : CMO test and Conference presentation (VIETNAM2004), Extended idea of XMoO4, cryogenic detector of CMO
4) 2005-2007 : Large CMO with 1st ISTC project
5) 2006 : Collaboration with F. Danevich group (CMO by Lviv)
6) 2007 : CMO R&D in cryogenic temperature started.
7) 2008 : 2nd ISTC project : 1kg of $^{48}$depl$^{100}$Ca$^{100}$MoO4 crystal
8) 2009 : AMORE collaboration formed
9) 2010-11 : $^{40}$Ca$^{100}$MoO4 internal background study
10) 2012 : Russian group (FOMOS) got funding for production line
11) 2013 : AMoRE project funded (Under Center for Underground Physics, Institute for Basic Scinece)
12) 2014 : Upgrade of Y2L lab for AMoRE-pilot and AMoRE-I
$^{40}\text{Ca}^{100}\text{MoO}_4$ Crystals for AMoRE-pilot

- All crystals for AMoRE-pilot are in the cryostat.

Total mass: 1.546 kg