AMoRE  $0\nu\beta\beta$ experiment using low temperature $^{40}\text{Ca}^{100}\text{MoO}_4$ calorimeters

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On behalf of AMoRE collaboration

Institute for Basic Science (IBS)
Korea Research Institute for Standards and Science (KRISS)
The AMoRE Project

AMORE: ‘Love’ in Italian

AMORE: “A cosmetic company in Korea”

AMoRE: Advanced Mo-based Rare process Experiment
to search for neutrinoless double decay of $^{100}$Mo
using cryogenic $^{40}$Ca$^{100}$MoO$_4$ detectors

That’s AMoRE for us!

Ø4cm x 4cm
CaMoO$_4$ crystal
AMoRE collaboration (since 2009)

8 counties, 18 institutions, ~90 collaborators
Neutrinoless double beta decay ($0\nu\beta\beta$)

Double Beta Decay with two neutrinos

$$ (A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e $$

Double Beta Decay with no neutrino

$$ (A, Z) \rightarrow (A, Z + 2) + 2e^- $$

It may answer

- Mass of neutrinos ($1/T_{1/2}^{0\nu} \propto m_{\nu}^2$)
- Majorana ($\nu = \bar{\nu}$), or Dirac particles ($\nu \neq \bar{\nu}$)
- Lepton number conservation?
Experimental Sensitivity of $T_{1/2}^{0\nu}$ ($0\nu\beta\beta$)

For sizeable background case:

$$T_{1/2}^{0\nu} (\text{exp}) = (\ln 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{MT}{b\Delta E}}$$

Isotopic Abundance
Detection Efficiency
Detector Mass
Time
Atomic mass
Background level (count/keV kg year)
Energy Resolution

For “zero” background case:

$$T_{1/2}^{0\nu} (\text{exp}) = (\ln 2) N_a \frac{a}{A} \varepsilon \frac{MT}{n_{CL}}$$
100Mo is chosen for 0νββ experiment

- 100Mo
  - High Q-value (ββ) of 3034.40 (12) keV.
  - High natural abundance of 9.6%
  - Relatively short half life (0νββ) expected from theoretical calculation

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

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Q (MeV)</th>
<th>Abund. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48Ca</td>
<td>4.271</td>
<td>0.19</td>
</tr>
<tr>
<td>76Ge</td>
<td>2.040</td>
<td>7.8</td>
</tr>
<tr>
<td>82Se</td>
<td>2.995</td>
<td>8.7</td>
</tr>
<tr>
<td>100Mo</td>
<td>3.034</td>
<td>9.6</td>
</tr>
<tr>
<td>116Cd</td>
<td>2.802</td>
<td>7.5</td>
</tr>
<tr>
<td>124Sn</td>
<td>2.228</td>
<td>5.8</td>
</tr>
<tr>
<td>130Te</td>
<td>2.533</td>
<td>34.1</td>
</tr>
<tr>
<td>136Xe</td>
<td>2.479</td>
<td>8.9</td>
</tr>
<tr>
<td>150Nd</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>

**AMoRE detector technology**

$^{40}\text{Ca}^{100}\text{MoO}_4 + \text{MMC : Source = Detector}$

- **$^{40}\text{Ca}^{100}\text{MoO}_4$**
  - Scintillating crystal
  - High Debye temperature: $T_D = 438 \text{ K}$, $C \sim (T/T_D)^3$
  - $^{48}\text{Ca}, ^{100}\text{Mo} 0\nu\beta\beta$ candidates
  - AMoRE uses $^{40}\text{Ca}^{100}\text{MoO}_4$ w. enriched $^{100}\text{Mo}$ and depleted $^{48}\text{Ca}$

- **MMC (Metallic Magnetic Calorimeter)**
  - Magnetic temperature sensor (Au:Er) + SQUID
  - Sensitive low temperature detector with highest resolution
  - Wide operating temperatures
  - Relatively fast signals
  - Adjustable parameters in design and operation stages
Temperature dependent CaMoO$_4$ scintillation

From RT to 7 K, the light yield increases 6 times
(V.B. Mikhailik et al., NIMA 583 (2007) 350)

CaMoO$_4$ absolute light yield @RT: 4900±590 ph/MeV
(H.J. Kim et al., IEEE TNS 57 (2010) 1475)

→ Light yield at low temp. : ~ 30,000 ph/MeV
→ Largest light yield among Mo contained crystals.
**40Ca^{100}MoO_4 crystals**

- **Enrichment of^{100}Mo (natural abundance : 9.6%)**
  - Gas-centrifuge method
  - Enrichment of^{100}Mo is higher than 96%.

- **Depletion of^{48}Ca (natural abundance : 0.157%)**
  - Electromagnetic separation
  - Composition of^{48}Ca is less than 0.001%.
Internal backgrounds of \(40\)Ca\(^{100}\)MoO\(_4\) crystals

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

4\(\pi\) gamma veto system

\(\beta\)–\(\alpha\) decay in \(^{238}\)U

\(^{214}\)Bi (Q-value : 3.27-MeV) \(\rightarrow^{214}\)Po (Q-value : 7.83-MeV) \(\rightarrow^{210}\)Pb

\(\alpha\)–\(\alpha\) decay in \(^{232}\)Th

\(^{220}\)Rn (Q-value : 6.41-MeV) \(\rightarrow^{216}\)Po (Q-value : 6.91-MeV) \(\rightarrow^{212}\)Pb

Crystal S35

\(^{210}\)Po : 1.13-MeV

\(^{216}\)Po : 1.62-MeV, 363 events, 0.26mBq/kg

\(^{214}\)Po : 1.13-MeV, 2445 events, 1.74mBq/kg

\(^{220}\)Rn : 1.44-MeV

Crystal SB28

\(^{214}\)Po : 1.93-MeV, 63 events, 0.08mBq/kg

\(^{216}\)Po : 1.61-MeV, 57 events, 0.07mBq/kg
**Metallic Magnetic Calorimeter (MMC)**

Magnetic material Au:Er(100~1000ppm)
- weakly-interacting paramagnetic system
- metallic host: fast thermalization (~ 1μs)

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

- \( g = 6.8 \)
- 5 mT \( \rightarrow \Delta \varepsilon = 1.5 \mu eV \)
- 1 keV \( \rightarrow 10^9 \) spin flips
MMC provides high resolution detection

- 1x1 mm² Au:Er layer designed for MeV signals
- Fabricated at KRISS

MMC with gold foil absorber with $C \sim 0.3$ kg CaMoO$_4$ •

Am241 full spectrum

 MMC with gold foil absorber with $C \sim 0.3$ kg CaMoO$_4$

0.3 keV FWHM for 60keV $\gamma$

0.86 keV FWHM for 6.5MeV $\alpha$

0.4keV FWHM <LTD16> G2.25

1.2keV FWHM Gaussian width for 5.5MeV $\alpha$

0.3 keV FWHM <LTD16> G2.25

S.R. Kim
We measure both thermal and athermal phonons.

**Phonon sensor for AMoRE**

- **Phonon collector**
- **Patterned gold film**
- **MMC**
- **Gold film**
- **Gold wires** (thermal connection)

### Experimental Pulse Shapes

- **New (42 mK)**
- **Old (44 mK)**

**rise-time:** ~ 0.5ms

<Heat flow optimization>
Light (patchable) sensor with MMC

Wafer holder
(Cu, heat bath)

Phonon collector
(Gold films)

Light absorber
(Ge wafer)

MMC chip

SQUID sensor

Temperature independent rise-time!

~0.2 ms rise time at 30 mK

Signal size ($\phi_0$)

Time (ms)

Rise time 10% to 90% (us)

Temperature (mK)
Phonon + Photon Assembly

Phonon collector film on bottom surface

196 g $^{40}\text{Ca}^{100}\text{MoO}_4$ (doubly enriched crystal)

Phonon collector film on bottom surface

Light detector
2 inch Ge wafer + MMC
Particle discrimination

Particle discrimination by light heat ratio

AMoRE@above-ground

Phonon pulse shape discrimination (PSD)

AMoRE@above-ground

4 MeV < $E_{\alpha e}$ < 7 MeV

DP = 8.5703
QF = 0.2157

DP = 17.5279
Energy spectrum (above-ground)

Electron and alpha events can be efficiently identified.

- Better than 9 keV energy resolution was obtained at 10 mK temperature.
- Internal alpha background levels of each isotopes were calculated successfully.
Other detector R&Ds in AMoRE

Integrated light sensors

Combined phonon and photon detector

G4.33, C. Hassel
AMoRE-pilot and AMoRE-phase1 will be run at Y2L. AMoRE-phase2 will be run at other place. (New underground lab.)

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 : 0νββ decay search experiment
AMoRE pilot: 1.5 kg $^{40}\text{Ca}^{100}\text{MoO}_4$

5 Crystals ($^{40}\text{Ca}^{100}\text{MoO}_4$) with total mass ~1.5 kg
AMoRE pilot: 5 phonon + 6 photons

All are installed in a dilution refrigerator.

with plastic scintillator muon veto
Now it is cold.

- All of the shields are mounted.
- The dil. fridge reaches 8 mK with 250kg lead attached to MC
- We are improving noise figures now.
  - High friq.: reasonably low.
  - Low friq.: should be improved.

with an external source at 20 mK
Schedule of the AMoRE project

- Crystal: $^{40}\text{Ca}^{100}\text{MoO}_4$, doubly enriched scintillating crystals
- MMC technology for heat and light measurement
- Temperature: 10-30 mK
- Zero background measurement in ROI
- Location: Y2L (till Phase I) and a new deeper place (after)

<table>
<thead>
<tr>
<th></th>
<th>Pilot</th>
<th>Phase I</th>
<th>Phase II</th>
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<tbody>
<tr>
<td><strong>Mass</strong></td>
<td>1.5 kg</td>
<td>~5 kg</td>
<td>~200 kg</td>
</tr>
<tr>
<td><strong>Background (keV kg year)$^{-1}$</strong></td>
<td>0.01</td>
<td>0.001</td>
<td>0.0001</td>
</tr>
<tr>
<td><strong>Sensitivity($T_{1/2}$) (year)</strong></td>
<td>$\sim10^{24}$</td>
<td>$\sim10^{25}$</td>
<td>$\sim5 \times 10^{25}$</td>
</tr>
<tr>
<td><strong>Sensitivity($m_{ee}$) (meV)</strong></td>
<td>&lt; 300-900</td>
<td>60-180</td>
<td>15-40</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>Y2L</td>
<td>Y2L</td>
<td>New Lab</td>
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<tr>
<td><strong>Schedule</strong></td>
<td>2015</td>
<td>2016-2018</td>
<td>2018-2022</td>
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</tbody>
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AMoRE (CMO + MMC) development

KRISS has been developing LTDs since 2005

First CMO + MMC

0.6 cm³

Presented at LTD13

Large crystal Ø4cm x 4cm

LTD14

Optimization

LTD15

Phonon + Photon at above-ground

LTD16

AMoRE pilot
Underground

5 crystals
⁴⁰Ca¹⁰⁰MoO₄
Total mass 1.5 kg
(Just started)
Physics results
Hopefully in LTD17

Presented at LTD13

LTD14

LTD15
“Postdoc positions are available in the AMoRE project.”