Status of the AMoRE experiment searching for neutrinoless double beta decay of $^{100}$Mo

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Neutrinoless double beta decay of $^{100}$Mo

The goal of the AMoRE (Advanced Mo-based Rare process Experiment) project is to search for neutrinoless double beta decay ($0\nu\beta\beta$) of $^{100}$Mo using Mo-based scintillating crystals and low-temperature sensors.

**Scheme:**

- $2\nu\beta\beta$ decay
  - 2nd order beta decay
  - Rare nuclear decay
  - (>10$^{18}$ years of half life)

- $0\nu\beta\beta$ decay
  - Massive neutrino
  - Majorana particle
  - Beyond the SM model
  - >10$^{25}$ years of half-life

$^{100}$Mo $\rightarrow$ $(Z+2, A) + 2e^- + 2\text{anti-}\nu_e$ ($\Delta L = 0$, conserved)

$^{100}$Mo $\rightarrow$ $(Z+2, A) + 2e^-$ ($\Delta L = 2$, violated)
Advanced Mo based Rare process Experiment

8 countries, 18 Institutes, ~90 collaborators
Choice of $^{100}$Mo

<table>
<thead>
<tr>
<th>Candidates</th>
<th>$Q_{\beta\beta}$(MeV)</th>
<th>N.A. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca$\rightarrow^{48}$Ti</td>
<td>4.271</td>
<td>0.187</td>
</tr>
<tr>
<td>$^{76}$Ge$\rightarrow^{76}$Se</td>
<td>2.040</td>
<td>7.8</td>
</tr>
<tr>
<td>$^{82}$Se$\rightarrow^{82}$Kr</td>
<td>2.995</td>
<td>9.2</td>
</tr>
<tr>
<td>$^{96}$Zr$\rightarrow^{96}$Mo</td>
<td>3.350</td>
<td>2.8</td>
</tr>
<tr>
<td>$^{100}$Mo$\rightarrow^{100}$Ru</td>
<td>3.034</td>
<td>9.6</td>
</tr>
<tr>
<td>$^{110}$Pd$\rightarrow^{110}$Cd</td>
<td>2.013</td>
<td>11.8</td>
</tr>
<tr>
<td>$^{116}$Cd$\rightarrow^{116}$Sn</td>
<td>2.802</td>
<td>7.5</td>
</tr>
<tr>
<td>$^{124}$Sn$\rightarrow^{124}$Te</td>
<td>2.228</td>
<td>5.64</td>
</tr>
<tr>
<td>$^{130}$Te$\rightarrow^{130}$Xe</td>
<td>2.533</td>
<td>34.5</td>
</tr>
<tr>
<td>$^{136}$Xe$\rightarrow^{136}$Ba</td>
<td>2.479</td>
<td>8.9</td>
</tr>
<tr>
<td>$^{150}$Nd$\rightarrow^{150}$Sm</td>
<td>3.367</td>
<td>5.6</td>
</tr>
</tbody>
</table>

- High Q-value (3.034 MeV)
- High natural abundance (9.6 %)
- Relatively short theoretically predicted half-life ($0\nu\beta\beta$)

Detector concept

- "Source = detector" approach
  - High detection efficiency
  - High energy resolution
  - MMCs
  - Fast response, high energy resolution, wide operating temperatures

- Metallographic Magnetic Calorimeter (MMC, low temperature sensor)

$^{40}\text{Ca}^{100}\text{MoO}_4$ (enriched $^{100}\text{Mo}$, depleted $^{48}\text{Ca}$) or other Mo-based scintillating crystal used as source and detector

Simultaneous measurement of heat and light
- Particle discrimination for rejection of $\alpha$-induced background

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AMoRE sensitivity to $0\nu\beta\beta$

**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
- Measurement time
- Energy Resolution
- Sensitivity to half-life of $0\nu\beta\beta$
- Atomic mass
- Background rate

**“Zero” background case**

\[
T_{1/2}^{0\nu}(\text{exp}) = (\ln 2) N_A \frac{a}{A} \varepsilon Mt
\]

AMoRE project towards “zero”-background conditions:

- **Reduction of the background**
  - $\alpha$-background rejection with particle discrimination (heat and light measurement)
  - less than 0.001% of depleted $^{48}$Ca (natural abundance: 0.157%, $Q_{\beta\beta} = 4.271$ MeV)
  - low levels of internal and external backgrounds

- **High energy resolution with MMCs**

- **High detection efficiency with “source = detector” approach**

- **Detector mass**
  - enrichment of $^{100}$Mo above 95%
Above-ground measurements (with a wet dilution refrigerator)

- Energy spectrum obtained with a $^{232}$Th source at 10 mK
- FWHM energy resolution: 8.7 keV @ 2.6 MeV (Region of interest: 3.034 MeV)
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
- COSINE : dark matter search experiment
- AMoRE-Pilot (followed by AMoRE-I)

Lab for AMoRE-Pilot / AMoRE-I
Six $^{40}\text{Ca}^{100}\text{MoO}_4$ crystals (from 0.2kg to 0.4kg each, for a total of $\sim$1.8kg) Each crystal module has a heat detector and a light detector

Operating temperatures as low as 8 mK reached using a Cryogen Free Dilution Refrigerator (CFDR)
The pulse tube refrigerator (PTR) of the cryostat generates mechanical vibration which turns into heat noise and disturbs the baseline. Mass spring (MS) damper was installed in Run-4 to reduce the vibration noise.
Comparison of light/heat ratio between Run-2 and Run-4

Large improvement of the light/heat ratio thanks to the reduction of vibration noise in the photon channels.
Setup upgrade for Run-5

Spring suspended still (SSS) with Eddy current dampers
Designed by Leiden Spin Imaging (Netherlands)

6th detector module

4K Still

Muon veto system
Current status of AMoRE-Pilot

• Four Pilot runs have been completed from summer 2015 to late 2016 with five $^{40}\text{Ca}^{100}\text{MoO}_4$ crystals
• Operating temperatures 10 mK – 30 mK
• Currently, Run-5 is running with 6 crystals (total mass ~1.8 kg) and two vibration damping systems

Two vibration dampers were installed

12 detector channels
(6 heat detectors + 6 light detectors)
Detector performance in Run-5 (preliminary)

\[ \text{FP} = \frac{X_{\beta/\gamma} - X_{\alpha}}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_{\alpha}}} \]

\( \beta/\gamma \) and \( \alpha \) particles can be distinguished using pulse shape discrimination via pulse rise time or mean time.

\( \beta/\gamma \) and \( \alpha \) particles can also be distinguished using the light/heat ratio.

FWHM Energy resolution at 2.615 MeV: 10~11 keV

no muon veto applied
Energy resolution throughout the Pilot runs

The energy resolutions have been significantly improved throughout the different runs.

FWHM energy resolution @ 2.615 MeV
averaged over the detector modules

Run-1  
~43 keV

Run-2  
~22 keV

Run-4  
~13 keV

Run-5 (very preliminary)
10~11 keV

Improved design of crystal and wafer holders
Installation of Mass Spring (MS) damper
Installation of Spring Suspended Still (SSS) damper

Run-5 : Baseline energy resolutions (FWHM @ 0 MeV) are now about 3~5 keV
AMoRE phases and schedule

- AMoRE-I at Y2L (same cryostat as Pilot), with CaMoO₄ crystals + a few others (ZMO, LMO, …)
- AMoRE-II at a new, larger laboratory (ARF), X¹⁰⁰MoO₄ crystals (X = Li, Na, ⁴⁰Ca, Zn or other)

<table>
<thead>
<tr>
<th></th>
<th>Pilot</th>
<th>AMoRE-I</th>
<th>AMoRE-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>1.8 kg</td>
<td>~5 kg</td>
<td>~200 kg</td>
</tr>
<tr>
<td>Channels</td>
<td>12</td>
<td>36</td>
<td>1000</td>
</tr>
<tr>
<td>Background (counts/keV/kg/year)</td>
<td>0.01</td>
<td>0.001</td>
<td>0.0001</td>
</tr>
<tr>
<td>Sensitivity(T½/2) (year)</td>
<td>~10²⁴</td>
<td>~10²⁵</td>
<td>~5×10²⁶</td>
</tr>
<tr>
<td>Sensitivity(mₑₑ) (meV)</td>
<td>380-720</td>
<td>120-230</td>
<td>17-32</td>
</tr>
<tr>
<td>Location</td>
<td>Y2L</td>
<td>Y2L</td>
<td>ARF (new lab)</td>
</tr>
</tbody>
</table>
Site for Astroparticle Research Facility (ARF)

**Handeok Iron Mine, Jeongseon**

- ARF will be located at the Handeok mine
- Contract signed at the end of 2016
- Construction will start in late 2017

Plan for two experimental halls (total area ~2000 m²) under 1100 m below surface
Overview

- AMoRE searches for neutrinoless double beta decay ($0\nu\beta\beta$) of $^{100}$Mo using Mo-based scintillating crystals and MMC sensors
- Throughout the different AMoRE-Pilot runs, several setup upgrades allowed us to reduce the vibration noise, which improved the energy resolution and particle discrimination powers (PSD, light/heat)
- Run-5 is currently running with 6 crystals (total mass ~1.8 kg), two vibration damping systems, and a muon veto system
- After some more tests, data taking will be carried out for several months this year

Thank you