AMORE neutrino-less double beta decay experiment

AMoRE (Advanced Mo-based Rare process Experiment)

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Kyungpook National University
On Behalf of AMoRE collaboration

Physics of Fundamental Interactions
6-9 June 2017
Kabardino-Balkaria State University, Nalchik, Russia
History of AMoRE

1) 2002 : First idea and try to grow CaMoO4(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 $^{48\text{depl}}\text{Ca}^{100}\text{MoO}_4$ crystal
8) 2009 : AMORE collaboration formed (Including Baksan group)
9) 2010-11 : $^{48\text{depl}}\text{Ca}^{100}\text{MoO}_4$ 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 Science)
12) 2014 : Upgrade of Y2L lab for AMoRE-pilot and AMoRE-I
13) 2015 : AMoRE-pilot commissioning
Temperature dependence of CaMoO$_4$

From RT to 7K, light yield increase factor 6

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

- Light yield at cryogenic temp. : ~ 30,000 ph/MeV
- Highest light yield among Mo contained crystals.
($^{100}$Mo, $^{48}$Ca 0$\nu$ $\beta\beta$ decay, Dark matter search possible)
AMoRE collaboration

8 countries, 18 Institutes, ~90 collaborators

V. Alenkov et al., Technical Design Report for the AMoRE 0ν2β Decay Search Experiment, arXiv:1512.05957v1
AMoRE parameters

- **Crystals**: $^{48\text{depl}}\text{Ca}^{100}\text{MoO}_4$ or other $^{100}\text{Mo}$ based crystals
  - $^{100}\text{Mo}$ enriched: $> 95\%$, $^{48}\text{Ca}$ depleted: $< 0.001\%$
  - Grown at FOMOS in Russia (AMoRE-pilot, -I)
- Low temperature detector: 10 – 30 mK
- Energy resolution: $\sim 5$ keV @ 3MeV
- The AMoRE goal: Zero background up to 200kg mass

<table>
<thead>
<tr>
<th>Detector Crystal</th>
<th>Pilot</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Mass</td>
<td>$^{48\text{depl}}\text{Ca}^{100}\text{MoO}_4$</td>
<td>$^{48\text{depl}}\text{Ca}^{100}\text{MoO}_4$</td>
<td>New crystal?</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>$\sim 10^{24}$</td>
<td>$2.7 \times 10^{25}$</td>
<td>$1.1 \times 10^{27}$</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>ARF</td>
</tr>
</tbody>
</table>
**100Mo, 48deplCa materials**

Mo–100 isotope production:
The ECP (Electrochemical plant) Zelenogorsk, Krasnoyarsky kray, Siberia

- **100MoO₃ oxide**
  1) Enrichment: Mo–100 = 96.1%
  2) Impurities (the results from ICP MS measurements):
     - U < 0.07 ppb to < 0.2 ppb, Th < 0.1 ppb to < 0.7 ppb
     - $^{226}$Ra < 2.3 mBq/kg, $^{228}$Ac < 3.8 mBq/kg with Baksan HPGe measurement

- CUP has contract with ECP for 100Mo delivery: 120 kg for AMoRE–II and 20 kg was delivered

Ca–48 isotope production
The industrial separator SU20, Lesnoy, Sverdlovky region
27 kg of Ca–48depl ($^{48}$deplCaCO₃) is available now at EKP, Lesnoy Ca–48 < 0.001%

- Impurities: U ≤ 0.1 ppb, Th ≤ 0.1 ppb, Sr = 1 ppm, Ba = 1 ppm
  - $^{226}$Ra = 51 mBq/kg $^{228}$Ac($^{228}$Th) = 1 mBq/kg with Baksan HPGe measurement
Internal background levels from Y2L@RT

β–α decay in $^{238}\text{U}$ (164 ms)
$^{214}\text{Bi}$ (Q-value : 3.27-MeV) → $^{214}\text{Po}$ (Q-value : 7.83-MeV)

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

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

<table>
<thead>
<tr>
<th>Element</th>
<th>U-238 chain</th>
<th>U-235 chain</th>
<th>Th-232 chain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activity (uB/kg)</td>
<td></td>
<td></td>
<td></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>

* 100 uBq/kg for U-238, 50 uBq/kg for Th232 decay chain for AMoRE-I
MMC (Metallic Magnetic Calorimeter) for LTD

S.J. Lee et al., Astroparticle Physics 34 (2011) 732–737

paramagnetic sensor:

Au:Er

Phonon collector film on bottom surface

Light detector 2 inch Ge wafer + MMC

Signal

Background

E_{phonons}

E_{light/PSD}
MMC cryogenic technique for AMoRE


Overground test at KRISS @ 10 mK
Wet DR

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>511</th>
<th>1461</th>
<th>2615</th>
</tr>
</thead>
<tbody>
<tr>
<td>FWHM (keV)</td>
<td>4.3</td>
<td>5.7</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Excellent $\alpha$/e separation by both Light and PSD
AMoRE-pilot: five $^{40}\text{Ca}^{100}\text{MoO}_4$ crystals of 1.5kg (SB28, S35, SS68, SE01, SB29); 5 phonon detectors + 6 photon detectors
AMoRE-pilot Run4 results, Run5 is running now

FWHM at 2.6 MeV: 10.9 – 13.6 keV
### AMoRE-I: 1.5+3.4 kg CMO + 1.8kg LMO or NMO

<table>
<thead>
<tr>
<th>ID#</th>
<th>U-235 (µBq/kg)</th>
<th>U-238 (µBq/kg)</th>
<th>Th-232 (µBq/kg)</th>
<th>Alpha (µBq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE#1</td>
<td>60 ± 8</td>
<td>40 ± 6</td>
<td>50 ± 6</td>
<td>N/A</td>
</tr>
<tr>
<td>SE#2</td>
<td>90 ± 10</td>
<td>35 ± 3</td>
<td>&lt; 100</td>
<td>N/A</td>
</tr>
<tr>
<td>SE#3</td>
<td>30 ± 6</td>
<td>6 ± 3</td>
<td>30 ± 6</td>
<td>28,000</td>
</tr>
<tr>
<td>SE#4</td>
<td>30 ± 6</td>
<td>10 ± 3</td>
<td>40 ± 6</td>
<td>3,200</td>
</tr>
<tr>
<td>SE#5</td>
<td>40 ± 6</td>
<td>10 ± 3</td>
<td>10 ± 3</td>
<td>N/A</td>
</tr>
<tr>
<td>SE#6</td>
<td>35 ± 6</td>
<td>100 ± 10</td>
<td>70 ± 10</td>
<td>N/A</td>
</tr>
<tr>
<td>SE#7</td>
<td>80 ± 10</td>
<td>30 ± 5</td>
<td>65 ± 10</td>
<td>N/A</td>
</tr>
<tr>
<td>SE#8</td>
<td>40 ± 6</td>
<td>20 ± 5</td>
<td>40 ± 6</td>
<td>N/A</td>
</tr>
<tr>
<td>SE#9</td>
<td>50 ± 6</td>
<td>&lt; 11</td>
<td>50 ± 6</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Illustrated by HJ Lee
GEANT4 simulation for AMoRE-I

Goal of AMoRE-I background level: $2 \times 10^{-3}$ counts/keV/kg/yr

- Stainless steel
- G10 fiberglass
- Cu Plate
- Inner Lead plate
- SC Lead Shield
- Copper Frame
- Vikuiti
- CMO Internal
- Random Coincidence
- Total

Background (count/keV/kg/yr)
## Crystal R&D for AMoRE-II (200 kg)

<table>
<thead>
<tr>
<th>Name</th>
<th>Chem. Form</th>
<th>Producers</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMO</td>
<td>CaMoO₄</td>
<td>FOMOS, NIIC, CUP, SICCAS</td>
</tr>
<tr>
<td>ZMO</td>
<td>ZnMoO₄</td>
<td>ISM, NIIC</td>
</tr>
<tr>
<td>LMO</td>
<td>Li₂MoO₄</td>
<td>KNU, ISM, CUP, CARAT, NIIC</td>
</tr>
<tr>
<td>PMO</td>
<td>PbMoO₄</td>
<td>NIIC</td>
</tr>
<tr>
<td>CsMO</td>
<td>Cs₂MoO₇</td>
<td>KNU</td>
</tr>
<tr>
<td>CsMO</td>
<td>Cs₂MoO₄</td>
<td>KNU</td>
</tr>
<tr>
<td>NaMO</td>
<td>Na₂Mo₂O₇</td>
<td>KNU, NIIC, FOMOS, CARAT</td>
</tr>
</tbody>
</table>

*NIIC: Nikolaev Institute of Inorganic Chemistry, SB RAS*
AMoRE summary & prospect

• Large volume of low background $^{48\text{depl}}\text{Ca}^{100}\text{MoO}_4$ (CMO) have been developed.
• Cryogenic MMC technique with CMO is successful.
• We are running AMoRE-pilot with 1.5kg of CMO.
• CMOs for AMoRE-I are delivered and will start beginning of 2018.
• We are working on R&D of chemical purification & new crystal R&D for AMoRE-II
• Fully funded up to AMoRE-II.

- Nuclear Matrix Element: QRPA (Faessler et al., 2012)
- AMoRE-I: 5 kg and 5 years
- AMoRE-II: 200 kg and 5 years
- It was assumed as “zero-background”.
Thank you
Shielding structure of AMoRE-pilot & AMoRE-I

Cryostat for AMoRE

15cm low background Pb

10cm ultra-low background Pb

muon shielding structure
AMoRE Experimental sensitivity

For sizeable background case;

\[ T^{0\nu}_{1/2} (\text{exp}) = (\ln 2) N_A \frac{a}{A} \varepsilon \sqrt{\frac{M t}{b \Delta E}} \]

- Isotopic Abundance
- Detection Efficiency
- Detector Mass
- Measurement time
- Energy Resolution
- Sensitivity to half-life of 0νββ
- Atomic mass
- Background rate

For “zero” background case;

# of background events \~ O(1)

\[ T^0_{1/2} (\text{exp}) = (\log 2) N_a \frac{a}{A} \frac{M T}{n_{CL}} \]

For AMoRE goal:

- AMoRE-I 5kg
- AMoRE-II 200kg

Graph shows the relationship between mass-time product and half-life for zero and non-zero backgrounds.
Yangyang (Y2L) Underground Laboratory

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

COSINE (Dark Matter Search)
AMoRE (Double Beta Decay Experiment)
Ultra-low background crystals for AMoRE-II

Ultra-low background powder R&D is difficult and need quick feedback
(Purification and measurement of 10 uBq/kg U-238, Th-232 & total radioactivity of alpha <1mBq)

- K1 chemical & Clean room
- KT1 & underground lab
- K1 lab.
- Y2L Underground lab
- Baksan lab.
- Company (K1 lab.)

**Powder purification**
- ICP-MS, HPGe, LSC
  - Yes
  - No

**Crystal growing**
- Scintillation (Phonon)
  - Yes
  - No

**Crystal growing optimization**
(Size and quality)

=> See talk by Dr. H.K.Park instrumentation session
## Major backgrounds from radionuclides for AMoRE–II (GEANT4)

<table>
<thead>
<tr>
<th>Background source</th>
<th>Activity [μBq/kg]</th>
<th>$B_g$ [$10^{-4}$ cnt/keV/kg/yr]</th>
<th>$B_g$ reduced by PSD [$10^{-4}$ cnt/keV/kg/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tl-208, internal</td>
<td>10 ($^{232}$Th)</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>Tl-208, in Cu</td>
<td>16 ($^{232}$Th)</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>BiPo-214, internal</td>
<td>10</td>
<td>0.11 1)</td>
<td></td>
</tr>
<tr>
<td>BiPo-214, in Cu</td>
<td>60</td>
<td>1.8 1) 2)</td>
<td></td>
</tr>
<tr>
<td>BiPo-212, internal</td>
<td>10 ($^{232}$Th)</td>
<td>0.08 1)</td>
<td></td>
</tr>
<tr>
<td>BiPo-212, in Cu</td>
<td>16 ($^{232}$Th)</td>
<td>0.36 1) 2)</td>
<td></td>
</tr>
<tr>
<td>Y-88, internal</td>
<td>20</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>$\Sigma$ int. (w/o $2\beta2\nu$)</td>
<td></td>
<td>0.74</td>
<td>$\leq 0.57$</td>
</tr>
<tr>
<td>$\Sigma$ Cu</td>
<td></td>
<td>2.40</td>
<td>$\leq 0.44$</td>
</tr>
<tr>
<td>Rand. coinc. from $2\beta2\nu$ decays of $^{100}$Mo</td>
<td>$8.7 \times 10^3$ (single evts.)</td>
<td>$3.1^{3)}$</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>6.2</strong></td>
<td>$\leq 2.2$</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 $\Delta t=0.5$ ms

Muon background: $\sim 1.4e^{-4}$ counts/keV/kg/yr @Y2L
$4\pi$ CsI(Tl) active setup with Pb shielding at Y2L

1) 2ν EC+ $\beta^+$, $\beta^+\beta^+$ study with 2 back to back $\gamma$ tagging
   (1) Sr–84 : SrCl$_2$ (4.6x10$^{17}$ yr by 90%CL)
   (2) Mo–92 : CaMoO$_4$ (2.3x10$^{20}$ yr NIMA 654, 157 (2011))

2) CMO internal background study with active veto
Considerable beta decays ($^{238}$U)

$^{234}$Th $Q_\beta$: 199 keV (78.0 %)
$^{234}$Pa $Q_\beta$: 2269 keV (97.6 %)

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

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

$^{210}$Bi $Q_\beta$: 1162 keV (100 %)
Considerable beta decays ($^{232}\text{Th}$)

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

- Not serious for small $Q$ value (44.8 keV)
- $^{211}\text{Pb}$ $Q_\beta$: 1367 keV (91.3%)
- 160 keV (6.3%)
- $^{207}\text{Tl}$ $Q_\beta$: 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:  \[ \text{Rn-220 (55.6 s)} \rightarrow \text{Po-216 (0.145 s)} \rightarrow \text{Pb-212} \]
1) ICP/MS $^{238}$U, $^{235}$U, & $^{232}$Th ~ppt level sensitivity
2) HPGe at Y2L (U, Th decay chains with $\gamma$, ~mBq/kg level)
3) $4\pi$ setup at Y2L vs Cryogenic measurement.

300K vs 20mK
Easy to measure vs Need time for setup
Limits on $\alpha$ tagging vs $\alpha$ spectroscopy
Similar sensitivity of $^{238}$U & $^{232}$Th decay chain (<10 uBq/kg)

Energy spectrum
Internal alpha background of SB28

U–238 decay chain:
Consistent with $4\pi$ setup measurement
(80 uBq/kg)

678 h measurement @ 20 mK

- $^{238}\text{U}$ 4270 keV
  $0.98 \pm 0.10$ mBq/kg

- $^{210}\text{Po}$ 5407 keV
  $7.3 \pm 0.7$ mBq/kg

- $^{223}\text{Ra}$ 5979 keV
  $0.30 \pm 0.06$ mBq/kg

- $^{211}\text{Bi}$ 6750 keV
  $0.47 \pm 0.06$ mBq/kg

- $^{232}\text{Th}$ < 2 µBq/kg

678 h measurement @ 20 mK

- $^{222}\text{Rn}$ 5590 keV
  $65 \pm 45$ µBq/kg
Plan for zero background for AMoRE

1. Background study
2. Enriched CMO
3. PSD, good $\Delta E$ by MMC

AMoRE-pilot (1.5kg, CMO)

- BG<0.01 -> 0.001
  - Yes
  - AMoRE-I (~5kg, CMO)
    - BG<0.001 -> 0.0001
      - Yes
      - AMoRE-II (~200kg)
        - BG<0.001
          - No

Commissioning

Technology developed (NeoChem + FOMOS)

Y2L

Technology will be be
Developed by us

Handuk mine
CMO?

- Background reduction R&D with purification will be presented by Dr. H.K. Park in instrumentation section
Chemical purification facility

- Deep purification of CaCo3 and MoO3 (<50uBq/kg for U, Th chain)
- Efficient CaMoO4 recovery
- People: 2 staff, 1 postdoc, 2 students, 1 technician (+ Russia, Ukraine collaboration)

=> See talk by Dr. H.K.Park (Team leader)
Low background Crystal growing facility

- We have one Czochalski, 2 Kyropoulous and 1 Bridgman crystal growing equipment at KT 1 lab. (1 more Czochalski this year)

Main goal:
1) CaMoO4 crystal growing R&D for AMoRE-200
2) Other DB or DM crystal R&D

Currently we are focused on CaMoO4 crystal Growth
Dark matter sensitivity of CaMoO$_4$ cryogenic experiment: AMoRE-DARK (KIMS-LT)
Conclusions (SWAPS2014 by Andrea Giuliani)

- **LUCIFER** – difficulties larger than expected in producing ZnSe crystals with the desired features in a reproducible way, complicated by geopolitical issues – now most of the technical problems have been solved - enriched crystal production starting from fall 2014 – about 36 crystals containing 10 kg of $^{82}$Se (irrecoverable loss 35%) in Gran Sasso

- **LUMINEU** – excellent radiopurity and performance of the ZnMoO$_4$ crystals (natural and enriched) – irrecoverable loss negligible – pilot experiment with 1 kg of enriched Mo in Modane within 2015 – demonstrator with 10 kg of enriched Mo in Modane or Gran Sasso in 2016 ⇒ MoU INFN – IN2P3 – ITEP

- **AMoRE**: excellent $^{40}$Ca$^{100}$MoO$_4$ detector performance – aggressive schedule foreseeing a 10 kg experiment at a 2 year scale and 200 kg at a 5 year scale

The scintillating bolometer technology has excellent prospects to reach zero background at the ton x year scale with high energy resolution and efficiency in more than one isotope