Status of the AMORE double beta decay experiment

AMoRE (Advanced Mo-based Rare process Experiment)

HongJoo Kim
Kyungpook National University
On Behalf of AMoRE collaboration

AMoRE Experimental sensitivity

For sizeable background case:

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

For “zero” background case; # of background events ~ O(1) <- AMoRE goal

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

DBU: counts/ (keV kg year)
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 $^{48}\text{depl}Ca^{100}MoO_4$ crystal
8) 2009 : AMORE collaboration formed
9) 2010-11 : $^{48}\text{depl}Ca^{100}MoO_4$ 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
AMoRE collaboration

V. Alenkov et al., Technical Design Report for the AMoRE $0\nu2\beta$ Decay Search Experiment, arXiv:1512.05957v1

8 countries, 18 institutions, ~90 collaborators
Yangyang(Y2L) Underground Laboratory

Korea Hydro & Nuclear Power Co.
Yangyang Pumped Storage Power Plant

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

KIMS (Dark Matter Search)
AMoRE (Double Beta Decay Experiment)
**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 0ν ββ decay, Dark matter search possible)*
Mo–100 isotope production:
The ECP (Electrochemical plant)
Zelenogorsk, Krasnoyarsky kray, Siberia

- $^{100}$MoO$_3$ oxide with mass of 2.5 kg
  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

- Current capacity is 25–30 kg per year.
  CUP has contract with ECP for $^{100}$Mo delivery: 120 kg for AMoRE–II

Ca–48 isotope production
The industrial separator SU20, Lesnoy, Sverdlovsky region
27 kg of Ca–48depl ($^{48}$deplCaCO$_3$) is available now at EKP, Lesnoy
Ca–48 < 0.001%
**Internal background levels from Y2L@RT**

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

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

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

<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>Po-214</td>
<td>60±8</td>
<td>200±14</td>
<td>30±7</td>
</tr>
<tr>
<td>SS68</td>
<td>200±14</td>
<td>700±26</td>
<td>80±9</td>
</tr>
<tr>
<td>NSB29</td>
<td>4400±66</td>
<td>1200±35</td>
<td>500±22</td>
</tr>
<tr>
<td>S35</td>
<td>80±9</td>
<td>N/A</td>
<td>70±8</td>
</tr>
<tr>
<td>SB28</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 (Metallc Magnetic Calorimeter) for LTD

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

paramagnetic sensor: Au:Er

$E_{\text{phonons}}$, $E_{\text{light/PSD}}$

$^{40}\text{Ca}^{160}\text{MoO}_4$

Mass: 200 g

Phonon collector film on bottom surface

Light detector 2 inch Ge wafer + MMC
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
Shielding structure of AMoRE-pilot & AMoRE-I
Preliminary results on AMoRE-pilot commissioning run

FWHM energy resolution at 2.6 MeV

<table>
<thead>
<tr>
<th>Crystals</th>
<th>AMoRE-Pilot run-1</th>
<th>AMoRE-Pilot run-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB28</td>
<td>36.8 keV</td>
<td>25.0 keV</td>
</tr>
<tr>
<td>S35</td>
<td>N/A</td>
<td>16.3 keV</td>
</tr>
<tr>
<td>SS68</td>
<td>52.6 keV</td>
<td>24.2 keV</td>
</tr>
<tr>
<td>SE01</td>
<td>39.7 keV</td>
<td>24.6 keV</td>
</tr>
<tr>
<td>NSB29</td>
<td>42.6 keV</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Background and vibration noise need to be improved
Goal of 0.001 DBU for AMoRE-I can be achieved
Zero background with 5kg of CMO, 3 years
### Major backgrounds from radionuclides for AMoRE-II (GEANT4)

<table>
<thead>
<tr>
<th>Background source</th>
<th>Activity [µBq/kg]</th>
<th>Bg $[10^{-4} \text{ cnt/keV/kg/yr}]$</th>
<th>Bg reduced by PSD $[10^{-4} \text{ cnt/keV/kg/yr}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tl-208, internal</td>
<td>10 ($^{232}\text{Th}$)</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>Tl-208, in Cu</td>
<td>16 ($^{232}\text{Th}$)</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>BiPo-214, internal</td>
<td>10</td>
<td>0.11 $^1)$</td>
<td>$\leq 0.01$</td>
</tr>
<tr>
<td>BiPo-214, in Cu</td>
<td>60</td>
<td>1.8 $^1)^2)$</td>
<td>$\leq 0.18$</td>
</tr>
<tr>
<td>BiPo-212, internal</td>
<td>10 ($^{232}\text{Th}$)</td>
<td>0.08 $^1)$</td>
<td>$\leq 0.01$</td>
</tr>
<tr>
<td>BiPo-212, in Cu</td>
<td>16 ($^{232}\text{Th}$)</td>
<td>0.36 $^1)^2)$</td>
<td>$\leq 0.04$</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>$\leq 0.57$</td>
</tr>
<tr>
<td>Σ Cu</td>
<td></td>
<td>2.40</td>
<td>$\leq 0.44$</td>
</tr>
<tr>
<td>Rand. coinc. from 2β2ν decays of $^{100}\text{Mo}$</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>6.2</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 $\Delta t=0.5 \text{ ms}$  

Muon background: $\sim 1.4 e^{-4} \text{ counts/keV/kg/yr @Y2L}$
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
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 started AMoRE-pilot with 1.5kg of CMO.
- CMOs for AMoRE-I are under delivery and will be tested by the end of this year.
- We are working on R&D of chemical purification & new crystal R&D for AMoRE-II
- Fully funded up to AMoRE-II.

<table>
<thead>
<tr>
<th>Detector Crystal</th>
<th>Pilot</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Crystal</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>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>$\sim 10^{24}$</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>Handuk mine</td>
</tr>
</tbody>
</table>
Thank you
The main source of vibration noise is the pulse tube refrigerator of the CF-DR. We are working on noise reduction such as new damping system.
CaMoO$_4$ crystal development


IEEE/TNS 2008
Crystal growing (Double crystalization)

SB28, SB29, SS61

natMoO3 0.01 gr
4π CsI(Tl) active setup with Pb shielding at Y2L

1) $2\nu$ EC+ $\beta^+$, $\beta^+\beta^+$ study with 2 back to back $\gamma$ tagging
   (1) Sr–84 : SrCl$_2$ (4.6x$10^{17}$ yr by 90%CL)
   (2) Mo–92 : CaMoO$_4$ (2.3x$10^{20}$ 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 %)

$^{234}$U $Q_\beta$: 5600 keV (89.6 %)

$^{238}$U $Q_\beta$: 6686 keV (62.0 %)

$^{232}$Th $Q_\beta$: 1287 keV (90.5 %)

$^{230}$Th $Q_\beta$: 1610 keV (92.1 %)

$^{214}$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 ($^{232}$Th)

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

- Not serious for small Q value (44.8 keV)
- $^{211}$Pb $Q_\beta$: 1367 keV (91.3%)
- 160 keV (6.3%)
- $^{207}$Tl $Q_\beta$: 1418 keV (99.7%)

Diagram showing the decay series of $^{235}$U.
Time-Amplitude analysis method

U-235 chain:  Rn-219 (3.965 s) → Po-215 (1.78 ms) → Pb-211

U-238 chain:  Bi-214 (20 m) → Po-214 (164 us) → Pb-210

Th-232 chain: Rn-220 (55.6 s) → Po-216 (0.145 s) → Pb-212
1) ICP/MS $^{238}\text{U}$, $^{235}\text{U}$, & $^{232}\text{Th}$ ~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 $\alpha$ spectroscopy
Similar sensitivity of $^{238}\text{U}$ & $^{232}\text{Th}$ decay chain (<10 uBq/kg)

CMO internal background measurement
Internal alpha background of SB28

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

678 h measurement @ 20 mK

 Counts/(5 keV)

Energy$_{ae}$ (keV)

Counts/(5 keV)

Energy$_{ae}$ (keV)

$^{238}$U 4270 keV

$^{216}$Po 5407 keV

$^{233}$Th < 2 µBq/kg

$^{223}$Ra 5979 keV

$^{211}$Bi 6750 keV

$^{222}$Rn 5500 keV

$^{222}$Rn 5590 keV

65 ± 45 µBq/kg

0.47 ± 0.06 mBq/kg

0.30 ± 0.06 mBq/kg

0.98 ± 0.10 mBq/kg

7.3 ± 0.7 mBq/kg
Plan for zero background for AMoRE

1. Background study
2. Enriched CMO
3. PSD, good ΔE by MMC

Done!

AMoRE-pilot (1.5kg, CMO)
- BG<0.01->0.001
  - No
  - Yes

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

AMoRE-II (~200kg)

• 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)
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
1. **Input**: ±10 V, 1 Mohm termination
2. 16 ch/module, stand alone
3. Variable attenuator
4. 18 bit, 2 Msa/s
5. 4 Gbyte DDR3 DRAM buffer
6. Digital processing and trigger
7. Continuous sampling possible
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 $^{82}\text{Se}$ (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 $^{40}\text{Ca}^{100}\text{MoO}_4$ 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