CANDLES Experiment
Current Status and Future Plan

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for the CANDLES Collaboration
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

$2\nu\beta\beta$ decay

$0\nu\beta\beta$ decay

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

- process beyond Standard Model
- Lepton number violation
- Majorana particle
- none-zero neutrino mass
- not observed yet
- predicted lifetime: $T_{1/2} > 10^{26}$ year

Detection Principle

- $2\nu\beta\beta$ decay target: $^{76}$Ge, $^{136}$Xe, …, $^{48}$Ca etc
- detect sum energy of two $\beta$ rays
  $2\nu\beta\beta$: spectrum is continuous up to $Q_{\beta\beta}$ value
  $0\nu\beta\beta$: a single peak at $Q_{\beta\beta}$ value
- reduce background
- improve energy resolution to separate $2\nu\beta\beta$ and $0\nu\beta\beta$
CANDLES Experiment

Choosing a $2\nu\beta\beta$ source isotope

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

- $^{48}\text{Ca}$ isotope
  - largest $Q_{\beta\beta}$ value in all the candidates
  - less environment radiation, e.g. $^{208}\text{Tl}$
  - potential to achieve BG free environment
  - large phase space factor that the decay rate is faster than other isotopes
- natural abundance is low
- some enrichment methods are under development

CANDLES’s idea

- use CaF$_2$ crystal scintillator and PMT to make a calorimeter
- develop a $4\pi$ active veto with liquid scintillator (LS) to reduce external gamma background by PSD (p.5)
Detector Structure

CANDLES Detector

- CaF$_2$ crystals (96, 300kg)
- LS
- light guide (R$_{Al}$$>$93%)
- PMTs (62)
- pure water
- tank (Φ:3m, H:4m)
- boron shield (5mm)
- lead shield (10cm)

Crystal Array

PMT and Light Guide

(n,γ) Shielding
Background Reduction

- DAQ records waveform and time information => Analysis calculates position, energy, Particle ID information of $\gamma/\beta$ and $\alpha$ to reduce BG

**LS cut**
- external $\gamma$ BG (LS[10ns]+CaF$_2$[1\,\mu s])
- $\beta\beta$ signal (CaF$_2$ [1\,\mu s]only)

**Position cut**
- reduce multi-hit event

**PSD cut**
- reduce Bi-Po event

**Passive B, Pb shielding**
- Data in 2014 (56.9 days)
- After cooling (28.1 days)
- After shielding (21.5 days)

3 - 4 MeV was reduced due to changing O-ring and Al sleeve.

*(n,\gamma) with environmental neutron was reduced by the shield!! ~1/100*
27 clean crystals (Th contamination < 10\(\mu\)Bq/kg) from all 96 crystals are selected. The result is compared with the one of all crystals.
Sensitivity of CANDLES

- Sensitivity for 0νββ in 1 year is calculated from expected backgrounds
  - data set: 21.5 days after shielding
  - Qββ region: 4170 ~ 4480 keV (Qββ -1σ +2σ)

<table>
<thead>
<tr>
<th></th>
<th>without multi-hit cut</th>
<th>with multi-hit cut</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>27 crystals</td>
<td>all crystals</td>
</tr>
<tr>
<td>events at Qββ region</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>expected 208Tl</td>
<td>0.22</td>
<td>2.2</td>
</tr>
<tr>
<td>expected (n, γ)</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>detection efficiency</td>
<td>46%</td>
<td></td>
</tr>
<tr>
<td>sensitivity for 1 year</td>
<td>0.7×10^{23}yr</td>
<td>1.0×10^{23}yr</td>
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Sensitivity of CANDLES experiment for 0νββ using 1 year data is 0.5 ~ 1.0×10^{23} year
The key to challenge $0\nu\beta\beta$ decay up to higher sensitivity is the enrichment of $^{48}$Ca isotope

- natural abundance 0.187\% $\Rightarrow$ Max $\times500$ enrichment factor is possible
- four enrichment methods are being developed at below facilities
  - crown ether resin + chromatography (Osaka Univ, TIT, …)
  - crown ether + micro reactor (Osaka Sangyo Univ)
  - laser separation (Fukui Univ)
  - multi-channel counter current electrophoresis (Osaka Univ)

The ultimate BG will be $2\nu\beta\beta$ decay after enrichment

- apply high energy resolution (0.5\%FWHM) technology to CANDLES
  - bolometer method
    - phonon statistics, better than photon statistics
  - bolometer experiment group
    - CUORE: 0.2\% ($^{130}$Te)
    - AMoRE ($^{100}$Mo)
    - CRESST (dark matter)
Next Generation: Scintillating Bolometer

SB overview

- Heat detector (CaF$_2$) + Light detector (Ge)
- simultaneously measuring heat and light by neutron transmutation doped germanium (NTD-Ge) sensor
- heat detector => CaF$_2$ crystal: $20 \times 20 \times 20$ mm$^3$
- light detector => Ge wafer: $22 \text{mm}\Phi \times 200\mu\text{m}$
- heat detector => energy calculation
- light detector => background reduction

- Quenching effect used for BG reduction
  - light outputs of same energy $\gamma/\beta$ and $\alpha$ are different

Future prospect is good, but at first 10mK
Development Status

Dilution Refrigerator

- Dilution refrigerator made by Tokyo Univ
- developed for dark matter research, so customized to low BG measurement
- we apply it to 0νββ decay search

- Cooling system reconstruction
- have made a new circulation pipeline for costly ³He without any leakage
- have achieved 4K, 1K and will challenge 10mK in April this year

CaF₂ Detector modules

- HPGe wafer
- CaF₂ crystal
- spring pin
CANDLES is a project to search for neutrinoless double beta decay using $^{48}\text{Ca}$ isotope in 300 kg CaF$_2$ scintillator, running at Kamioka underground laboratory.

The sensitivity of CANDLES detector is $0.5 \sim 1.0 \times 10^{23}$ year with 1 year data.

The next generation detector “Scintillating Bolometer” with high energy resolution is being developed.

Thank you