Search for Neutrino-less Double Beta Decay of $^{48}\text{Ca}$

- CANDLES -

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CANDLES Collaboration
Outline

- Double beta decay
  - Double beta decay of $^{48}\text{Ca}$
- CANDLES System
  - $\text{CaF}_2$ (pure) scintillators + Liquid scintillator
  - CANDLES III system at Kamioka underground lab.
    - Expected backgrounds
    - Shielding system for background reduction
- Further improvement
- Summary
Neutrino-less double beta decay ($0\nu\beta\beta$)
- Process beyond the Standard Model
- Non-zero neutrino mass
- Lepton number violation
- Predicted lifetime: $T_{1/2} > 10^{25}$ years

Why $^{48}$Ca?
- Higher $Q_{\beta\beta}$-value (4.27 MeV) . . .
  - Low background because $Q_{\beta\beta}$-value is higher than BG
  - $E_{\max} = 2.6$ MeV ($^{208}$Tl, $\gamma$-ray), 3.3 MeV ($^{214}$Bi, $\beta$-ray)

Double beta decay of $^{48}$Ca by using CaF$_2$ scintillators
  - We installed the CANDLES III system at Kamioka Lab.
CANDLES III

CANDLES at Kamioka underground laboratory

CaF$_2$ scintillator (CaF$_2$(pure))
- 305 kg (96 modules $\times$ 3.2 kg)
- $\tau \sim 1\mu$s

Liquid scintillator (LS)
- $4\pi$ active shield
- Volume: $2m^3$
- $\tau \sim$ a few ten nsec

Large photomultiplier tube
- 13inch PMT $\times$ 48
- 20inch PMT $\times$ 14

Light pipe system
- Guide scintillation light to PMTs
- Light collection effi.: $\times 1.8$

Active Shielding Technique by FADC
- Different time constants
  - CaF$_2$(pure): $\sim 1\mu$s
  - Liquid scintillator: a few 10 nsec
CANDLES III

Main detector
CaF$_2$ Scintillators (305 kg)

Liquid Scintillator Tank ($2 m^3$)

CaF$_2$ scintillator (CaF$_2$(pure))
305 kg (96 modules × 3.2 kg)
$\tau \sim 1 \mu$sec

Liquid scintillator (LS)
4 $\pi$ active shield
Volume: $2 m^3$
$\tau \sim$ a few ten nsec

Large photomultiplier tube
13inch PMT × 48
20inch PMT × 14

Light pipe system
Guide scintillation light to PMTs
Light collection effi. : $\times 1.8$

Active Shielding Technique by FADC
Different time constants
CaF$_2$(pure) : $\sim 1 \mu$sec
Liquid scintillator : a few 10 nsec

13inch and 20inch PMTs with light pipes
Backgrounds in CANDLES

2νββ Events: negligible for CANDLES III
Possible to reduce by good energy resolution (∼4% at 4.27MeV)

Radioactive Contaminations in CaF₂ Crystals

Pile-up Events

Th-Chain

$^{232}$Th $\rightarrow$ $^{212}$Bi $\rightarrow$ $^{212}$Po $\rightarrow$ $^{208}$Pb

$T_{1/2} = 0.3 \mu sec$

$Q_{\beta} = 5.0$MeV

$64\%$

$36\%$

$E_{max} = 5.3$MeV (Th-chain)
$5.9$MeV (U-chain)

Pile-up because of $\tau$ of CaF₂ signal = 1μsec

$^{208}$Tl Event

Th-Chain

$^{232}$Th $\rightarrow$ $^{212}$Bi $\rightarrow$ $^{208}$Tl $\rightarrow$ $^{208}$Pb

$T_{1/2} = 3.0$min

$Q_{\alpha} = 5.0$MeV

$E_{max} = 5.0$MeV

Identification of the "pile-up" shape
Particle identification between $\alpha$ and $\gamma$ rays

γ-rays from neutron capture

High energy $\gamma$-rays from neutron capture on Fe, Ni, Si within stainless steel (main tank), rock in the mine.

To reject these BG events:

Pile-up event: identification of the "pile-up" shape
Particle identification between $\alpha$ and $\gamma$ rays

$^{208}$Tl event: identification of prompt $^{212}$Bi (by $\alpha$-$\gamma$ rays PI)

High energy $\gamma$-ray: the shielding system

$^{212}$Bi +$\alpha$ $\rightarrow$ prompt $^{212}$Bi (by $\alpha$-$\gamma$ rays PI)
Rejection of pile-up events

$^{212}\text{Bi} \rightarrow ^{212}\text{Po}$ decay

Th-Chain

$^{232}\text{Th}$

$T_{1/2} = 1.1 \times 10^{10}\text{year}$

Pile-up

$^{212}\text{Bi}$

$Q_{\beta} = 2.2\text{MeV}$

operator

$\alpha$

$^{212}\text{Po}$

$Q_{\alpha} = 7.8\text{MeV}$

delayed

$T_{1/2} = 0.3\mu\text{sec}$

Typical pulse shape of pile-up events

Prompt $\beta$

Delayed $\alpha$

Decay Constant of $\text{CaF}_2$(pure):

$1\mu\text{sec}$

with small $\Delta \tau$

Sum-up signal of 62 PMT

We can identify the pile-up events.

current rejection efficiency $> 95\%$
Pulse Shape discrimination between α and γ-rays

Particle identification between α and γ rays

Event distribution by using “shape indicator”

α-ray : ${}^{214}\text{Po}$ 7.6MeV ($E_e=2.6\text{MeV}$)
γ-ray : ${}^{208}\text{TI}$ 2.6MeV

ref: Shape Indicator (PRC67(2003) 014310)

We applied not only “shape indicator” but also “χ² fitting” for PI.

97 % rejection efficiency at 2.6MeV (γ ray: 3%)
→ 97% (β+α) at 4.27MeV (γ: 3%)

- for rejection of β−α pile-up events
- for identification of proceeding $^{212}\text{Bi}$ event
Background from neutron capture

Neutron source run ($^{252}$Cf)
- 1 hour of source run = 1 year of physics run
- Energy spectrum: well reproduced by MC of neutron capture γ-ray.
- ($n,γ$) BG in 0νββ window is evaluated from MC spectrum.
- ($n,γ$) BG: 3.4±0.4(stat.) evt/26 crystals/60 days (Run data, 3±1 evt)
- Currently, most serious background component in CANDLES

Loose event selection cut!
Normal BG (88 days)

\[
\chi^2 / \text{ndf} = 256.4 / 62
\]
\[
N_{\text{rock}} = 3150 \pm 225 \text{ evt}
\]
\[
N_{\text{ SUS}} = 6938 \pm 186 \text{ evt}
\]
\[
N_{\overline{\text{C}} \gamma} = 3053 \pm 116 \text{ evt}
\]

\[
\chi^2 / \text{ndf} = 54.8 / 39
\]
\[
N_{\text{rock}} = 616 \pm 49 \text{ evt}
\]
\[
N_{\text{ SUS}} = 273 \pm 46 \text{ evt}
\]

Fit range
Shielding system

**Toward “Background Free Measurement”**

Schematic view of the shielding system

- **CANDLES tank** (stainless steel)
- **Pb** (γ-ray shield)
- **B sheet** (neutron shield)

**Shielding system**: BG ~1/100

**Pb bricks**
- 7 ~ 12 cm in thickness
- Reduce (n,γ) BG from rock.
- BG γ-rays from rock decrease by factor of ~1/120

**B sheet**
- B₄C loaded silicone rubber sheet
  ~ 5 mm in thickness
- Reduce thermal neutron
- N-capture events decrease by factor of ~1/30

**Construction of the shielding system**

Shieldings inside/outside the tank

BG rate: ~1/100
CANDLES shield system

Construction was finished in February 2016

Complete shield system

Main tank

Construction under way

B sheet

Upper view

without the shield

BG Reduction factor

$^{252}\text{Cf}$ Run: reduction test of fast neutron
Source position: near the rock
Correction of live time, $^{252}\text{Cf}$ activity ($T_{1/2}=2.7$ year)

Reduction factor: $\sim 2$ order of magnitude (near the rock)

Rough analysis

Q$_{\beta\beta}$ region

High energy region

Preliminary

Before shield construction

After shield construction
Energy spectra

BG spectra and simulation:
before(60days), after(8.6days) data

Before shield construction
26 crystals

After shield construction
27 crystals

γ-ray background: reduced by the shielding system

*208Tl events will be reduced by improved analyses.

Preliminary 2016, INPC2016
Further improvement

CANDLES III upgrade

- Shielding system: Installation in 2016
- Cooling system: Already installed and operation started
- CaF₂ light output increases with low temperature (~-20°C)

Sensitivity and R&D

<table>
<thead>
<tr>
<th></th>
<th>CANDLES III</th>
<th>Next CANDLES</th>
<th>Next CANDLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal</td>
<td>3.2kg × 96 (305kg)</td>
<td>2% ⁴⁸Ca (2 ton)</td>
<td>50% ⁴⁸Ca (6 ton)</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>(4.0%)</td>
<td>2.8%(Req.)</td>
<td>0.5%(Req.)</td>
</tr>
<tr>
<td>Expected BG</td>
<td>0.27/year</td>
<td>&lt;0.7 /3year</td>
<td>&lt;0.2 /9year</td>
</tr>
<tr>
<td>&lt;mₜ&gt;</td>
<td>0.5 eV</td>
<td>0.08</td>
<td>0.009</td>
</tr>
</tbody>
</table>

- Current system with cooling system bolometer
- Enrichment: now on stage of mass production
- Good energy resolution by bolometer
- CaF₂(Eu) is OK. ref: NIMA386(1997)453 by Milano group
- Now we have developed at sea level laboratory
Summary

- **Double beta decay measurement**

- **R&D for CANDLES system**
  - Analysis for background rejection: pile-up events
  - **CANDLES III at Kamioka Lab.**
  - We installed the shielding system for detector sensitivity of 0.5 eV.
  - BG rate will be reduced by ~1/100.

- **R&D for next CANDLES**
  - Scintillating bolometer by using CaF$_2$(pure)
  - Enriched $^{48}$CaF$_2$(pure) scintillators
  - Now: on stage of “cost effective” mass production of $^{48}$Ca
208Tl rejection

\[ \ce{^{212}Bi \rightarrow ^{208}Tl \rightarrow ^{208}Pb} \]

- Th-Chain
- \( ^{232}\text{Th} \)
- \( ^{212}\text{Bi} \)
- \( \alpha \rightarrow 36\% \)
- \( Q_\alpha = 6.2\text{MeV} \) (\( E_e = 1.7\text{MeV} \))
- \( ^{208}\text{Tl} \)
- \( T_{1/2} = 3.0\text{min} \)
- \( Q_\beta = 5.0\text{MeV} \)
- \( \beta + \gamma \)
- \( ^{208}\text{Pb} \) stable

\( E_{\text{max}} = 5.0\text{MeV} \)

\( ^{212}\text{Bi} \) and \( ^{208}\text{Tl} (T_{1/2}=3\text{min}) \)

Space-Time Correlation Cut

Energy spectrum of prompt \( ^{212}\text{Bi} \)

- Prompt events
- Accidental coincidence events
- Delayed event = 3.5-5.1\text{MeV}

\[ \Delta t \text{ spectrum of delayed } ^{208}\text{Tl} \]

- Obtained data of \( \Delta t \)
- Fitting
- Due to \( ^{208}\text{Tl} \)
- Accidental

- Obtained half-life = 241±46\text{sec}

- We can identify the prompt \( ^{212}\text{Bi} \)
- We improved these efficiencies by DAQ upgrade etc.
Result of ELEGANT VI

Obtained Result

Energy Spectra

$Q_{\beta\beta}$ of $^{48}$Ca

Run summary (Measurement for 4 years)

<table>
<thead>
<tr>
<th>Run</th>
<th>Number of Event</th>
<th>Expected BG ($^{212}$Bi, $^{214}$Bi, $^{208}$Tl)</th>
<th>Live Time kg·day</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Run</td>
<td>0</td>
<td>1.30</td>
<td>1553</td>
</tr>
<tr>
<td>Second Run</td>
<td>0</td>
<td>0.27</td>
<td>3394</td>
</tr>
</tbody>
</table>

No events in $0\nu\beta\beta$ Energy Window

$0\nu\beta\beta$ Half-Life of $^{48}$Ca: > $5.8 \times 10^{22}$ year (90% C.L.)

$\langle m_\nu \rangle < (3.5\text{-}22)$ eV

- $4\pi$ active shield is effective for background free measurement.
- Expected backgrounds are $^{212}$Bi and $^{208}$Tl

For higher sensitivity, we need a large amount of $^{48}$Ca.