Neutrino-less double beta decay of $^{48}\text{Ca}$ studied by CaF$_2$(pure) scintillators

--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
  Low background measurement

Summary
Double beta decay of $^{48}\text{Ca}$

**Double beta decay nuclei**

$^{48}\text{Ca}$ : low background $\rightarrow$ large scale detector

higher $Q_{\beta\beta}$ value (4.27MeV) . . .

$\rightarrow$ low background

because $Q_{\beta\beta}$ value is higher than BG

$E_{\text{max}}=2.6\text{MeV}(^{208}\text{Tl, }\gamma\text{-ray})$

$3.3\text{MeV}(^{214}\text{Bi, }\beta\text{-ray})$

**Double beta decay of $^{48}\text{Ca}$ by using $\text{CaF}_2$ scintillators**

**ELEGANT VI** : $\text{CaF}_2$(Eu) scintillator

$\rightarrow$ realized low background condition

**CANDLES system** : for large scale detector

**CANDLES III** : current system
CANDLES III

CANDLES at Kamioka underground laboratory

- **CaF$_2$ scintillator (CaF$_2$(pure))**
  - 305 kg (96 modules × 3.2 kg)
  - $^{48}$Ca : 350 g
  - Time constant $\tau \sim 1 \mu$sec

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

- **Large photomultiplier tube**
  - 13 inch PMT × 36
  - 20 inch PMT × 14
  - 10 inch PMT × 12

- **Light pipe system**
  - Guide scintillation light to PMTs

Pulse shape difference between CaF$_2$ and liquid scintillators

- (4 μsec) (a few 10 nsec)
- Background rejection
CANDLES III

CANDLES at Kamioka underground laboratory

Main detector

CaF$_2$ scintillators (305kg)

Liquid scintillator tank (2m$^3$)

Liquid scintillator (LS)

4π active shield

volume :2m$^3$

time constant $\tau \sim$ a few ten nsec

Large photomultiplier tube

13inch PMT × 36
20inch PMT × 14
10inch PMT × 12

Light pipe system

guide scintillation light to PMTs

Pulse shape difference between

CaF$_2$ and liquid scintillators

(4μsec) (a few 10nsec)

→background rejection

CaF$_2$ scintillator (CaF$_2$(pure))

305 kg (96modules × 3.2kg)

$^{48}$Ca : 350g

time constant $\tau \sim$ 1μsec

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CANDLES at Kamioka underground laboratory

Main detector

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Liquid scintillator tank (2m$^3$)

Liquid scintillator (LS)

4π active shield

volume :2m$^3$

time constant $\tau \sim$ a few ten nsec

Large photomultiplier tube

13inch PMT × 36
20inch PMT × 14
10inch PMT × 12

Light pipe system

guide scintillation light to PMTs

Pulse shape difference between

CaF$_2$ and liquid scintillators

(4μsec) (a few 10nsec)

→background rejection
Background rejection by liquid scintillator

Rejection of external γ-ray backgrounds by pulse shape discrimination

Typical pulse shape in CANDLES III

\[ \tau \text{ of } \text{CaF}_2 = \sim 1000 \text{nsec} \]
\[ \text{LS} = \sim 20 \text{nsec} \]

In CANDLES system . . .
- Short pulse (LS scintillator ~ a few 10ns) and long pulse (CaF\(_2\) = \sim 4 \mu \text{sec})
- CaF\(_2\) selection by using FADC → rejection of backgrounds → realized 4π active shield
Backgrounds in CANDLES

2νββ events: negligible for CANDLES III
Possible to reduce by good energy resolution
current energy resolution 6% (4.27 MeV)

γ-ray from neutron capture
high energy γ-ray from neutron capture on Fe, Ni, Si
within stainless steel (main tank), rock in the mine.
→ new shielding system

Radioactive contaminations in CaF₂ crystals

Pile-up events

232Th → 212Bi → 212Po
T₁/₂ = 0.3 μsec
Q_β = 2.25 MeV
β = 64%
α = 8.95 MeV

208Tl → β + γ → α
Q_α = 6.09 MeV
T₁/₂ = 3.1 min
Q_β = 4.99 MeV

To reject these BG events:
High energy γ-ray: construction of the shielding system
Pile-up event: identification of the “pile-up” shape
208Tl event: identification of prompt 212Bi (by particle identification α-γ ray)

212Bi and 208Tl (T₁/₂ = 3 μmin)...
rejection by 212Bi tagging (α-γ particle identification)
Shielding system

Toward "background free measurement"

Schematic view of the shielding system

Shielding system: BG ~1/100

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

B sheet
- B_4C loaded silicone rubber sheet
  ~ 5mm in thickness
- reduce thermal neutron
  → reduce BG from (n,γ) in main tank.
- N-capture events will decrease by factor of ~1/30

Construction of the shielding system

Shieldings inside/outside the tank
BG rate: ~ 1/100
Shielding system

**Construction was finished in 2016**

Complete shielding system

Main tank
Pb+B$_4$C sheet

Under construction

Inside the tank
B$_4$C sheet

**BG reduction factor**

- Energy spectra before/after shield construction

γ-rays from neutron capture were reduced by shielding system
$\sim 1/100 \sim 1/70$

![Graph showing energy spectra before and after shielding construction. The x-axis represents energy in keV, and the y-axis represents the number of events per 50keV bin over 56.9 days. The graph shows a significant reduction in background radiation after shielding.]
Backgrounds in CANDLES

γ-ray from neutron capture

high energy γ-ray from neutron capture on Fe, Ni, Si within stainless steel (main tank), rock in the mine.

Radioactive contaminations in CaF$_2$ crystals

Pile-up events

\[ ^{232}\text{Th} \xrightarrow{\beta} ^{212}\text{Bi} \xrightarrow{\alpha} \]

\[ Q_\beta = 2.25\text{MeV}, \quad T_{1/2} = 0.3\mu\text{sec} \]

\[ ^{212}\text{Po} \xrightarrow{\alpha} \]

\[ Q_\alpha = 8.95\text{MeV} \]

\[ ^{208}\text{Tl} \xrightarrow{\beta} \]

\[ Q_\beta = 4.99\text{MeV} \]

\[ ^{208}\text{Pb} \quad \text{stable} \]

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

rejection by $^{212}\text{Bi}$ tagging (α-γ particle identification)

To reject these BG events;

High energy γ-ray : construction of the shielding system

Pile-up event : identification of the “pile-up” shape

$^{208}\text{Tl}$ event : identification of prompt $^{212}\text{Bi}$ (by particle identification α-γ ray)
Rejection of pile-up events

**Pile-up events:** $^{212}\text{Bi} \rightarrow ^{212}\text{Po}$ decay

Radioactive contamination in CaF$_2$ : Th-chain

- **$^{232}\text{Th}$**
  - $T_{1/2} = 1.1 \times 10^{10}$ year

- **$^{212}\text{Bi}$**
  - $T_{1/2} = 0.3$ μsec
  - $Q_\beta = 2.2 \text{MeV}$
  - $64\%$ prompt

- **$^{212}\text{Po}$**
  - $T_{1/2} = 295 \pm 13$ nsec
  - $Q_\alpha = 7.8 \text{MeV}$
  - $64\%$ decayed

**Maximum energy:** 5.2 MeV

We can identify the pile-up events current rejection efficiency > 95%

**Typical pulse shape**

- Prompt $\beta$-ray
- Delayed $\alpha$-ray

**Energy spectrum**

- Decayed $\alpha$-ray
- Prompt $\beta$-ray

**Time distribution**

- $T_{1/2} = 295 \pm 13$ nsec

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208Tl rejection: 212Bi tagging

Energy spectrum of proceeding 212Bi

$E_{\text{max}} = 5.0\text{MeV}$

$212\text{Bi}$ and $208\text{Tl}(T_{1/2} = 3\text{min})$... rejection by 212Bi tagging

Half-life $= 178\pm 55\text{sec}$

- we can reject $208\text{Tl}$ event by 212Bi tagging
- obtained half life 178sec ($208\text{Tl}$ 183sec)
- current rejection efficiency $\sim 75\%$, acceptance $\sim 83\%$
Energy spectra

95 crystals

- Experimental data
- $^{212}$Bi rej. (<20nsec)
- LS signal rej.
- $^{208}$Tl rej.
- Position cut ±2σ

27 crystals

Num of event

<table>
<thead>
<tr>
<th></th>
<th>95 crystals</th>
<th>27 crystals (high purity crystals)</th>
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<tbody>
<tr>
<td>Qββ 4-5MeV</td>
<td>115</td>
<td>12</td>
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<tr>
<td>Qββ 5.5-6.5MeV</td>
<td>257</td>
<td>23</td>
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<tr>
<td>without $^{208}$Tl cut</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>with $^{208}$Tl cut</td>
<td>19</td>
<td>3</td>
</tr>
<tr>
<td>Position 2σ cut</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1</td>
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</table>

No event in high purity crystals
Result of measurement for 131 days

<table>
<thead>
<tr>
<th></th>
<th>results</th>
</tr>
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</table>
| $0
\nu\beta\beta$ efficiency | $0.39 \pm 0.06$                              |
| Num. of eve.(exp)    | 0(27CaF), 10(95CaF)                          |
| Expected BG          | $\sim 1.2, \sim 11$                          |
| Half life of $^{48}$Ca | $>6.2 \times 10^{22}$ year (27 crystals)     |
|                      | $>3.8 \times 10^{22}$ year (95 crystals)     |
| Sensitivity          | $3.6 \times 10^{22}$ year (27 crystals)      |
|                      | $6.2 \times 10^{22}$ year (95 crystals)      |

*ELEGANT VI
measurement time : 4947kg \cdot day (2 years <)
half life limit : $5.8 \times 10^{22}$ year

- experimental data
  - simulation (total)
  - $\gamma$-ray from N capture
  - contamination : $^{208}$Tl
  - $2\nu\beta\beta$
  - other BG

Energy spectrum and BG simulation

Preliminary

(Chi$^2$<1.5, -3\σ<SI<1\σ),
-2\σ<position<2\σ,
with $^{208}$Tl cut
Measurement of $^{48}\text{Ca}$ double beta decay

We installed the shielding system in 2016.

BG from neutron capture is reduced by 1/70~1/100

Obtained half-life limit: >$6.2 \times 10^{22}$

We updated half-life limit of $^{48}\text{Ca}$.

Now we continue the measurement.

Future

We will apply:

- Scintillating bolometer by using CaF$_2$(pure)
- Enrichment of $^{48}\text{Ca}$: $^{48}\text{CaF}_2$(pure) scintillator

Now on stage of “cost effective” mass production
Background from neutron capture

For design of shielding system: neutron capture on Fe, Ni, Si

Neutron source ($^{252}$Cf) run: rock, main tank

Where neutron was captured on?

Measurement with/without $^{252}$Cf

Energy spectra

$^{252}$Cf run (3 hours)

Normal run (without $^{252}$Cf) (88 day)

(including CaF$_2$ events with low LS signal)

High energy region: represent energy spectrum by (n,γ) in stainless, rock

→ design of shielding system
Particle identification between α and γ-ray

Event distribution by using “shape indicator”
- α-ray: $^{214}$Po 7.6MeV ($E_e=2.6$MeV)
- γ-ray: $^{208}$Tl 2.6MeV

We applied not only “shape indicator” but also “$\chi^2$ fitting” for PI.

97% rejection efficiency at 2.6MeV (γ-ray:3%)
→ 97% (β-α pile-up event) at 4.27MeV (γ-ray:3%)
- for rejection of β-α pile-up events
- for identification of prompt $^{212}$Bi event

Shape Indicator

$\gamma$-ray (2.6MeV)
$\alpha$-ray ($^{214}$Po 7.6MeV)

CaF$_2$ γ-signal +small LS signal

$\gamma$-ray (2.6MeV)

mean : -0.008 (γ-ray)
: 1.005 (α-ray)
σ : 0.260 (α-ray)
MCCCE
Multi-channel counter-current electrophoresis

Conceptual drawing of MCCCE

1. Electric field: ~200V/cm
2. Flow rate: ~1mm/sec
3. Sampling

Migration path: 1 cm

Enriched $^{48}\text{Ca}$

Boron nitride plate

Principle was demonstrated.
→ stable driving, large amount

Maximum isotopic ratio
$x3 \times 6$ of $^{48}\text{Ca}/^{40}\text{Ca}$

Isotopic ratio of obtained solution
Isotopic ratio of Feed solution
Enrichment by using Crown Ether

**Experimental setup**
- Crown-ether rings adsorb Calcium ions
- For calcium, $^{40}$Ca adsorption in crown-ether is slightly prior

**Crown-Ether**

1. Crown-ether resin packed in column of 8mmφ × 100cm
2. Ca solution ~0.1mol/l CaCl$_2$
3. Sampling

**Result**
- Obtained isotopic ratio
- Maximum Isotopic ratio
- Isotopic effect by crown ether

- Isotopic ratio of feed solution
- Enriched $^{48}$Ca
- $^{40}$Ca : captured

**Next R&D**
- cost effective system e.g. crown-ether monomer
- Water pump
- Water thermo. bath
- Fixed flow rate by pump for long migration: many column are connected.
Scintillating bolometer

bolometer: for good energy resolution
Reduce BG from $2\nu\beta\beta$ events
But... other background
α-ray from contamination in CaF$_2$

Scintillating bolometer: particle identification
for background free measurement

Particle identification by scintillating bolometer
Scintillation

$\beta / \gamma$
$\beta$-α sequential decay

4.27MeV

CaF$_2$ detector: crystal part

Cooling test (now ~1K)
Signal reading test

Dilution refrigerator

$\nu\beta\beta$ region

4.27MeV

Omeara, Saori, 25th Jul. 2017, TAUP2017
future : CANDLES sensitivity

CANDLES series

<table>
<thead>
<tr>
<th></th>
<th>CANDLES III</th>
<th>Next CANDLES</th>
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<tbody>
<tr>
<td>Crystal</td>
<td>0.19% 3.2 kg × 96 crystals</td>
<td>2% $^{48}$CaF$_2$</td>
</tr>
<tr>
<td>CaF$_2$($^{48}$Ca)</td>
<td>305 kg (350 g)</td>
<td>2 ton (25 kg)</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>(6%)</td>
<td>2.8%</td>
</tr>
<tr>
<td>$&lt;m_\nu&gt;$</td>
<td>0.5 eV</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Energy spectra in CANDLES III

Energy resolution 4%
Energy resolution 2.8%
Energy resolution 1%

Energy spectra in CANDLES IV

Energy resolution 2.8%

Energy spectra in CANDLES V

Energy resolution 1%

CaF$_2$ cooling system

Current detector

~2% $^{48}$Ca

Bolometer

~50% $^{48}$Ca

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