for the study of 48Ca double beta decay and its future prospect

T. Kishimoto
Osaka University

CANDLES Collaboration

Osaka University, Graduate school of science
吉田斉、Masoumeh Shokati、李暁龍、Temuge Batpurev、Ken Lee Keong、芥川一樹、Bui Tuan Khai、佐藤勇吾、水越彗太、山本康平、宮本幸一郎

Osaka University, RCNP
梅原さおり、能町正治、岸本忠史、竹本康浩、松岡健次、濱平勇吉、鉄野高之介

Fukui University
玉川洋一、小川泉、中島恭平、戸澤理詞、清水慧悟、清水健生、森勇太、池山佑太、松岡耕平

Tokushima University
伏見賢一

Osaka Sangyo University
硝隆太、中谷伸雄、Noithong Pannipa、田坪博貴

Tsukuba University
飯田崇史

Saga University
大隅秀晃

The Wakasa wan Energy Research Center
鈴木耕拓

Sendai2019/3/7
Why $^{48}$Ca

- Highest Q value
  - 4.27 MeV, ($^{150}$Nd: 3.3 MeV)
  - Least BG ($\gamma$: 2.6 MeV, $\beta$: 3.3 MeV)
  - Large phase space factor
- Small natural abundance:
  - 0.187%
  - Separated isotope $\rightarrow$ expensive
- Next generation
  - $<m_\nu>$ $\sim T^{-1/2} \sim M^{-1/2}$ (no BG) $M$: mass
    $\sim M^{-1/4}$ (BG limited)
  - Enrichment: mass + S/N: 500 times
  - High resolution: bolometer (crystal)
- Beyond inverted hierarchy
  - $^{48}$Ca + enrichment + bolometer

Sendai 2019/3/7
CANDLES III @ Kamioka

- Site: Kamioka U.G.L. ~1000 m
- Size: 3mΦ × 4mh (water tank)
- Liquid scintillator
  - Reservoir tank
  - Purification system (liq-liq)

Kamioka Lab. Map

Sendai 2019/3/7
CANDLES III(UG)

CANDLES at Kamioka underground laboratory

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

**liquid scintillator** (LS)
- $4\pi$ active veto
- $2m^3$
- $\tau \sim$ a few 10nsec

**PMT’s**
- 13inch PMT × 48
- 20inch PMT × 14

**light pipe**
- Light collection: energy resolution

**Veto**

Pulse shape difference
- CaF$_2$(pure) : $\sim 1\mu$sec
- Liquid scintillator : a few 10 nsec
CANDLES III(UG)
CANDLES at Kamioka underground laboratory

CaF$_2$ (305kg)

Liquid scintillator tank (2m$^3$)

PMT

Light pipe

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

Liquid scintillator (LS)
4$\pi$ active veto
2m$^3$
$\tau \sim$ a few 10nsec

PMT's
13inch PMT × 48
20inch PMT × 14

Light pipe
light collection : energy resolution

Veto

Pulse shape difference
CaF$_2$(pure) : $\sim 1\mu$sec
Liquid scintillator : a few 10 nsec
$4\pi$ active veto by Liquid scintillator (LS)

- Rejection of external $\gamma$–ray background
  - Pulse shape information by 500 MHz Flash ADC.
  - Distinguish event type by offline pulse shape analysis taking advantage of different decay time.

\[ \begin{align*}
\text{CaF}_2 & \quad (1\mu\text{sec}) \\
\text{CaF}_2 + \text{Liquid Scintillator} & \\
\text{Liquid Scintillator} & \quad (\sim 10\text{ns})
\end{align*} \]
Internal backgrounds and reduction

- External BGs were reduced by LS active shield.
- Remaining BGs originate from internal radioactivity of Th chain ($^{208}\text{Tl}$ and $^{212}\text{Bi-}^{212}\text{Po}$).
- $2\nu\beta\beta$ is not serious BG in current sensitivity. (it will be major BG after $^{48}\text{Ca}$ enrichment)
- We reject remaining BGs by analysis.
Rejection of Double Pulse

\[ Q_\beta = 3.27 \text{MeV} \]
\[ Q_\beta = 2.25 \text{MeV} \]
\[ Q_\alpha = 7.83 \text{MeV} \]
\[ Q_\alpha = 8.95 \text{MeV} \]

Typical Pulse Shape

\[ T_{1/2} = 0.299 \mu \text{sec} \]

BG in \( Q_\beta \beta \) region: Sum \( E \)

\[ E_\alpha (1/3 \text{ Quench}) + E_\beta \approx 5.3 \text{ MeV} \]

Reduction

100MHz FADC (old) \( \Delta T > 30 \text{ns (3ch)} \); \( \sim 5\% \)

500MHz FADC \( \ldots \Delta T > 10 \text{ns} \); \( \sim 2\% \)
208\textsuperscript{Tl} event cut

1. Find parent \textsuperscript{212}Bi \(\alpha\)-decay candidate by pulse shape analysis.
2. Apply 12min veto from \textsuperscript{212}Bi candidate in the same crystal.

\textbf{Energy spectrum of prompt events}

- \textsuperscript{212}Bi candidate
- Accidental event
- \textsuperscript{212}Bi candidate-Accidental

Delayed: 3.1-5MeV
Time gate: \textasciitilde 180sec

\(T_\frac{1}{2} = 178 \pm 55\text{sec}\)

\(208\text{Pb}\) stable
\(T_\frac{1}{2} = 3.05\text{min}\)
\(Q_\beta = 5.00\text{MeV}\)

\(Q_\alpha = 6.21\text{MeV}\)

\(T_\frac{1}{2} = 60.6\text{m}\)

\(232\text{Th}\)

Sendai2019/3/7
To confirm our assumption that high E gamma ray BG’s are from \((n, \gamma)\) reactions, \(^{252}\text{Cf}\) neutron source was set on the detector and data were taken.

- Spectra for neutron source run and physics run are consistent.
- MC simulation of \((n,\gamma)\) can well reproduce the BG spectrum.

We identified main BG as \((n,\gamma)\)!!
Shield for \((n, \gamma)\) background reduction

**CANDLES shield overview**

- **CANDLES tank**
- **Pb shield (7-12cm)**
  - Reduce \(\gamma\)-ray from surrounding rock
  - Effect of Pb \((n, \gamma)\) is one order smaller than that of stainless tank
- **Boron sheet (4-5mm)**
  - Reduce \(n\) captured by stainless tank

- \((n, \gamma)\) BGs in CANDLES is expected to become \(1/80\) by MC.
- Expected number of backgrounds after shield installation:
  - **Rock**: \(0.34 \pm 0.14\) event/year
  - **Tank**: \(0.4 \pm 0.2\) event/year
Pb shield construction

- Pb shield construction was started from March 2015.
- All the collaborators worked very hard!
Position reconstruction and crystal selection

- Position of each event is reconstructed by weighted mean of observed charge in each PMT.
- Crystal separation is $\sim 7\sigma$ peak to peak.
- Crystal selection criteria is within $3\sigma$ from the peak.
- 27 clean crystals (Th contamination $< 10 \, \mu\text{Bq/kg}$) out of 96 crystals are selected and the results are compared to all crystals.

\[
\sum \frac{N\text{pe}(i) \times \text{PMT}(i)}{\sum N\text{pe}(i)}
\]

\[
\pm 3\sigma
\]
Energy Spectra & Event Selection

LiveTime: 131 days

95 crystals

27 crystals ($^{232}$Th < 10uBq/kg)

<table>
<thead>
<tr>
<th># event</th>
<th>95 crystals</th>
<th>27 crystals</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\beta\beta}$</td>
<td>4–5MeV</td>
<td>5.5–6.5MeV</td>
</tr>
<tr>
<td>LS Cut</td>
<td>115</td>
<td>257</td>
</tr>
<tr>
<td>$^{208}$Tl Cut</td>
<td>19</td>
<td>49</td>
</tr>
<tr>
<td>Position Cut</td>
<td>10</td>
<td>34</td>
</tr>
</tbody>
</table>

No event in high purity crystals is confirmed.
Results

<table>
<thead>
<tr>
<th></th>
<th>95 CaF₂</th>
<th>27 CaF₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Livetime</td>
<td>131</td>
<td></td>
</tr>
<tr>
<td>$0 \nu \beta \beta$ eff.</td>
<td>0.39 ± 0.06</td>
<td></td>
</tr>
<tr>
<td>Event in ROI</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Expected BG</td>
<td>~11</td>
<td>~1.2</td>
</tr>
<tr>
<td>$T_{0\nu\beta\beta}^{1/2}$ $^{48}$Ca (yr)</td>
<td>$&gt;3.8 \times 10^{22}$</td>
<td>$&gt;6.2 \times 10^{22}$</td>
</tr>
<tr>
<td>Sensitivity (yr)</td>
<td>$6.2 \times 10^{22}$</td>
<td>$3.6 \times 10^{22}$</td>
</tr>
</tbody>
</table>

*ELEGANT IV*
Exposure: $4947\text{kg} \cdot \text{d (2yr<)}$
$0 \nu \beta \beta$ eff.: 0.53
$T_{0\nu\beta\beta}^{1/2}$ $^{48}$Ca: $5.8 \times 10^{22}$ yr

Exp. Data and BG MC
In 27 CaF₂

**CANDLES is now giving the best lifetime limit!**
- further measurement
- developments for future

Sendai2019/3/7
Statistics : 504 days
- The obtained spectra as expected from BG estimation
- We have ~ 300 days more statistics (not yet finished analysis)
- BG from (n,γ) is reduced by ~ 100 with shield installation.

0νββ analysis
- $\text{CaF}_2$ Crystal × 21
  - $^{228}\text{Th}$ contents within crystal < 10 μBq/kg
- All BG cuts are applied, but cut condition is not optimized yet.
  - LS veto & β-events cut
  - $^{212}\text{Bi}$-Po sequential decay, $^{208}\text{Tl}$ veto after $^{212}\text{Po}$-decay (18 min.)
48Ca enrichment

- Natural abundance of 48Ca is 0.187%.
- 48Ca has a room of 500 times improvement (S & S/N) by enrichment
- Commercial 48Ca → too expensive (M$/10g but kg-ton)
- Enrichment is crucial for large volume 48Ca DBD search.

Challenges in CANDLES:
- Crown ether resin + chromatography
  - 1.3 times
- Crown ether + micro reactor
- Laser separation
- Multi-channel counter current electrophoresis (MCCCE)
Laser Isotope Separation of $^{48}$Ca

Principle

Absorption spectrum of Ca

Isotope shift: a few hundred MHz

Laser line width: $<1$ MHz

Experiment

Ionization Method

Optimization of various parameters
- Excitation laser power density
- Ionization laser wavelength power

Deflection Method

We confirmed the enrichment of $^{48}$Ca in the deflected atomic beam

Optimization of laser power density

Deflection Method

Position of the collection plate will be adjusted to the optimal position

Mid. Concentration
Continuous operation

Development of collection system of $^{48}$Ca
Increase atomic beam/laser power
Optimization of various parameters

For the future mass production...
We continue R&D of Deflection Method

For more details... see K. Matsuoka’s Poster
Multi-channel counter current electrophoresis

- Separation using difference of migration speed between $^{40}\text{Ca}$ / $^{48}\text{Ca}$.
- High power + effective heat removal
  - Migration path: thermal conductor and insulator (BN)
- Pulsed flow to get uniform flow speed

$R(\text{MCCCE}) = \frac{43\text{Ca} / 48\text{Ca(MCCCE)}}{43\text{Ca} / 48\text{Ca(natural)}}$

Enrichment
- $(48/43): 3.08$
- $(48/40): 6$

Calcium isotope enrichment by means of multi-channel counter-current electrophoresis for the study of particle and nuclear physics

Sendai 2019/3/7

T. Kishimoto$^{1,2,*}$, K. Matsuoka$^2$, T. Fukumoto$^3$, and S. Umehara$^2$

Prog. Theor. Exp. Phys. 2015, 03D03 (10 pages) DOI: 10.1093/ptep/ptv020
Tabletop instrument
history

• 2012: got MCCCE idea
• 2015: 10mm BN $\sim 3^{48}\text{Ca}/^{43}\text{Ca}$, (6 $^{48}\text{Ca}/^{40}\text{Ca}$) PTEP
  – then faced difficulty
• 2017 year end
  – After 2 years struggle, results become reproducible
• 2018 February: $\sim 10$ times
• 2018 April: modification to give uniform T and E
  – $\sim$ a few 10’s times
  – May: $\sim$ 100 times
• Condition
  – BN 20 mm
Highly enriched samples

Number of samples

TK, T. Ohata, K. Matsuoka

Obtained samples

$^{48}\text{Ca}/^{43}\text{Ca}$ (Enrichment/natural)
**48Ca/40Ca ratio**

- **48Ca/43Ca** is so high then **48Ca/40Ca**?
  - We usually measure **48Ca/43Ca**, since no interference
  - Similar nat. ab. **48Ca**: 0.187%, **43Ca**: 0.135%

- **40Ar** forbids **40Ca** measurement in ICP-MS
  - Reaction(collision)-cell ICP-MS + reaction-gas (H₂, He, NH₃)

\[
\begin{align*}
40\text{Ar}^+ + \text{Ca}^+ &\rightarrow 40\text{Ar}^+ + \text{H}^+ \\
\text{H}_2 &\rightarrow 40\text{Ca}
\end{align*}
\]

Ar\textsuperscript{+} + H \rightarrow \text{H}^+ + \text{Ar}

Reduce Ar\textsuperscript{+} \rightarrow 40\text{Ca}
Enrichment

- **Migration distance** \( l = \mu E t \)
  
  - \( \mu \): mobility difference \( \Delta \mu = \mu(^{40}Ca) - \mu(^{48}Ca) \)
  
  - Separation \( \Delta \ell = \Delta \mu E t \)

- **Diffusion**: deteriorate separation
  
  - Diffusion constant: \( D \)

- **Enrichment**
  
  \[
  \frac{\sigma}{\Delta \ell} \propto \frac{1}{E \sqrt{t}} \propto \frac{1}{E \sqrt{\ell}}
  \]

  increase of \( E t (\ell) \)

- **Yield \( \sim 5\% \)** (concentration)
  
  - Migration speed difference \( \sim 5\% \)
  
  - Long Migration distance \( \sim 20/0.05 \sim 400 \text{ mm} \)
  
  - Enrichment and yields are consistent
Enrichment

- Enrichment $\rightarrow$ Reduction of $^{40}\text{Ca}$
  - $10\text{mm }\text{BN }1/6 \rightarrow \sigma \sim 10\text{mm}$
  - $20\text{mm }\text{BN }1/50 \rightarrow \sigma \sim 10\text{mm}$
- Width
  - Hagen-Poiseuille flow $\rightarrow$ (send pause, 1 sec)
  - Every $2\text{mm}$ times $200 \rightarrow \sigma$ small $(1/\sqrt{200})$

Next step
- $40\text{mm }\text{BN }1/300 \rightarrow \sigma \sim 14\text{mm}$
  - $99.7\%$ enrichment is possible
  - Practical goal is set to $80\%$ enough for DBD

$\sigma = \frac{400}{\sqrt{12}} \sim 115\text{mm}$

$\sigma = \frac{2}{\sqrt{12}} \sqrt{200} \sim 8\text{mm}$

$\sigma = \sqrt{\frac{\text{BN}}{\text{thickness}}}$

80%
Production of enriched $^{48}\text{Ca}$

- **Current system**
  - 16(10)% ($^{48}\text{Ca}/^{40}\text{Ca}$)
  - 12 cm$^2$, 0.01 N → 0.1 mg/day

- **Next system**
  - 80% or more
  - 1.2 m$^2$, 0.03 N → 0.3 g/day → 100 g/year
  - Tons; require plant → further needs
  - Our field
  - Other fields (beam, medical use,.. )

- CANDLES works for 80%
本研究会では、不安定核物理、加速器、二重ベータ崩壊、放射化学、医学利用、異分野連携、新同位体濃縮法といった視点からの講演を通して、濃縮同位体を用いた研究と今後の発展を概観することを目指しています。

研究会概要

日時：2019年3月21日（木）12:25～17:00
受付開始は12時です。

会場：大阪OBPクリスタルタワー20階A会議室
http://www.crystaltower.jp/map.html

参加料：無料

ワークショップのプログラム

12:25- 岸本忠史
12:30- 中村隆司(東工大理)
13:00- 奥武志也(KEK)
13:20- 依田哲彦(RCNNP)
13:40- 野海博之(RCNNP/KEK)
14:00- 井上邦雄(東北大RCNS)

14:30- 休憩

15:00- 篠原厚(阪大理)
15:30- 中野貴志(RCNNP)
16:00- 畑澤順(阪大医)
16:30- 岸本忠史(RCNNP)

「はじめに」
「ビーム物理と濃縮同位体」
「超重核質量の直接測定と48Ca」
「加速器技術と濃縮同位体」
「ハドロン物理と濃縮同位体」
「136Xeの二重ベータ崩壊」

「放射化学と超重元素」
「加速器が拓くイノベーション」
「放射性同位体の医学利用」
「新同位体濃縮法と基礎科学」
Development for CaF$_2$ Scintillating Bolometer:

- Sei Yoshida, ....

- Collaborative research with Korean colleague
  Yong-Hamb Kim (IBS & KRISS)
  Minkyu Lee (KRISS)
  Inwook Kim
  Do-Hyoung Kwon
  Hyejin Lee
  Hye-Lim Kim
Tail of 2νββ spectrum
- Improving energy resolution

48CaXX internal radioactivities
- Th-chain (β-α sequential decays) → Bolometer
- Th-chain (208Tl)
  → Segmentation, Multi-crystal
- Environmental neutrons
  → Improving resolution + Multi-crystal

Possible to further reduce the BG by developing Bolometer

But... new BG candidate
- Q value of 48Ca: 4267.98(32) keV @ arXiv:1308.3815
- Q-value of 238U (α-decay): 4270 keV
  Impossible to avoid
  → required particle ID

⇒ Developing CaF$_2$ Scintillating Bolometer
CaF$_2$(pure) Scintillating Bolometer

**First Challenge using CaF$_2$(pure) and MMC**

- **Crystal:** CaF$_2$(pure)
  - Volume: 300g (5cmφ × 5cm)
  - Emission peak: **280nm**
  - Light output: 25,000 photons/MeV

**Problem**

- UV scintillation of CaF$_2$ is absorbed on Au-deposit for heat signal. There is position dependence of scintillation absorption. ⇒ make worse E-resolution.

*Sendai 2019/3/7*
**CaF$_2$(Eu) scintillating Bolometer**

- New trial to overcome UV absorption
  - $\text{CaF}_2$(Eu) + Ag-deposit instead of $\text{CaF}_2$(pure) + Ag-deposit

![Absorption spectra](image)

- Improved light signal properties.
- In the heat channel, peaks of $\alpha$'s are widely spread.
  - (due to position dependence)
- Due to doping Eu?

---

see Xiaolong Li’s Poster
Evaluate energy resolution w/o position dependence

- We use contaminated CaF$_2$ crystal for R&D, $^{226}$Ra; $\sim$ 30 mBq within crystal
- Delayed coincidence ($^{222}$Rn $\rightarrow$ $^{218}$Po $\rightarrow$ $^{214}$Pb)
- Apply energy, PID parameter, $\Delta$time cuts

3.10 min.

$0 < \text{Time difference} < 3\text{min}$

Correlated events (α-α events) from same position

Evaluated energy resolution without position dependence, $< 0.2\% \ (\sigma)$ @ $Q_{\beta\beta}$
Prospects for the development

- Improving E-resolution of CaF$_2$(pure) scintillating bolometer
  - Radio-pure CaF$_2$(pure) crystal had been developed.
  - Doping Eu may affect phonon propagation in CaF$_2$ crystal.

- New trial in the next step
  - CaF$_2$(pure) crystal with **smaller but thicker Au-deposit** phonon collector.
    - Smaller $\rightarrow$ reducing scintillation absorption effect
    - Thicker $\rightarrow$ increasing the strong electron-phonon interaction.
CANDLES project

• CANDLES:
  – CANDLES III(UG): current detector
    • First result gives the best limit
    • Measurement and analysis underway
    • CaF$_2$ crystals with low BG (will be replaced)

• Future prospect
  – Enrichment $^{48}$Ca
    • MCCCE works for future tons
  – Bolometer
    • CaF$_2$ Scintillating Bolometer

Still lot to do
Promising
Thank you !!
CANDLES for the Study of $^{48}$Ca double beta decay and its future prospect

T. Kishimoto
Osaka University

CANDLES Collaboration

Osaka University, Graduate school of science
岸本忠史、吉田斉、鈴木耕拓、角畑秀一、Wang Wei、Chan Wei Min、Van Trang、石川貴志、田中大樹、田中美穂、土井原正明、前田剛、太畑貴綺、鉄野高之介

Osaka University, RCNP
能町正治、味村周平、梅原さおり、中島恭平、飯田崇史、松岡健次

Fukui University
玉川洋一、小川泉水、中島忠平、川村篤史、富田啓悟、藤田剛志、原田知優、坂本康介、吉澤真敦、犬飼祐司

Tokushima University
伏見賢一

Osaka Sangyo University
谷隆太、中谷伸雄

Tsukuba University
飯田崇史

Sendai2019/3/7
48/40 Caの濃度 [ppm]