Development of CANDLES
Low Background HPGe Detector and Half-life Measurement of $^{180m}_{\text{Ta}}$

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for the CANDLES Collaboration
Contents

- HPGe Detector System of CANDLES
  - Construction and Development
  - Detector Performance

- Half-life Measurement of $^{180m}$Ta
  - Introduction of $^{180m}$Ta Decay
  - Tantalum Phase I & Phase II

- Data Analysis & Result
  - Pulse Shape Discrimination
  - Monte Carlo Simulation
  - Half-life limit of $^{180m}$Ta

- Summary
HPGe Detector System of CANDLES

- Construction and Development
- Detector Performance
CANDLES

- Neutrinoless double beta decay experiment using $^{48}$Ca isotope
- Location: Kamioka Underground Observatory (2700 m.w.e.)
  
  [Muon flux is 5 order magnitude lower than ground]

- Rare event -> ultra-low background condition is very essential

[Session 6: “Performance of Upgraded Shielding System in CANDLES”

by Dr Nakajima Kyohei]

- An ultra-low background HPGe detector system was installed in the same experimental hall for support of CANDLES.
Construction Works

- Assembly of detector and shields (year 2013)
- Shields [150 mm Hermetic Pb + 50 mm OFHC Cu + Inner Cu (if need)]

Construction site
[Back Experimental Room of CANDLES]

Hermetic lead shield
HPGe detector & Dewar

Zig-zag shape copper blocks
Completed HPGe Detector System

Data taking was started from year 2013
- Material Screening of CANDLES
- Tantalum Phase I & II
- Others
Performance of Passive Shields

**HPGe detector:**
crystal size $\Phi 65\text{mm}$, relative efficiency = 50%, FWHM $\sim 1.9\text{ keV at 1.3 MeV}$

**Full Shields:**
9 mm Fe + 150 mm Pb + 50 mm Cu + inner Cu around detector
- Continuous nitrogen gas flow

Without full shields

Full shields + Boil-off nitrogen gas flow
Comparison of Background Spectrum [1 day]

- With hermetic shields, background level has reduced 4 orders of magnitude.

![Graph showing comparison of background spectrum with and without a shield](image)

- Total event rate: ~40 counts/hour
- Total event rate: ~480,000 counts/hour
Data taking of HPGe detector

- Digital Signal Processor (DSP) was used.
- Fast signal is the **timing** filter, Slow signal is the **energy** filter (trapezoidal filter).

Event Format:
- Time
- Channel (Energy)
- Pulse shape at rising part (640 ns)
Half-life Measurement of $^{180m}\text{Ta}$

- Introduction of $^{180m}\text{Ta}$ Decay
- Tantalum Phase I & Phase II
Motivation to study $^{180m}$Ta Decay

- $^{180m}$Ta is **the longest natural isotope that exist in excited state.**
  - Long-lived isomeric state $J_\pi = 9^- \&$ short-lived ground state $J_\pi = 1^+$
- Half-life of $^{180m}$Ta **has never been determined.**
- Lower limit of half life
  - $4.5 \times 10^{16}$ years [PRC, Lehnert 2017]

$^{180m}$Ta is predicted to decay in 3 ways:

1. Isomeric transition to $^{180}$Ta [$>10^{27}$ yrs]
2. Beta decay to $^{180}$W
3. Electron capture to $^{180}$Hf

Observe events produced by $\gamma$ decays

- $6^+ \rightarrow 4^+, 4^+ \rightarrow 2^+, 2^+ \rightarrow 0^+$
- ROI is 90 – 360 keV
- Backgrounds at low energy region

Challenge: To obtain the world most stringent half-life limit for $^{180m}$Ta.
Tantalum Phase I & Phase II Measurements

- Tantalum cylinder sample was inserted for long-term measurement.

<table>
<thead>
<tr>
<th>Tantalum</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass (g)</td>
<td>863.0 ± 0.1</td>
<td>848.8 ± 0.1</td>
</tr>
</tbody>
</table>

![Tantalum Cylinder Sample](image1.png)

![Tantalum Sample Configuration](image2.png)

[Phase II with Inner Cu Shield]
Tantalum Physics Runs

- After pre-analysis process [energy calibration by background peaks, bad run cut, noise rejection, etc.], two phases of tantalum physics runs were obtained.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physics Runs</td>
<td>237</td>
<td>32</td>
<td>269</td>
</tr>
<tr>
<td>Live time (days)</td>
<td>300.6</td>
<td>57.6</td>
<td>358.2</td>
</tr>
</tbody>
</table>

Phase 1: 
~50 events/hour

Phase 2: 
~27 events/hour

Event rate reduction: - 46%

Energy range: 40 keV – 1540 keV
Data Analysis & Result

- Pulse Shape Discrimination
- Monte Carlo Simulation
- Half-life limit of $^{180mTa}$
Background Reduction by Pulse Shape Discrimination (PSD)

- Different pulse shape distribution at low energy region
- Photopeak (mostly surface) vs background (uniformly distributed) regions

Example: 186 keV ±1 keV limit 250 events
**PSD method**

**Current Pulse Amplitude Method**

Current Pulse, $I = \frac{dQ}{dT}$

dQ = charge integral (pulse height)

dT = time window

$A = \text{maximum amplitude}$

**Procedure:**

i. Plot pulse shape event-by-event

ii. Plot current pulse

iii. Find the maximum amplitude

iv. Plot maximum amplitude distribution
Distribution of Maximum Current Amplitude [186 keV]

- **Peak region**
  - Maximum Current Amplitude Distribution

- **Background region**
  - Maximum Current Amplitude Distribution

Comparison of Maximum Current Time Distribution [ROI ± 1 keV]

- 186 keV Full Energy Peak
- Background
- Peak Region - Background Region

PSD Cut Efficiency, ε

- Background
- Peak
Monte Carlo Simulation
To obtain detection efficiency, GEANT4 simulation was used.

1) Define geometrical setup
   - Material, volume

2) Define physics involved
   - Particle, physics process, attenuation of γ-ray

3) How an event starts
   - Primary event generation

4) Extract useful information
   - Visualization, physics output (energy, position, trajectory)
HPGe Detector

- Assembly of Ge crystal, inner structure and Al endcap

Cross Section View from top
Cross Section View from bottom
Detailed line graphic
Full Assembly Geometry

- Illustration was presented with cross sectional view.

Tantalum Phase II Physics Run

Calibration Run [Top shield opened]
Trajectory of gamma-ray

- The path of gamma-rays travel within detector system can be observed.

![Diagram showing gamma-ray and electron ionization paths](image)

**Gamma point source**
Distance from endcap = 250 mm
Solid angle = 0.016 $\pi$

**Gamma point source**
Distance from endcap = 5 mm
Solid angle = 1.359 $\pi$
Comparison of Simulation and Experiment Data

The simulated spectrum shape agree very well with the actual experiment data.

- Prove that geometry of surrounding shielding was well simulated.

Experiment data [Co-60]  
Simulation spectrum [Co-60]
Dead Layer Adjustment

- Several fine tuning of the simulation were done.
- For example, adjustment of surface dead layer of germanium crystal.

![Graph showing detection efficiency vs energy for different dead layer thicknesses](image)
Verification of Simulation

Dead layer = 0.0 mm
Simulation is 18.7\% higher than experiment.
-> Not good.

Dead layer = 0.3 mm (best fit)
Simulation agreed well with experiment.
Systematic uncertainty = 8.7\%
Half-life limit of $^{180\text{m}}$Ta

- The most stringent half-life limit has been obtained

<table>
<thead>
<tr>
<th>Decay Branch</th>
<th>ROI (keV)</th>
<th>$I_\gamma$ (%)</th>
<th>$\varepsilon_{Det}$ (%) Phase I</th>
<th>$\varepsilon_{Det}$ (%) Phase II</th>
<th>$T_{1/2}$ limit (yrs) Phase I</th>
<th>$T_{1/2}$ limit (yrs) Phase II</th>
<th>$T_{1/2}$ limit (yrs) Phase I + II</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC</td>
<td>93.3</td>
<td>17.5</td>
<td>0.69</td>
<td>0.69</td>
<td>1.21$\times 10^{16}$</td>
<td>5.59$\times 10^{15}$</td>
<td>1.33$\times 10^{16}$</td>
</tr>
<tr>
<td></td>
<td>215.3</td>
<td>81.5</td>
<td>4.11</td>
<td>4.11</td>
<td>1.29$\times 10^{17}$</td>
<td>8.19$\times 10^{16}$</td>
<td>1.47$\times 10^{17}$</td>
</tr>
<tr>
<td></td>
<td>332.3</td>
<td>94.4</td>
<td>4.73</td>
<td>4.81</td>
<td>1.72$\times 10^{17}$</td>
<td>1.30$\times 10^{17}$</td>
<td>1.99$\times 10^{17}$</td>
</tr>
<tr>
<td>$\beta^-$</td>
<td>103.5</td>
<td>22.5</td>
<td>0.92</td>
<td>0.93</td>
<td>4.15$\times 10^{16}$</td>
<td>1.96$\times 10^{16}$</td>
<td>4.58$\times 10^{16}$</td>
</tr>
<tr>
<td></td>
<td>234.0</td>
<td>84.4</td>
<td>4.32</td>
<td>4.42</td>
<td>1.44$\times 10^{17}$</td>
<td>9.81$\times 10^{16}$</td>
<td>1.66$\times 10^{17}$</td>
</tr>
<tr>
<td></td>
<td>350.9</td>
<td>94.8</td>
<td>4.74</td>
<td>4.78</td>
<td>1.45$\times 10^{17}$</td>
<td>7.71$\times 10^{16}$</td>
<td>1.62$\times 10^{17}$</td>
</tr>
</tbody>
</table>

Achievement:
The world most stringent half-life limit for $^{180\text{m}}$Ta is obtained.

- $T_{1/2}^{EC} > 1.99 \times 10^{17}$ yrs
  - $logft = 25.0$
- $T_{1/2}^{\beta^-} > 1.66 \times 10^{17}$ yrs
  - $logft = 23.6$

Latest published value = $4.5 \times 10^{16}$ yrs
[Factor of 2 higher than Lehnert 2017]
Summary

- **HPGe detector system at CANDLES Experimental Hall** was completed and started for data taking since year 2013.
  - CANDLES Material Screening, Tantalum Half-life Measurement, etc.

- **New simulation model** and **PSD method** were developed for the HPGe detector.

- With Tantalum Phase I & Phase II results (livetime of 358.2 days), the **world most stringent half-life limit for $^{180m}$Ta** is achieved.
~Thank you~

Q & A

Kamioka, Japan @Winter2017

CANDLES