Research of a new TOF method for neutrino-less double beta decay search

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• Brief introduction of neutrino-less double beta decay

• A new concept of experimental approach for neutrino-less double beta decay search

• Preliminary study with Monte Carlo simulation

• Summary
Neutrino-less double beta decay

\((A, Z) \rightarrow (A, Z + 2)^{++} + 2e^-\)

- Lepton number violation
- Majorana neutrino
- Access to the absolute neutrino mass scale
- Neutrino mass hierarchy
- ...

\[
\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu} |M^{0\nu}|^2 |f(m_i, U_{ei})|^2 > O(10^{24-25} \text{ yr})\text{ current limit}
\]

Phase space factor  Particle physics
Nuclear matrix element

- In the case of exchange of light Majorana neutrino

\[
f(m_i, U_{ei}) \equiv \frac{m_{\beta\beta}}{m_e} = \frac{1}{m_e} |\sum_{k=1,2,3} U_{ek}^2 m_k| \]

\[
\approx c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_1} m_2 + s_{13}^2 e^{i\alpha_2} m_3
\]

\(m_{\beta\beta}\): Effective Majorana mass  \(\alpha_1, \alpha_2\): Majorana phase
Experimental signature

- Two electrons
  - back-to-back
  - from a common vertex
- Sum of their kinetic energies is equal to the Q-value

**Experimental requirements**
- ✔ Good energy resolution
- ✔ High efficiency
- ✔ Very low background
- ✔ Large isotope mass

\[
S^{0\nu} = \ln 2 \cdot \frac{1}{n_\sigma} \cdot \frac{x \eta N_A}{M_A} \cdot \varepsilon \sqrt{\frac{MT}{B\Delta E}}
\]

- \(\varepsilon\): detection efficiency
- \(\Delta E\): FWHM energy resolution [keV]
- \(T\): measuring time [y]
- \(M\): detector mass [kg]
- \(B\): background level [/keV/y/kg]
- \(M_A\): compound molar mass
- \(x\): stoichiometric multiplicity of the element containing \(\beta\beta\) candidate
- \(\eta\): \(\beta\beta\) candidate isotopic abundance
- \(N_A\): Avogadro number
- \(n_\sigma\): confidence level
Main experimental approaches

• Calorimeter
  😊 Large source mass
  😊 Very high resolution (≈0.1% FWHM)

• External source
  😊 Event topology
  😊 Source replaceable
  😞 Smaller source mass
  😞 Lower energy resolution (>4%)
  😞 Less efficiency (~30%)
Major technique for external source

- **SuperNEMO** ($^{82}$Se or $^{150}$Nd)
  - Measure the energy of the two electrons by the plastic scintillator + PMT.
    - $\Delta E = 4\% \text{ FWHM, } \varepsilon \sim 30\%$
  - Reconstruct the event topology by the drift chamber etc.

- **DCBA** ($^{150}$Nd)
  - Reconstruct the momentum of the two electrons by the drift chamber in B-field, and calculate the energy.
    - $\Delta E = 6\% \text{ FWHM, } \varepsilon \lesssim 30\%$

- **MOON** ($^{100}$Mo or $^{82}$Se or $^{150}$Nd)
  - Measure the electron energy by the scintillator + PMT ($\Delta E = 6\% \text{ FWHM}$)
  - Measure the position by the scintillating fiber + PMT.

Possible to improve $\Delta E$ and $\varepsilon$ with another different technique?
A new idea for external source

• Reconstruct the kinetic energy by measuring the velocity $\beta$:
  
  $$ E = \frac{m_e}{\sqrt{1 - \beta^2}} - m_e $$

• Measure $\beta$ from TOF of the electron
  
  1. Calculate the vertex $(x_0, y_0, 0; t_0)$ from Cherenkov photon hit positions and timings.
  2. Identify the electron hit position and timing $(x, y, L; t)$ where the electron emit Cherenkov light in the sensor window.
  3. Calculate $\beta c = \sqrt{(x-x_0)^2+(y-y_0)^2+L^2} / (t-t_0)$

  $$ \Delta \beta = \frac{\beta^2 c}{L} \Delta t $$

• Need a good time resolution
• and a long flight length.
• Lower Q-value source is better.
Advantage compared to the other external source experiments

• Vacuum → Expect no background except $\nu \nu \beta \beta$
• Possible to achieve $\Delta E \sim$ a few %
  – $^{130}\text{Te}$ ($Q = 2.527$ MeV, $\beta = 0.9576$)
    • 25 keV (FWHM) at 2.5 MeV $\rightarrow \sigma_\beta = 0.00037$ and $\sigma_t = 5.4$ ps for $L = 4$ m
  – $^{154}\text{Sm}$ ($Q = 1.215$ MeV, $\beta = 0.8895$)
    • 12 keV (FWHM) at 1.2 MeV $\rightarrow \sigma_\beta = 0.00077$ and $\sigma_t = 12.9$ ps for $L = 4$ m
  * Photon sensor of the best time resolution: MCP-PMT ($\sigma_t \sim 30$ ps)
• Better efficiency than 30% could be achieved.

[Disadvantage]

• Large vacuum chamber
  $\rightarrow$ Scalability similar to the other experiments
Monte Carlo simulation (all-too-easy way) out of consideration of cost

• Construct the detector only with the existing technologies.
  – A kind of the first trial; no optimization yet for the detector, analysis etc.
  – However every important parameter is included.
  – No background except the $\nu\nu\beta\beta$ decay and the PMT dark noise.
  – Primary electrons are generated at the center and normal to the source in this simulation and there is no sensor on the side walls (as the coding is still on the way).

$^{130}\text{Te} (10 \times 10 \text{ m}^2 \times 100 \mu\text{m})$

62.4 kg ($\eta = 33.8\%$)

$Q = 2.527 \text{ MeV}$

Array of 2-inch MCP-PMTs (single anode)

$\Delta t = 30 \text{ ps for single photons}$

Peak QE = 33% at 280 nm (High-QE UV)

Collection efficiency = 60%

Photocoverage = 79.6%

Dark rate = 30 Hz/cm$^2$

Optical film (0.6 mm thick)

$n = 1.53, 1.02 \text{ g/cm}^3$

PHOTONIS PLANACON®
0νββ MC simulation

MC event display

Generated Cherenkov photons ~ 80 / film

Need 3 hits or more to reconstruct the vertex

20% loss

Cherenkov photon
Dark noise in 200 ns
Reconstruction ($0\nu\beta\beta$ MC)

- Vertex reconstruction
  \[ \sigma_x = 30 \text{ mm} \]

- Energy reconstruction
  \[ \Delta E = 240 \text{ keV FWHM} \]
  \[ \varepsilon = 19\% \]
  \[ \Delta E \text{ is dominated by the sensor time resolution} \]
Spectrum (MC)

\[ S^{0\nu} = 4.8 \times 10^{25} \text{ y} \]
MC simulation (challenging option) with realistic cost

• Given that I can realize a novel photon sensor in my mind.
  – It will be very low-cost and be feasible to construct the large scale detector.

• The other conditions in MC are the same as the previous one.

$^{130}$Te (10 x 10 m$^2$ x 100 μm)
62.4 kg (η = 33.8%)
Q = 2.527 MeV

A novel photon sensor in my mind
Δt = 20 ps for single photons
Peak QE = 33% at 280 nm (High-QE UV)
Collection efficiency = 80%
Photocoverage = 100%
Dark rate = 30 Hz/cm$^2$
Will be very low-cost

Optical film (0. mm thick)
n = 1.53, 1.02 g/cm$^3$
Spectrum (MC, challenging option)

\[ \Delta E = 200 \text{ keV FWHM} \]
\[ \varepsilon = 42\% \]

\[ S^{0
\nu} = 8.0 \times 10^{25} \text{ y} \]
Competitive to the other experiments?

S. Dell’Oro et al., Advance in High Energy Physics, 2016, 2162659.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Technique</th>
<th>$^{130}\text{Te}$</th>
<th>M [kg]</th>
<th>Exposure [kg y]</th>
<th>FWHM at Q [keV]</th>
<th>B [counts /keV/kg/y]</th>
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<td>Bolometer</td>
<td>741</td>
<td>1030</td>
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<td>SNO+</td>
<td>LScintillator</td>
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<td>3980</td>
<td>270</td>
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<td>SuperNEMO</td>
<td>Ext. source</td>
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<td>500</td>
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<td>10</td>
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<tr>
<td>This exp. (MC)</td>
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Very preliminary
Competitive to the other experiments?

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**YES**

Just buy the components, but the cost will be comparable to SuperKEKB.

or

Develop the novel photon sensor of much low cost.

However a breakthrough idea is necessary after those next generation experiments.

Very preliminary
$^{130}\text{Te} (10 \times 16 \text{ m}^2 \times 100 \text{ m})$

100 kg

Space chamber in JAXA
Summary

• “Everyone wants to find a neutrino-less double beta decay.”
• The new technique with TOF is encouraging.

• To do
  – (I have just started this study, all from scratch.)
  – Proof of principle of this new TOF technique with a small prototype (four MCP-PMTs) using cosmic rays.
  – Monte Carlo simulation for optimization of the detector and analysis.
  – Background estimation.
  – Choose the best isotope for this experiment.
  – Development of a novel photon sensor. (no difficulty involved)