ジルコニウム96を用いたニュートリノを放出しない二重ベータ崩壊事象の探索

Supported by Grant-in-Aid for Scientific Research on Innovative Areas 26105502

日本物理学会 2015年秋季大会
2015年9月27日

宮城教育大学教育学部 福田 善之、那仁格日楽、小畑 旭*
東京大学宇宙線研究所 森山 茂栄
福井大学工学部 小川 泉
東京理科大学理工学部 郡司天博、塚田 学、速水良平
Neutrinoless double beta decay

\[
[T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)]^{-1} = G_{0\nu}(E_0,Z) | M_{0\nu} |^2 <m_{\nu}>^2 / m_e^2
\]

\[
[T_{1/2}]^2 \sim a \left( \frac{M_t}{\Delta E \cdot B} \right)
\]

a: abundance  
M: target mass  
t: measuring time  
\( \Delta E \): energy resolution  
B: BG rate

Requirement: Low BG, Large target mass, High energy resolution
Zirconium Complex in Organic Liquid Scintillator for neutrinoless double beta decay (ZICOS) experiment

Goals for development of LS:
1. high solubility
2. 3.5% at 3.35MeV of energy resolution, if ZICOS have PMTs with 40% photo coverage and long attenuation length (~10m)

Pure water surrounding inner detector to veto external backgrounds.

Inner detector with 40% photo coverage 10” PMT including Zirconium loaded 14.1 tons LS
Backgrounds around 3.35MeV

Measured by KamLAND-Zen

208Tl $\beta + \gamma$'s

$\gamma$ 2.6MeV + 
① $\beta_{\text{max}}$ 1.89 MeV  
$+ \gamma$ 0.58 MeV  
$(8.45 \times 10^{-01})$

② $\beta_{\text{max}}$ 1.29 MeV  
$+ \gamma$ 1.09 MeV  
$(3.97 \times 10^{-03})$

③ $\beta_{\text{max}}$ 1.53 MeV  
$+ \gamma$ 0.86 MeV  
$(1.24 \times 10^{-01})$

I.Shimizu@Neutrino2014
Neutrino mass sensitivity of ZICOS experiment

Results from NEMO-3 ($^{96}$Zr) \[ T_{1/2}^{0\nu} > 9.2 \times 10^{21} \text{y} \]
\[ <m_\nu > = 7.2 - 10.8 \text{ eV (g}_A=1.25, g_{pp}=1.11, QRPA) \]

(Ref: M.B.Kauer  Doctor thesis for UCL(2010))

Assuming same energy resolution, BG rate and measurement time as KamLAND-Zen
\[ (T_{1/2}^{0\nu} > 2.6 \times 10^{25} \text{y} ) \] (Ref: I.Shimizu  arXiv:1409.0077 (2014))

Mass : 14.1ton \[ \rightarrow \] 10wt.% Zr(iprac)\_4 = 1.57ton
includes 216kg of Zirconium
\[ = 6.5kg \text{ of } ^{96}\text{Zr} \]
\[ (= 9.2kg \text{ of } ^{136}\text{Xe} = 0.03 \times KL-Zen) \]

\[ T_{1/2}^{0\nu} > 4.4 \times 10^{24} \text{y} \] ← Not enough for $0\nu\beta\beta$ search
Neutrino mass sensitivity of ZICOS experiment

1) Zr enrichment
   58.5% enrichment of $^{96}$Zr (e.g. 57.3% for NEMO-3)
   then $^{96}$Zr will be 126kg (0.56 times $^{136}$Xe 320kg)

   $T_{1/2}^{0\nu} > 1.9 \times 10^{25}$y;
   $<m_\nu> < 0.16 - 0.3$ eV ($g_A=1.25, g_{pp}=1.11$, QRPA)

2) Lowering BG rate
   i.e. $<1/30 \times KL$-Zen

   $T_{1/2}^{0\nu} > 1.0 \times 10^{26}$y;
   $<m_\nu> < 0.04 - 0.09$eV
Measurement of backgrounds of LS

Using subtracted # of events around 2.6MeV and 2.2MeV

$^{214}\text{Bi} < 4.9 \times 10^{-20}$ g/g

$^{208}\text{Tl} < 2.7 \times 10^{-22}$ g/g

($^{238}\text{U} < 6.4 \times 10^{-6}$ g/g)

($^{232}\text{Th} < 7.4 \times 10^{-7}$ g/g) (c.f. KL 10^{-16} g/g)
Background reduction

Residual backgrounds as shown in KamLAND-Zen are $^{208}$Tl $\beta$ decay + $\gamma$ 2.6MeV + $\gamma$ 0.58 MeV/$\gamma$ 1.09 MeV/$\gamma$ 0.86 MeV

Need additional technique except energy spectral shape obtained by scintillation light in order to reduce those backgrounds efficiently.

Can we use Cherenkov light for background reduction?
Property of Cherenkov light

- Refractive index of anisole: \( n = 1.518 \)
- Cherenkov angle is determined by \( \cos \theta = \frac{1}{n\beta} \)
- Assuming 1.65MeV electron, then \( \beta = 0.951 \) and Cherenkov angle \( \theta = 46.2 \) degree are expected.
- Cherenkov light should be measured.

(350nm – 550nm: 150-200 photon/MeV)

\[
\frac{dN}{dx} = 2\pi z^2 \alpha \sin^2 \theta_c \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda} = 475 z^2 \sin^2 \theta_c \text{photon/cm}
\]

c.f. Light yield of Scintillation: \(~12000\text{photon/MeV}\)

Cherenkov light = 1~2% of scintillation light
Light yield of scintillation in anisole

Relative scintillation light yield of anisole is 9.8% to standard cocktail (due to difference of quantum efficiency of PMT)
Measurement of Cherenkov light

Comparison of light yields between SC-37 filter off and on for anisole LS using back scattering method.
Light yield of Cherenkov lights

Cherenkov light yield (>400nm)
\[
\frac{158.9/0.183/0.95}{156.0/0.046/0.098} = \approx 0.026
\]
Consistent with expectation.
ZICOS proto-type detector

Performance test:
• Energy resolution
• BG reduction study using Cherenkov light

Physics goal:
• $^{96}$Zr: 12g (NEMO-3: 10g) using natural abundance Zirconium.
• Measure $2\nu\beta\beta$ half-life.
• Obtain limits beyond the NEMO-3 results.
Photon yield ratio between Cherenkov and scintillation lights in one PMT

Photon yield ratio between Cherenkov light and scintillation light is ~0.2.

It might be useful to identify PMTs which receive Cherenkov light, but can not extract those PMTs among the scintillation light by using only this information.
How to extract Cherenkov hits

Emission time
- Cherenkov light: ~3ps
- Scintillation light: ~20ns

Using difference of timing shape, we can extract PMTs received Cherenkov light.
Cherenkov rings calculated by toyMC

MC
ZICOS sensitivity: $T_{1/2}^{0\nu} > 1.0 \times 10^{26}$y and $\langle m_\nu \rangle < 0.1$ eV ($g_A=1.25, g_{pp}=1.11, QRPA$) if we can use 58.5% enriched $^{96}$Zr and reduce BG at $1/30 \times$ KamLAND-Zen.

Cherenkov light was observed and the light yield is almost 1~2 % of scintillation light.

ZICOS proto-type is now planning and it will demonstrate not only good energy resolution but also establish the background reduction method using Cherenkov light.