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VIII

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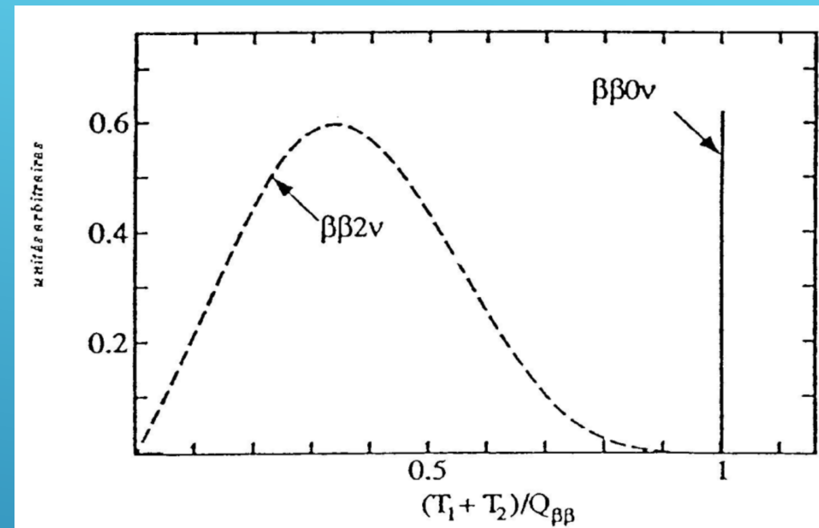
Neutrinoless double beta decay

$\beta\beta$ emitters with $Q_{\beta\beta} > 2$ Mev

Transition	$Q_{\beta\beta}$ (keV)	Abundance (%) ($^{232}Th = 100$)
$^{110}Pd \rightarrow ^{110}Cd$	2013	12
$^{76}Ge \rightarrow ^{76}Se$	2040	8
$^{124}Sn \rightarrow ^{124}Te$	2288	6
$^{136}Xe \rightarrow ^{136}Ba$	2479	9
$^{130}Te \rightarrow ^{130}Xe$	2533	34
$^{116}Cd \rightarrow ^{116}Sn$	2802	7
$^{82}Se \rightarrow ^{82}Kr$	2995	9
$^{100}Mo \rightarrow ^{100}Ru$	3034	10
$^{96}Zr \rightarrow ^{96}Mo$	3350	3
$^{150}Nd \rightarrow ^{150}Sm$	3667	6
$^{48}Ca \rightarrow ^{48}Ti$	4271	0.2



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

$[T_{1/2}]^2 \sim a(Mt/\Delta E \cdot B)$ a: abundance   M: target mass

t: measuring time ΔE: energy resolution   B: BG rate

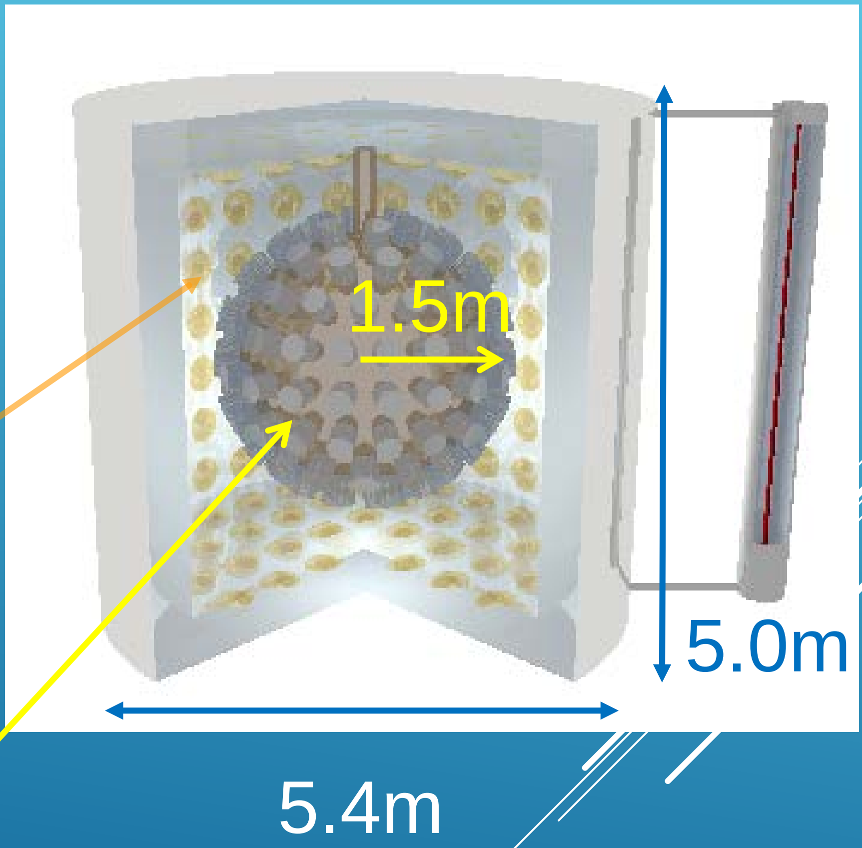
Requirement : Low BG, Large target mass, High energy resolution

Zirconium Complex in Organic Liquid Scintillator for neutrinoless double beta decay (ZICOS) experiment

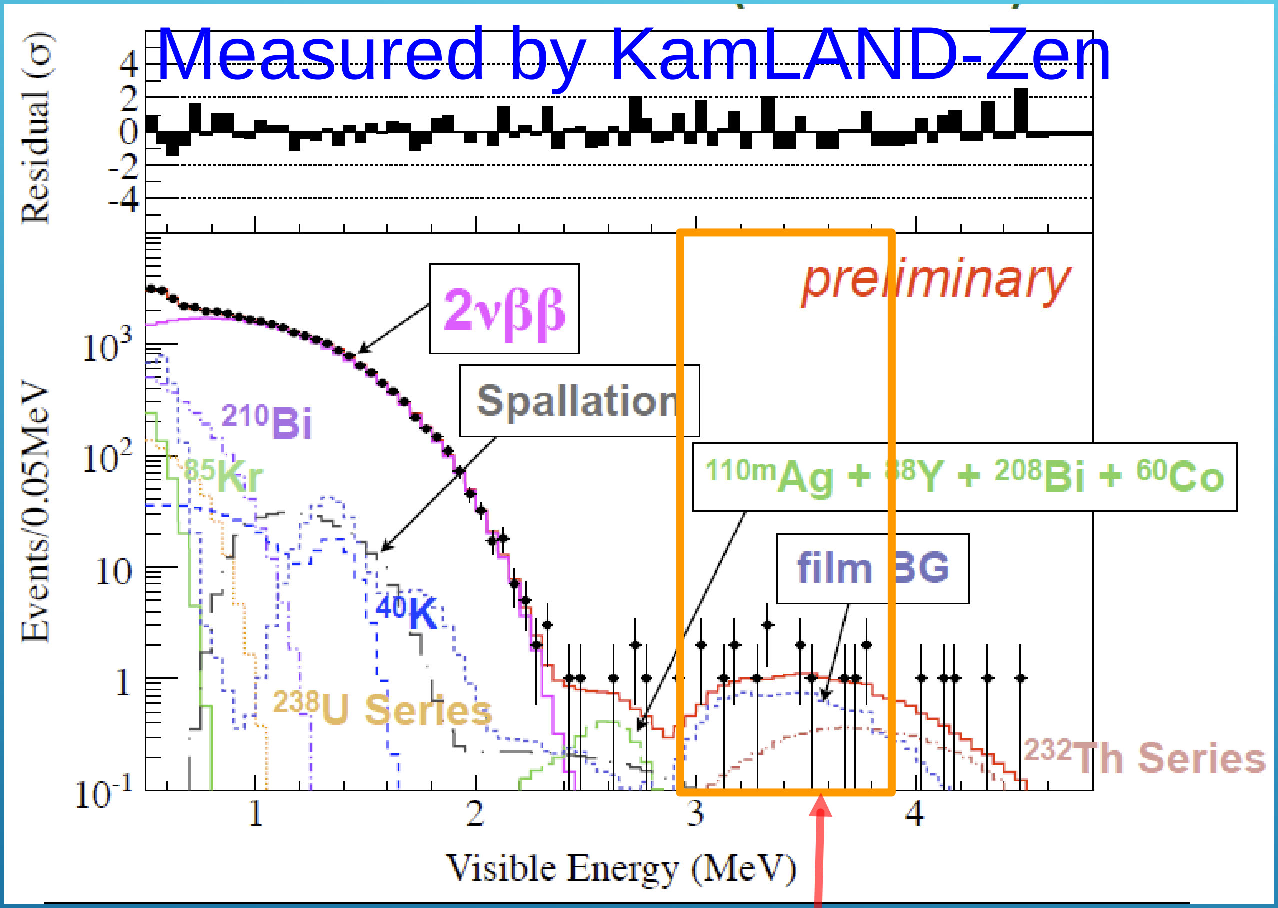
Goals for development of LS ：
(1) high solubility
(2) 3.5% at 3.35MeV of energy resolution, if ZICOS have PMTs with 40% photo coverage and long attenuation length (~10m)

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



I.Shimizu@Neutrino2014

$0\nu\beta\beta$ signal region for ^{96}Zr

^{208}Tl $\beta + \gamma$'s

γ 2.6MeV +

① β_{max} 1.89 MeV + γ 0.58 MeV (8.45×10^{-01})

② β_{max} 1.29 MeV + γ 1.09 MeV (3.97×10^{-03})

③ β_{max} 1.53 MeV + γ 0.86 MeV (1.24×10^{-01})

Neutrino mass sensitivity of ZICOS experiment

Results from NEMO-3 (^{96}Zr) : $T_{1/2}^{0\nu} > 9.2 \times 10^{21}$y

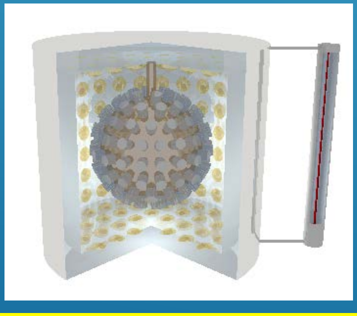
$\langle m_\nu \rangle$ 7.2 – 10.8 eV (g_A=1.25,g_{pp}=1.11,QRPA)

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

Assuming same energy resolution, BG rate and measurement time as KamLAND-Zen

($T_{1/2}^{0\nu} > 2.6 \times 10^{25}$y) (Ref: I.Shimizu arXiv:1409.0077 (2014))

Mass : 14.1ton → 10wt.% Zr(iprac)$_4$ = 1.57ton



includes 216kg of Zirconium

= 6.5kg of ^{96}Zr

(= 9.2kg of ^{136}Xe = 0.03 ×KL-Zen)

$T_{1/2}^{0\nu} > 4.4 \times 10^{24}$y ← Not enough for $0\nu\beta\beta$ search

Neutrino mass sensitivity of ZICOS experiment

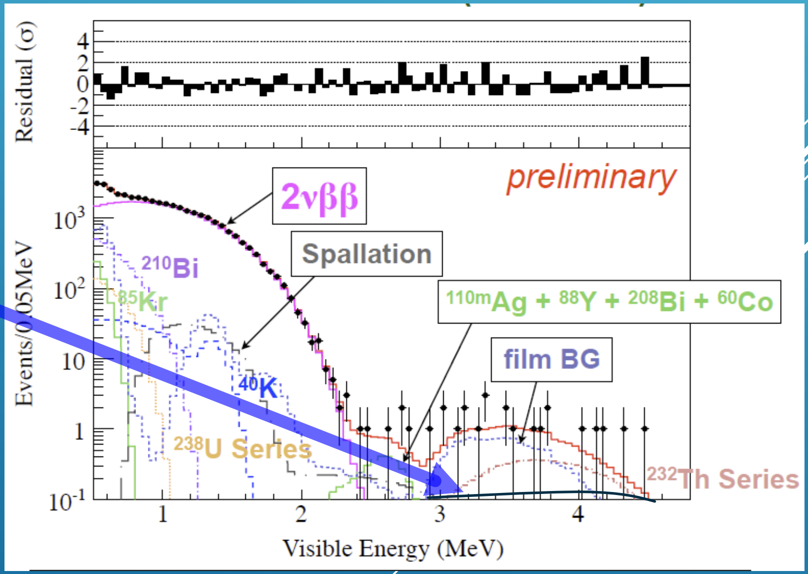
1) Zr enrichment

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)

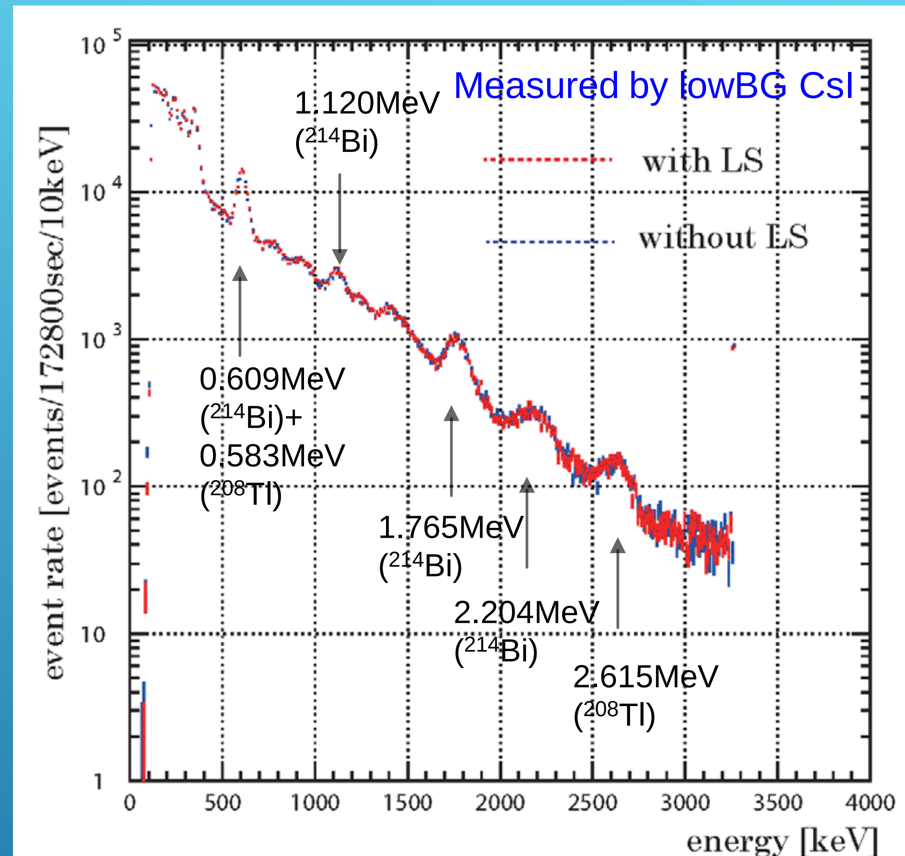
$T_{1/2}^{0\nu} > 1.9 \times 10^{25}$y ;
$\langle m_\nu \rangle <$ 0.16 – 0.3 eV (g_A=1.25,g_{pp}=1.11,QRPA)

2) Lowering BG rate
i.e. < 1/30 × KL-Zen

$T_{1/2}^{0\nu} > 1.0 \times 10^{26}$y ;
$\langle m_\nu \rangle <$ 0.04 – 0.09eV



Measurement of backgrounds of LS



Using subtracted # of events around 2.6MeV and 2.2MeV

^{214}Bi $< 4.9\times10^{-20}$g/g ^{208}Tl $< 2.7\times10^{-22}$ g/g

(^{238}U $< 6.4\times10^{-6}$ g/g) (^{232}Th $< 7.4\times10^{-7}$ g/g) (c.f. KL 10^{-16}g/g)

Background reduction

Residual backgrounds as shown in KamLAND-Zen are ^{208}Tl β decay + γ 2.6MeV+ γ 0.58 MeV/γ 1.09 MeV/γ 0.86 MeV

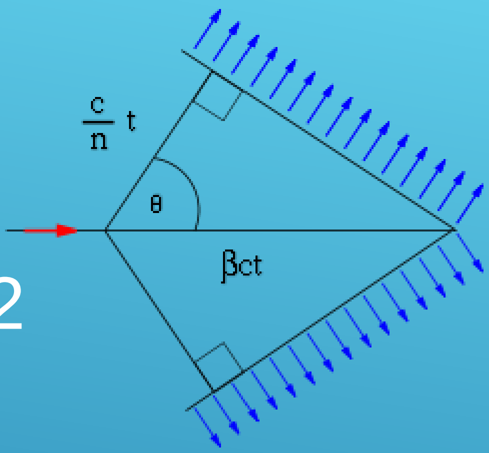
↓

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
  cosθ= 1/nβ
- Assuming 1.65MeV electron, then β=0.951 and Cherenkov angel θ=46.2 degree are expected.
- Cherenkov light should be measured.
  (350nm – 550nm : 150-200 photon/MeV)

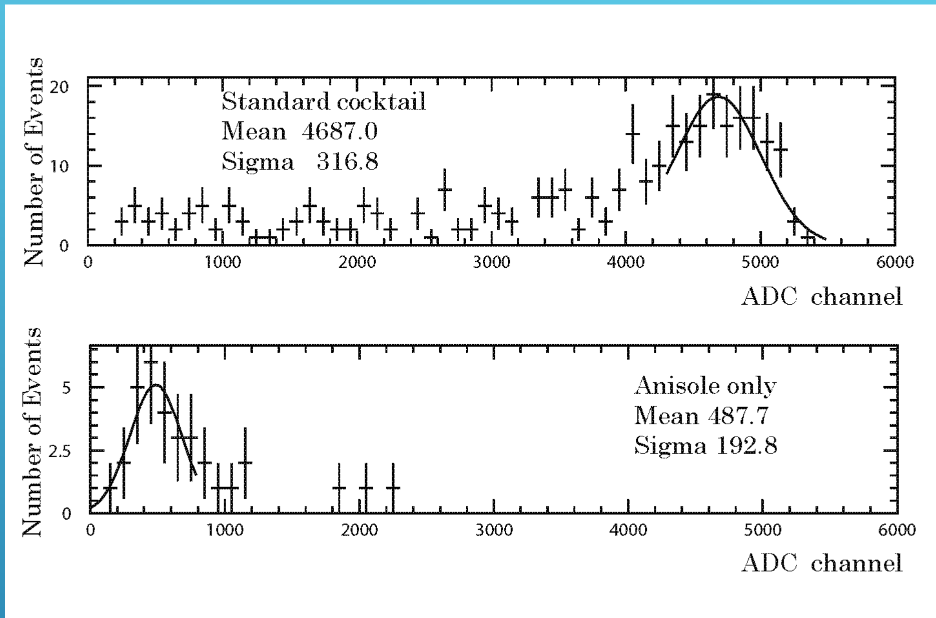


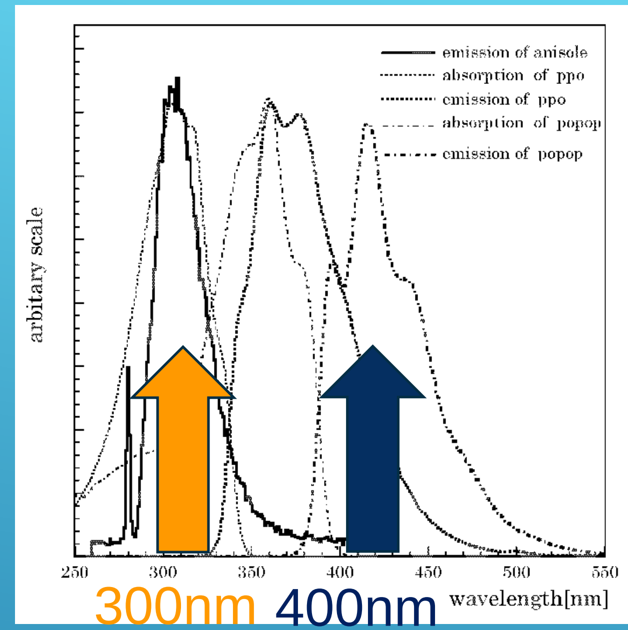
$$\frac{dN}{dx} = 2\pi z^2 \alpha \sin^2 \theta_c \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda} = 475 z^2 \sin^2 \theta_c \mathrm{photon/cm}$$

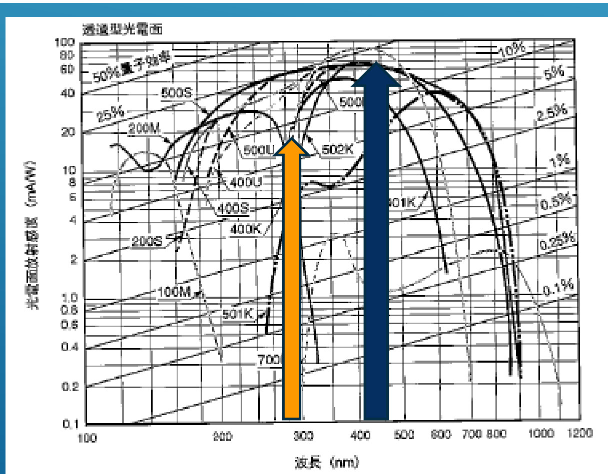
c.f. Light yield of Scintillation : ~12000photon/MeV

Cherenkov light = 1~2% of scintillation light

Light yield of scintillation in anisole

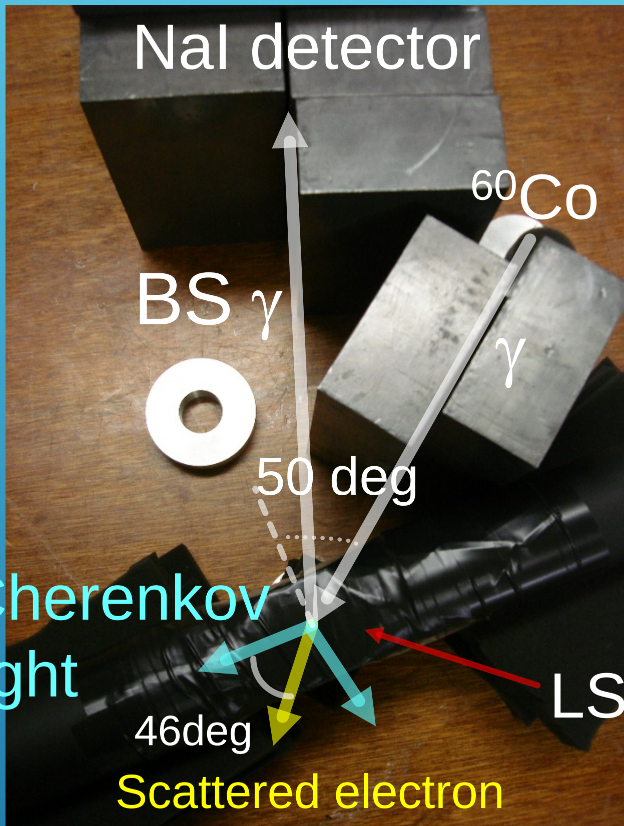




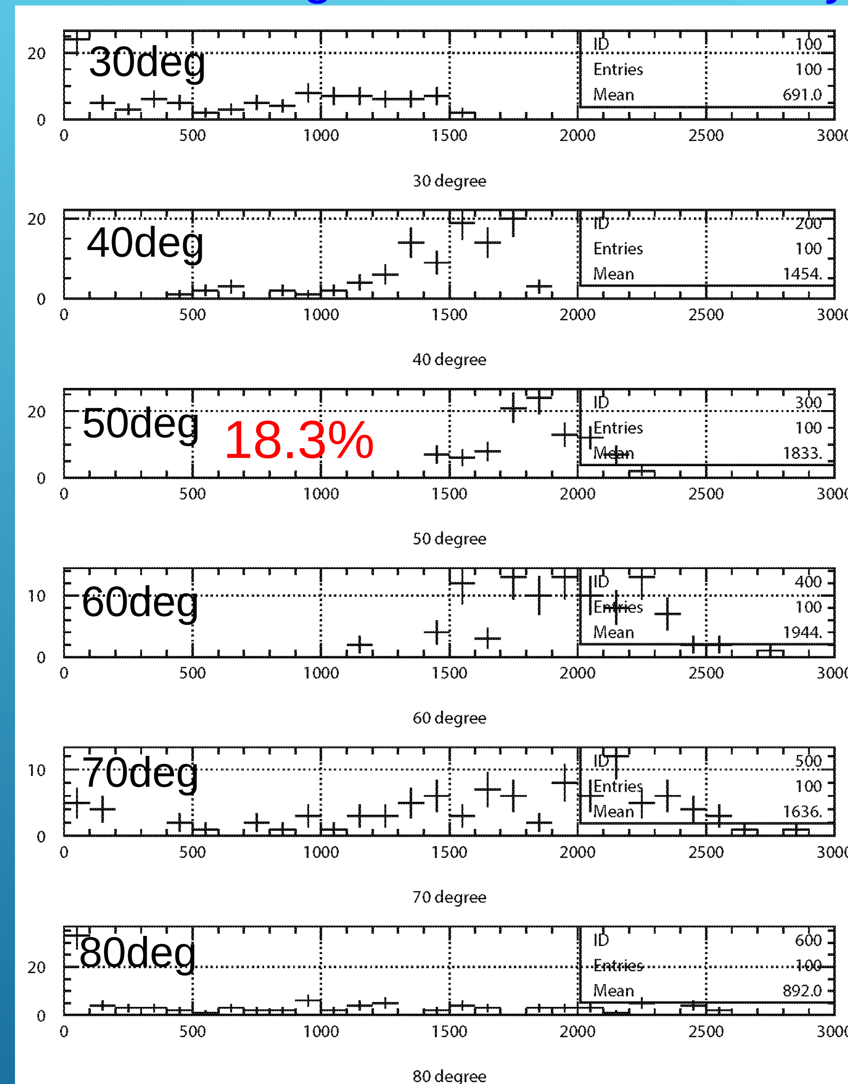


Relative scintillation light yield of anisole is 9.8% to standard cocktail (due to difference of quantum efficiency of PMT)

Measurement of Cherenkov light

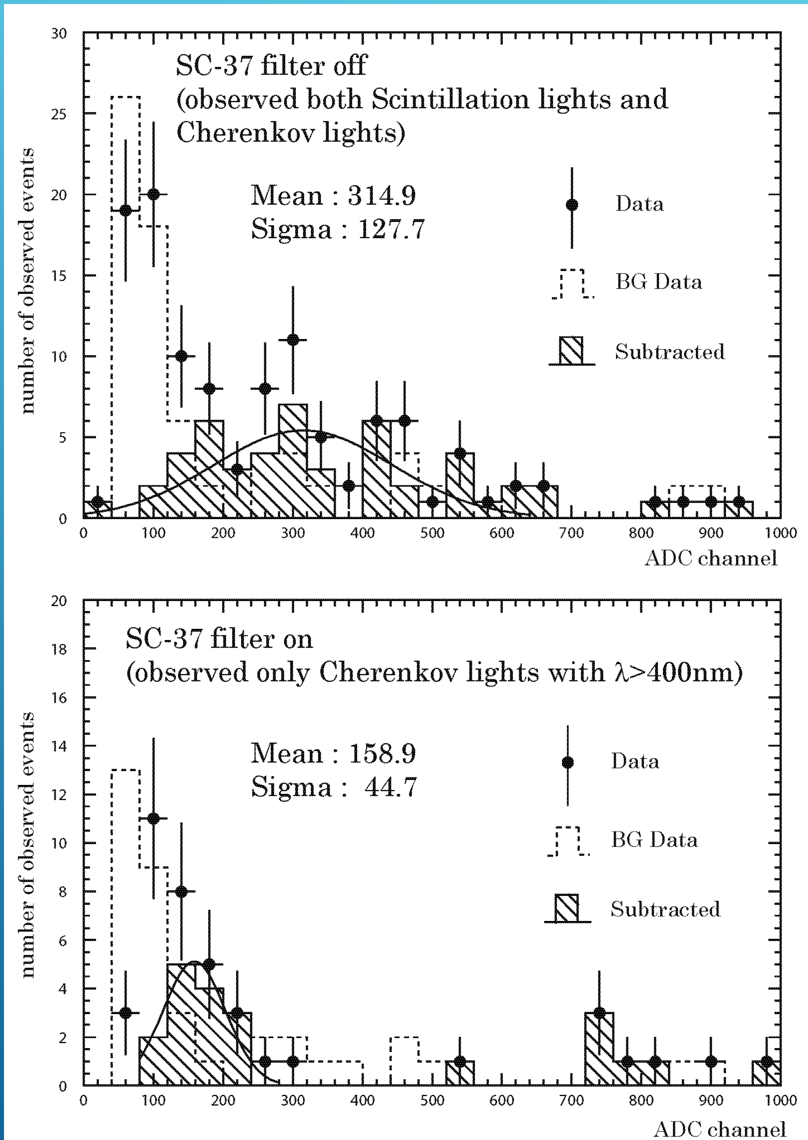


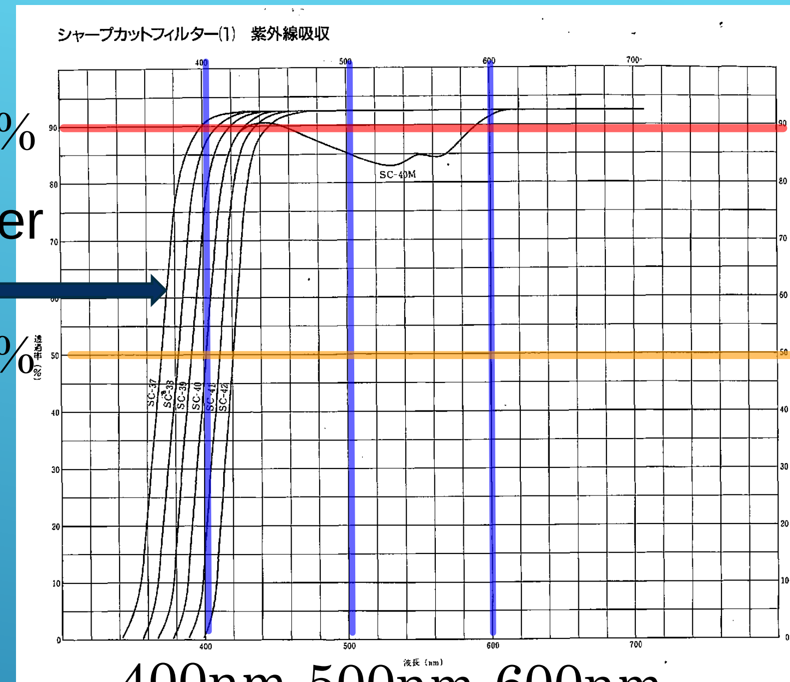
Geometric light collection efficiency



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

Light yield of Cherenkov lights

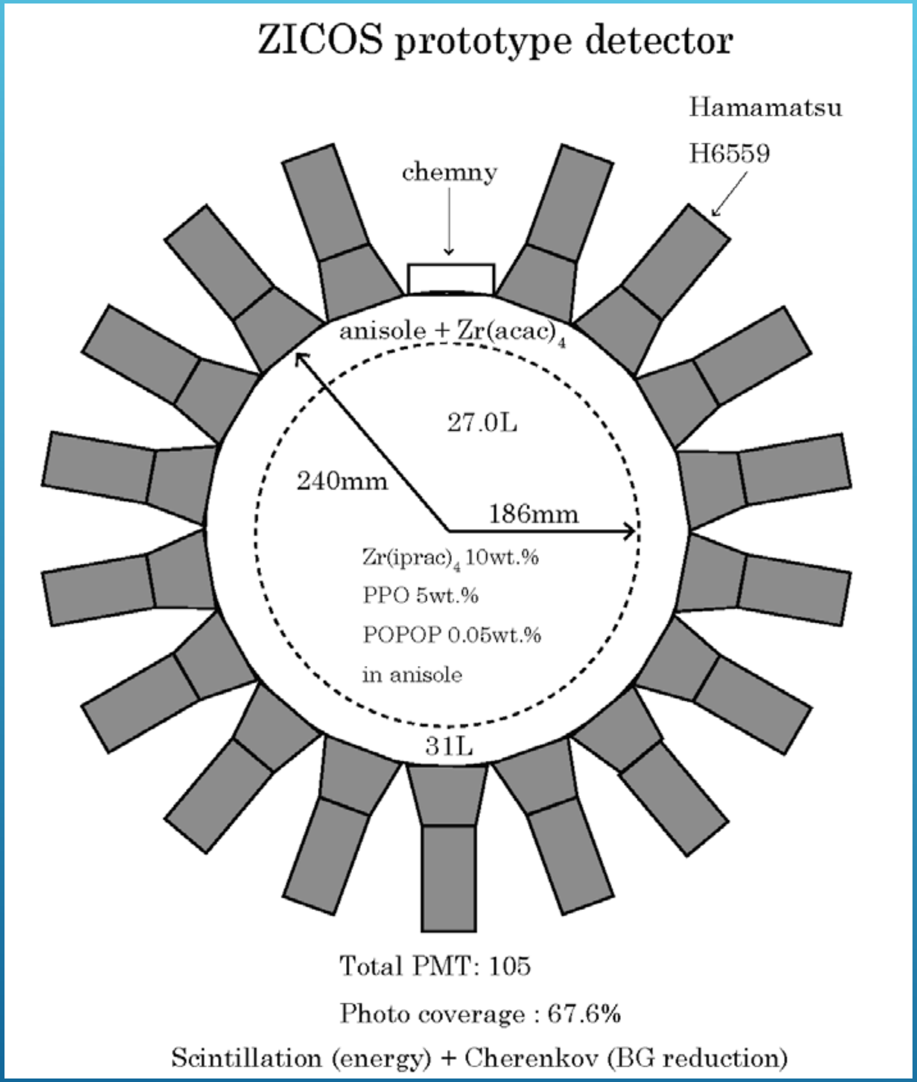




$$\frac{\text{Cherenkov light yield (>400nm)}}{\text{Scintillation light yield of std. LS}} = \frac{158.9/0.183/0.95}{156.0/0.046/0.098} = \sim 0.026$$

Consistent with expectation.

ZICOS proto-type detector



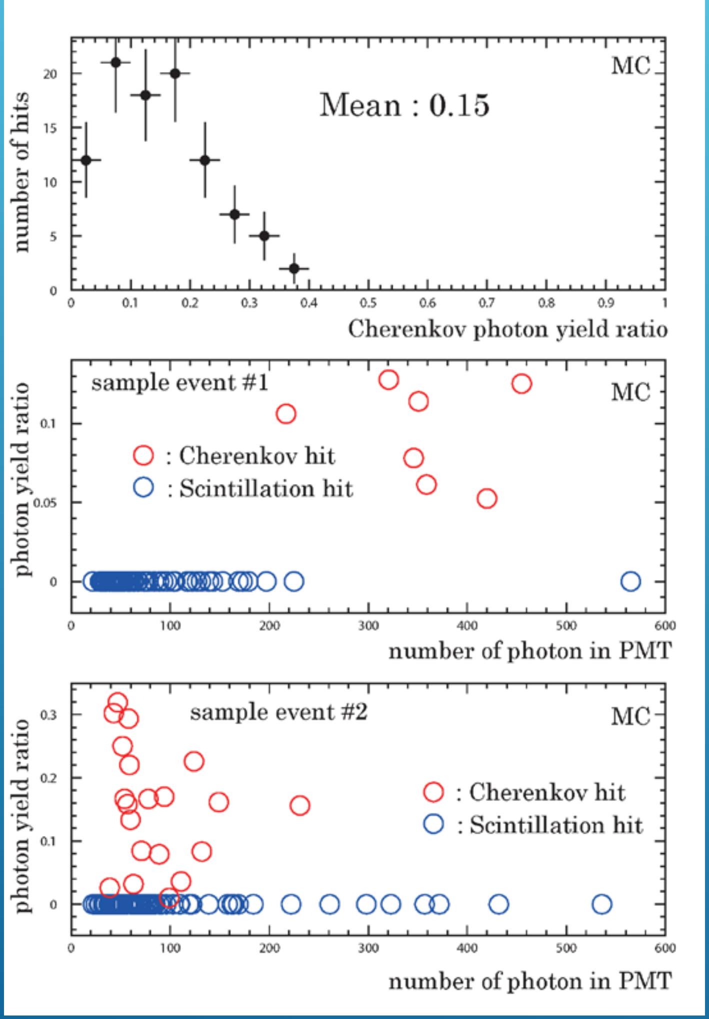
Performance test :

- 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



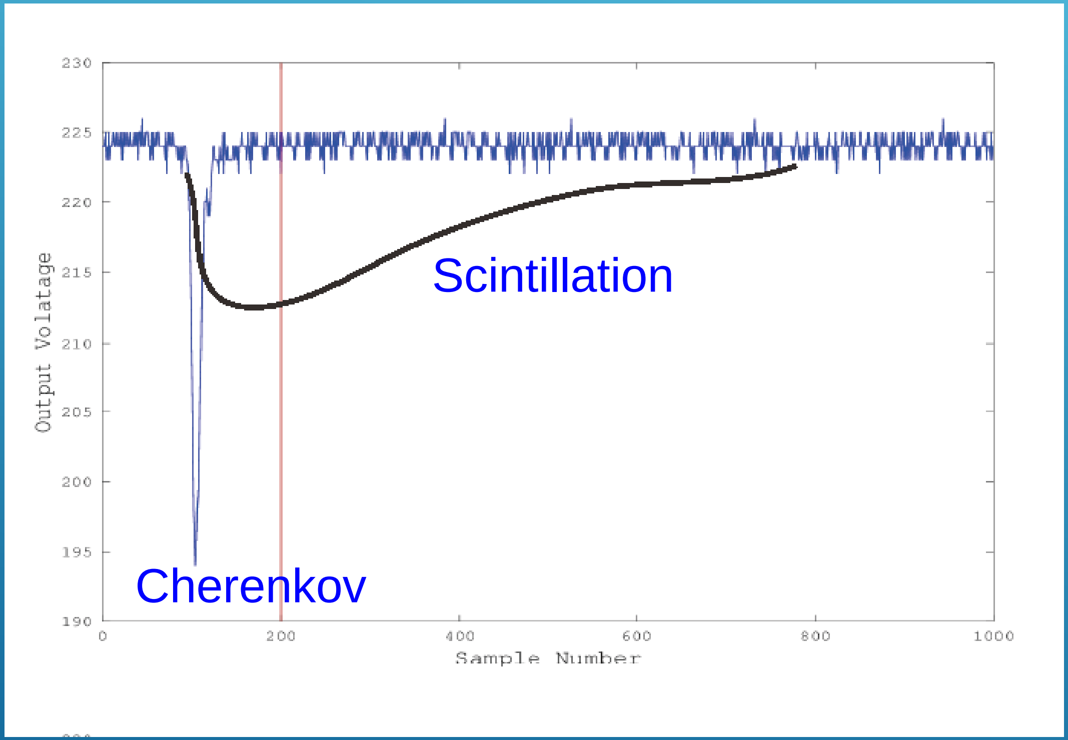
Photon yield ratio between Cherenkov light and scintillation light is ~0.2.

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

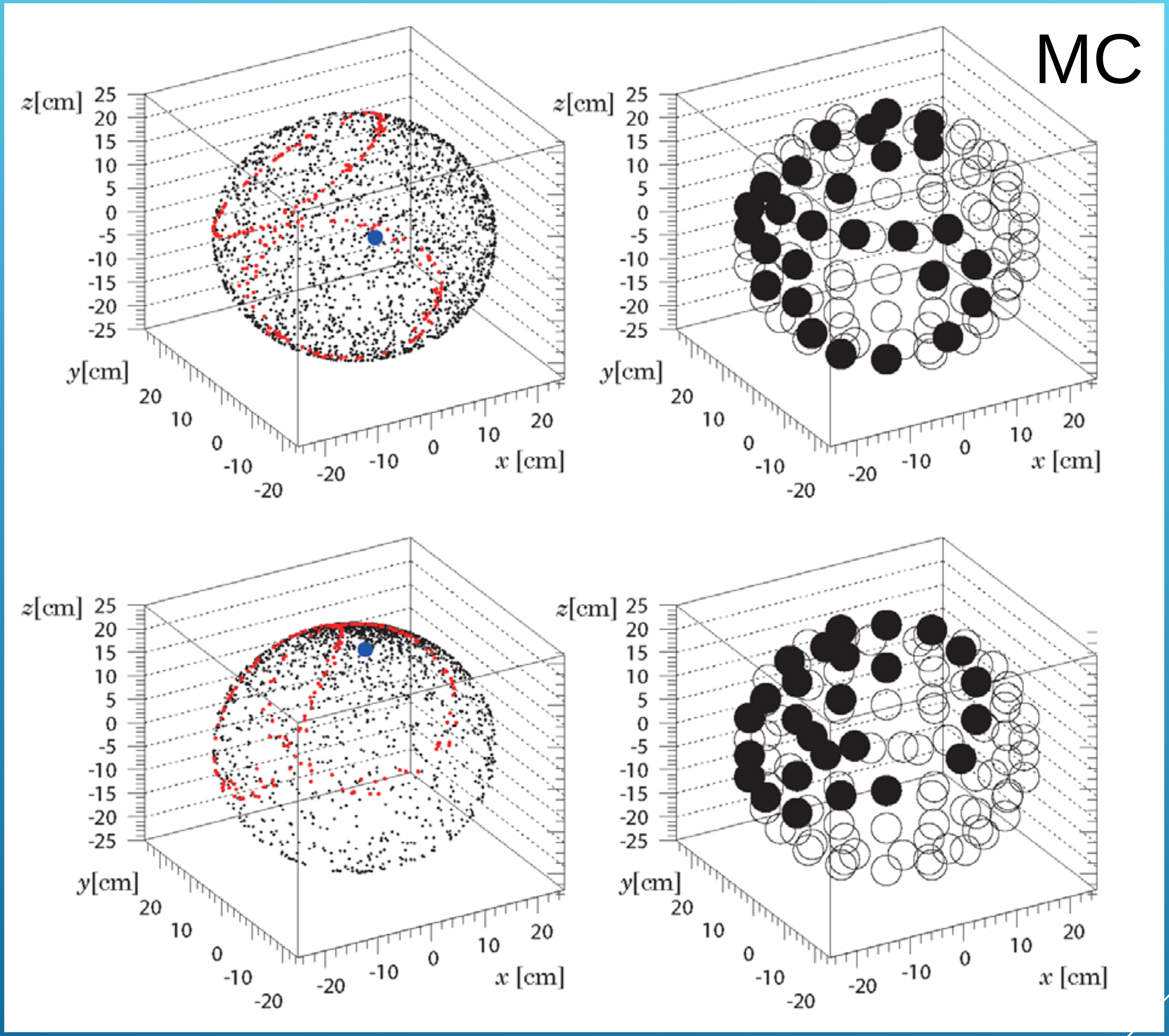
Emission time

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



Using difference of timing shape, we can extract PMTs received Cherenkov light.

Cherenkov rings calculated by toyMC



SUMMARY

- 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 × 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.