ZICOS – NEW PROJECT FOR NEUTRINOLESS DOUBLE BETA DECAY EXPERIMENT USING ZIRCONIUM COMPLEX IN ORGANIC LIQUID SCINTILLATOR –

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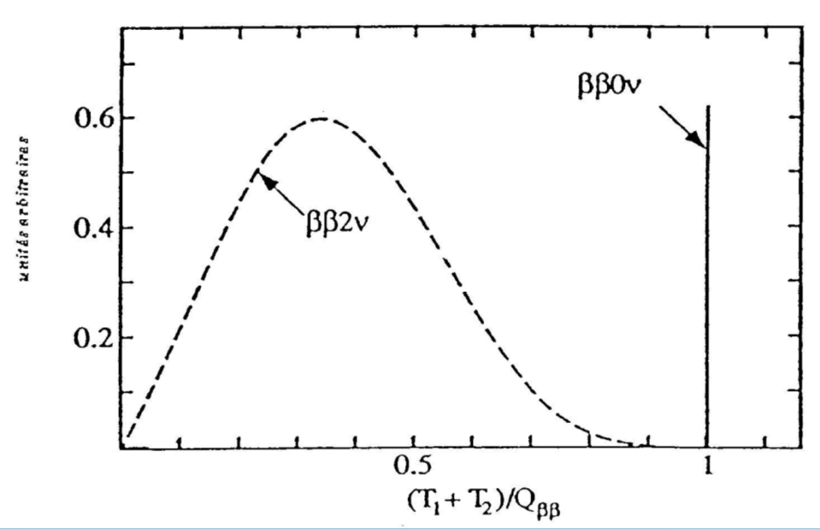
Neutrinoless double beta decay

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

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



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

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

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

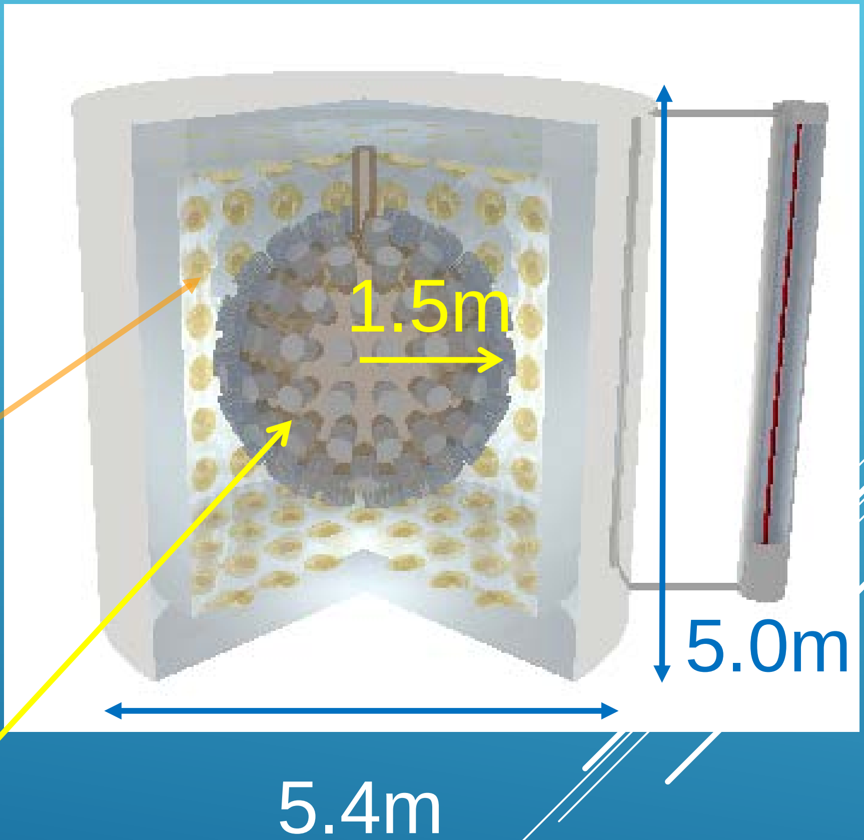
Requirement : Low BG, Large target mass, High energy resolution

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

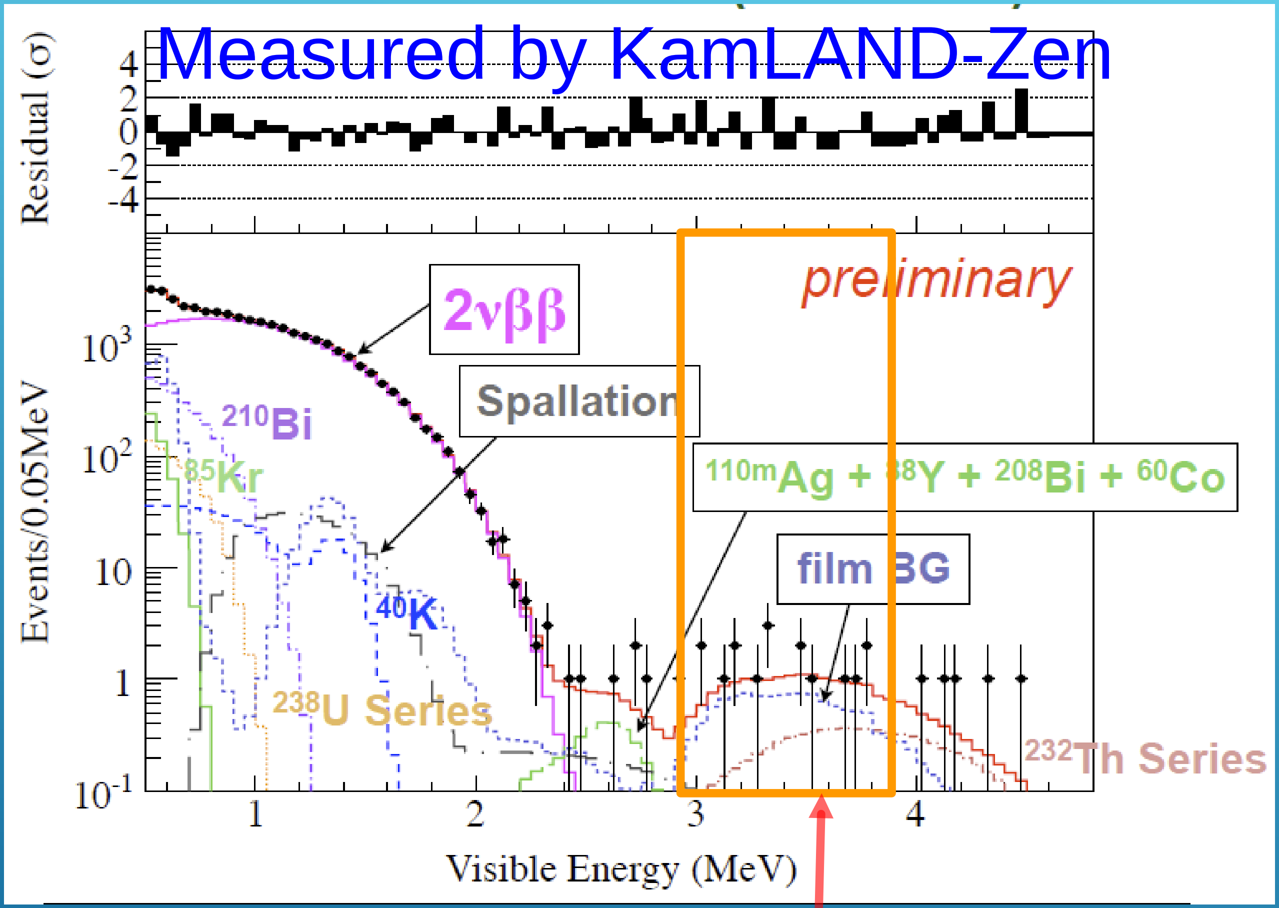
Goals for development of LS :
(1) high solubility
(2) 3.5% at 3.35MeV of energy resolution, if ZICOS have PMTs with 40% photo coverage and long attenuation length (~10m)

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

0νββ signal region for ^{96}Zr

- ^{208}Tl β + γ '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

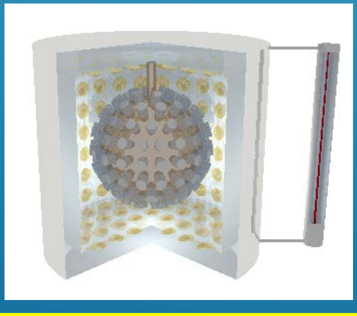
($T_{1/2}^{0\nu} > 2.6 \times 10^{25}$y) (Ref: I.Shimizu arXiv:1409.0077 (2014))

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)

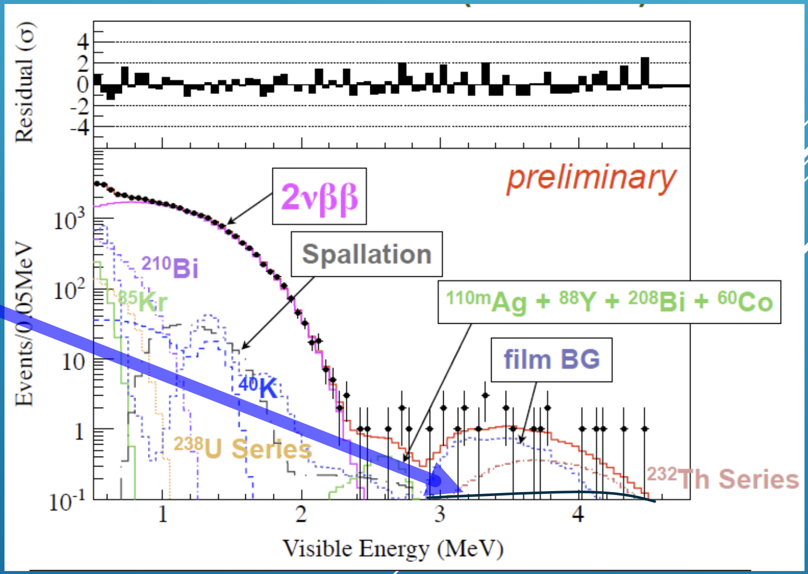
$T_{1/2}^{0\nu} > 1.9 \times 10^{25}$y ; $<m_\nu> <$ 0.16 – 0.3 eV (QRPA)

2) Lowering BG rate

i.e. < 1/30 × KL-Zen

$T_{1/2}^{0\nu} > 1.0 \times 10^{26}$y ;

$<m_\nu> <$ 0.04 – 0.09eV

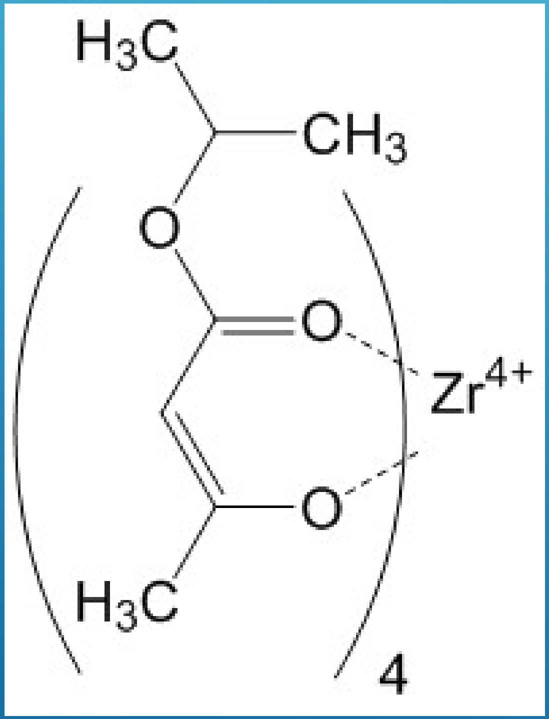


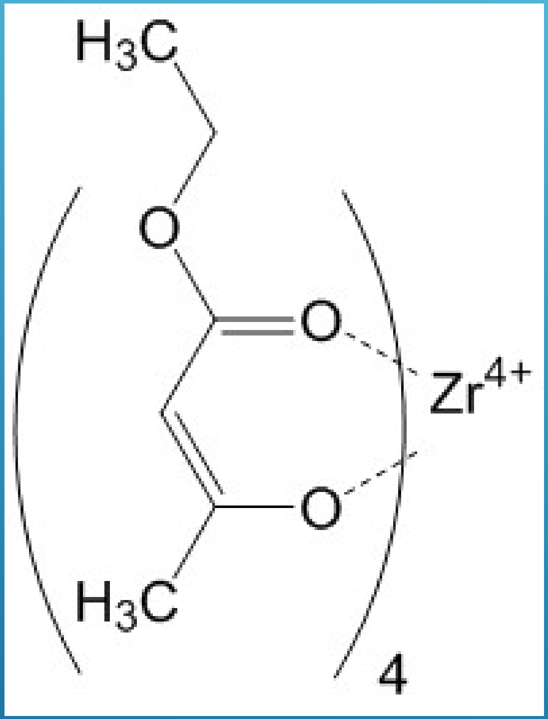
Development of Liquid scintillator

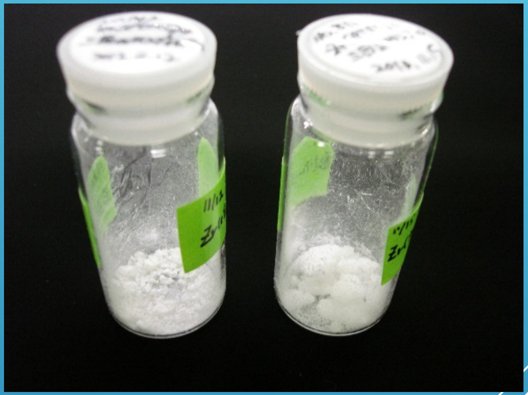
Zirconium β-keto ester complex

$Zr(CH_3COCHCOOCH(CH_3)_2)_4$
= $Zr(iprac)_4$
mw : 663.87

$Zr(CH_3COCHCOOCH_2CH_3)_4$
= $Zr(etac)_4$
mw : 607.76





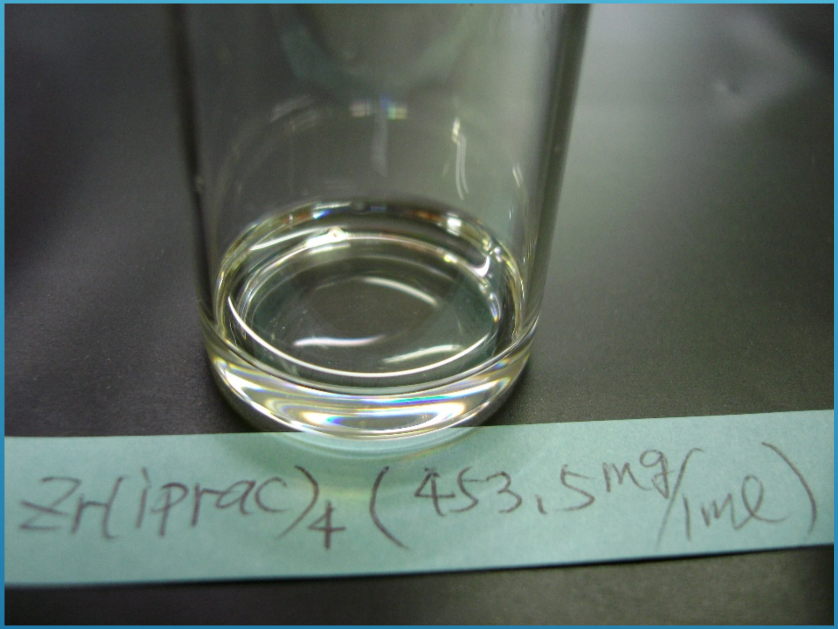


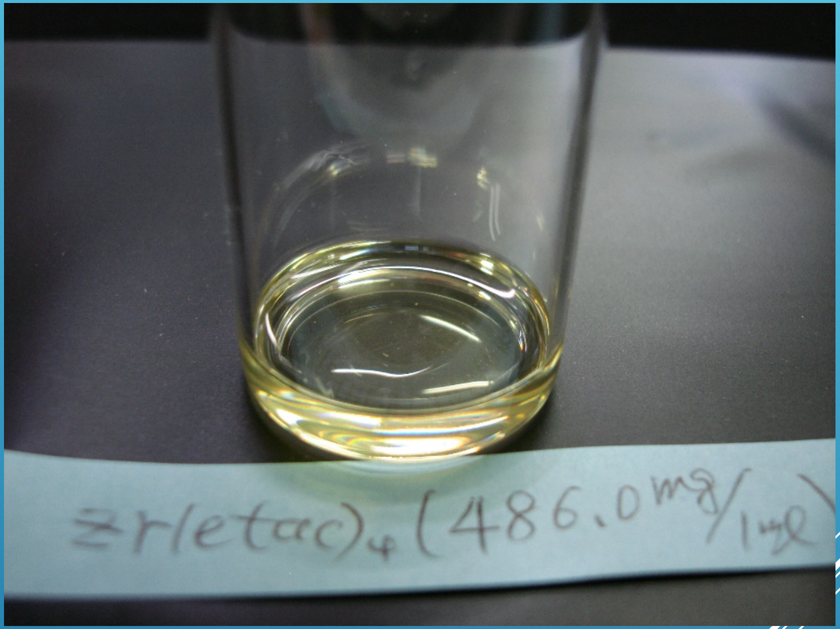
Synthesized by Prof. T.Gunji

Stable solid powder was obtained.

Solubility of Zirconium β-keto ester complex for anisole

Zr(iprac)$_4$: 31.2wt.%　　Zr(etac)$_4$: 32.7wt.%

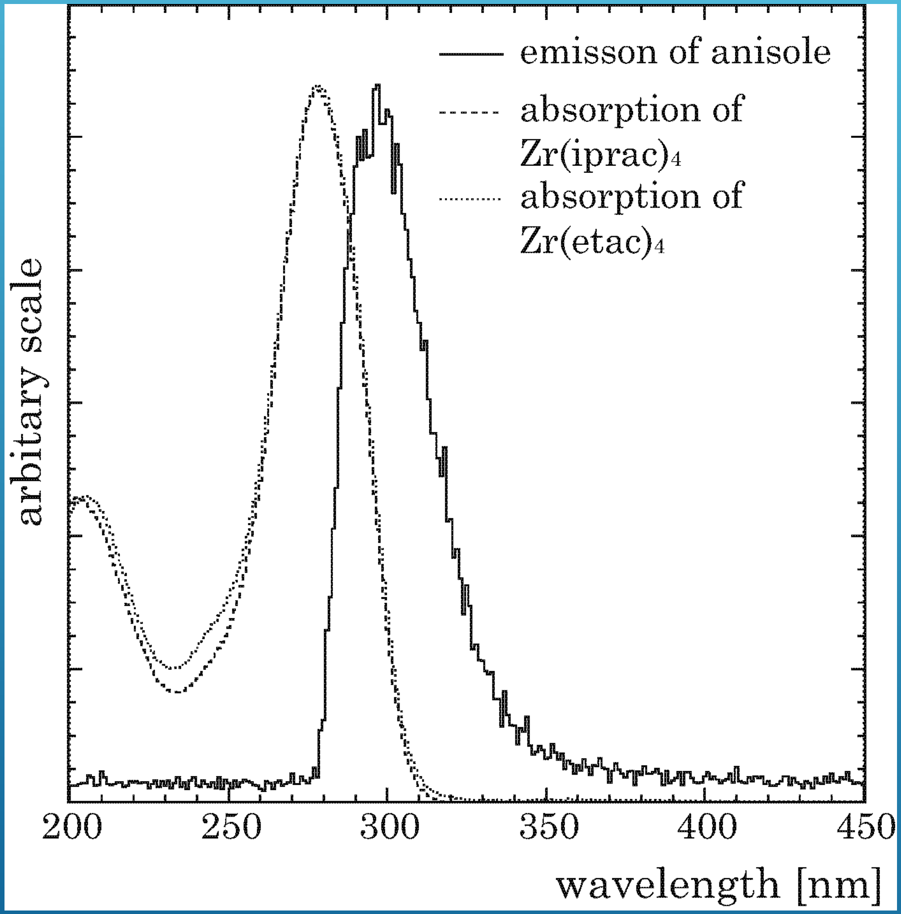




Very huge solubility !

> 70g/L of Zirconium could be solved in anisole.

Absorbance spectra for zirconium β-keto ester complex

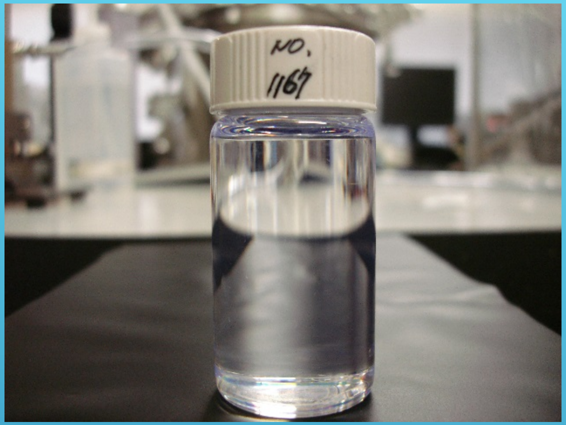


Absorption peaks of $Zr(iprac)_4$ and $Zr(etac)_d$ were found around at 278nm.

Part of region of emission and absorption spectrum was overlapped.

Light yield quenching by Zr complex

$$\text{Light yield} = L_0 \times \frac{\sigma_1 N_{ppo}}{\sigma_1 N_{ppo} + \sigma_2 N_{Zr}}$$



L_0 : Light yield of anisole

N_{ppo} : Number of PPO molecular in mole

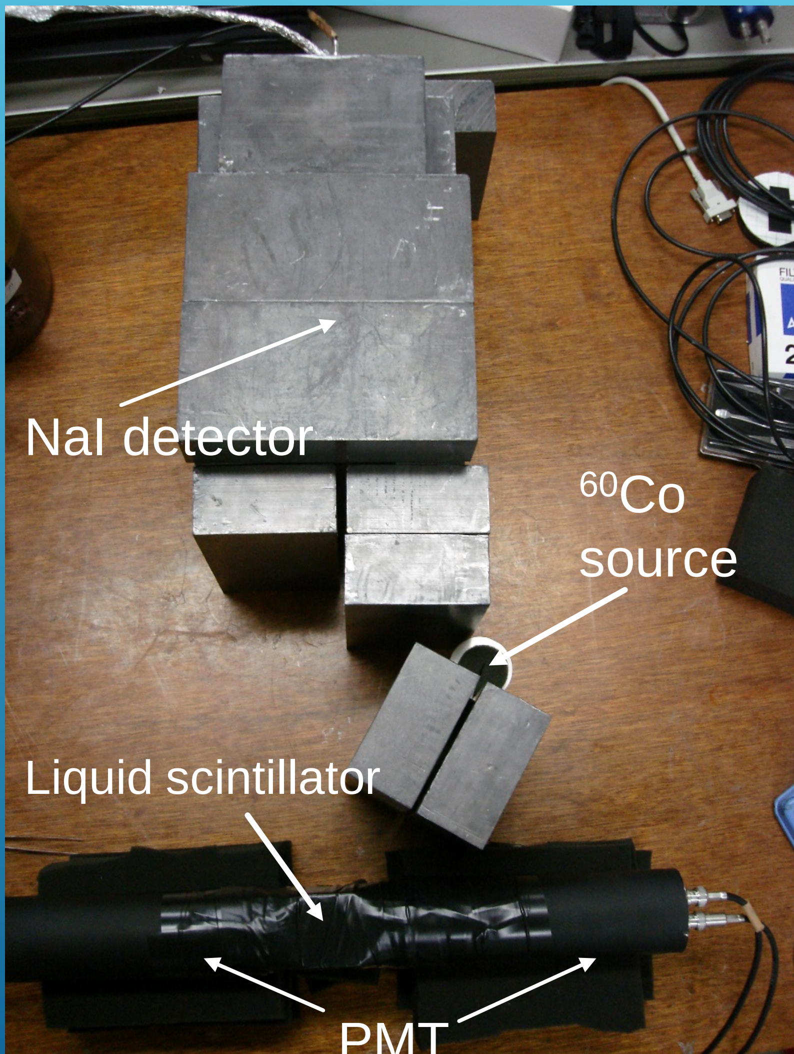
N_{Zr} : Number Zr complex molecular in mole

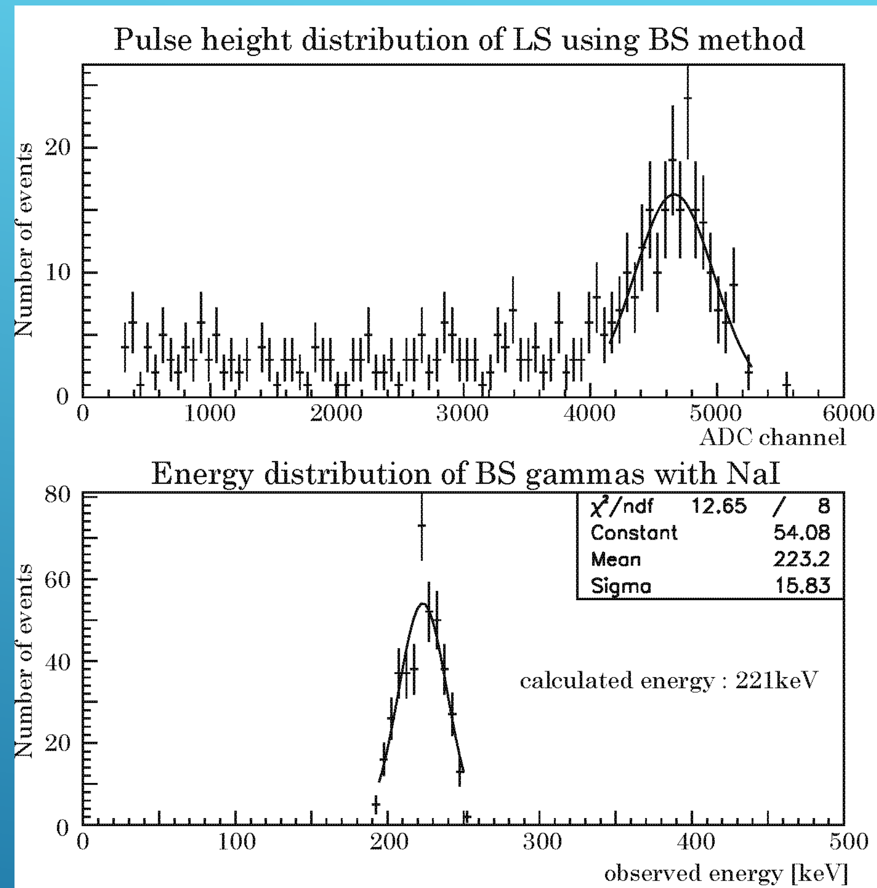
σ_1 : absorbance of PPO (mol^{-1})

σ_2 : absorbance of Zr complex (mol^{-1})

PPO could help recovering the performance.

BACK SCATTERING METHOD

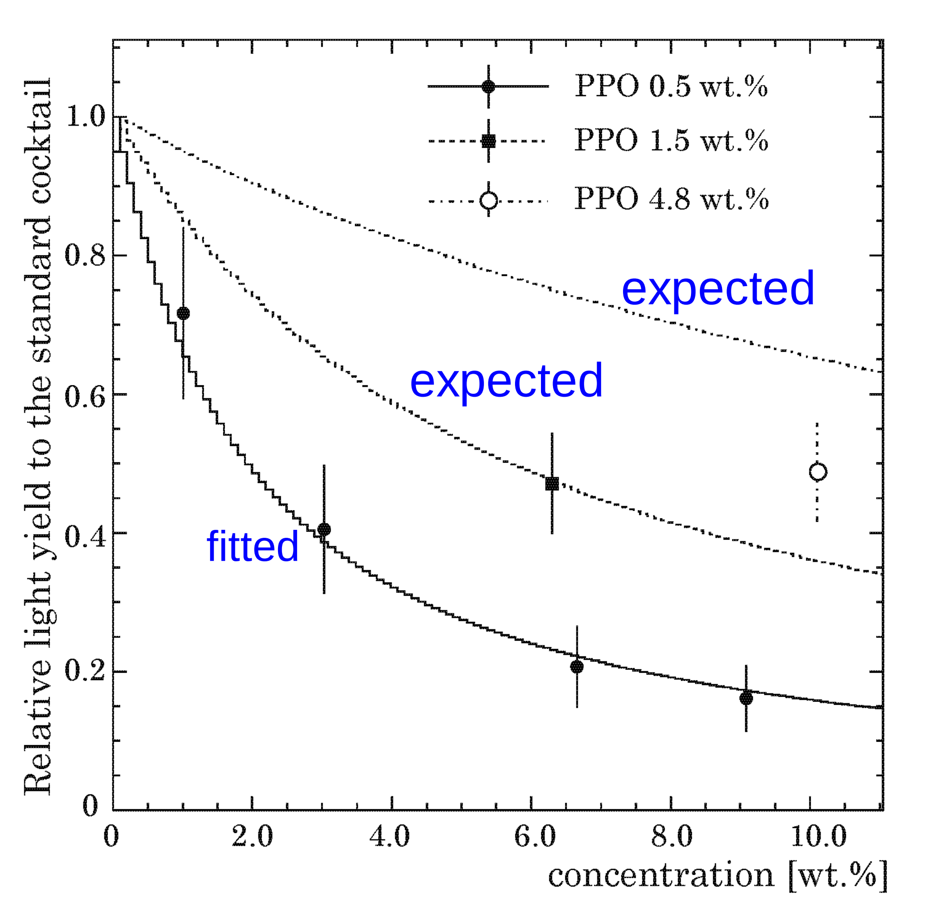




Single peak could be used even in liquid scintillator.

Recovering the light yield

Several conditions of PPO concentration

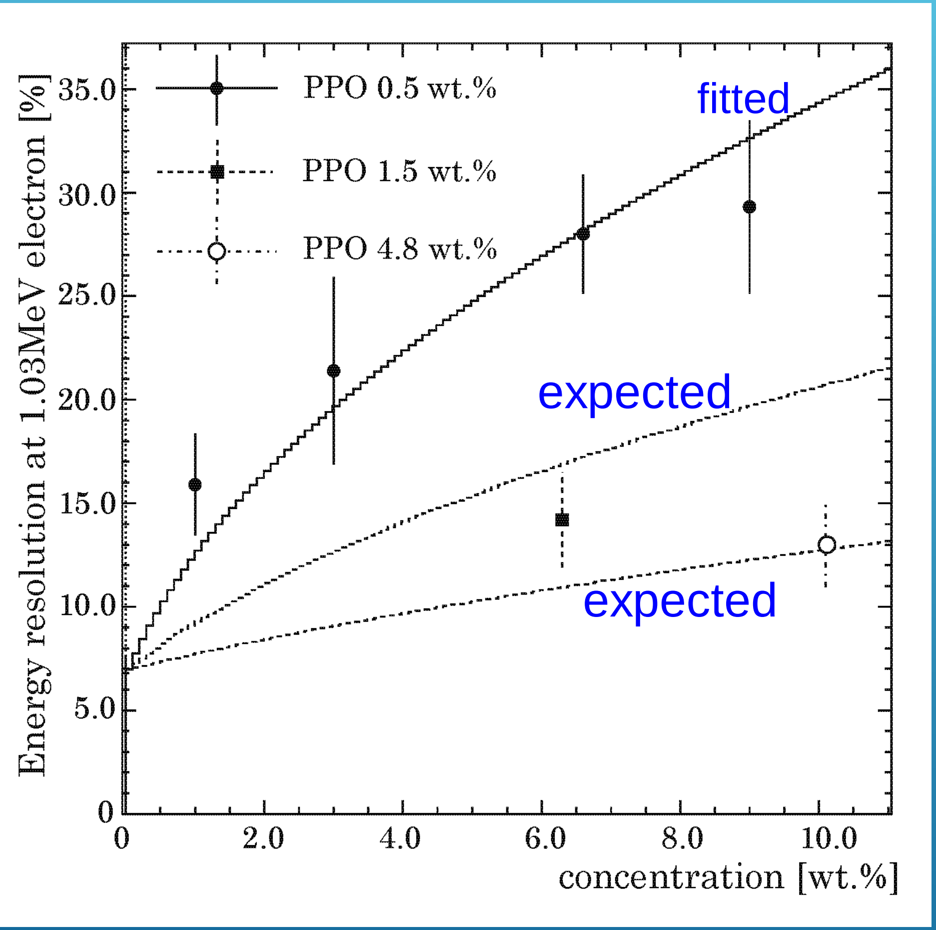


5wt.% PPO helps actually recovering the scintillation light yield.

48.7±7.1% light yield to standard cocktail was obtained at 10wt.% concentration.

Recovering the energy resolution

Several conditions of PPO concentration



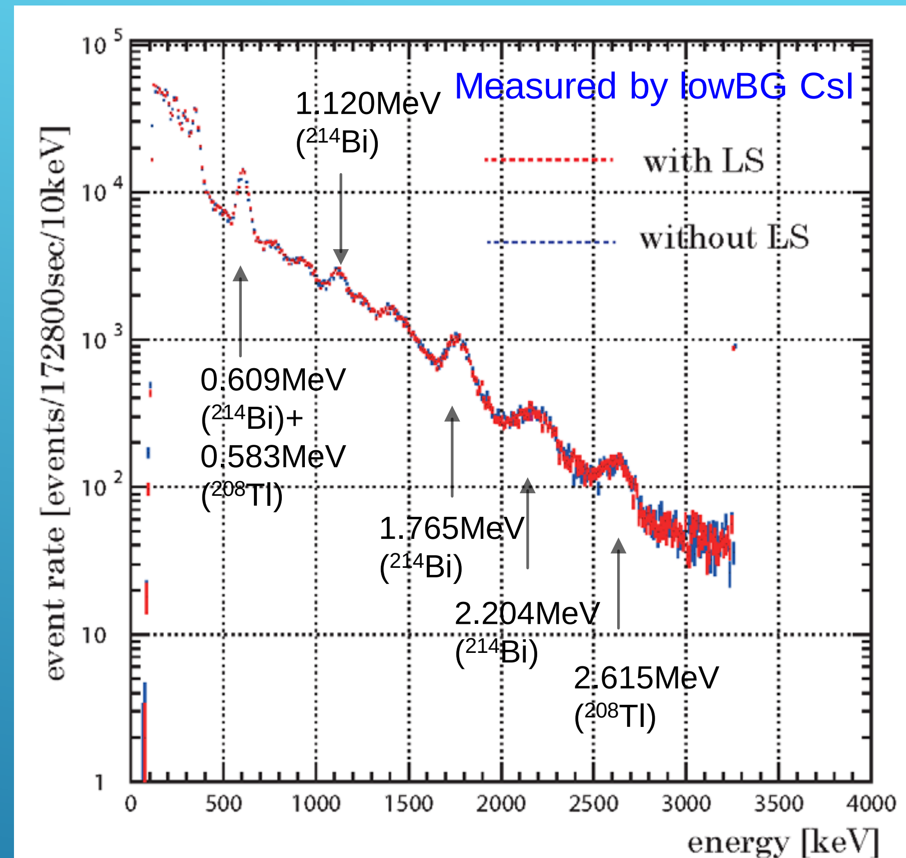
5wt.% PPO helps again the energy resolution 35% → 13%. at 10wt.% of $Zr(iprac)_4$.

$$\frac{13.0 \pm 2.0\%}{\sqrt{(40\%/9.2\%) X (3.35MeV/1.03MeV)}}$$

= 3.5±0.5% at 3.35MeV

Achieved goal for our development of LS !

Measurement of backgrounds of LS



Using subtracted # of events around 2.6MeV and 2.2MeV

^{214}Bi < 4.9×10^{-20}g/g ^{208}Tl < 2.7×10^{-22} g/g

(^{238}U < 6.4×10^{-6} g/g) (^{232}Th < 7.4×10^{-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

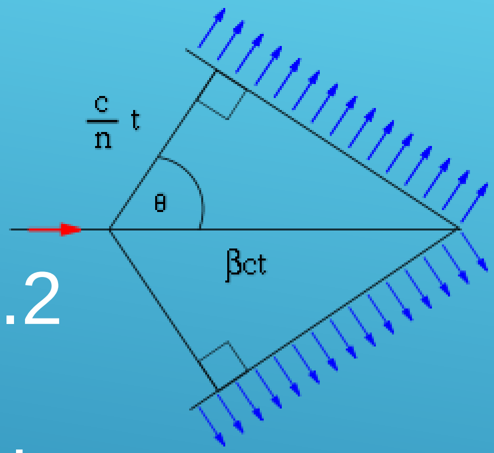
↓

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

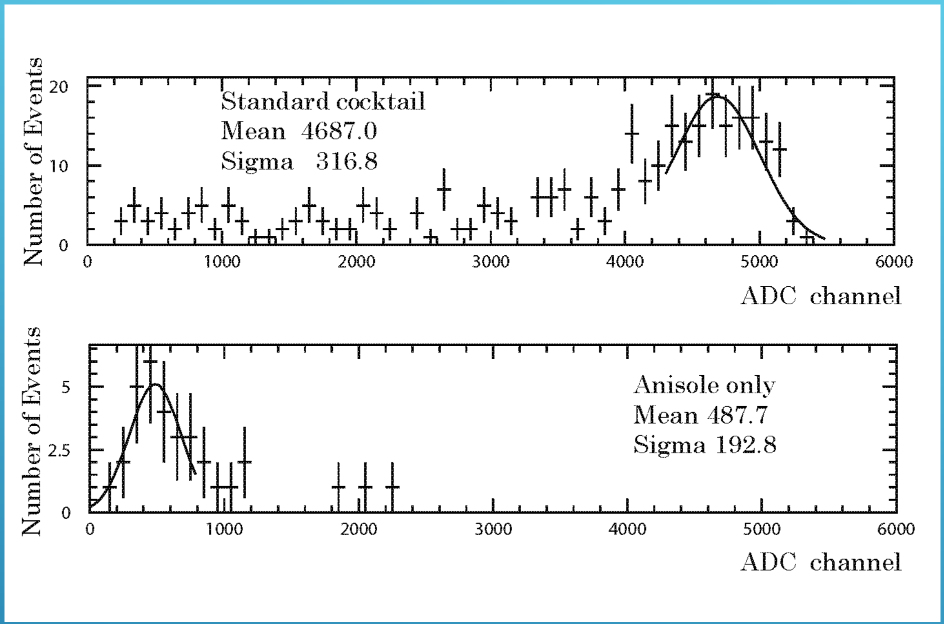
- Refractive index of anisole : n=1.518
- Cherenkov angle is determined by $\cos\theta = 1/n\beta$
- Assuming 1.65MeV electron, then $\beta=0.951$ and Cherenkov angel $\theta=46.2$ degree are expected.
- Cherenkov light should be measured. (350nm – 550nm : 120 photon/MeV)

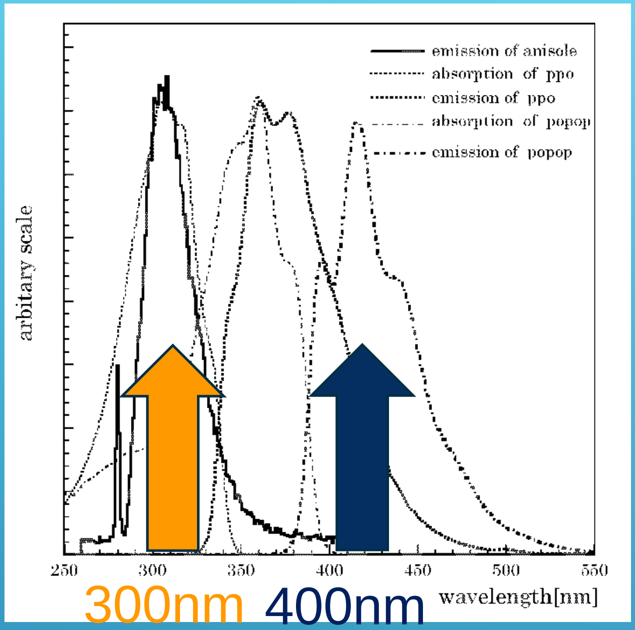


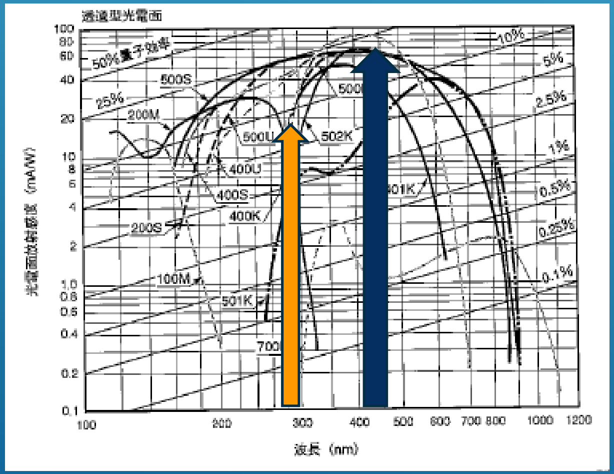
$$\frac{dN}{dx} = 2\pi z^2 \alpha \sin^2\theta_c \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda} = 475 z^2 \sin^2\theta_c \mathrm{photon/cm}$$

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

Light yield of scintillation in anisole

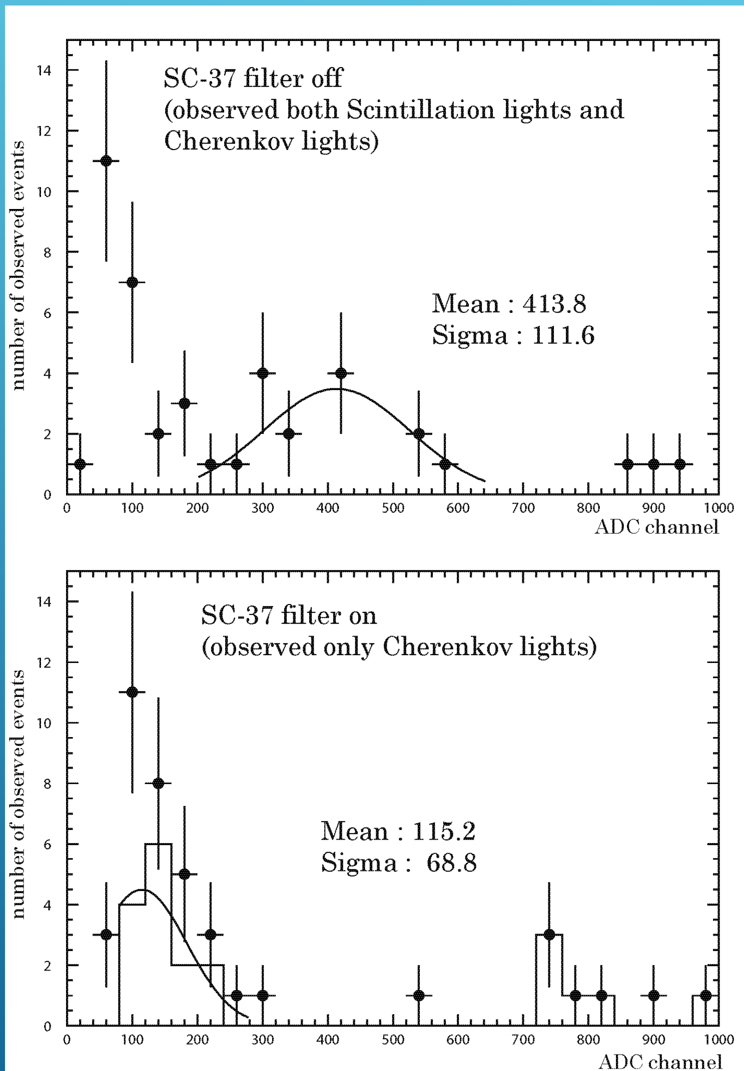


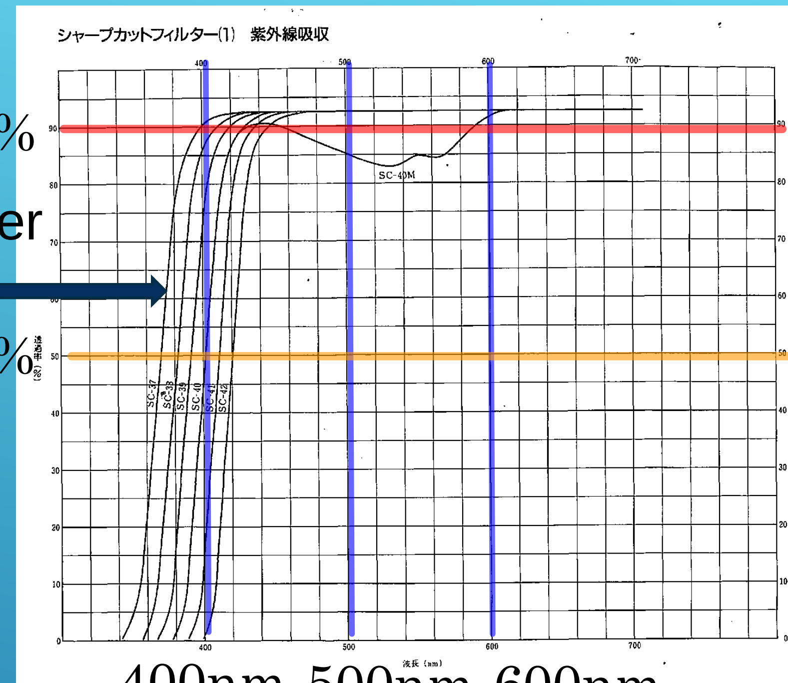




Relative scintillation light yield of anisole is 9.8% to standard cocktail (due to difference of quantum efficiency of PMT)

Light yield of Cherenkov lights

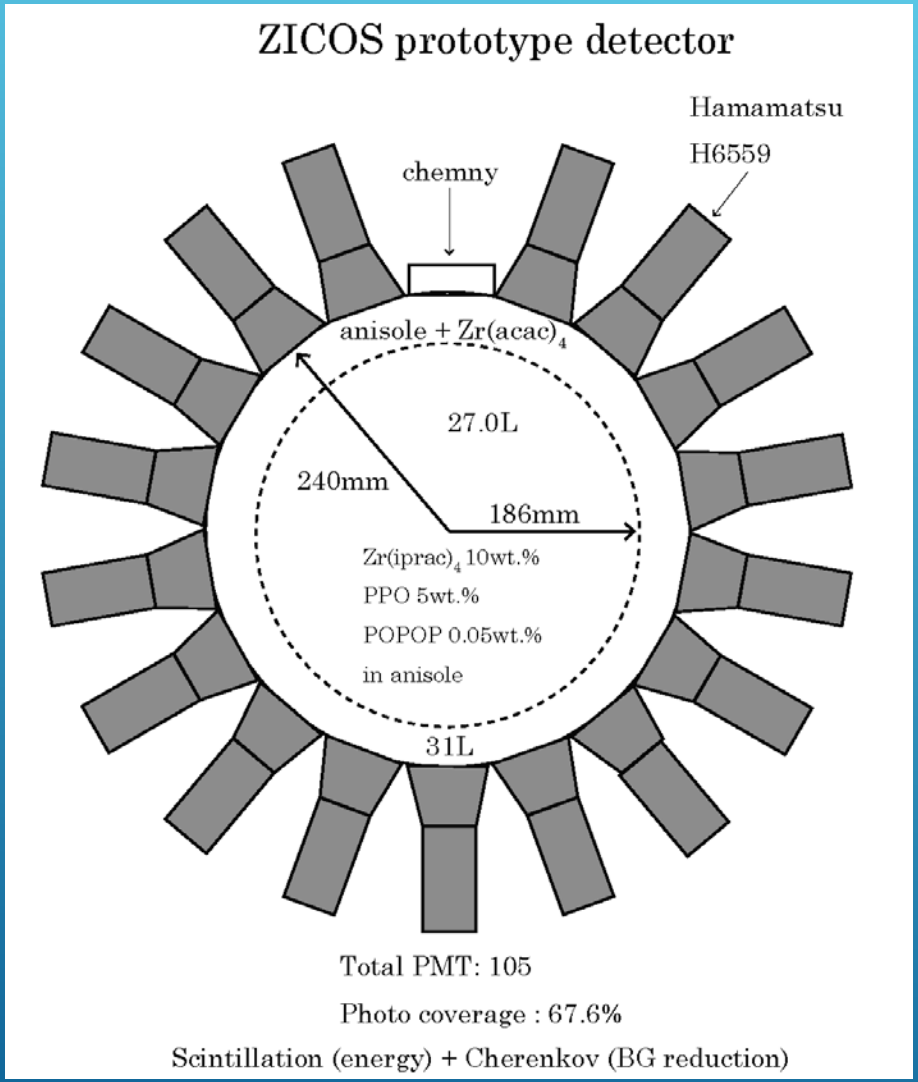




$$\frac{\text{Cherenkov light yield (>400nm)}}{\text{Scintillation light yield of std. LS}} = \frac{115.2/0.183}{298.6/0.046/0.098} = \sim 0.01$$

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.

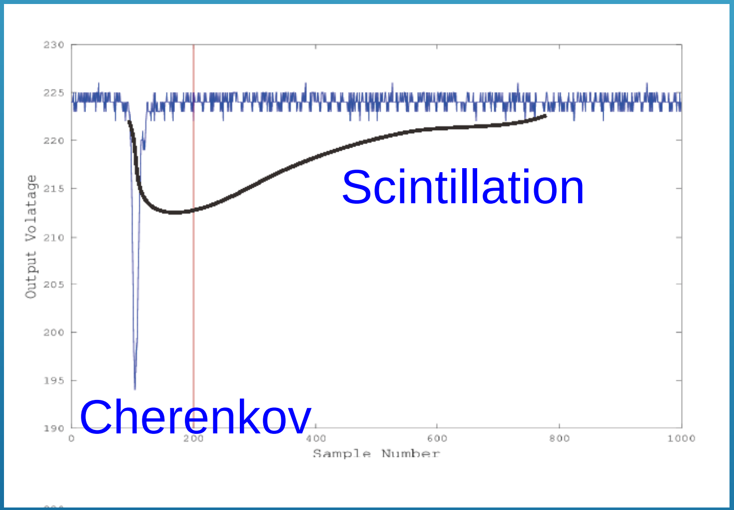
MPPC (Multi-Pixel Photon Counter)

Hamamatsu S13360-6050CS

- effective area : 6.0mm × 6.0mm
- # of pixels /channel : 14400
- Time resolution (FWHM) : 200~300ps

Emission time of

- Cherenkov light : ~3ps
- Scintillation light : ~10ns



Using difference of timing shape, we might be able to extract Cherenkov light.

SUMMARY

- ZICOS sensitivity : **$T_{1/2}^{0\nu} > 1.0 \times 10^{26}$y; $<m_\nu>$ < 0.1 eV (QRPA)** using **58.5% enriched ^{96}Zr** and reduced BG at **1/30 × KamLAND-Zen**.
- Liquid scintillator containing zirconium β-keto ester complex has been developed.
- Liquid scintillator with **10 wt.%** concentration of **$Zr(iprac)_4$** has **48.7±7.1% for light yield to BC505** and **3.5±0.5% at 3.35MeV (assuming 40% photo coverage) for energy resolution.**
- ZICOS proto-type will demonstrate not only good energy resolution but also ability of background reduction using Cherenkov light.