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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VII

日本物理学会　第７０回年次大会

2015年3月21日

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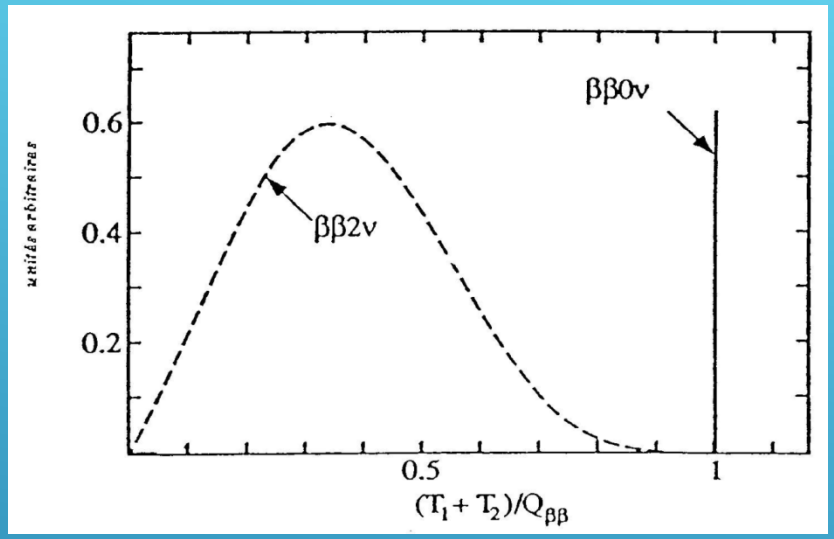
Neutrinoless double beta decay

$\beta\beta$ 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



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

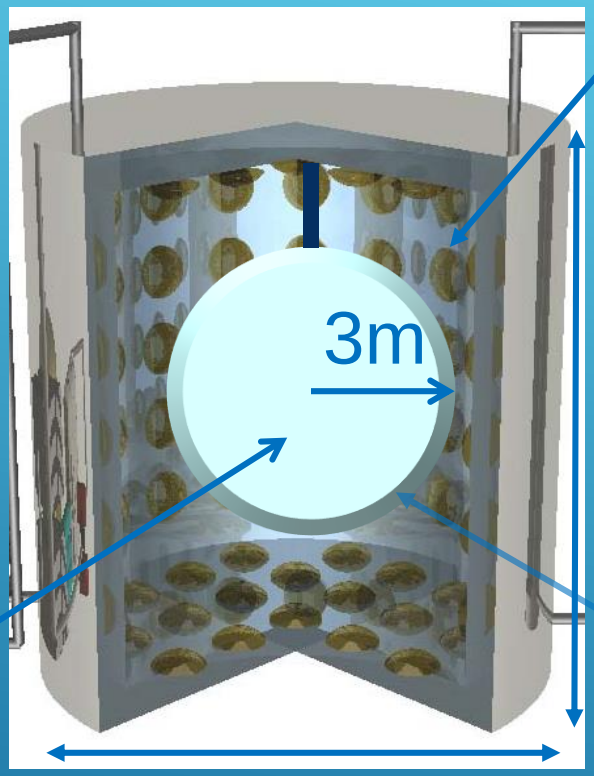
$T_{1/2} \sim a(Mt/\Delta E \cdot B)$ a: abundance M: target mass

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) > 10wt.% solubility
(2) 3.5% at 3.35MeV of energy resolution, if ZICOS have PMTs with 40% photo coverage and long attenuation length (~15m)



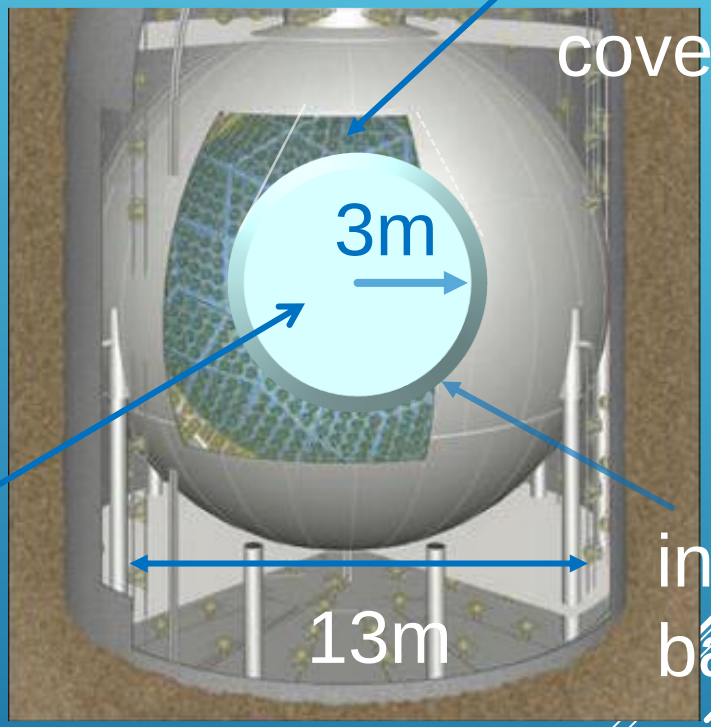
LS surrounding inner balloon to veto external BG

Zirconium loaded 113 tons LS

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

Goals for development of LS :
(1) > 10wt.% solubility
(2) 3.5% at 3.35MeV of energy resolution, if ZICOS have PMTs with 40% photo coverage and long attenuation length (~15m)

PMT with 40% photo coverage



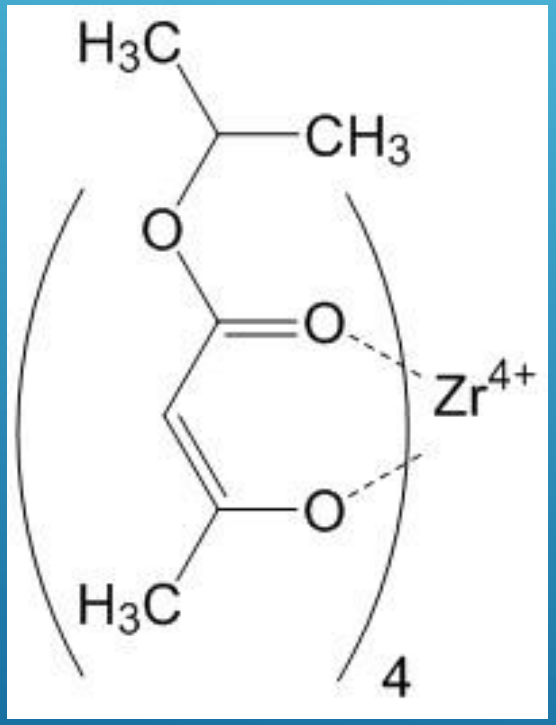
inner balloon

LS surrounding inner balloon to veto external BG

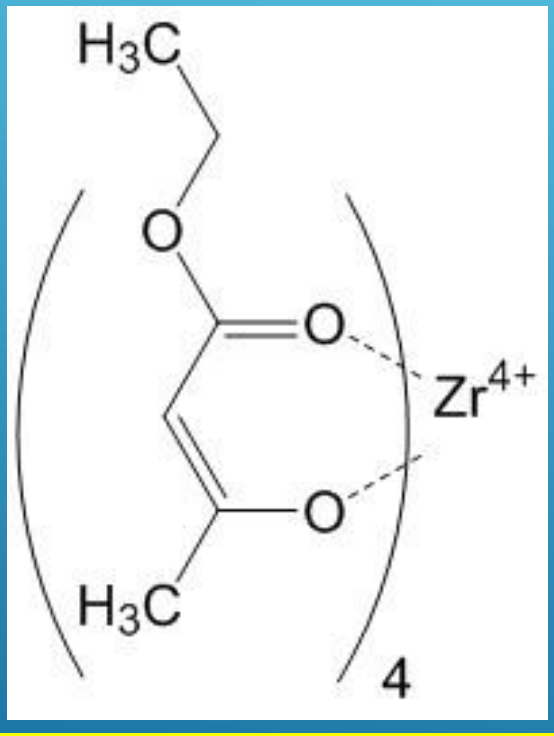
Zirconium loaded 113 tons LS

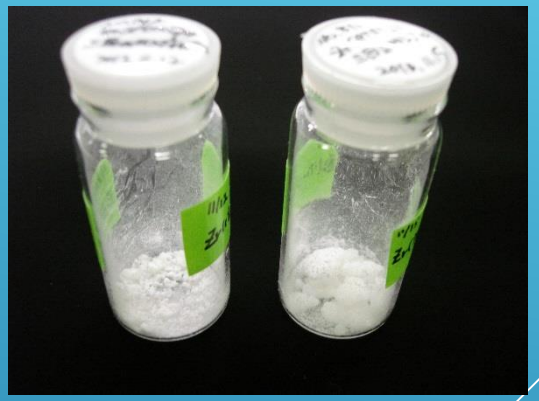
Zirconium β-keto ester complex

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



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



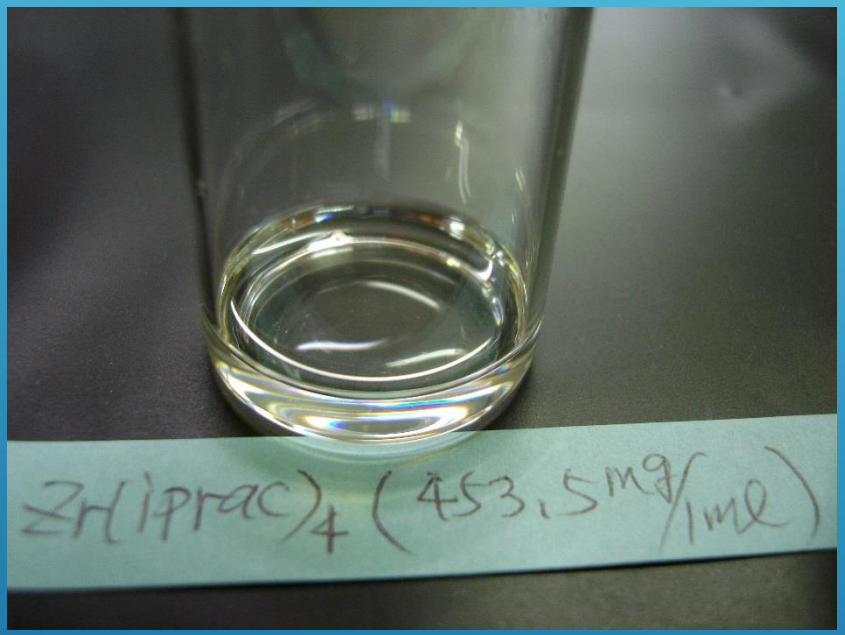


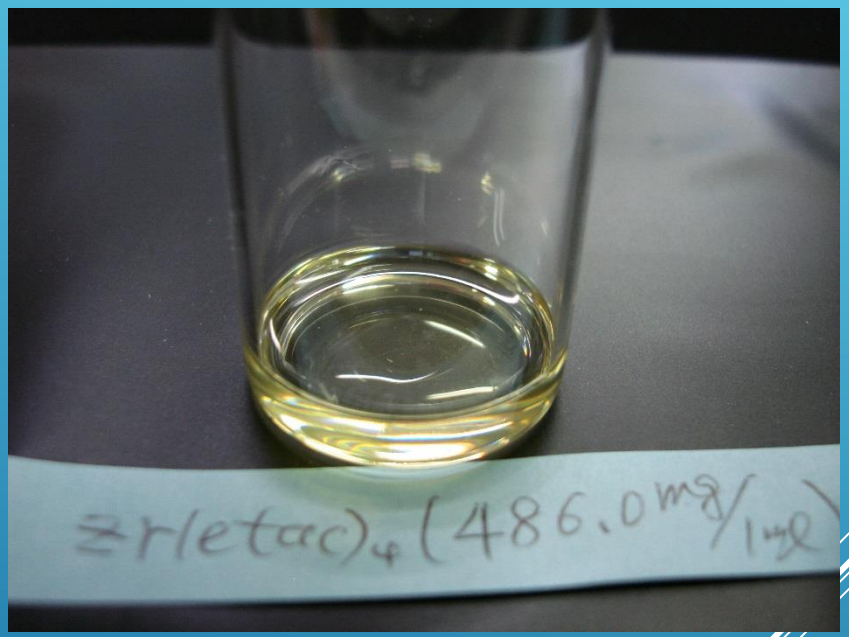
Synthesized by
Prof. T.Gunji

Absorption wavelength could be shorten.

Solubility of Zirconium β-keto ester complex for anisole

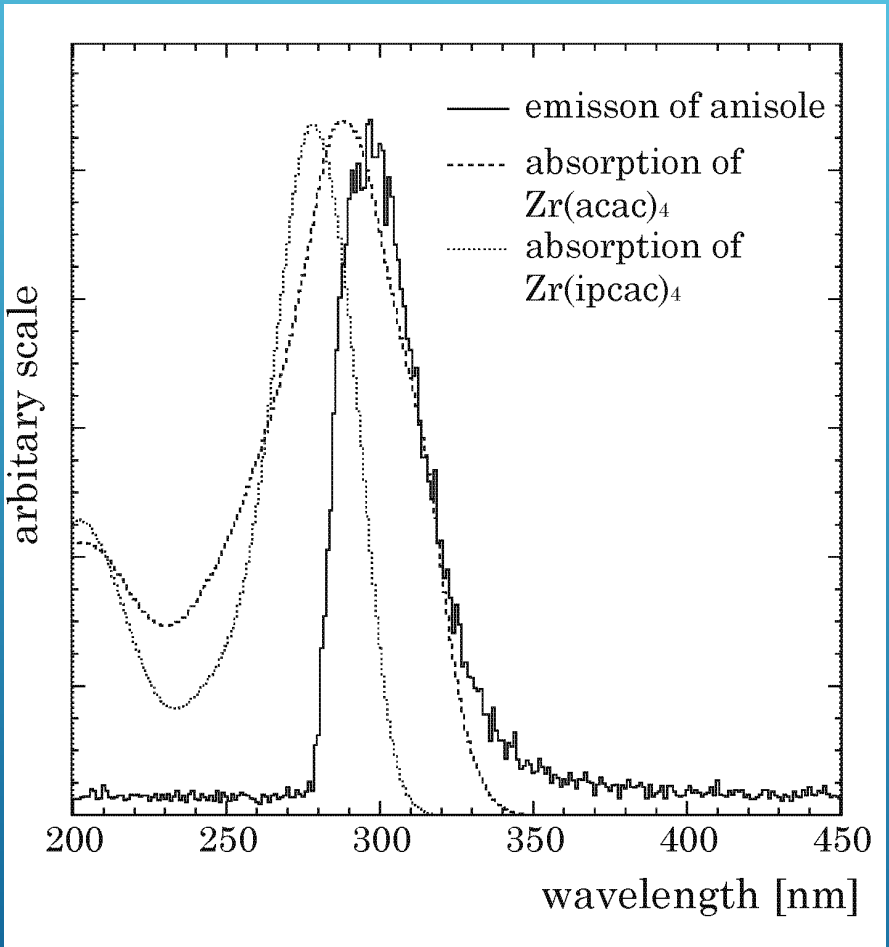
$Zr(iprac)_4$: 31.2wt.%　　$Zr(etac)_4$: 32.7wt.%





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

Absorbance spectra for zirconium β-keto ester complex

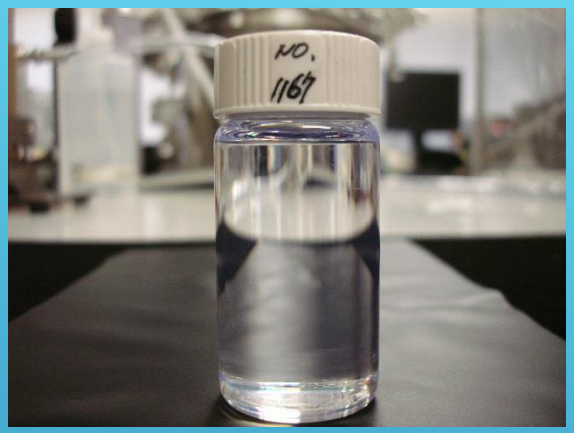


Absorption peaks of $Zr(iprac)_4$ was found around at 278nm.
Peak moved only 10nm.

Overlap region for the absorption spectrum of $Zr(iprac)_4$ became smaller than that of $Zr(acac)_4$.

Light yield calculated by quenching

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



L_0 : Light yield of anisole

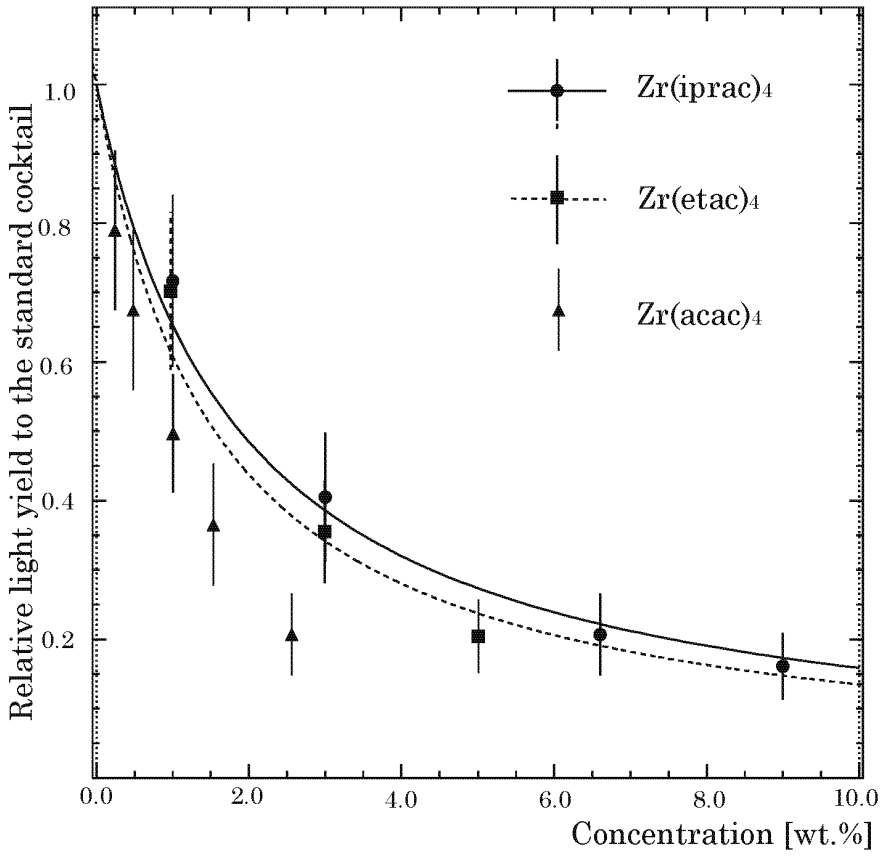
N_{ppo} : Number of PPO molecular in mole

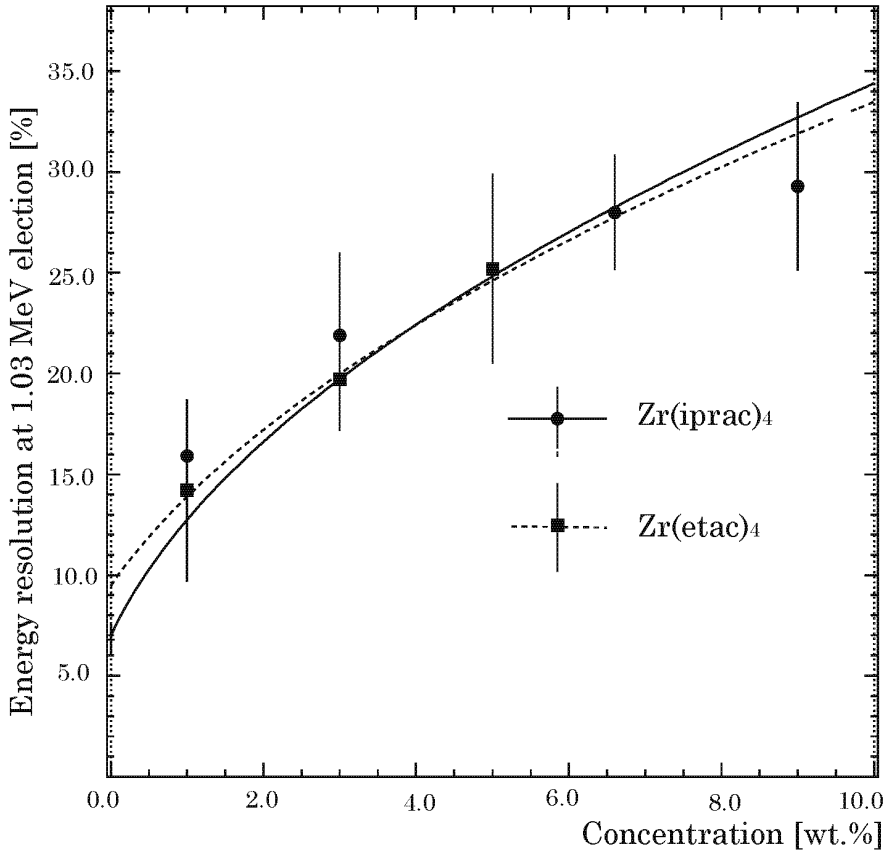
N_{Zr} : Number Zr complex molecular in mole

σ_1 : absorbance of PPO (mol^{-1})

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

Light yield and energy resolution

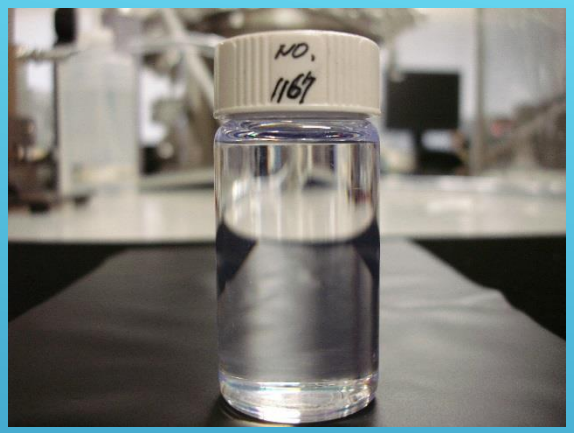




$Zr(ipcac)_4$ and $Zr(etac)_4$ are almost same performance.

Light yield calculated by quenching

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



L_0 : Light yield of anisole

N_{ppo} : Number of PPO molecular in mole

N_{Zr} : Number Zr complex molecular in mole

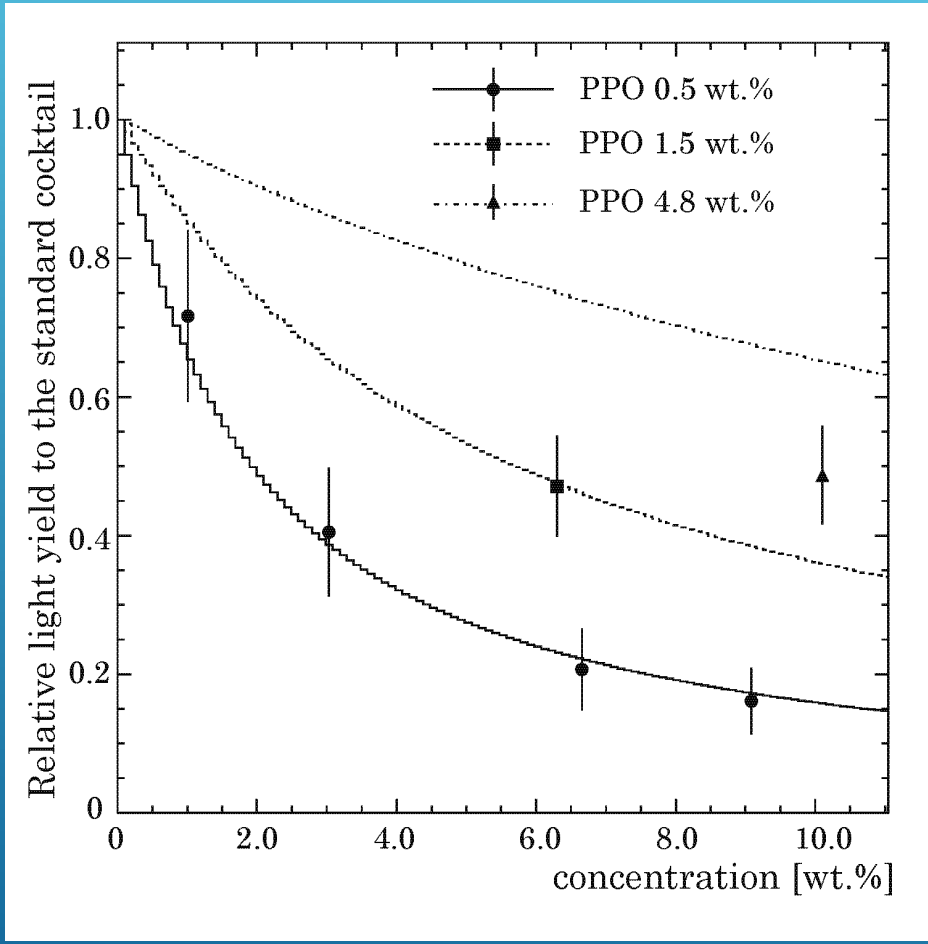
σ_1 : absorbance of PPO (mol^{-1})

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

N_{ppo} should help recovering the light yield.

Modification of light yield

Zr(iprac)$_4$ in several conditions of PPO concentration.

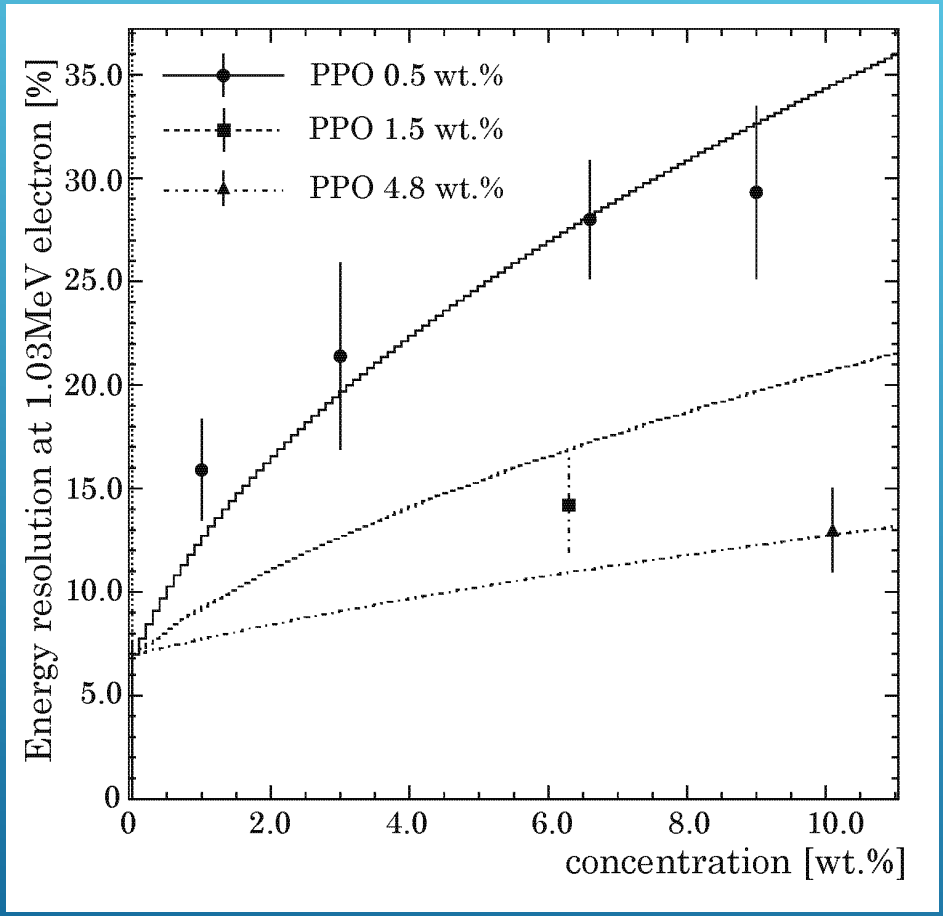


Light yield decreased as calculated formula. However, PPO helps actually the light yield recovering.

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

Modification of energy resolution

$Zr(iprac)_4$ in several conditions of PPO concentration



PPO helps again the energy resolution at 10wt.% concentration to be 35% → 13%.

$$\frac{13.0 \pm 2.0\%}{\sqrt{40\%/9\% * 0.72 * 3.35\text{MeV}/1.03\text{MeV}}}$$

$= 4.1 \pm 0.6\%$ at 3.35MeV

Achieved our initial goal!

Neutrino mass sensitivity of ZICOS experiment

Results from NEMO-3 : $T_{1/2}^{0\nu} > 9.2 \times 10^{21}$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 3m radius, and same Eres, BG rate and mes.time as KamLAND-Zen ($T_{1/2}^{0\nu} > 1.9 \times 10^{25}$y)

(Ref: I.Shimizu arXiv:1409.0077 (2014))

Volume: 113ton → 10wt.% $Zr(iprac)_4$ = 12.6ton

includes 1.73ton of Zr

includes 51.9kg of ^{96}Zr (0.23 times ^{136}Xe 320kg)

Sensitivity of ZICOS experiment :

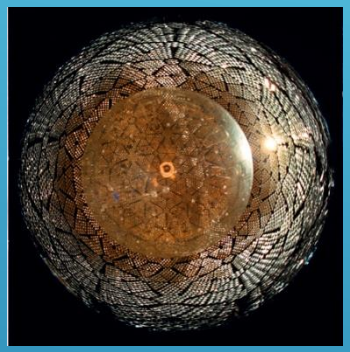
$T_{1/2}^{0\nu} > 4.4 \times 10^{24}$y ; $\langle m_\nu \rangle$ < 0.3 – 0.5eV

(g_A=1.25,g_{pp}=1.11,QRPA)

To reach for $\langle m_\nu \rangle < 0.1$eV

1) If a radius of balloon is 3m,
   - 30wt.% $Zr(iprac)_4$ = 156kg of ^{96}Zr
   - ^{96}Zr enriched to 10% - 15% using Centrifuge

$\langle m_\nu \rangle < 0.09 - 0.11$ eV



2) To reach for $\langle m_\nu \rangle \sim 0.03$eV
   - need 5tons of ^{96}Zr
   - 6m radius + 30wt.% $Zr(iprac)_4$ + ^{96}Zr enriched to 10% - 15%

Need KamLAND balloon or SNO+ acrylic vessel

SUMMARY

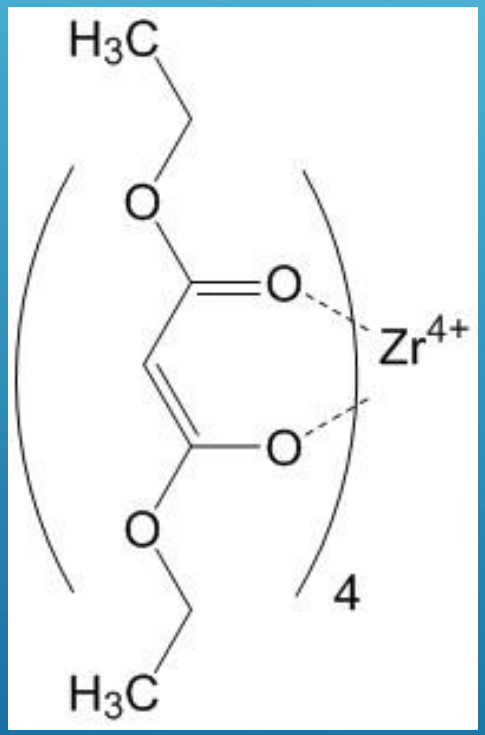
- Liquid scintillator containing zirconium β-keto ester complex for ZICOS experiment was developed.
- The absorption peak of zirconium β-keto ester complex stayed at 268nm, but **smaller overlap** with emission of anisole than zirconium acetylacetone.
- Liquid scintillator with **10 wt.%** concentration of **$Zr(iprac)_4$** has **48.7±7.1% for light yield to BC505** and **4.7±0.8% at 2.5MeV** (assuming 40% photo coverage and 15m attenuation length) **for energy resolution**, so that **we have really achieved our initial goal !**
- Sensitivity of ZICOS experiment : **$T_{1/2}^{0\nu} > 4.4 \times 10^{24}$y; $\langle m_\nu \rangle < 0.3 - 0.5$eV ($g_A$=1.25,$g_{pp}$=1.11,QRPA)** assuming BG rate of KamLAND-Zen.

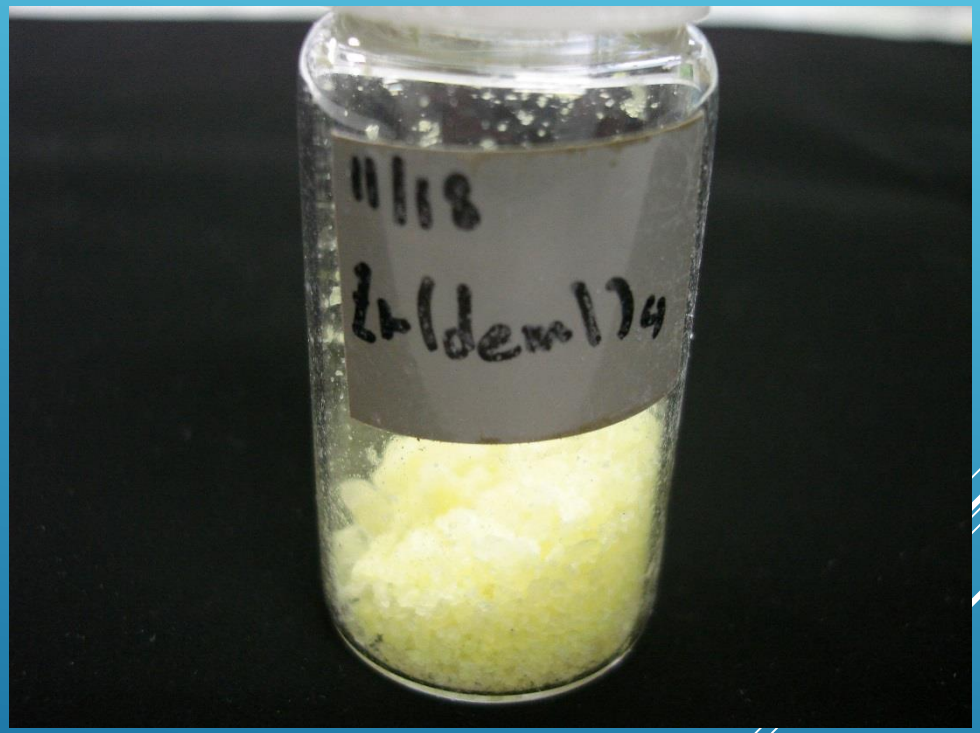
Synthesis of Tetrakis(diethyl malonato) Zirconium

$Zr(CH_3CH_2OCOCHCOOCH_2CH_3)_4$

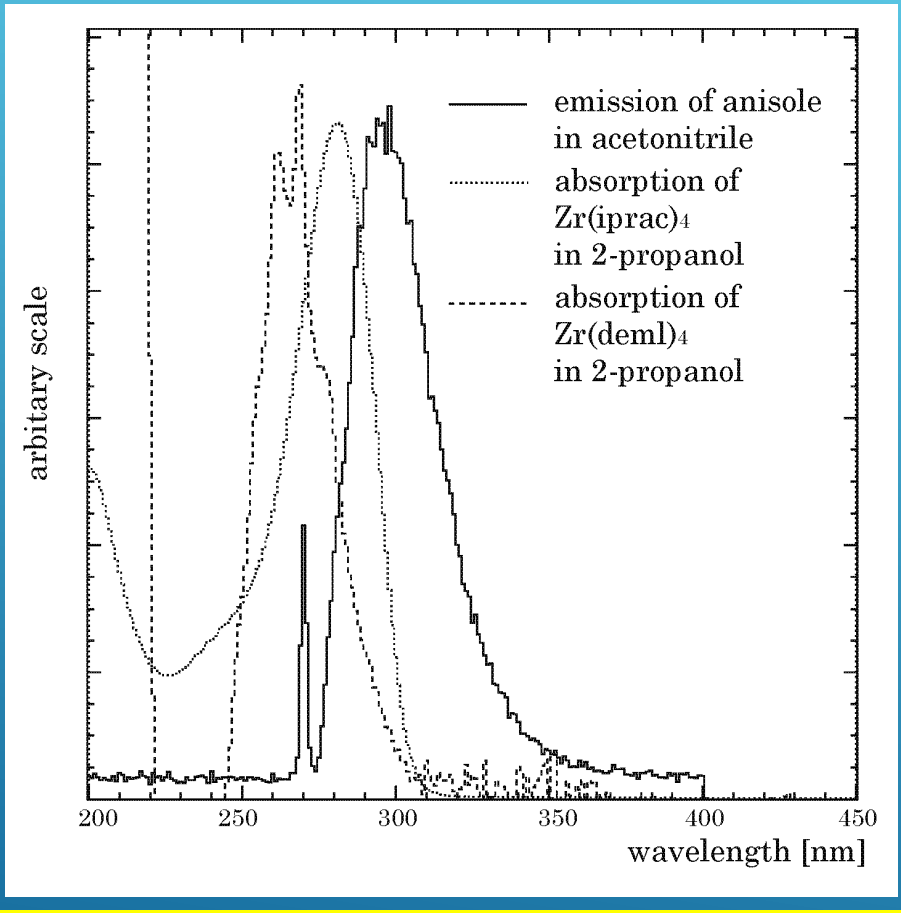
$= Zr(deml)_4$ mw : 727.87

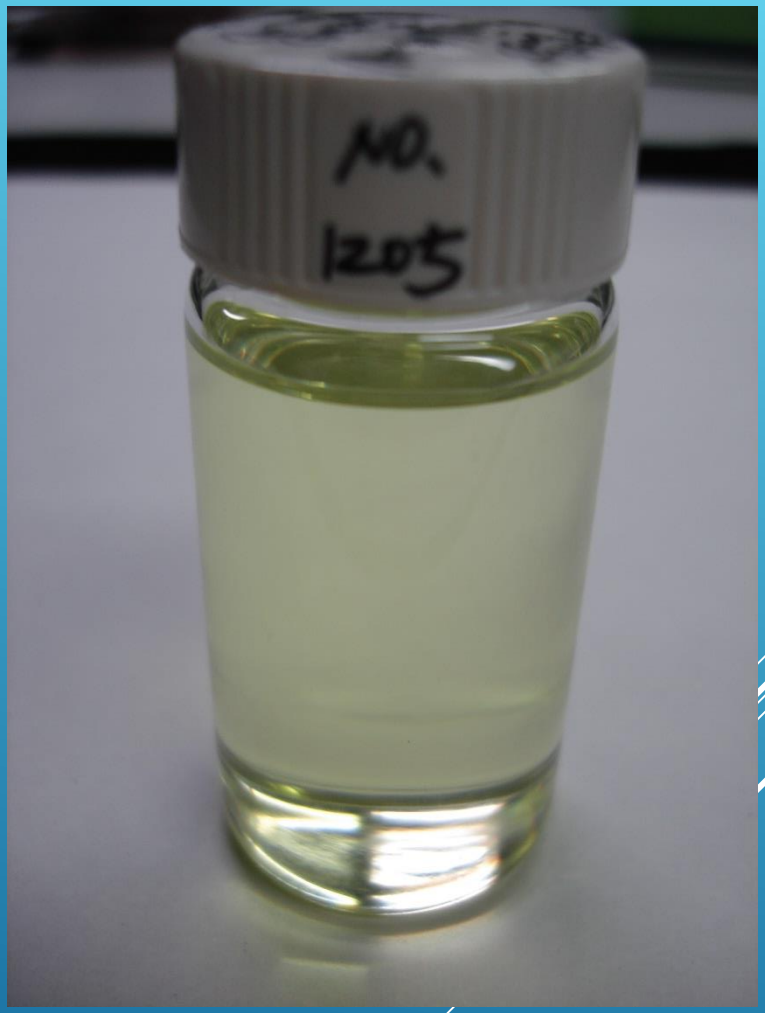
Yellow crystal





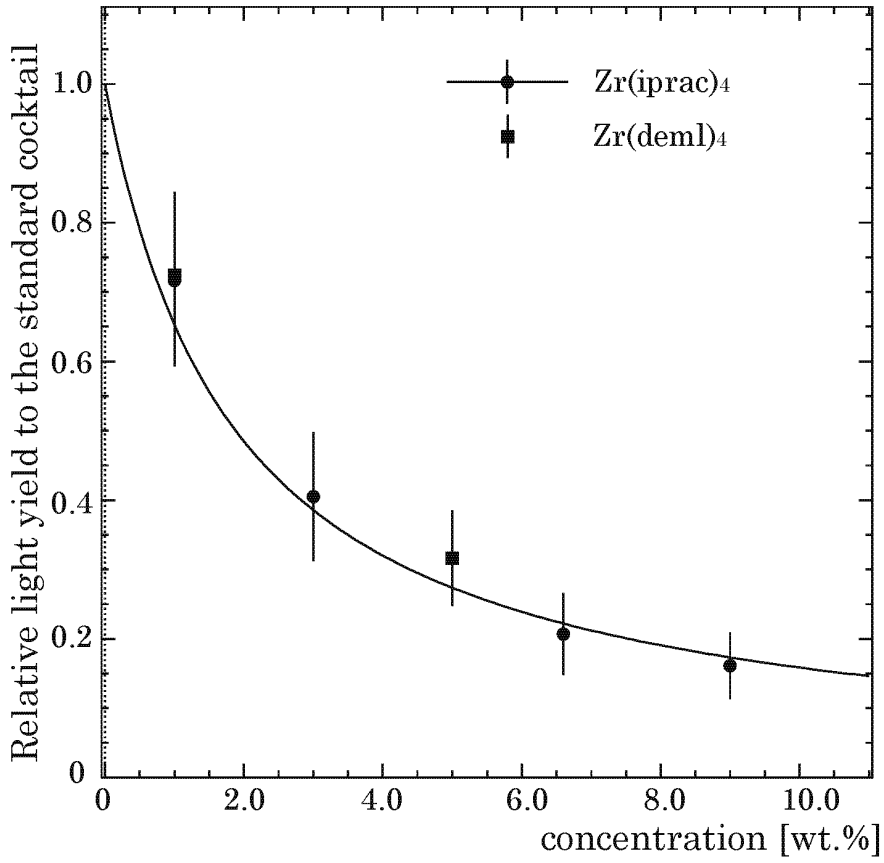
Absorbance of Tetrakis (diethyl malonato) Zirconium

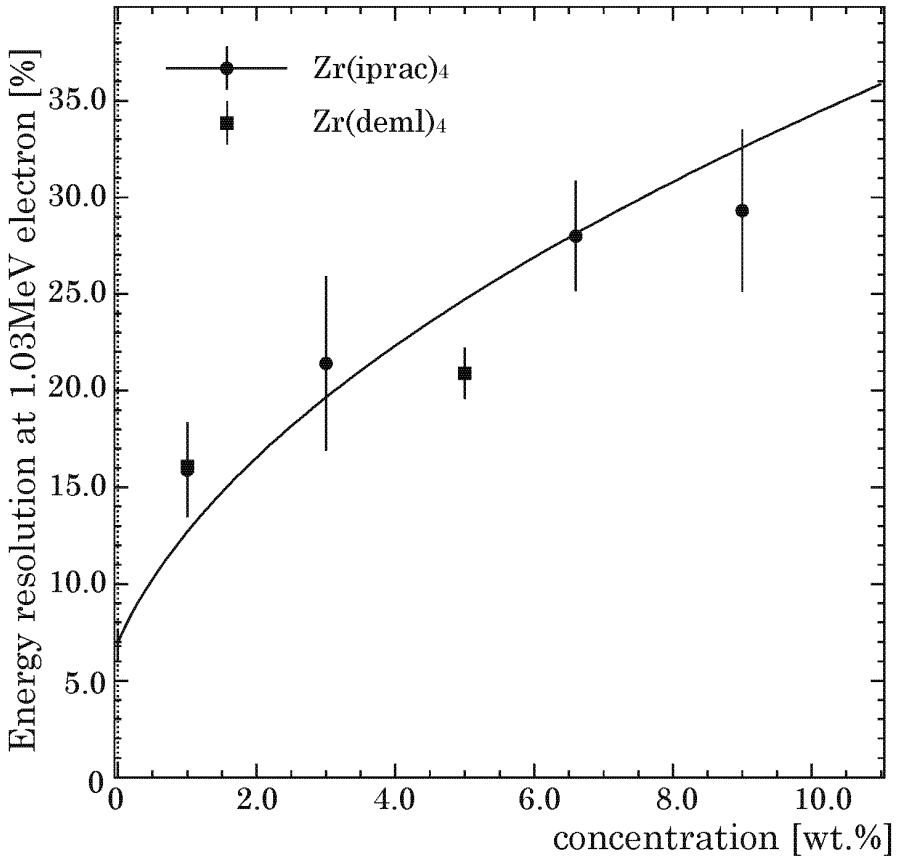




peak wavelength : 265.2nm

Light yield and energy resolution of $Zr(deml)_4$

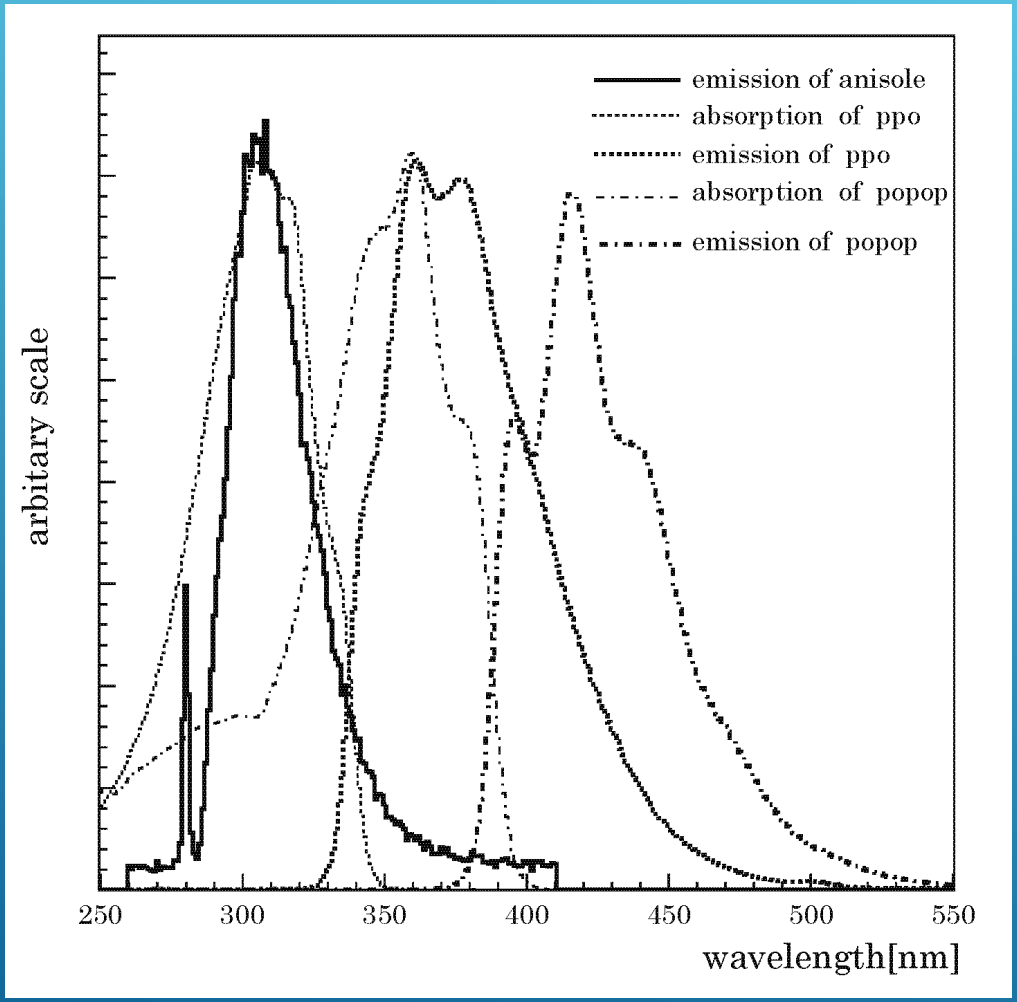




$Zr(deml)_4$ has a little better performance than $Zr(iprac)_4$.

BACKUP

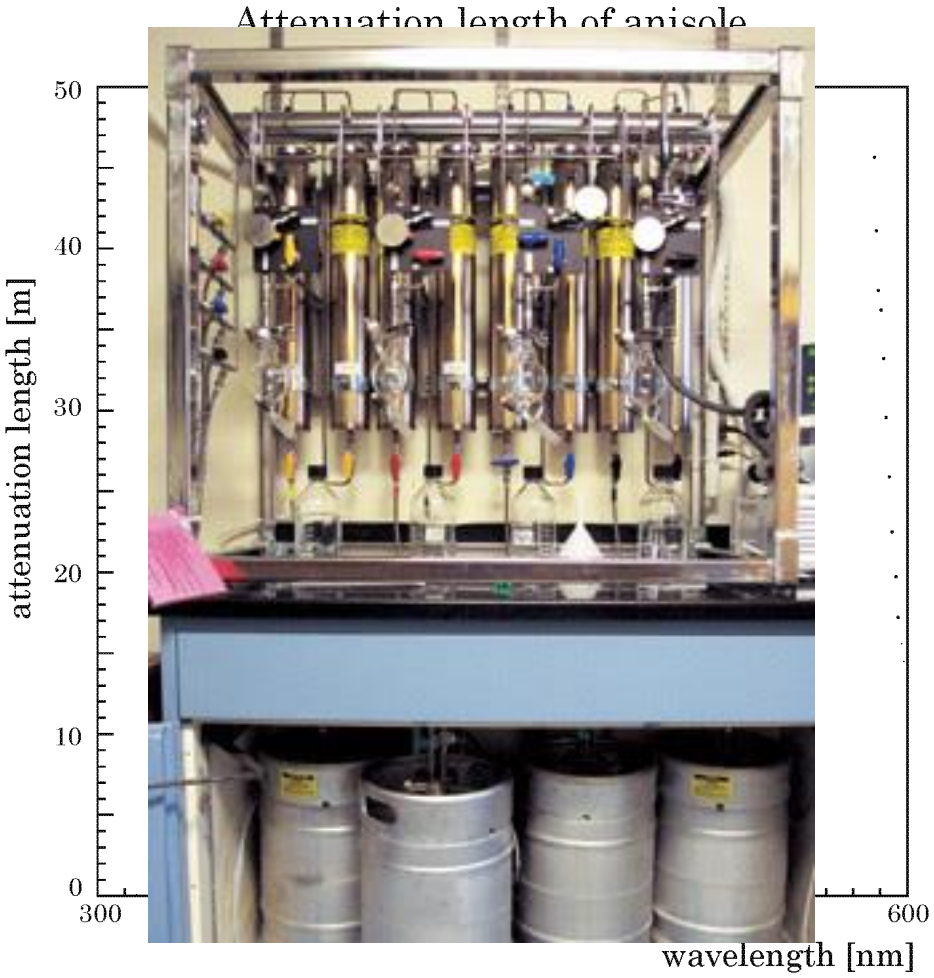
Emission and absorption spectra for solvent and solute in standard cocktail



PPO absorbed most of emission lights from anisole.

Effectively the energy was transferred to the secondary scintillator.

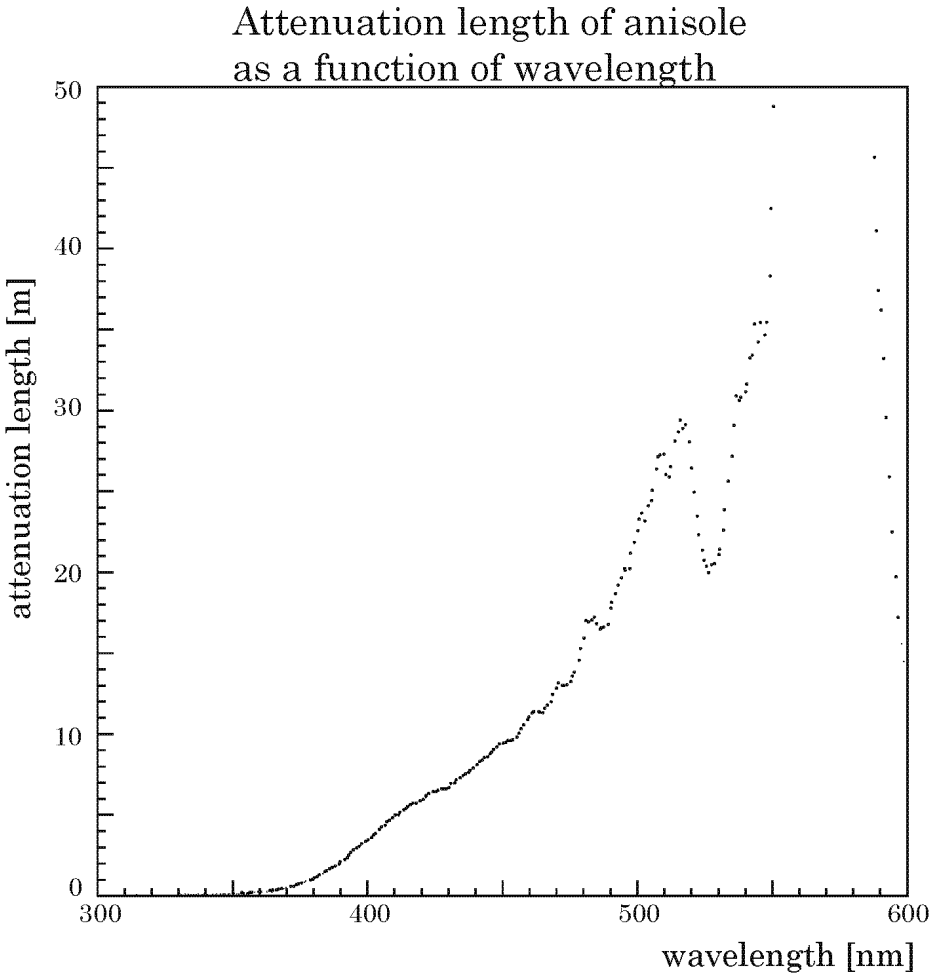
ATTENUATION LENGTH OF ANISOLE



Attenuation length of light from POPOP was obtained as ~6m for current liquid scintillator.

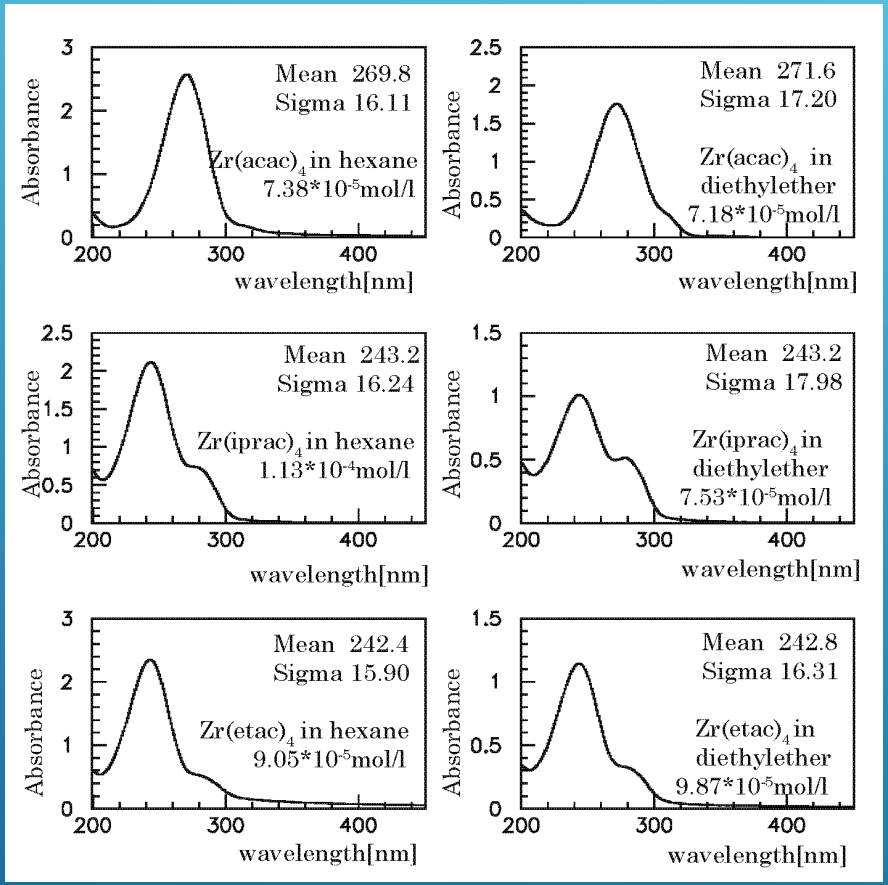
Attenuation length will be recovered ~15m by same purification method as RENO with Al_2O_3. (Ref: H.Grubbs et al., Org.Mat. 1996 15,1518-1520)

ATTENUATION LENGTH OF ANISOLE



Attenuation length of light from POPOP was obtained as ~6m. It is almost equivalent with the detector size.

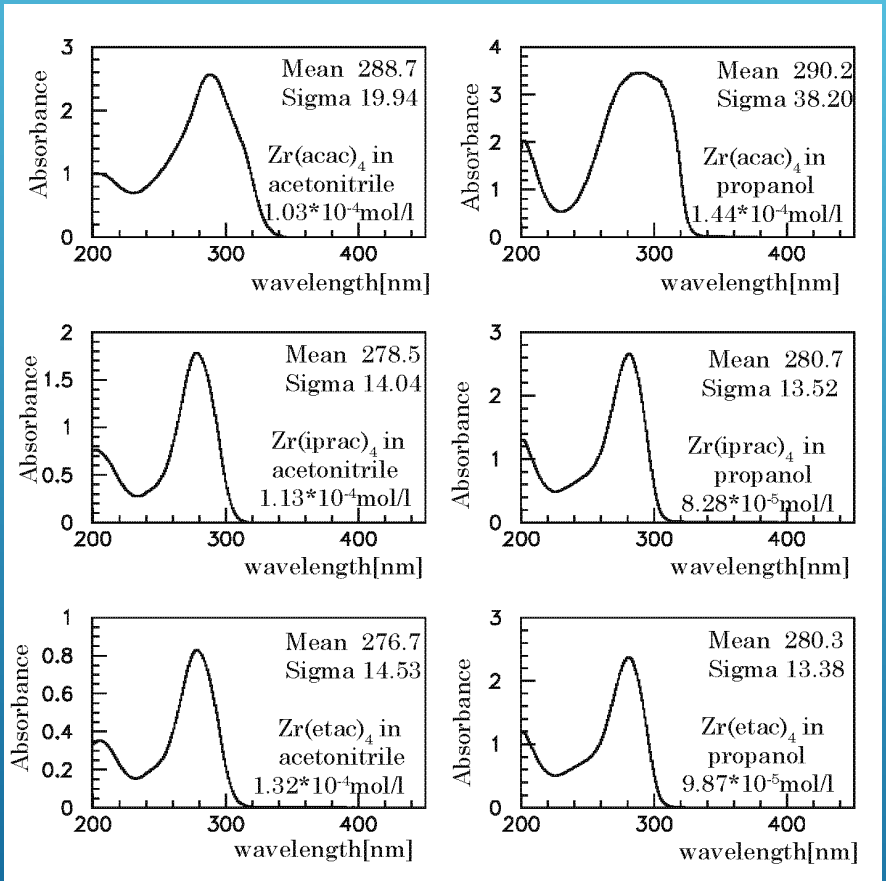
Absorbance spectra in hexane / dietyl ether



~280nm peak disappeared and a precipitate appeared.

Most of solved Zr atom was found in the precipitate, and no Zr atom in the residual solvent by ICP - Atomic Emission Spectrometry.

Absorbance spectra in acetonitrile / 2-propanol



They are stable and quite transparent.

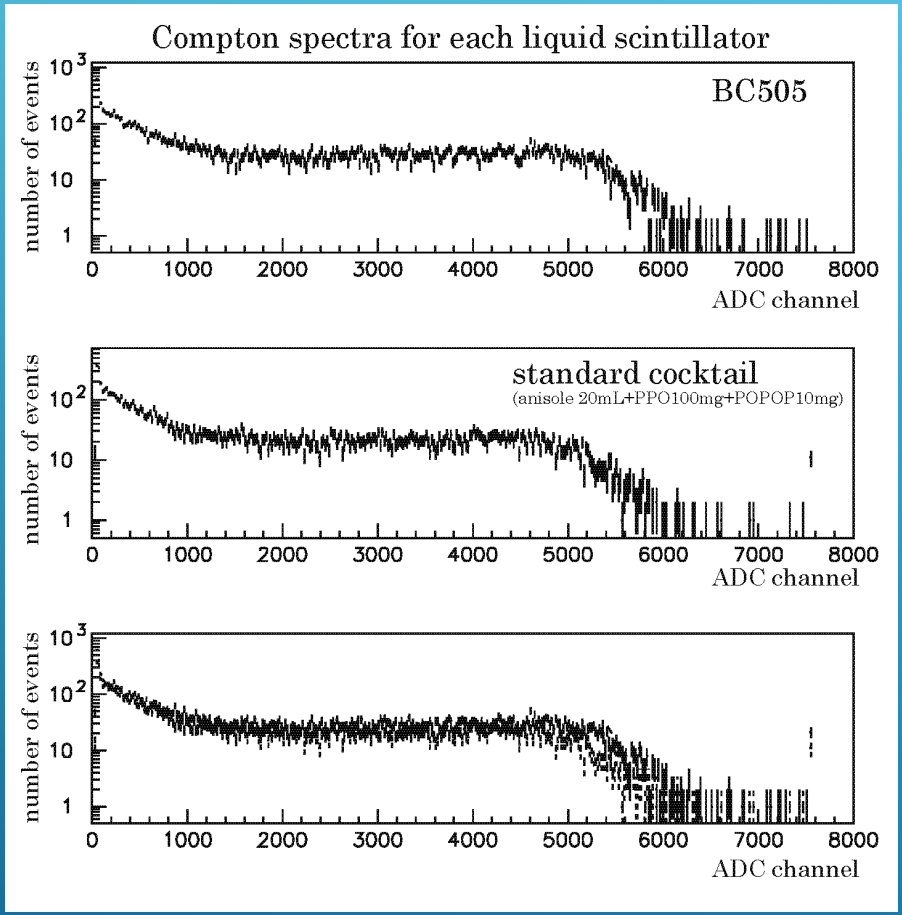
Solved Zr atoms were found in every region.

~280nm peak should be due to $Zr(iprac)_4$ and $Zr(etac)_4$.

Results from ICP Atomic Emission Spectrometry

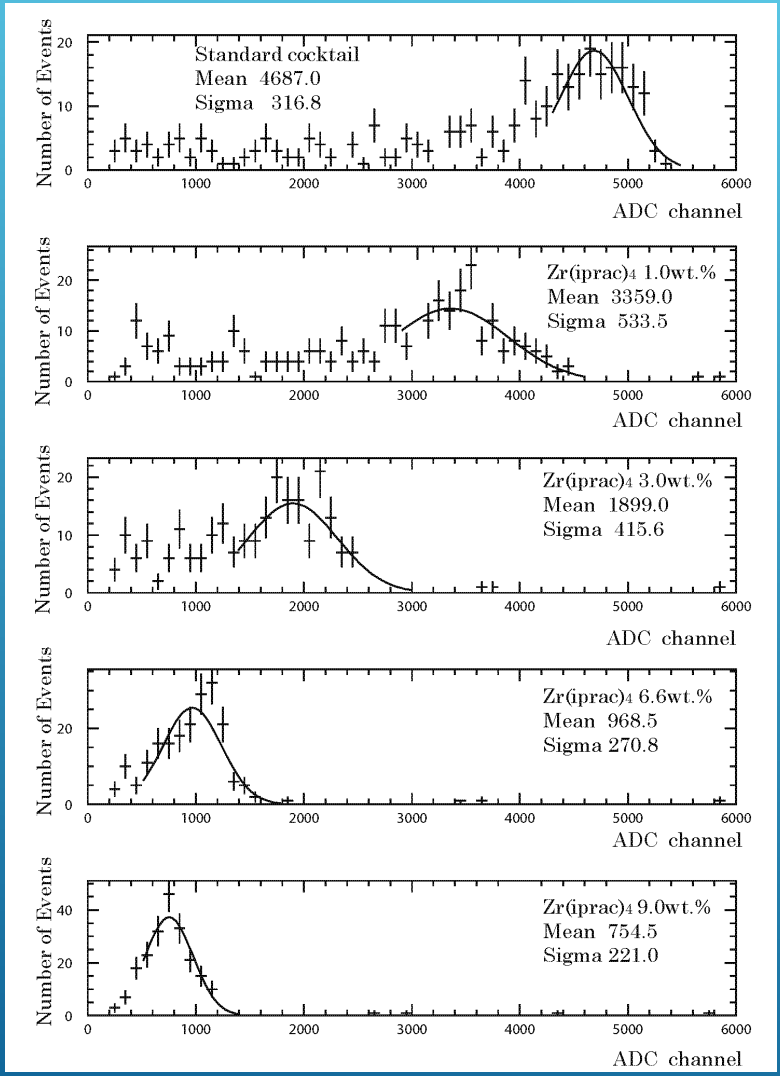
搬入日	試料名		ジルコニウム濃度 (mg/L)
平成26年11月28日	①	ジエチルエーテル $Zr(iprac)_4$ 8.3mg/20mL 上澄み液 2014.11.11 No.1075	0.50
	②	2014.10.17 $Zr(iprac)_4$ 5.9mg ジエチルエーテル No.980	150
平成26年12月10日	③	プロパノール $Zr(iprac)_4$ (1.5/20) 上5mL	5.6
	④	2-プロパノール(20mL)+$Zr(iprac)_4$ (1.5mg) 2013.11.22 No.497	18
	⑤	2-プロパノール+$Zr(iprac)_4$ 吸収1回目測定 2013.11.22 No.497から No.525	1.1
	⑥	アニソール $Zr(iprac)_4$ 2.0/20mL No.673(上)5mL	2.6

LIGHT YIELD COMPARISON BETWEEN BC505 AND STANDARD COCKTAIL



Light yield of BC505 and our standard cocktail (100mg PPO and 10mg POPOP solved in 20mL anisole) is almost same quality.

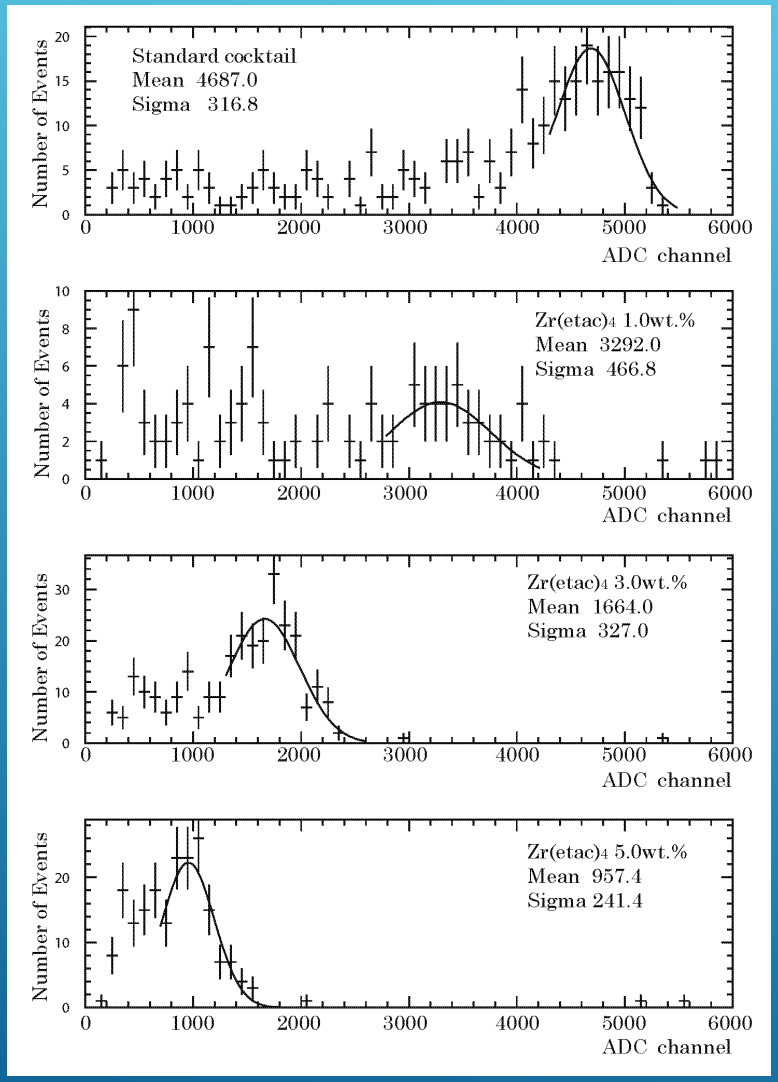
ENERGY SPECTRA FOR SEVERAL CONCENTRATION OF ZR(IPRAC)4



Peak values decreased as a function of the concentration of $Zr(iprac)_4$.

Energy resolutions are also getting worth as a function of the concentration of $Zr(iprac)_4$.

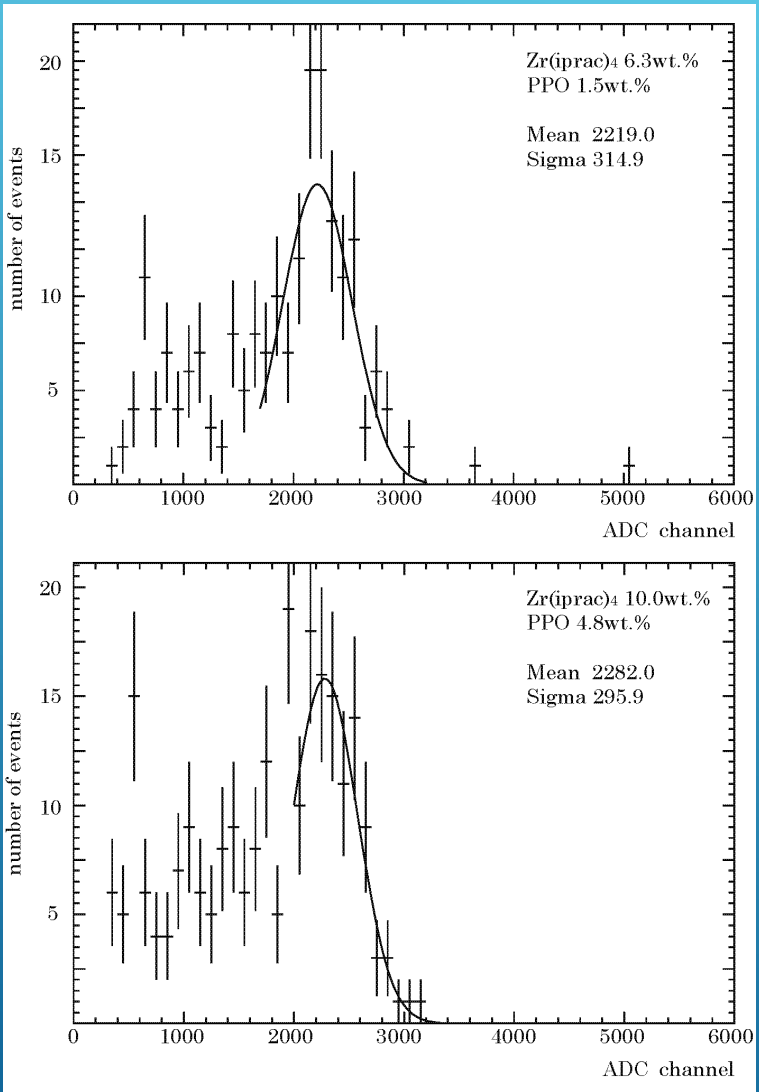
ENERGY SPECTRA FOR SEVERAL CONCENTRATION OF ZR(ETAC)4



Peak values decreased as a function of the concentration of $Zr(etac)_4$.

Energy resolutions are also getting worth as a function of the concentration of $Zr(etac)_4$.

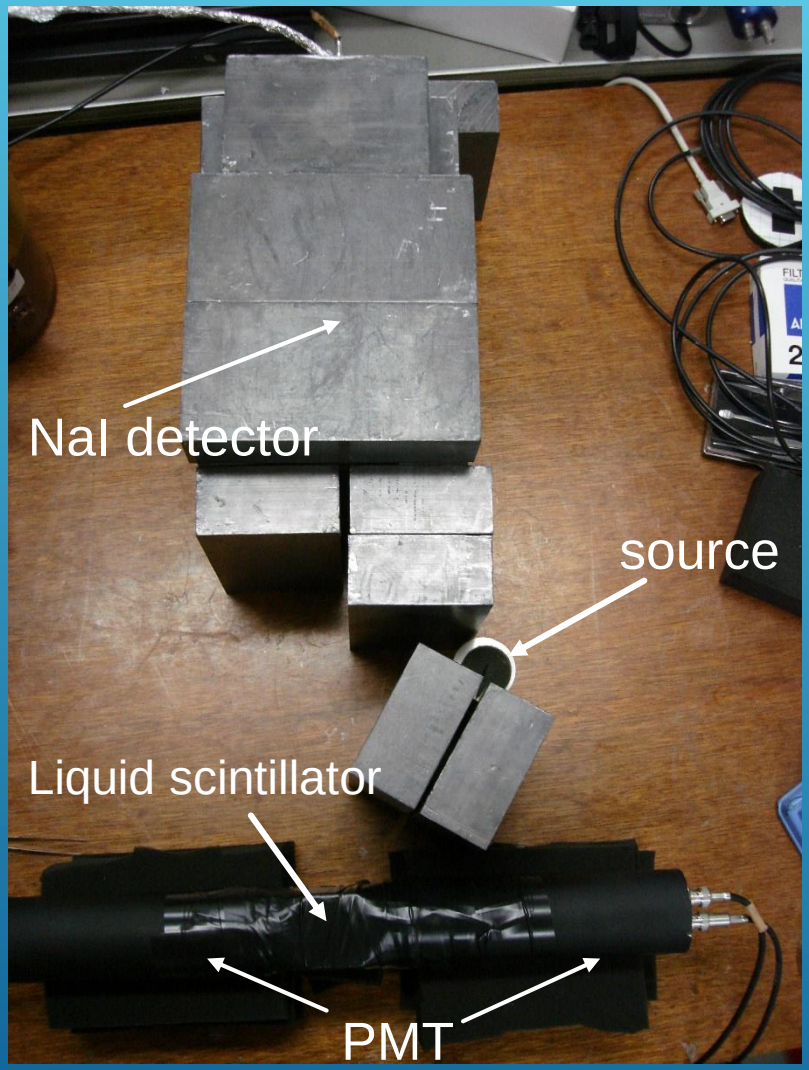
RECOVERY FOR ABILITY OF LIGHT YIELD AND ENERGY RESOLUTION

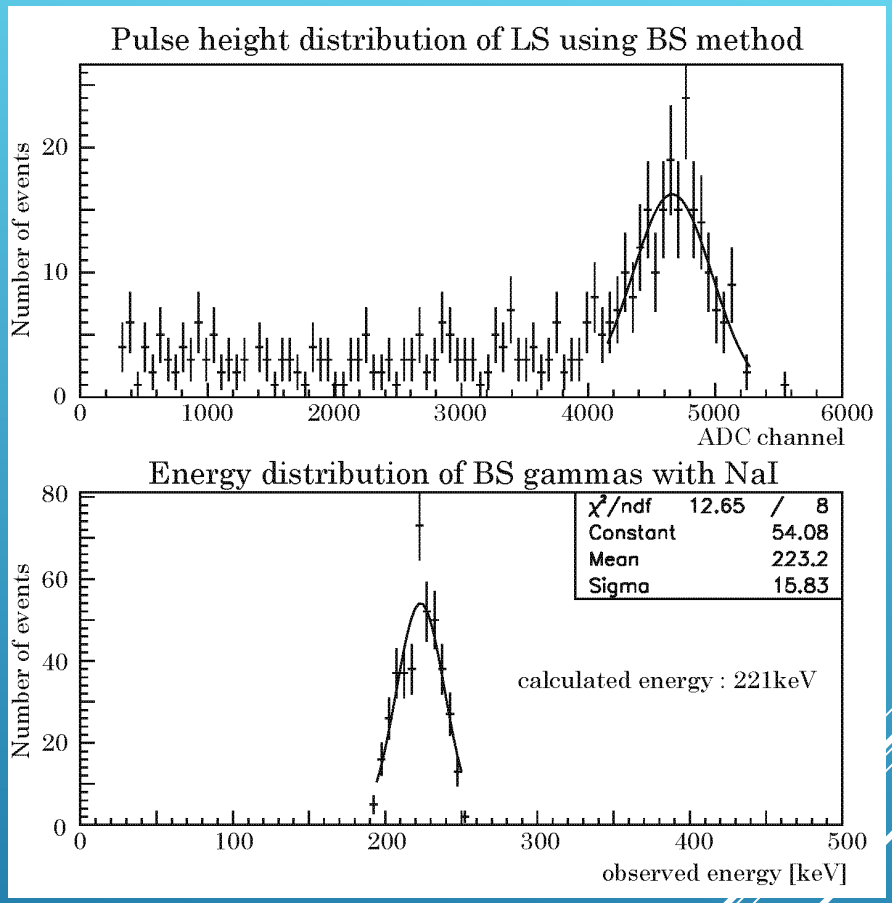


PPO helps recovering the light yield and the energy resolution.

Confirmed our assumption and obtained optimized real cocktail (PPO 5wt.% POPOP 0.5wt.%)

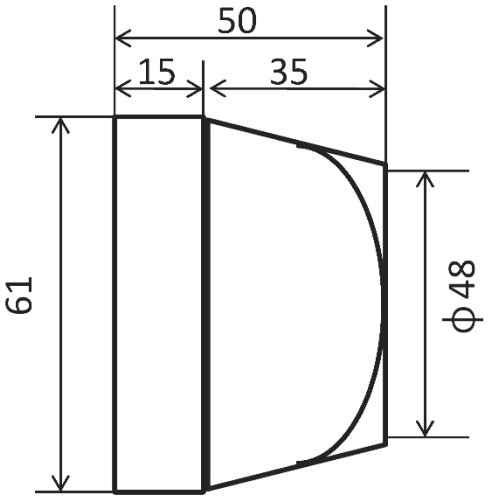
BACK SCATTERING METHOD

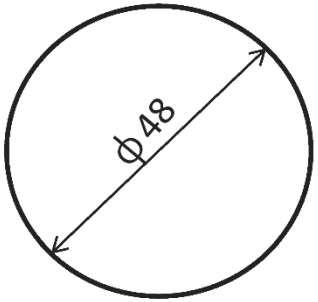


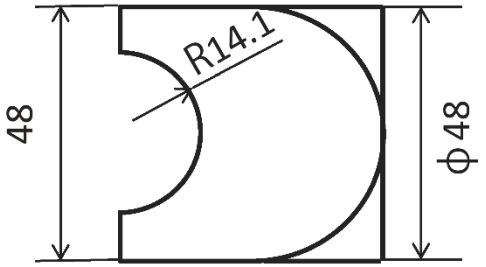


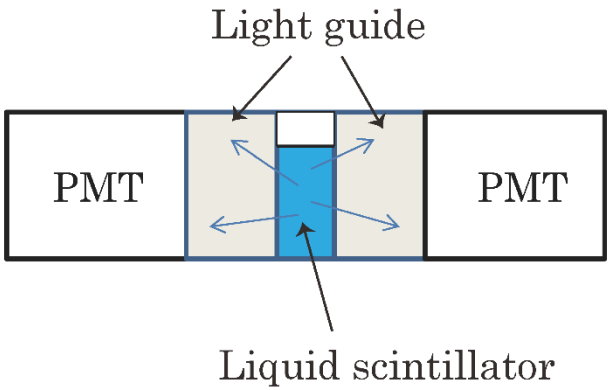
Single peak could be used even in liquid scintillator.

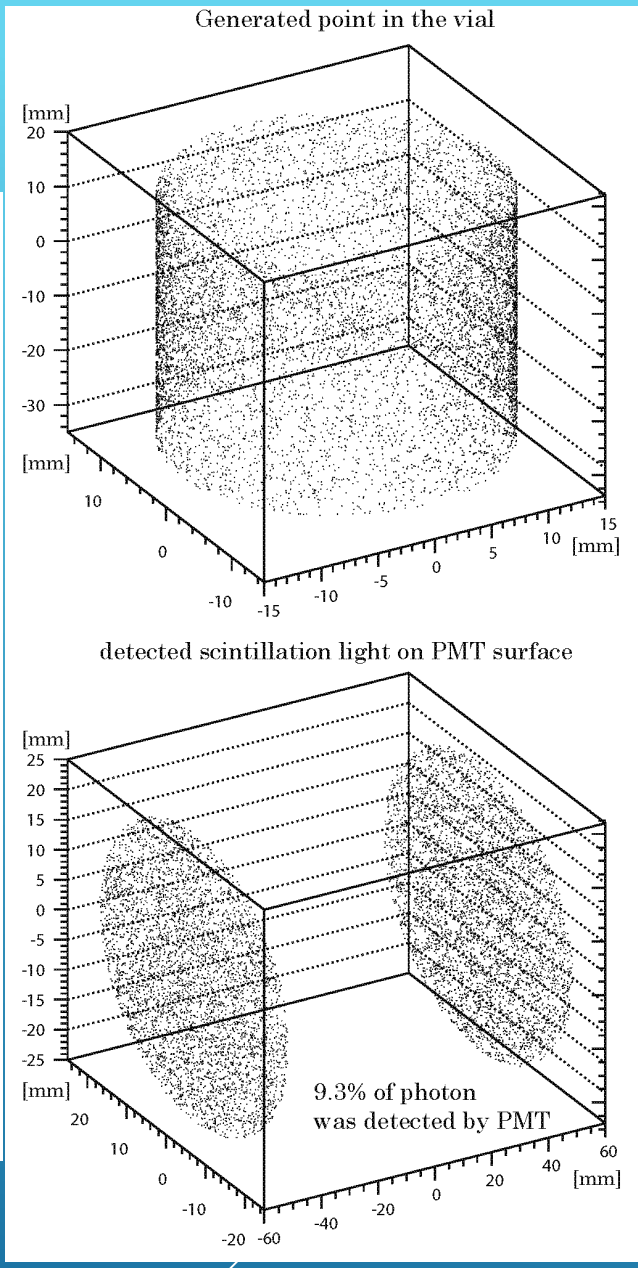
Photo coverage



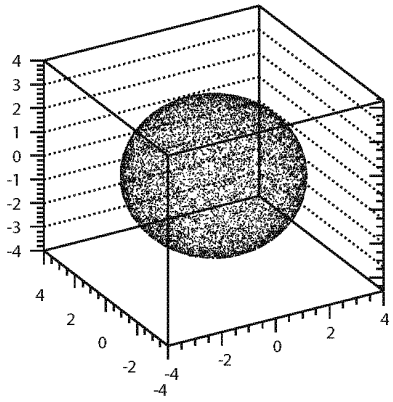




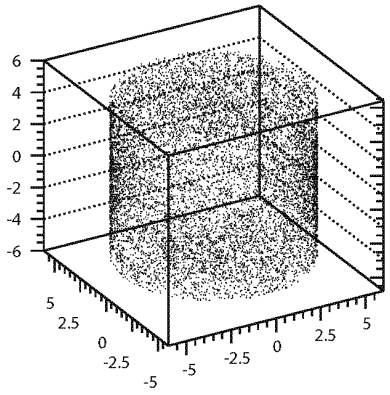




Photon attenuation in ZICOS detector

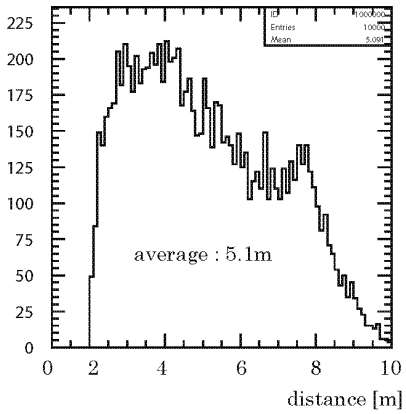


vertex position in baloon

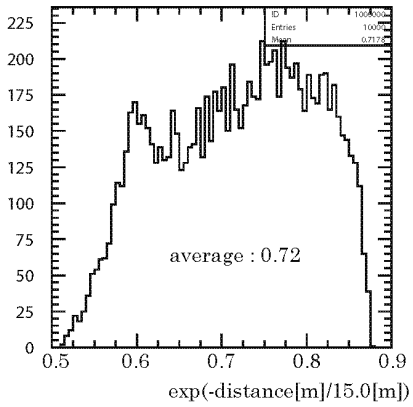


photon arrival position on the wall

distance between vertex and arrival point



attenuation of photn in ZICOS detector



Assuming 3m radius balloon and 5m radius of tank with 15m attenuation length of anisole, the photon attenuation will be 0.72 in average.

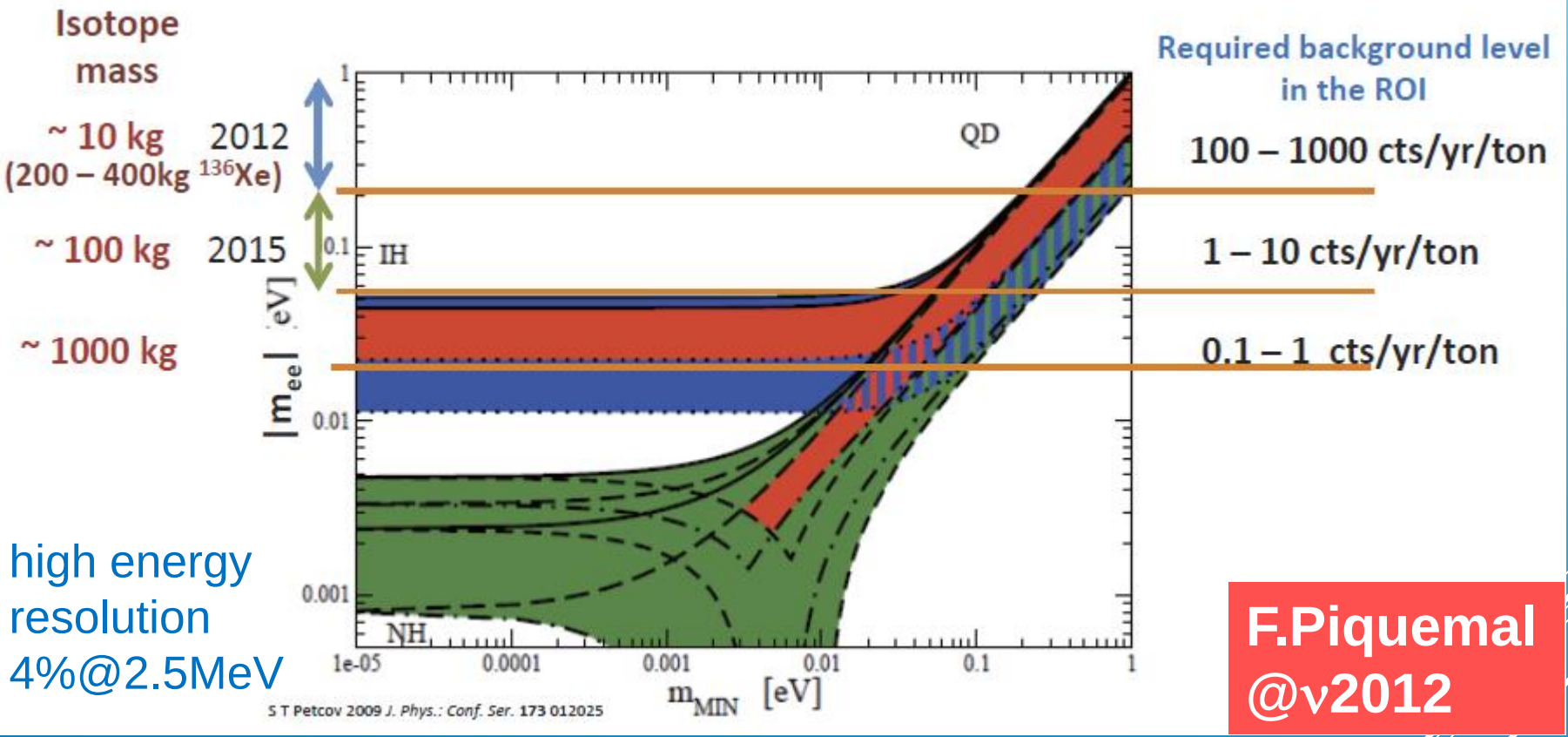
Solubility of PPO in anisole with 10wt.% concentration of $Zr(iprac)_4$

$$\frac{205.5\text{mg}}{205.5\text{mg}+2.0\text{g}}$$

= 9.3 wt.%

Maybe solved in 20 wt.% of $Zr(iprac)_4$

FOR FUTURE EXPERIMENTS



high energy resolution 4%@2.5MeV

F.Piquemal @ν2012

http://kds.kek.jp/getFile.py/access?contribId=37&sessionId=16&resId=2&materialId=slides&confId=9151

~tons of target will be necessary for next generation detector