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VIV

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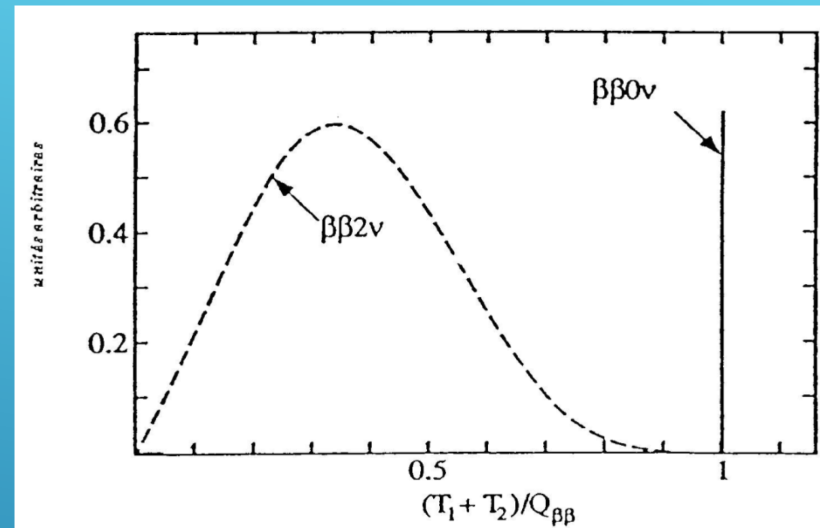
Neutrinoless double beta decay

$\beta\beta$ 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



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

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

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

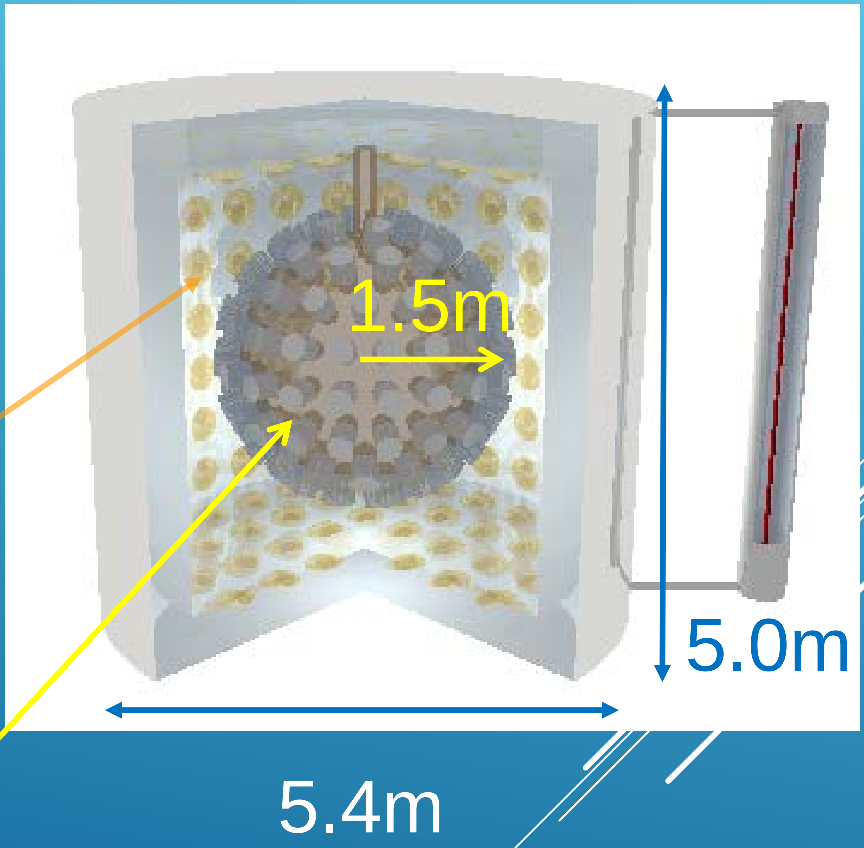
Requirement : Low BG, Large target mass, High energy resolution

ZICOS -Zirconium Complex in Liquid Scintillator experiment for neutrinoless double beta decay

Liquid scintillator ：
(1) 10 wt.% Zr(iprac)$_4$ and 5wt.% PPO solved in PhOMe
(2) 3.5% at 3.35MeV of energy resolution, if 40% photo coverage of Photomultiplier

Pure water surrounding inner detector to veto and shield from external backgrounds.

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



Neutrino mass sensitivity of ZICOS experiment

1) Zr enrichment

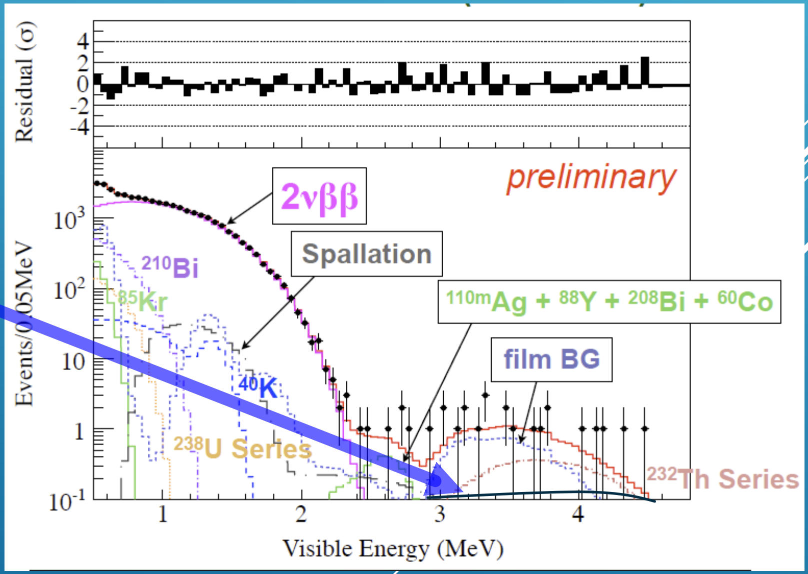
58.5% enrichment of ^{96}Zr (e.g. 57.3% for NEMO-3)
then ^{96}Zr will be 126kg (0.56 times ^{136}Xe 320kg)

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

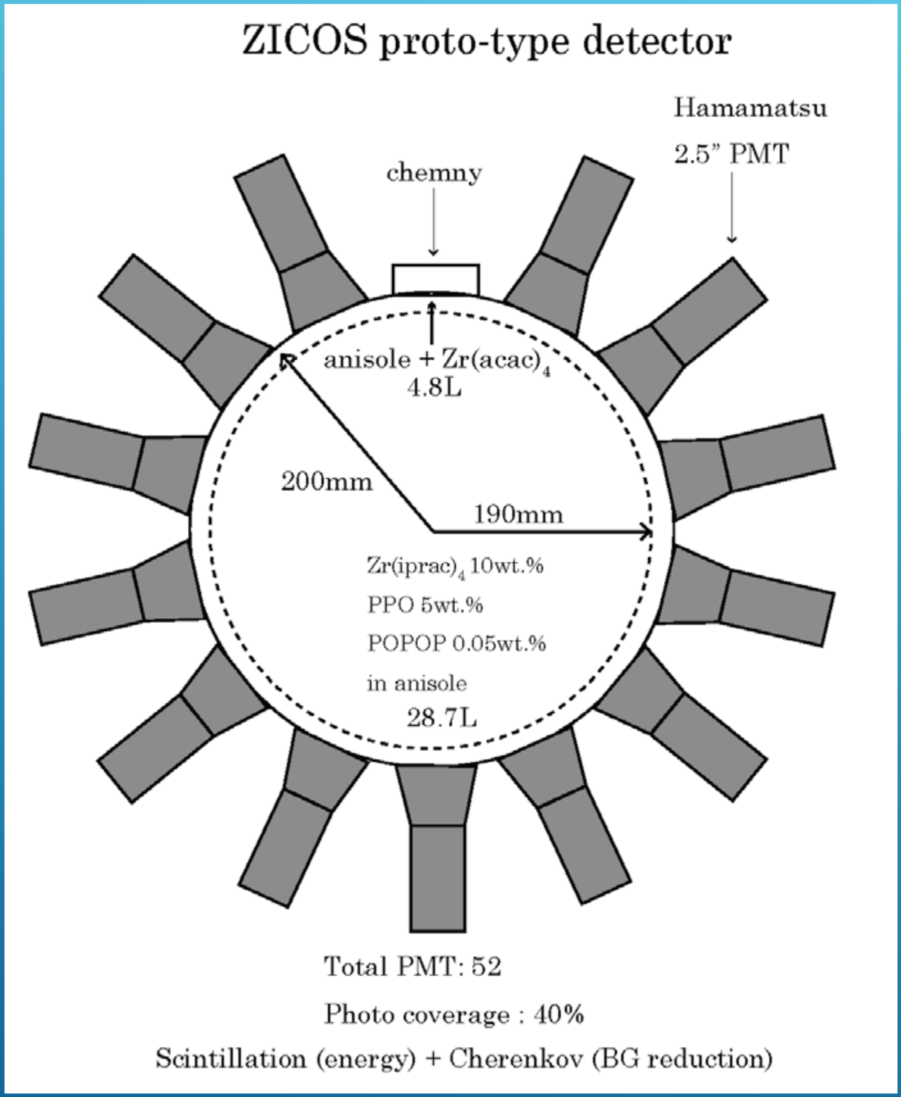
2) Lowering BG rate

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



ZICOS proto-type detector



Performance :

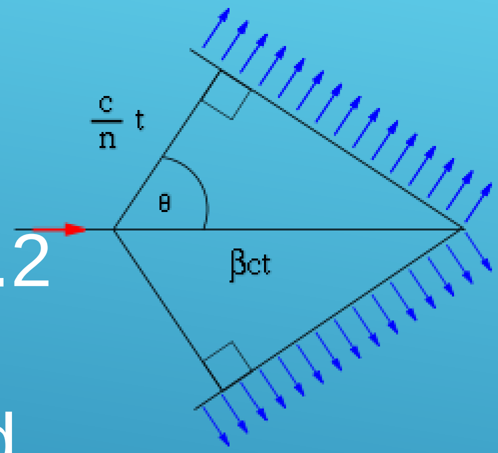
- Energy resolution
- BG reduction study using Cherenkov light

Physics goal :

- ^{96}Zr : 10g (same as NEMO-3) using natural abundance Zirconium.
- $T_{1/2}(0\nu\beta\beta) > 1.0 \times 10^{22}$ years, if no BG was found in 200 days' measurement.

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 β=0.951 and Cherenkov angel θ=46.2 degree are expected.
- Cherenkov light should be measured. (400nm – 600nm : 100 photon/MeV)

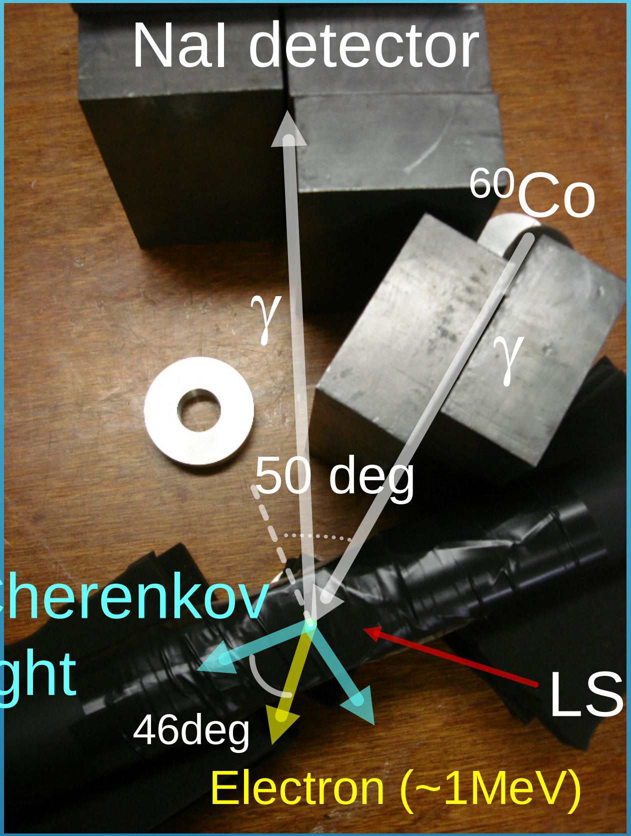


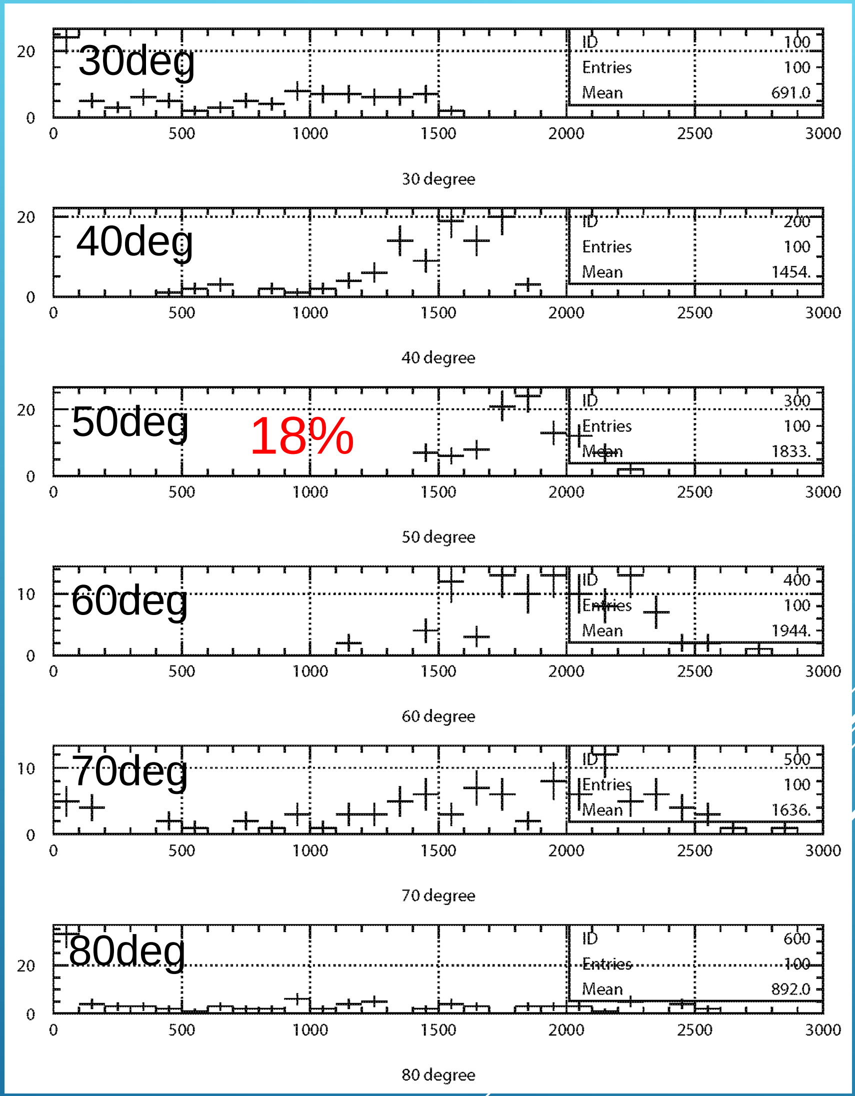
$$\frac{dN}{dx} = 2\pi z^2 \alpha \sin^2\theta_c \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda} = 475 z^2 \sin^2\theta_c \text{photon}/\text{cm}$$

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

Cherenkov light = 1~2% of scintillation light

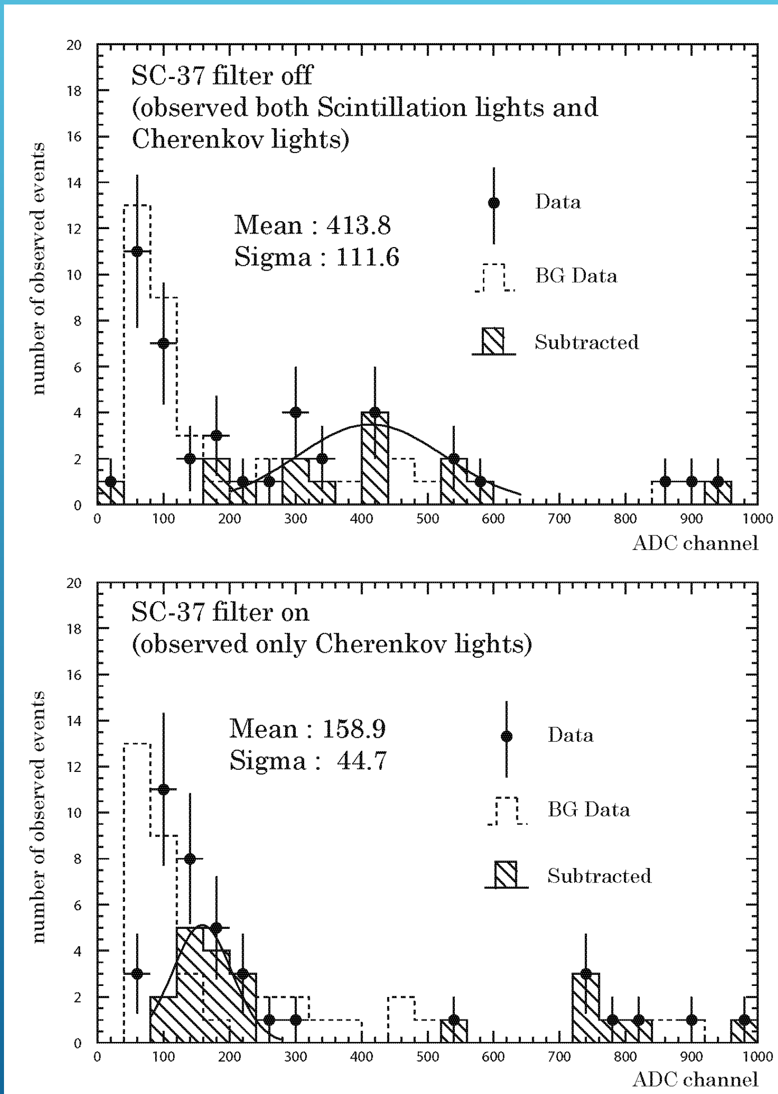
Measurement of Cherenkov light (1)

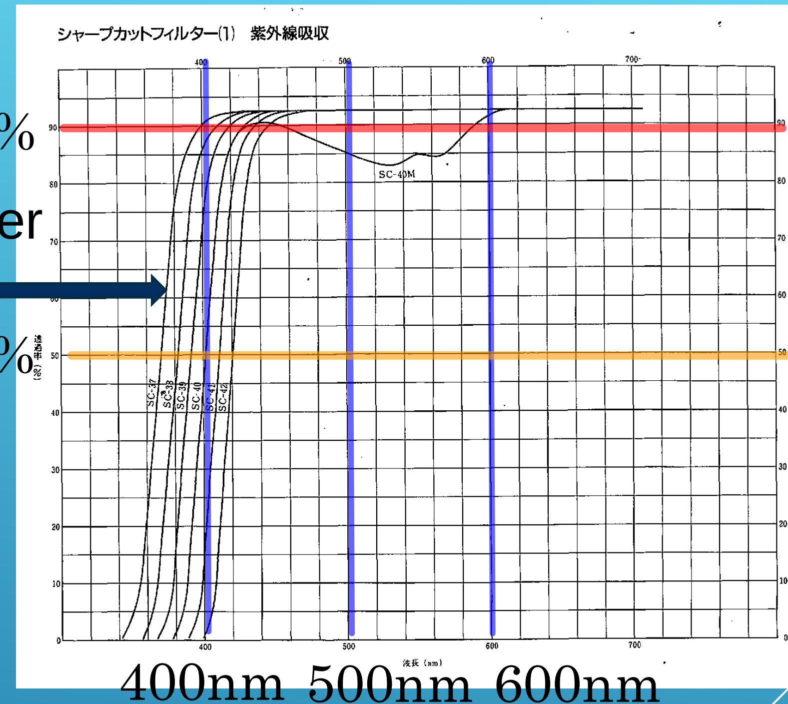




Comparison of light yields between SC-37 filter off and on for anisole only LS using back scattering method.

Light yield of Cherenkov lights (1)





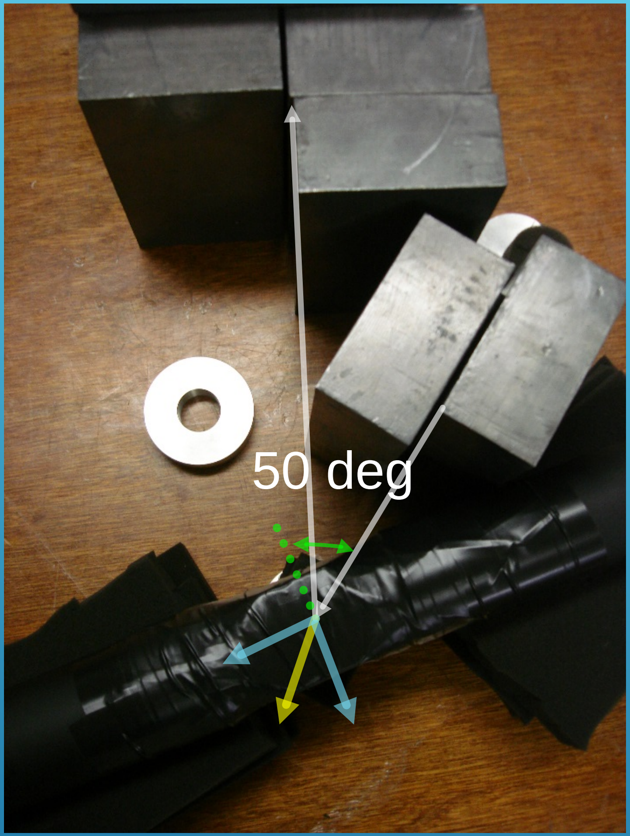
Cherenkov light yield (λ>400nm)

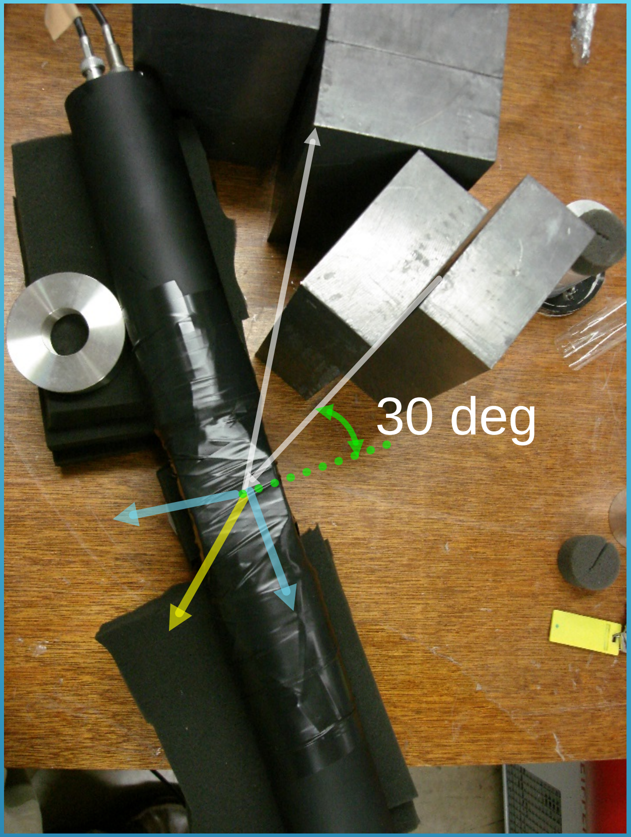
Scintillation light yield of std. LS

$$= \frac{158.9/0.18/0.95}{254.9/0.046/0.098} = \sim 0.02$$

Consistent with expectation.

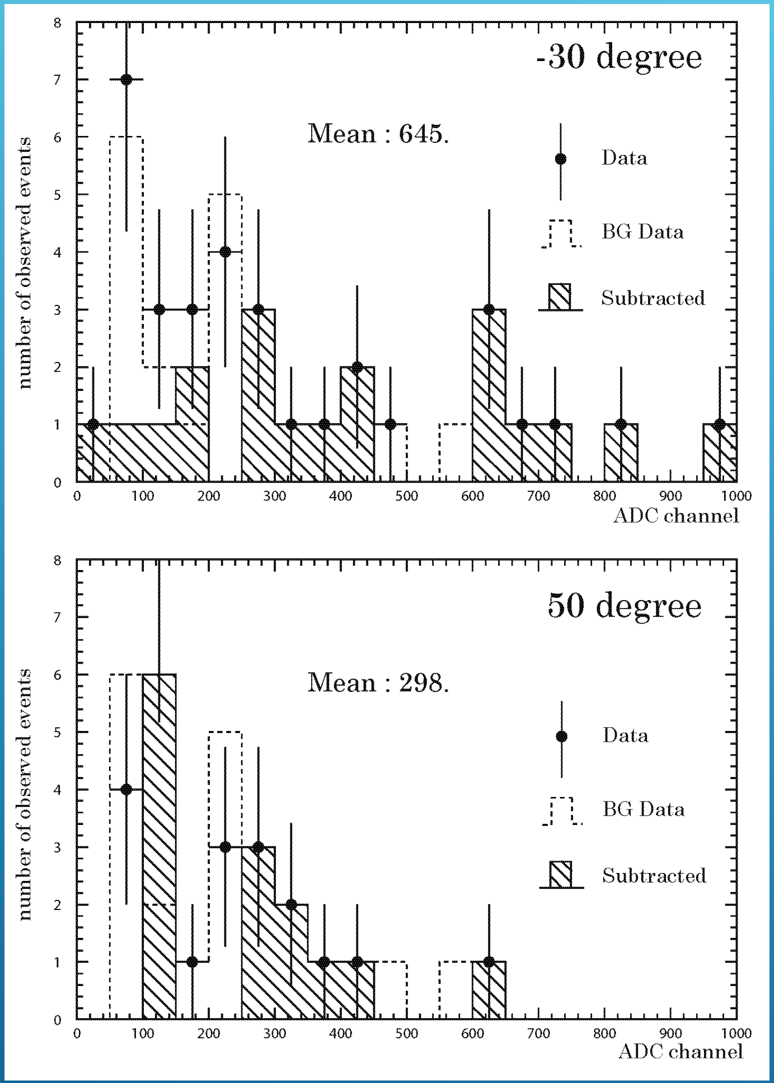
Measurement of Cherenkov light (2)





Comparison of light yield between the case of Cherenkov light on and off

Light yield of Cherenkov lights (2)



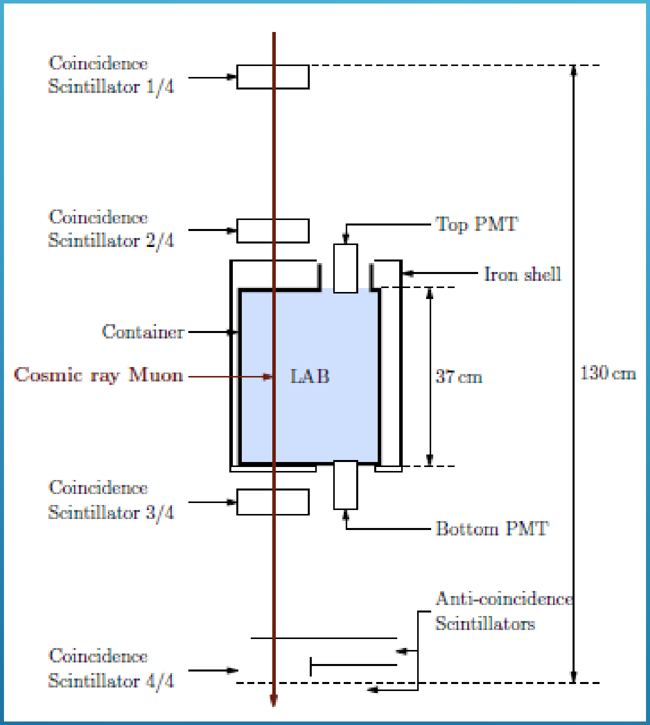
$$\frac{\text{Cherenkov light yield}}{\text{Scintillation light yield of std. LS}} = \frac{347/0.18}{298/0.046/0.098} = \sim 0.03$$

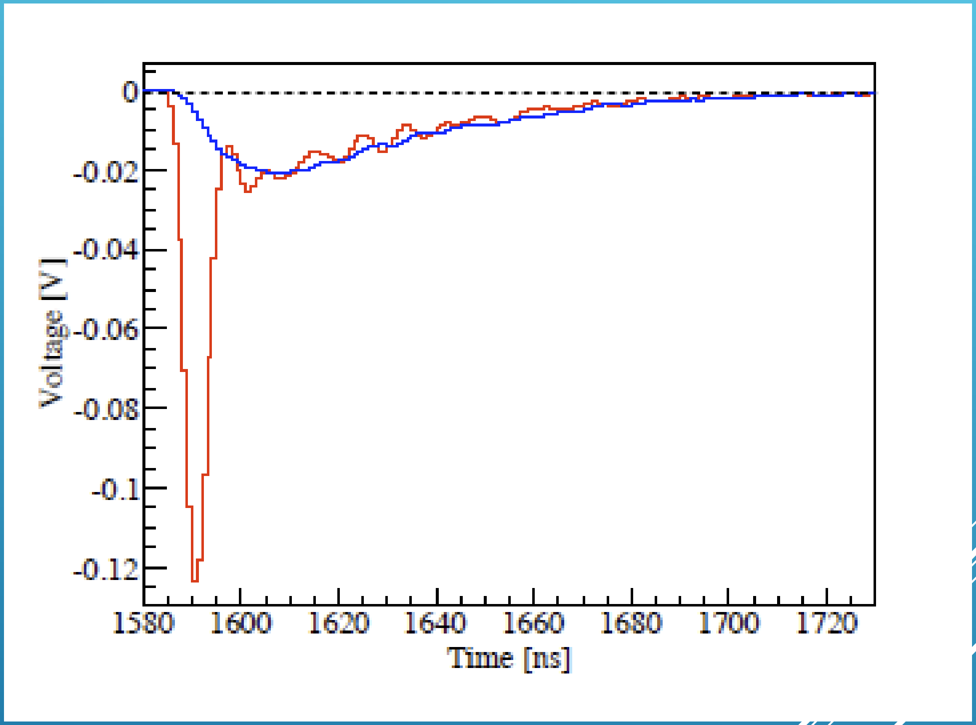
Consistent with previous measurement.

Cherenkov lights should have directionality. (not so bad!)

How to extract Cherenkov signal

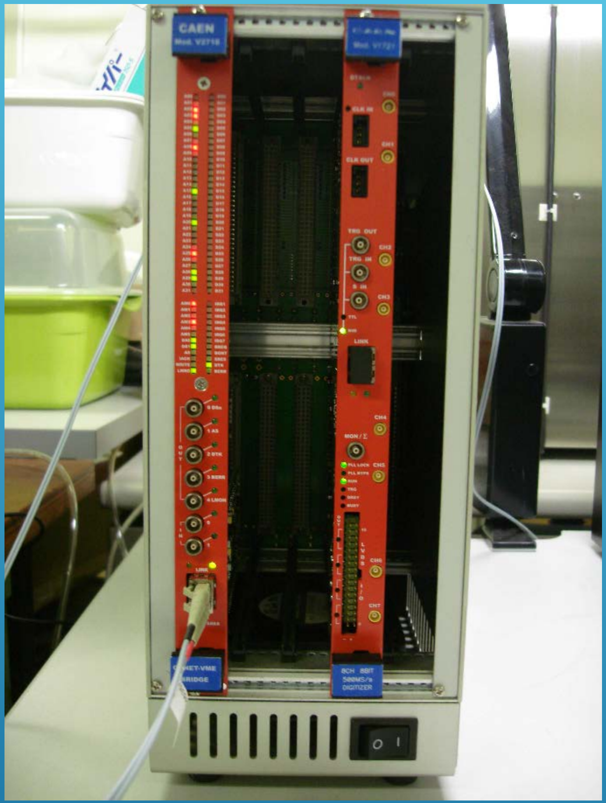
Separation of scintillation and Cherenkov lights using timing shape C.Shaomin et al. arXiv:1511.09339





Cherenkov has a faster peak than scintillation.

Waveform measurement setup



- CAEN V1721 8 channel 8bit 500MS/s FADC
- CAEN V2718 VME-PCI Optical Link Bridge

Stability of material state

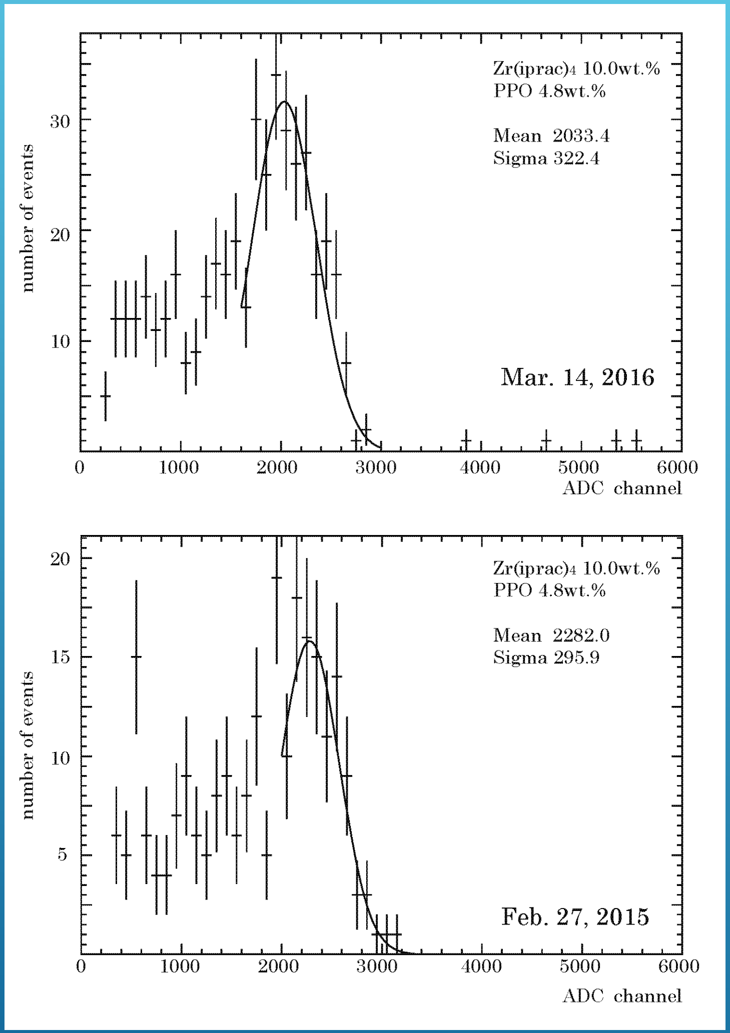
$Zr(iprac)_4$ 2242mg, PPO 999mg and POPOP 10mg solved in 20mL Anisole.

Feb. 27,2015

Mar. 14, 2016

Keep clear and transparent liquid and found no precipitate.

Stability of performance



Light Yield : -10.9%

Energy resolution : -2.9%

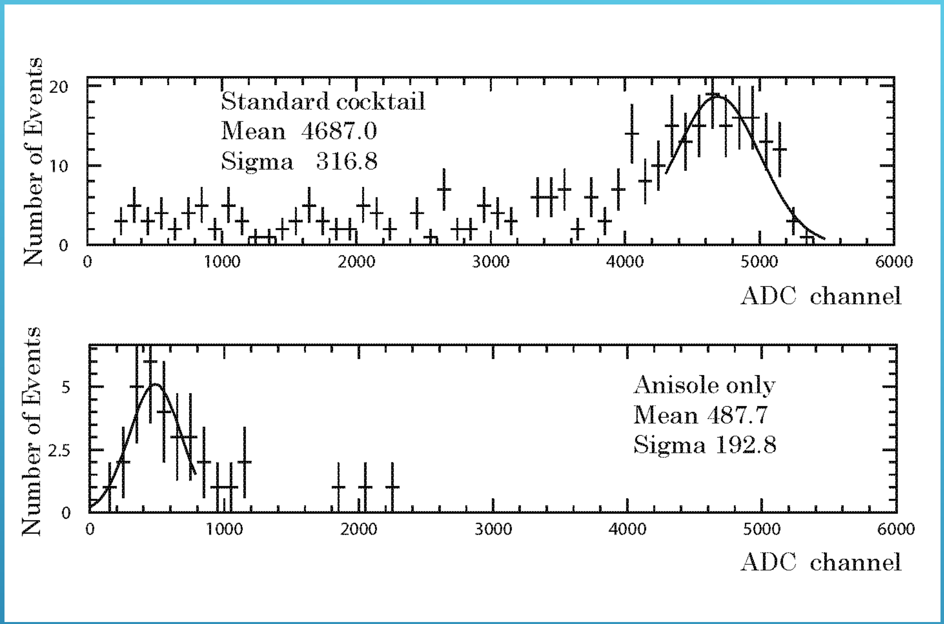
Slightly worse, but not by same condition (no purge, temperature…)

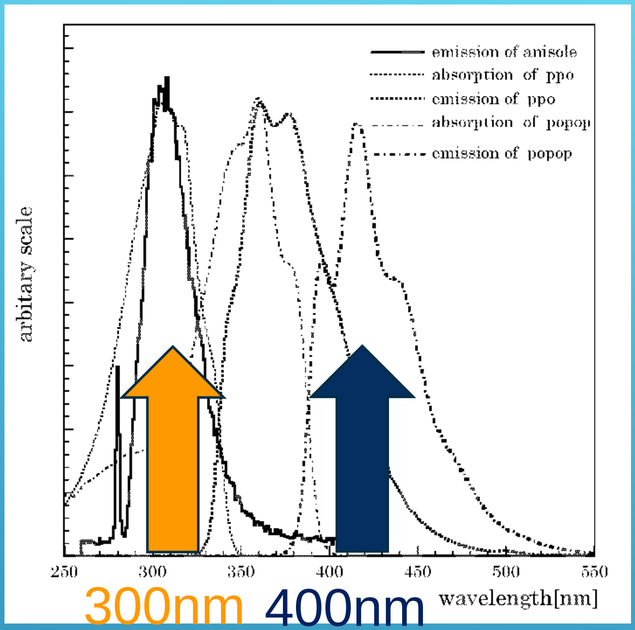
SUMMARY

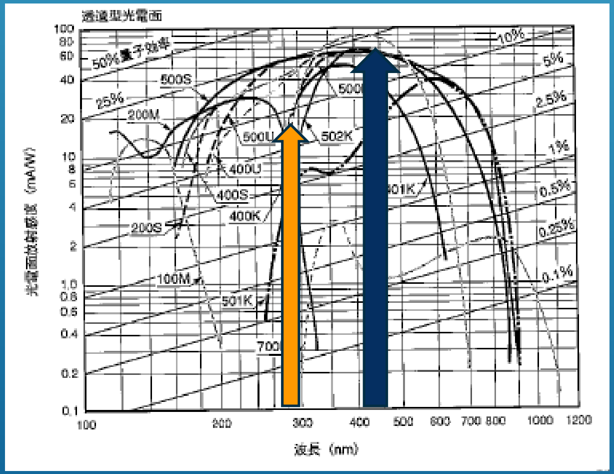
- Cherenkov lights from 1MeV electron have directionality and the light yield has been confirmed to be a few % of scintillation.
- Separation of Cherenkov lights from 1MeV electron will be tested by FADC time profile.
- ZICOS proto-type detector with 30cm diameter is actually planning and it will demonstrate an ability of background reduction using Cherenkov light, and try to get a limit of half-life for $0\nu\beta\beta$ up to 10^{22} years.
- $Zr(iprac)_4$ loaded liquid scintillator is almost stable for the material state and the performance.

BACKUP

Light yield of scintillation in anisole

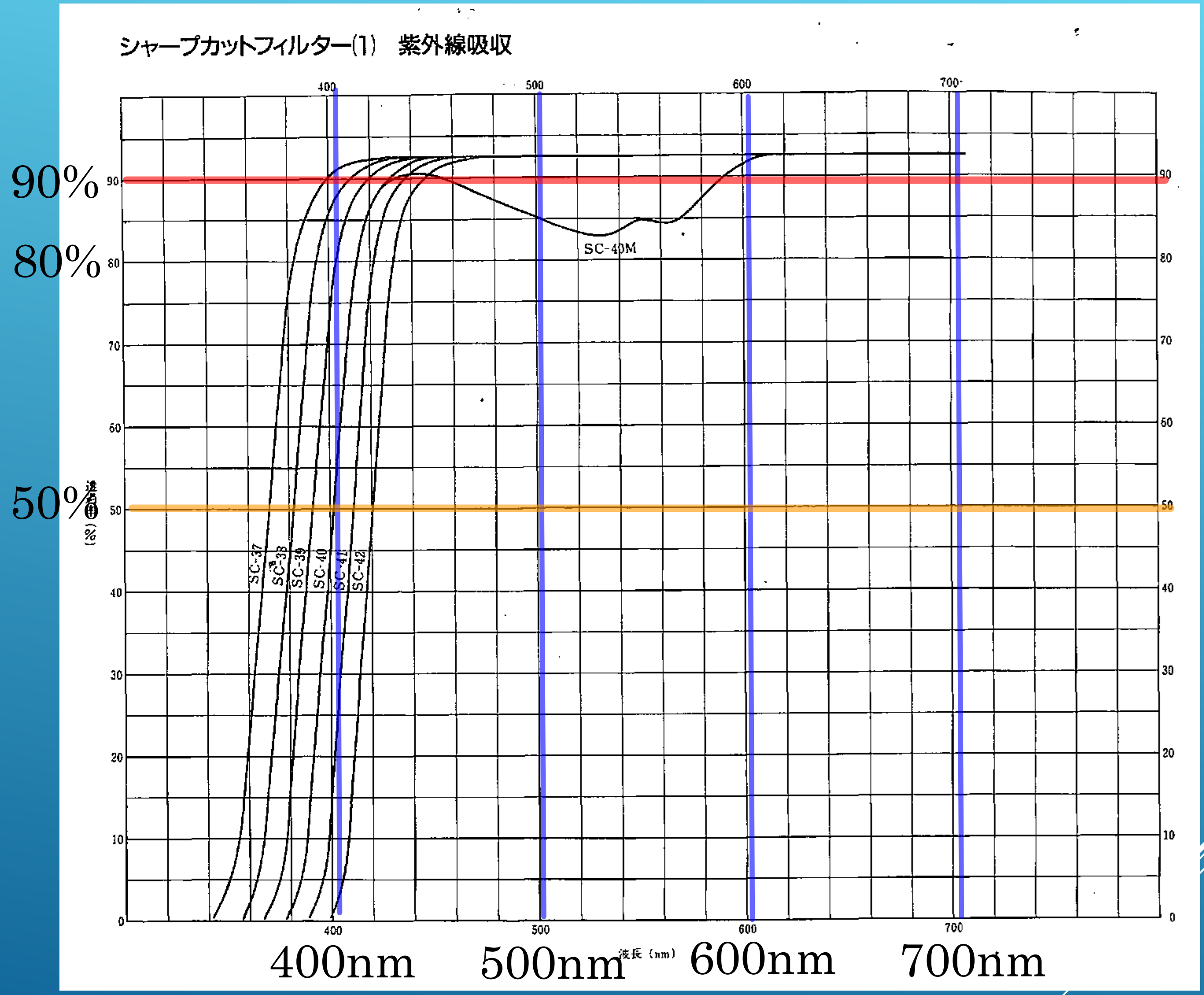






Relative scintillation light yield of anisole is 9.8% to standard cocktail (due to difference of quantum efficiency of PMT)

UV sharp cut filter (Fuji films)



Physical constants of Liquid Scintillator

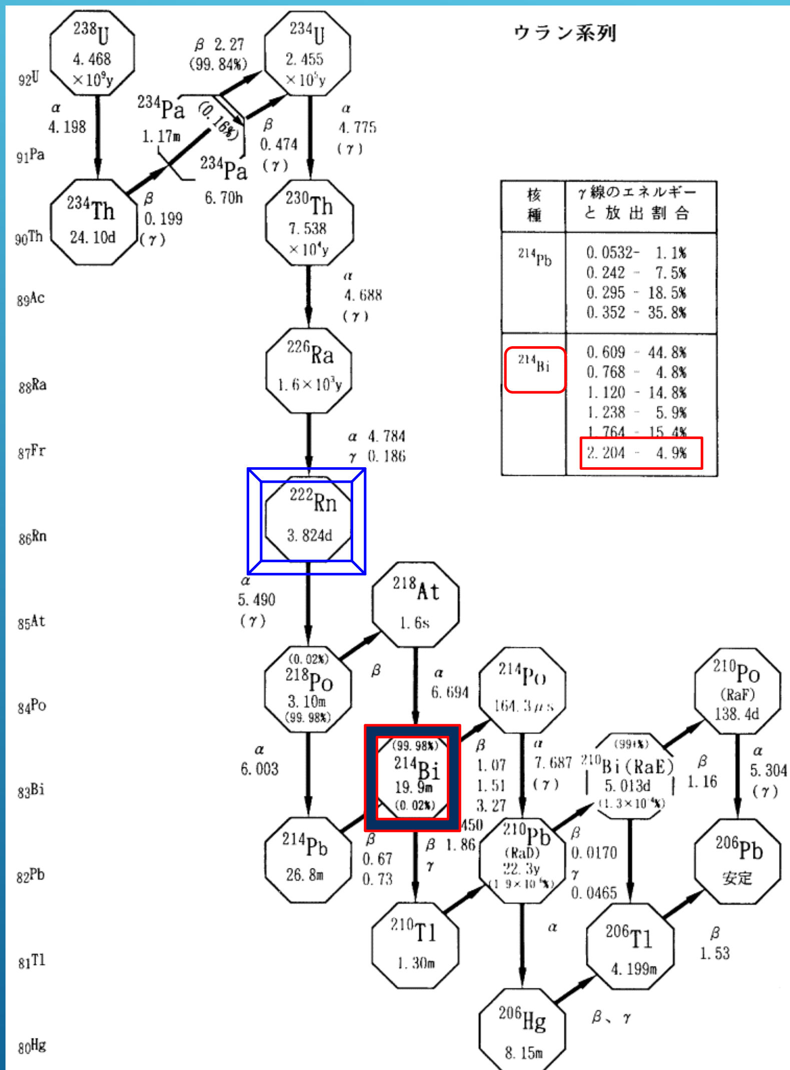
Physical Constants of SGC Liquid Scintillators

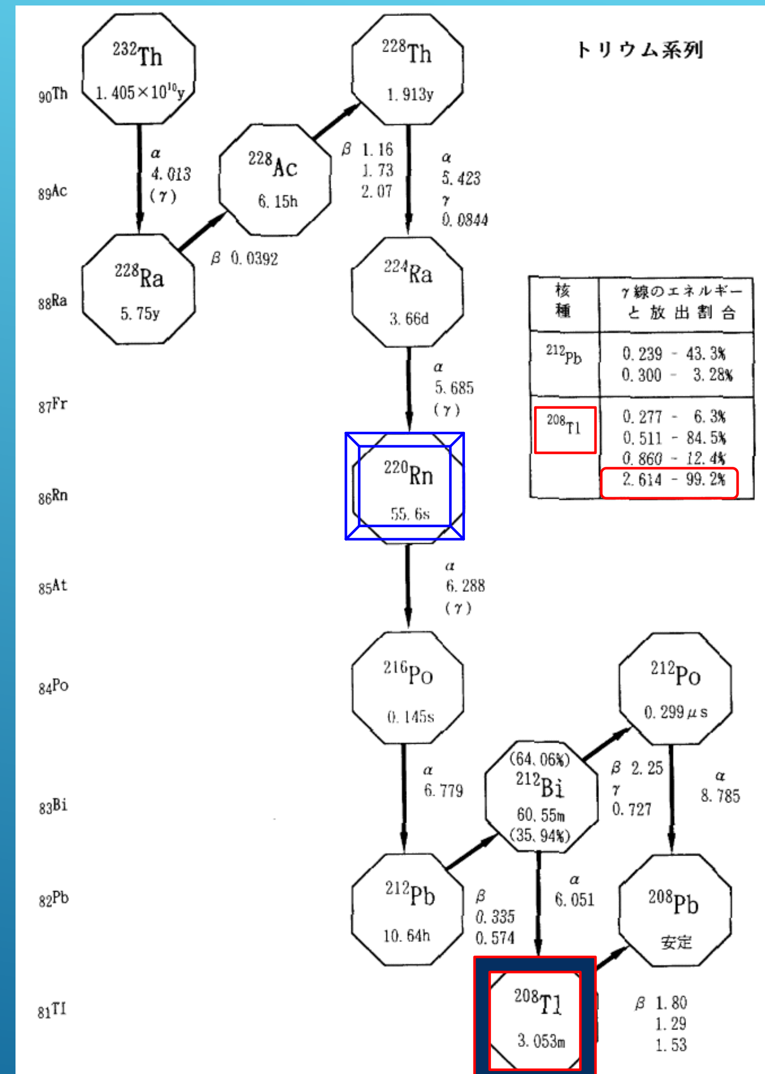
Scintillator	Light Output % Anthracene[1]	Wavelength of Maximum Emission, nm	Decay Constant, ns	H:C Ratio	Loading Element	Density	Flash Point °C
BC-501A	78	425	3.2[1]	1.212		0.87	26
BC-505	80	425	2.5	1.331		0.877	48
BC-509	20	425	3.1	.0035	F	1.61	10
BC-517L	39	425	2	2.01		0.86	102
BC-517H	52	425	2	1.89		0.86	81
BC-517P	28	425	2.2	2.05		0.85	115
BC-517S	66	425	2	1.70		0.87	53
BC-519	60	425	4	1.73		0.87	63
BC-521	60	425	4	1.31	Gd (to 1%)	0.89	44
BC-523	65	425	3.7	1.74	Nat. ^{10}B (5%)	0.916	-8
BC-523A	65	425	3.7	1.67	Enr. ^{10}B (5%)	0.916	-8
BC-525	55	425	3.8	1.56	Gd (to 1%)	0.88	91
BC-531	59	425	3.5	1.63		0.87	93
BC-533	51	425	3	1.96		0.80	65
BC-537	61	425	2.8	0.99 (D:C)	^{2}H	0.954	-11

* Anthracene light output = 40-50% of NaI(Tl)   [1] Fast component; mean decay times of first 3 components = 3.16, 32.3 and 270 ns

LY of NaI(Tl) : 4×10^4 photon/MeV → LY of BC505 : 1.2×10^4 photon/MeV

Natural radiative U/Th decay chain





Strategy of background reduction

- No Cherenkov ring
  - α-particle and low energy e/γ
- One Cherenkov ring
  - Single radioactive BG and ^{208}Tl decay as described later.
- Multi Cherenkov ring from ^{208}Tl
  - β (E>0.9MeV) and 2.6MeV γ emit CL.
  - 1.09MeV γ also emits CL. (3 ring)
  - 0.51 MeV, 0.58MeV and 0.86 MeV γ don't emit CL. (2 ring)
- Ultimate contamination
  - β (E>0.9MeV) and 2.6MeV γ with low energy γs.

→ Need consistency of total energy and vertex position reconstructed by SL and CL.