R&D of water-based liquid scintillator as a reactor anti-neutrino detector

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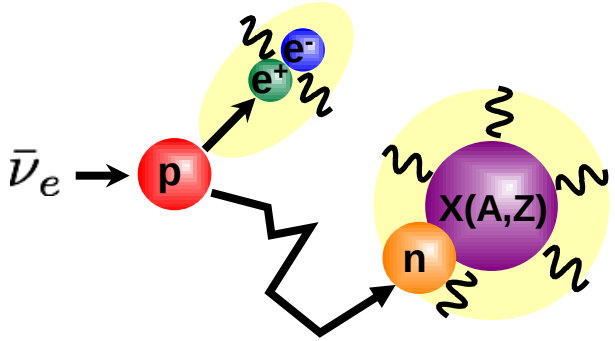
Why water-based ?

Neutrino energy measurement is important for

- neutrino oscillation experiments (currently organic solvent scintillators are used in DoubleChooz,DayaBay, and RENO).
- **reactor monitor requested by IAEA (International Atomic Energy Agency) as one of the safeguards.**

Requirements for a reactor monitor:

1. **nonflammable and nonvolatile for the use near a reactor**
   → **water-based scintillator**
2. **Gd is soluble to identify neutrino interactions by delayed coincidence measurement.**



Principle for R&D

We try to dissolve following things into the water:

1. **Luminescent agent (PPO) with a surfactant**
2. Aromatic molecules with hydrophilic group as a material taking energy transmission, and luminescent agent (PPO)
3. Water-soluble luminescent agent

Light Yield Measurement by ^{60}Co

We use the Compton edge energy (maximum energy of recoil electrons) .

$$E_e^{max} = E_\gamma - \frac{E_\gamma}{1 + \frac{2E_\gamma}{m_e c^2}}$$

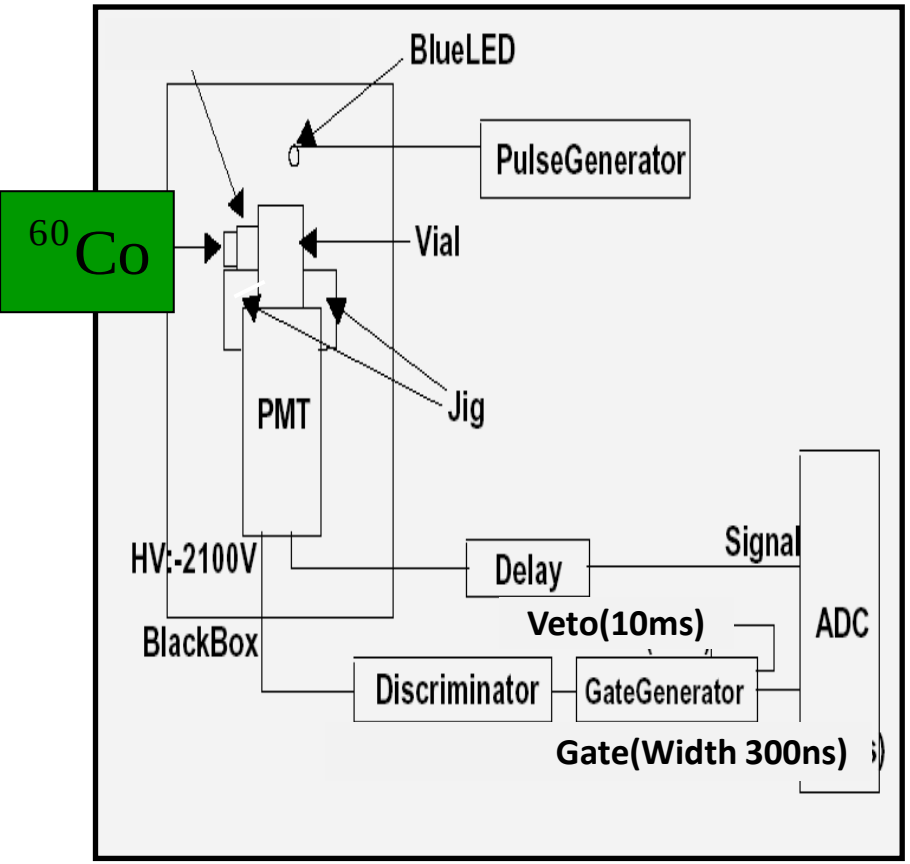
E_e^{max} : **maximum energy of the Compton electron**

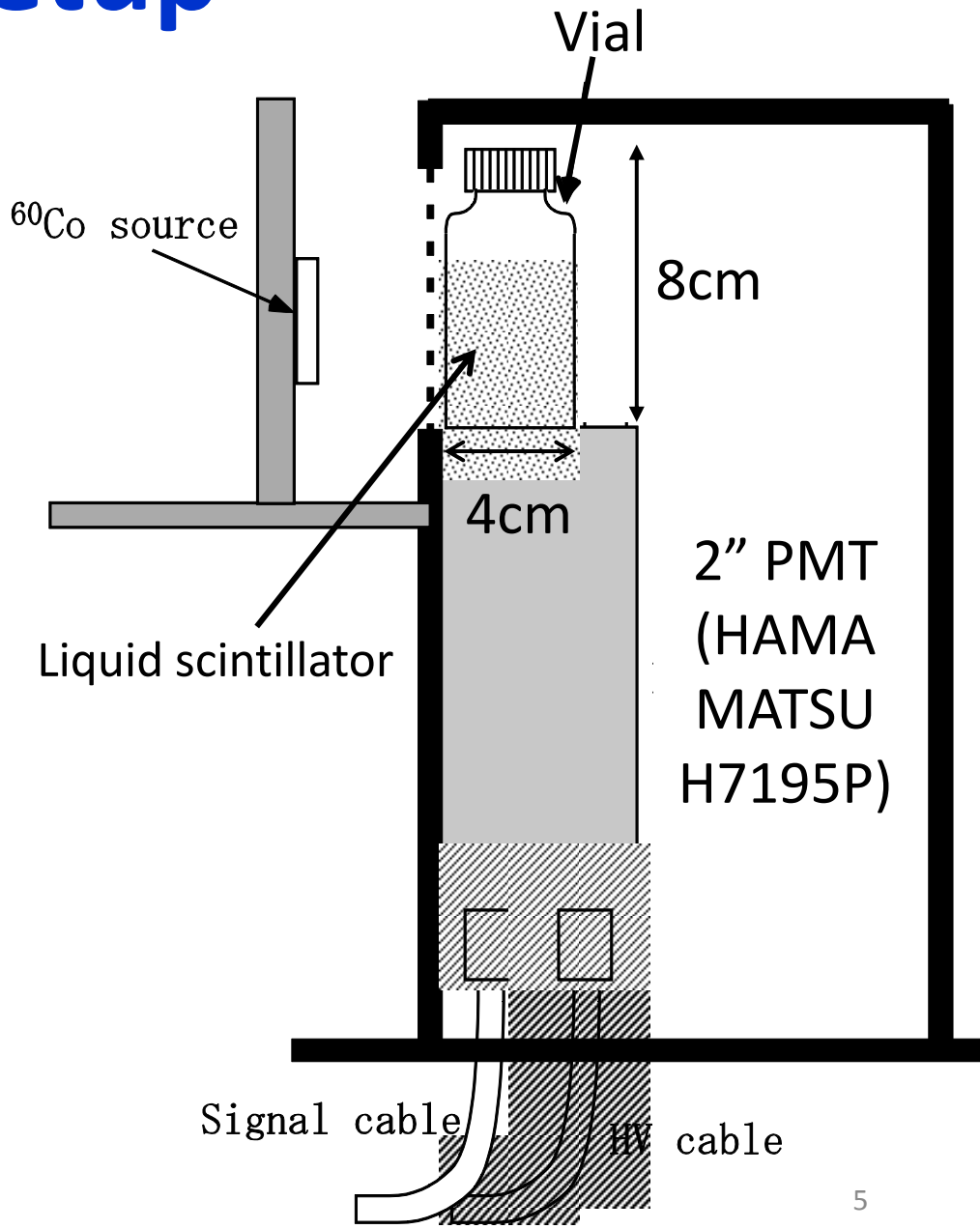
E_γ : **energy of induced γ ray**

$m_e c^2$: **rest mass energy of electron**

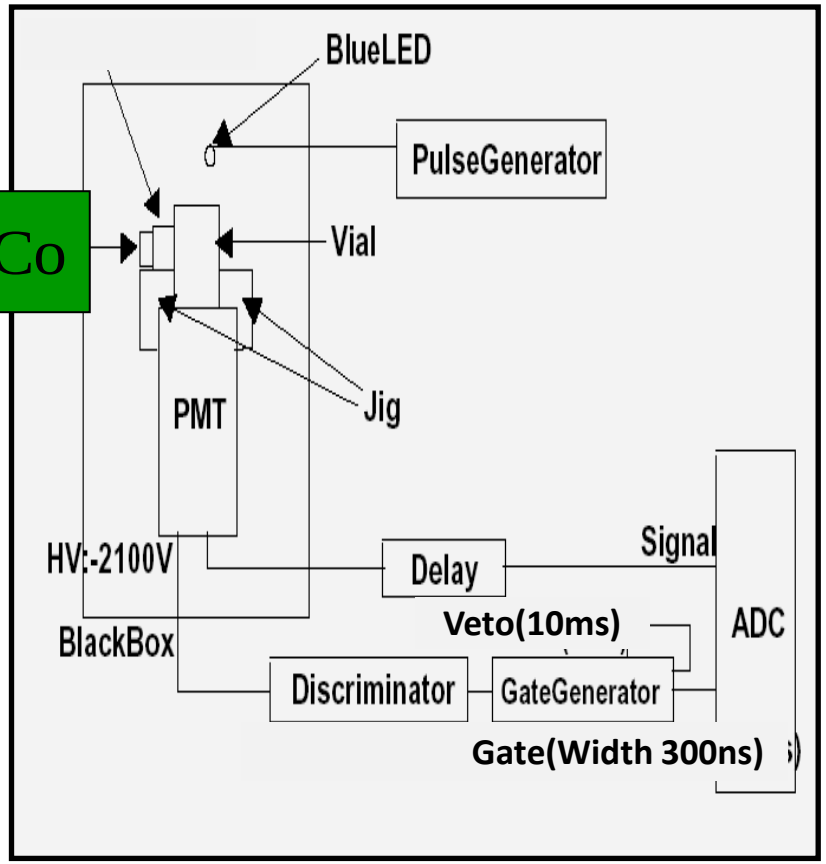
^{60}Co
- 1.17MeV γ ray → 0.96MeV
- 1.33MeV γ ray → 1.12MeV

Setup


BlueLED
PulseGenerator
^{60}Co
Vial
PMT
Jig
HV:-2100V
Delay
Signal
Veto(10ms)
BlackBox
ADC
Discriminator
GateGenerator
Gate(Width 300ns)


Vial
^{60}Co source
8cm
4cm
2” PMT
(HAMA
MATSU
H7195P)
Liquid scintillator
Signal cable
HV cable

Setup

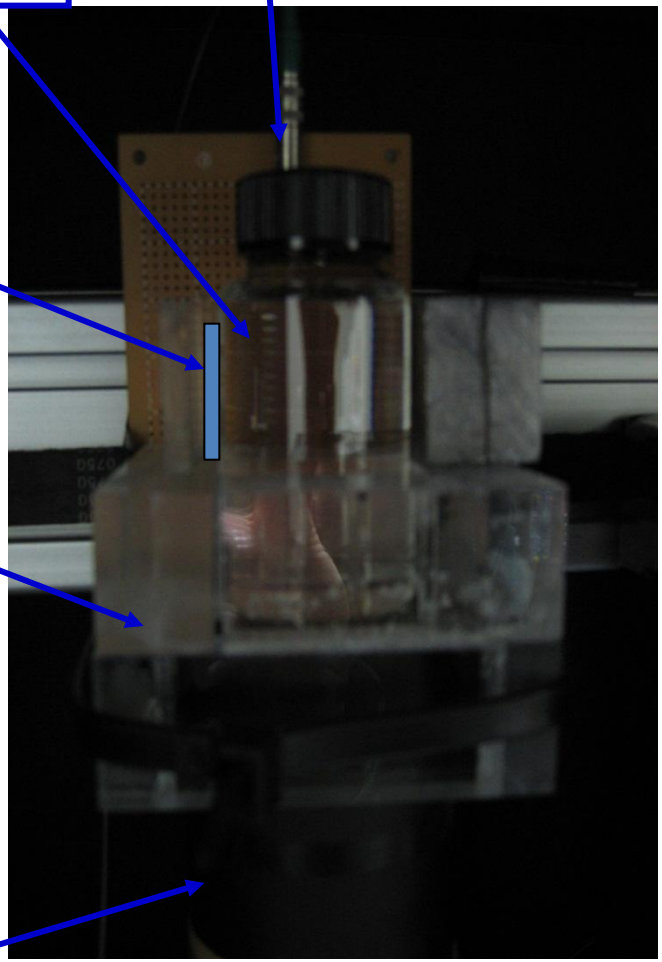


Liquid scintillator

Blue LED

^{60}Co

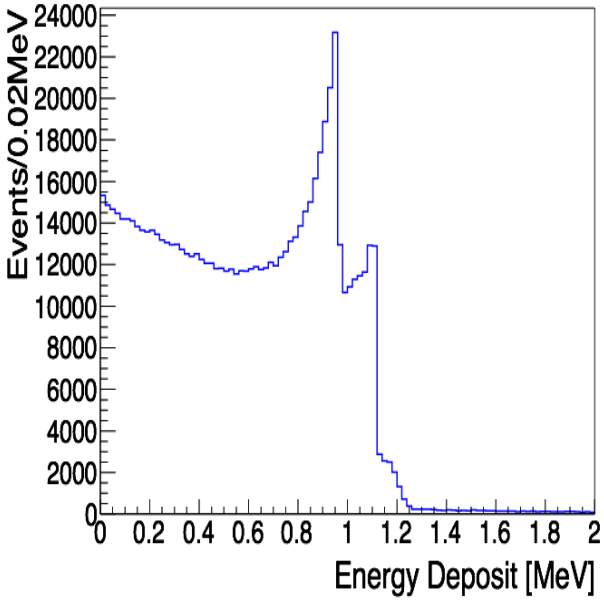
Acrylic jig



PMT
HAMAMATSU
H7195P

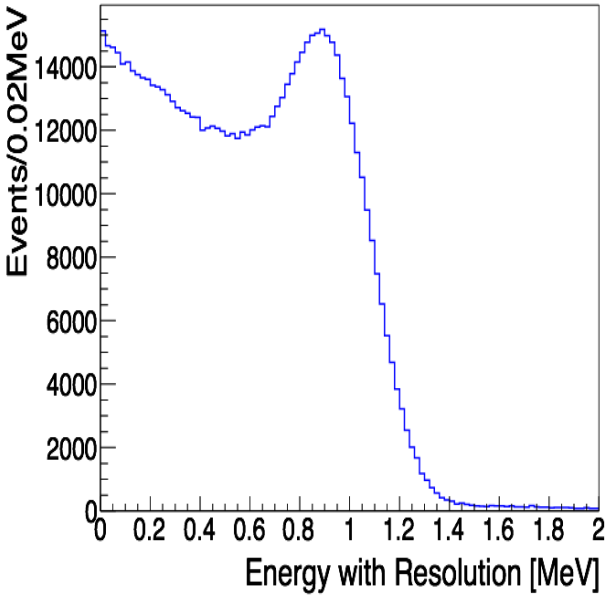
Energy Doposit by ^{60}Co irradiation

Energy distribution



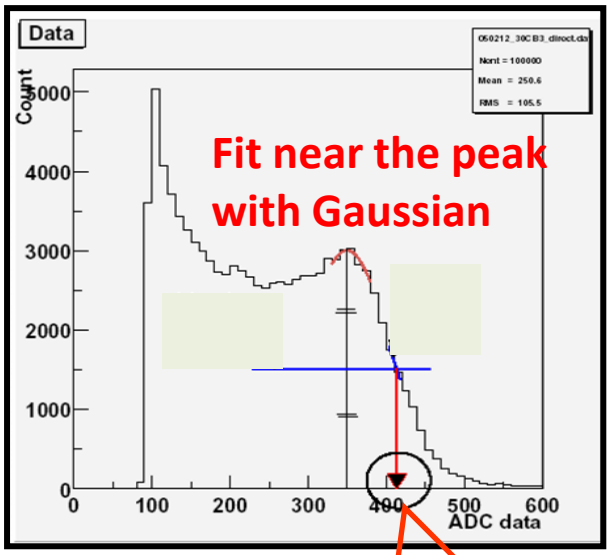
Compton edges of 1.17MeV and1.33MeV γ rays

Simulation



In the case of energy resolution10%/√E[MeV]

Measurement

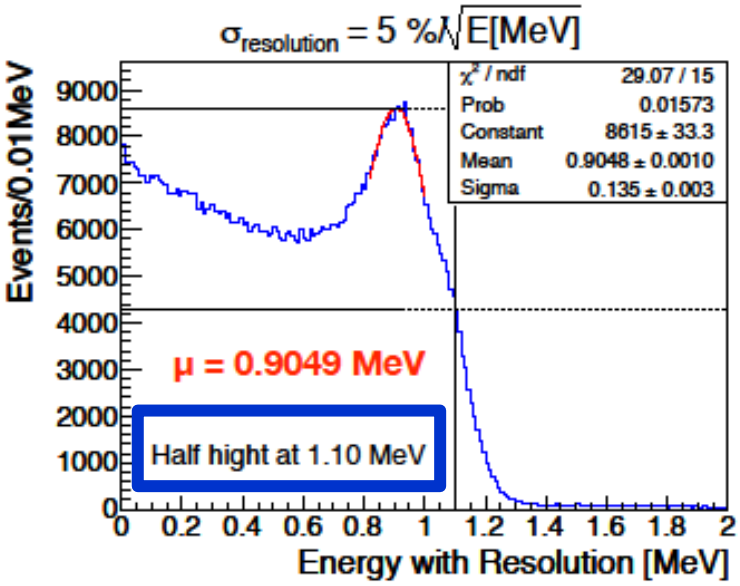


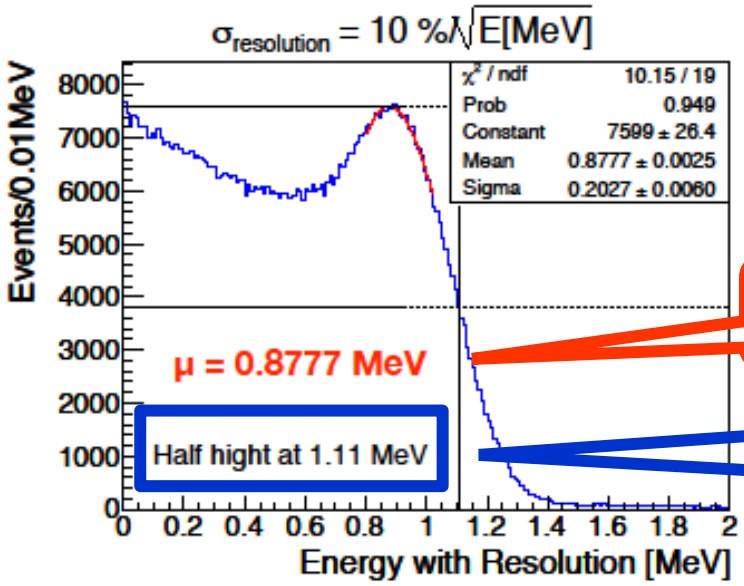
Compton edge !

ADC value at the half maximum

 Simulated by K. Nakajima(Osaka Univ.) & H. Furuta (Tohoku Univ.)

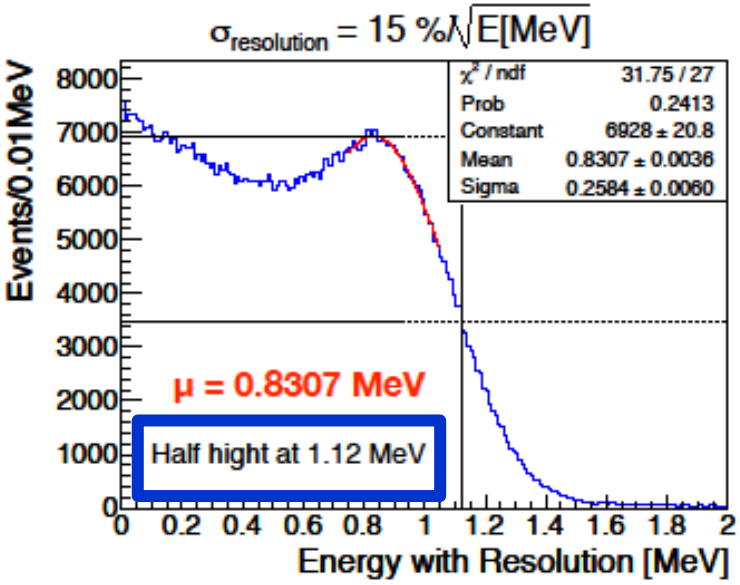
Compton edge value as a function of energy resolution

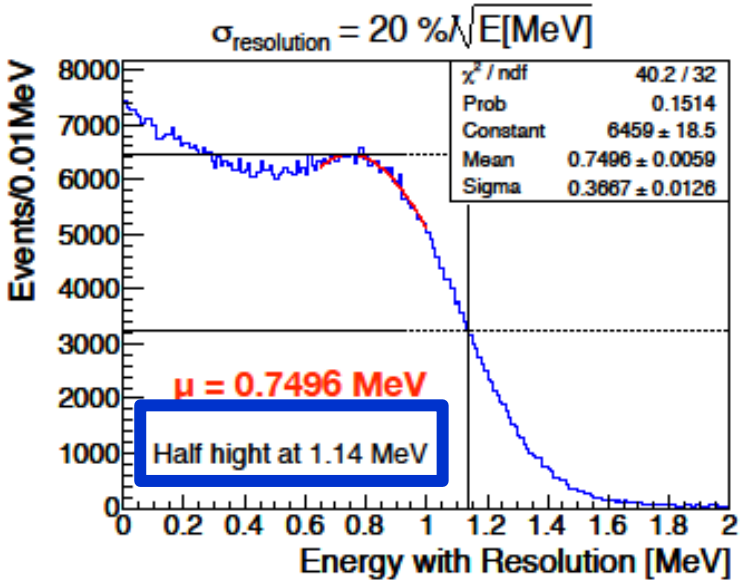




Peak value

Compton edge value





Compton edge is constant !

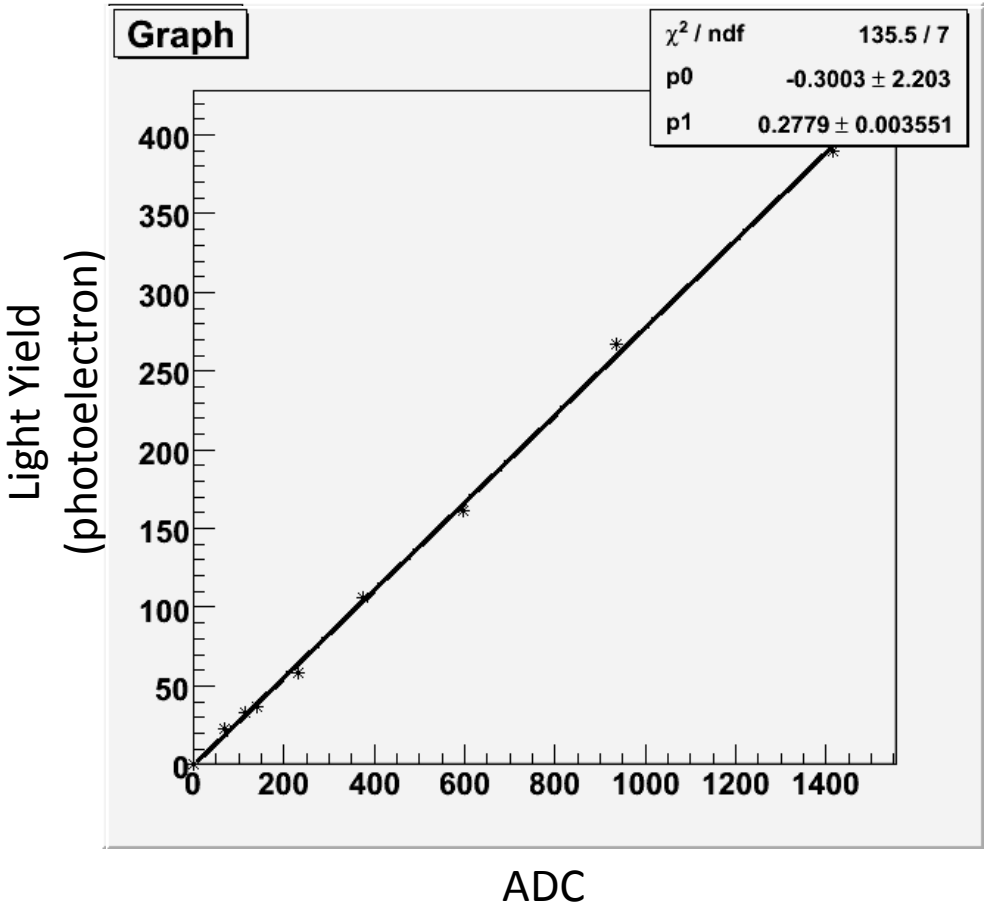
LED calibration
(ADC→light yield)

- Suppose the light yield follows Poisson distribution
- Calculate the light yield in photoelectrons from the mean and standard deviation of LED light yield distribution using the following formula:

$$\text{Light Yield} = \left(\frac{Mean}{Sigma} \right)^2 \text{[pe]}$$

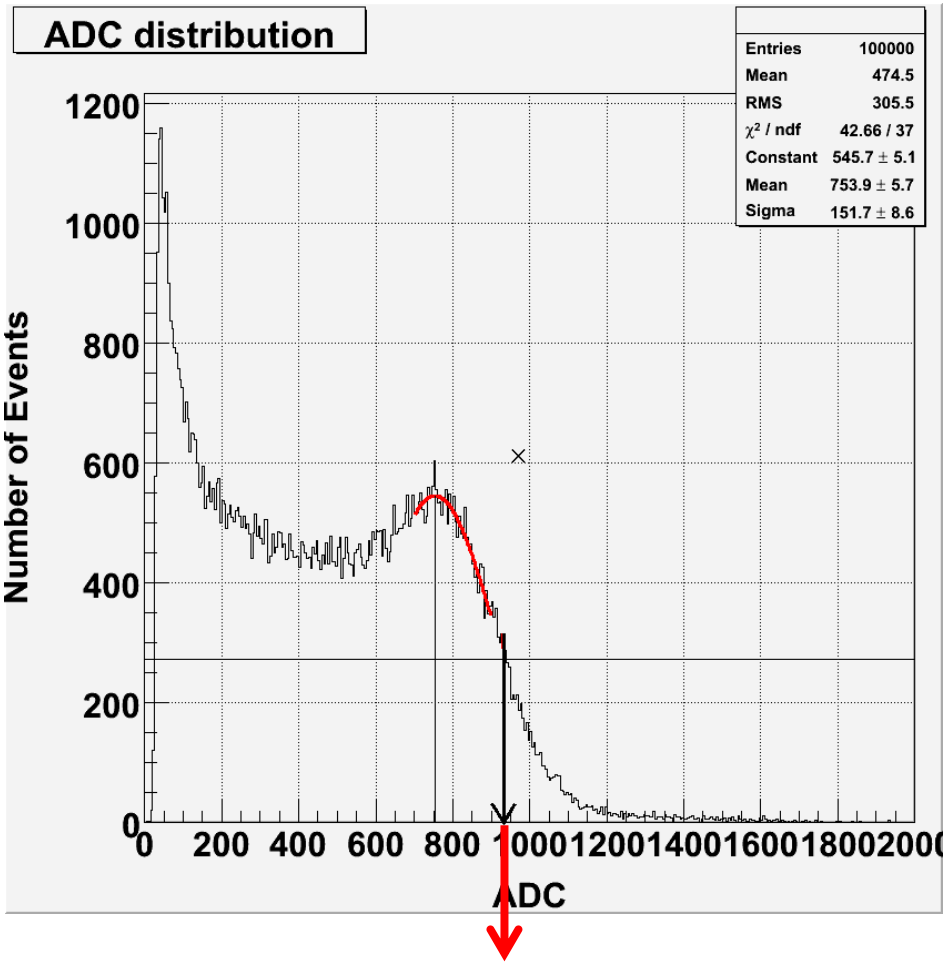
- Obtain the relation between light yield and ADC value like the right figure varying the brightness of LED.

Light Yield [pe] vs ADC



Inclination : 0.278

Light yield of the benchmark scintillator (pseudocumene + PPO (3g/ℓ))

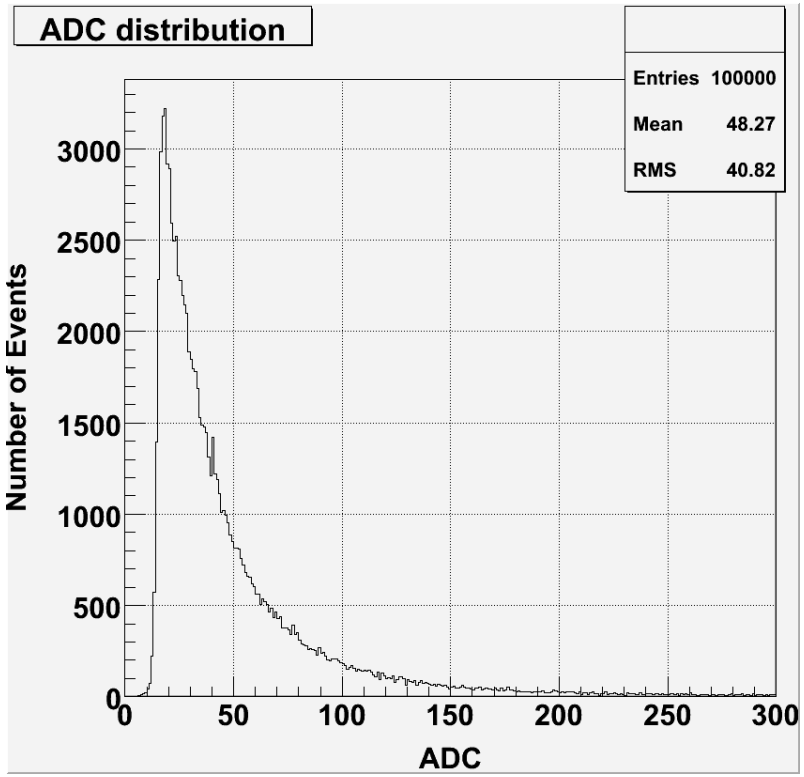


ADC value=932

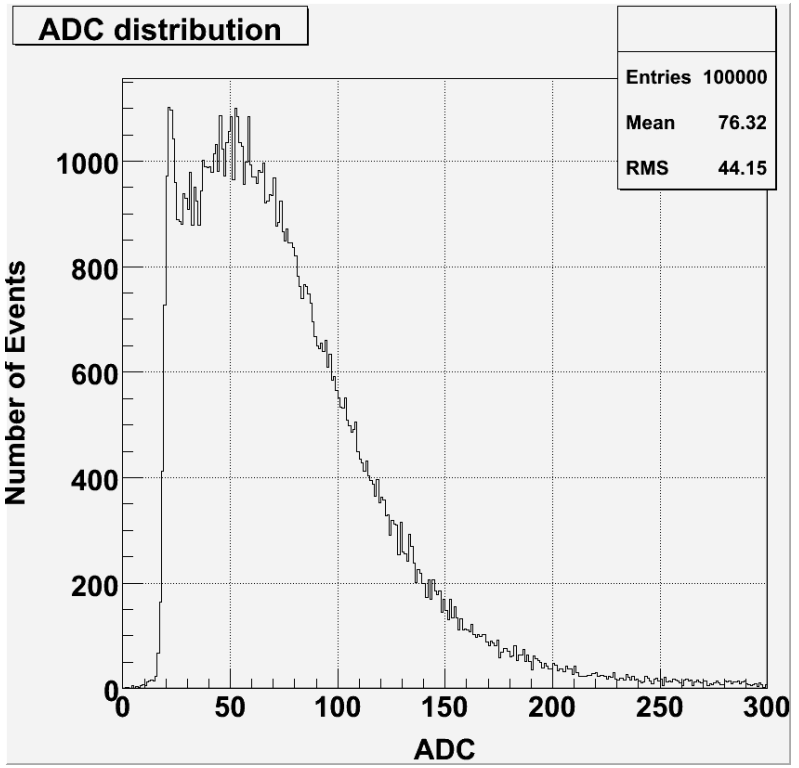
Light yield=0.278 × 932= 259 [pe]

Light yield measurement of water-based scintillator

Sodium dodecyl sulfite (SDS) is a hopeful surfactant.



30% SDS + 70% H_2O



30% SDS + 70% H_2O + 30g/ℓ PPO

Light yield measurement of water-based scintillator

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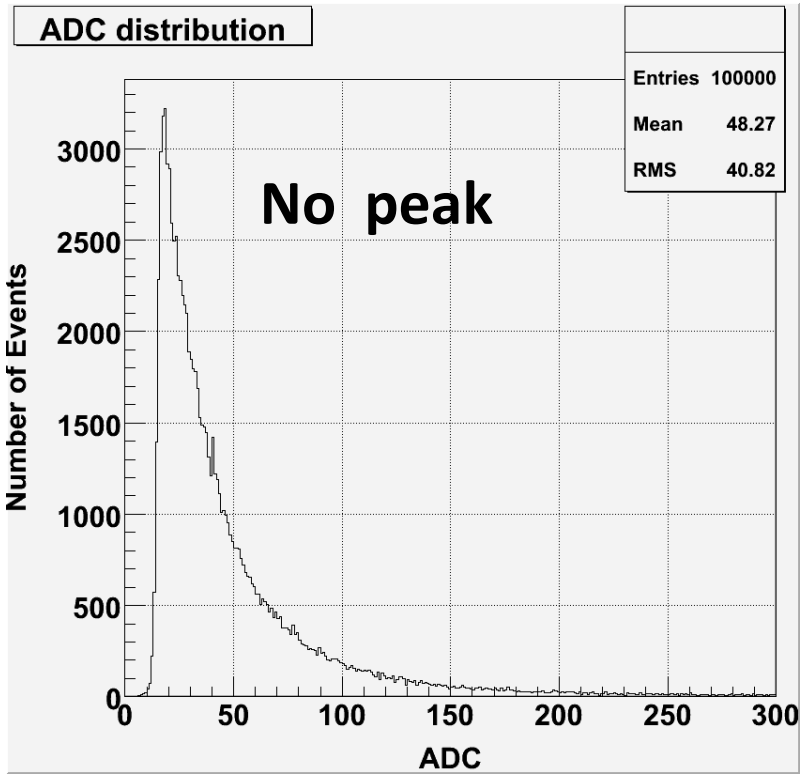
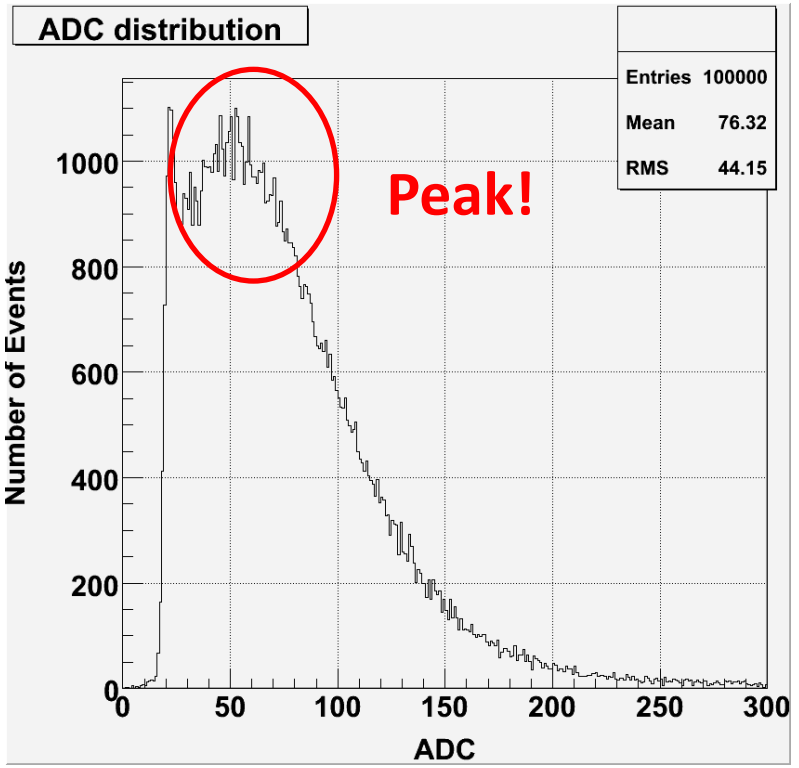
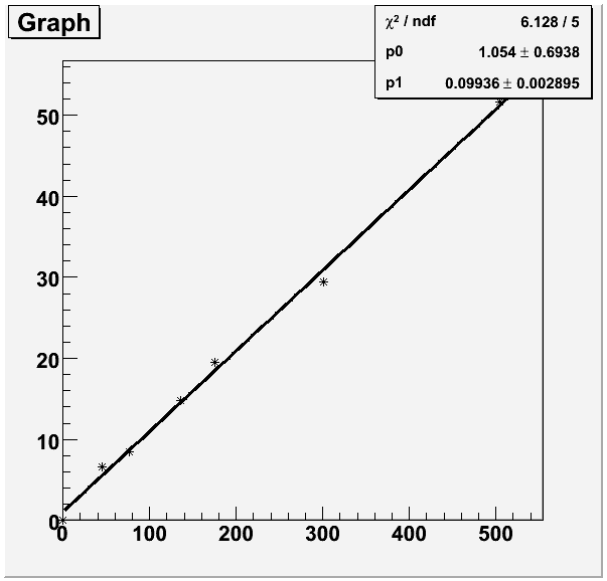


30% SDS + 70% H_2O

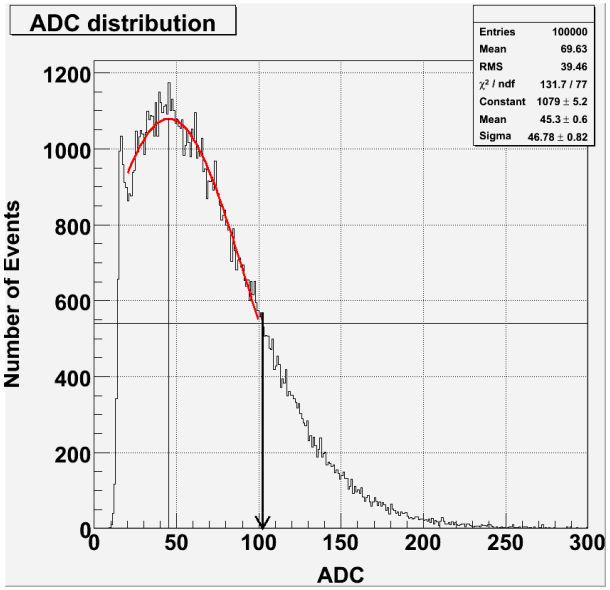


30% SDS + 70% H_2O + 30g/ℓ PPO

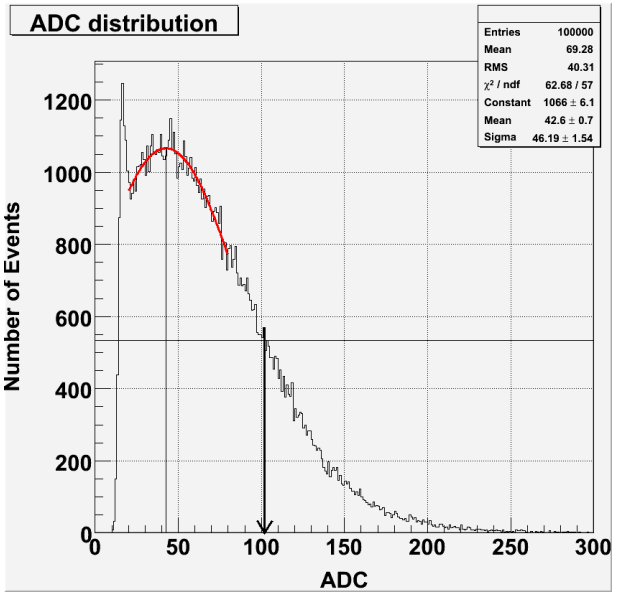
Light yield measurement: 30%SDS+70%H_2O+PPO 30g/l(H_2O)



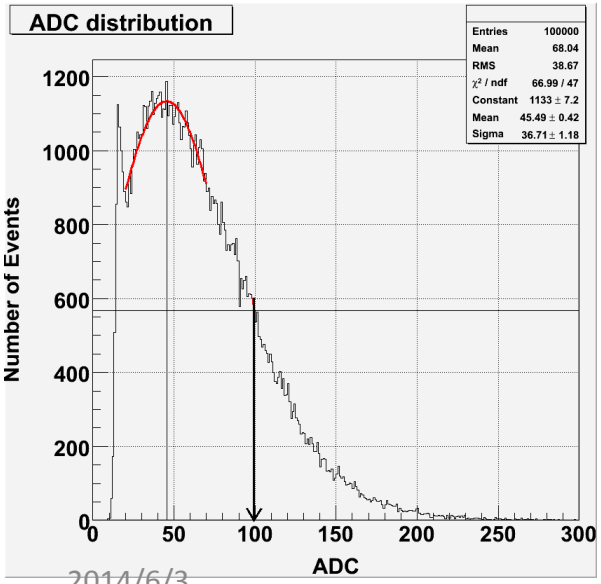
LED calibration
Inclination: 0.099



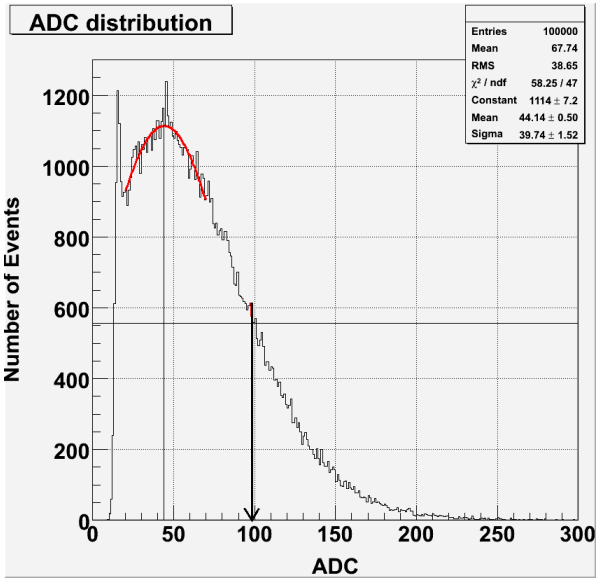
10.2[pe]



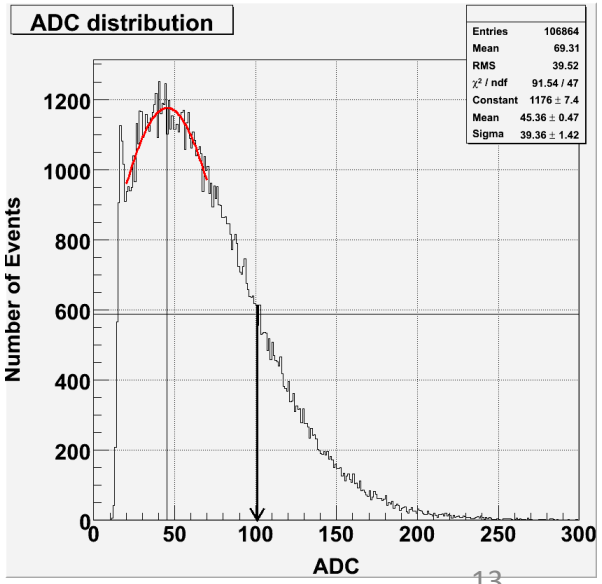
10.1[pe]



9.88[pe]

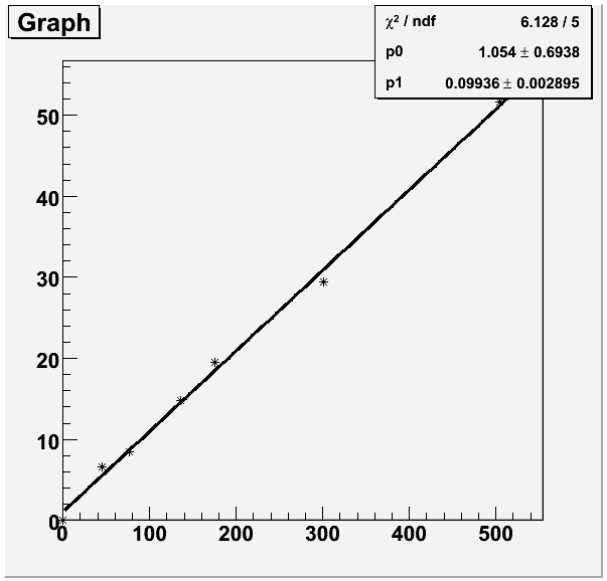


9.76[pe]



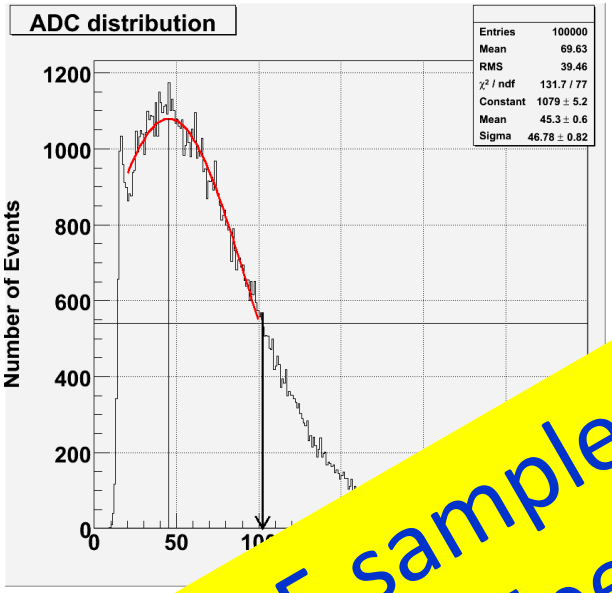
10.0[pe]

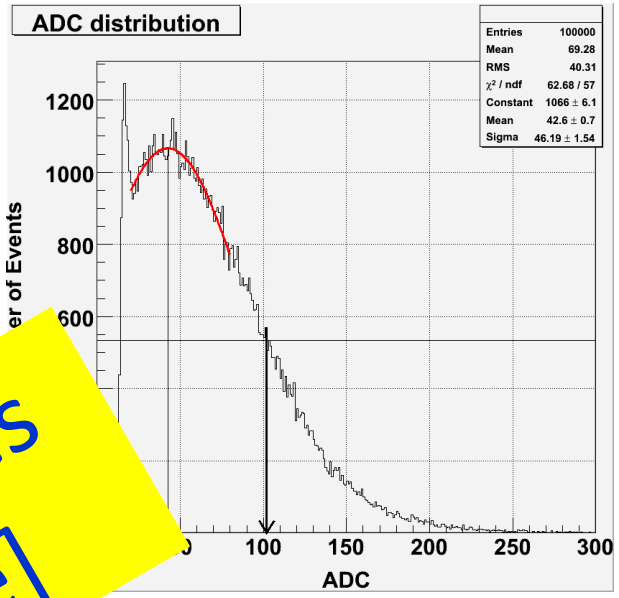
Light yield measurement: 30%SDS+70%H_2O+PPO 30g/l(H_2O)



LED calibration

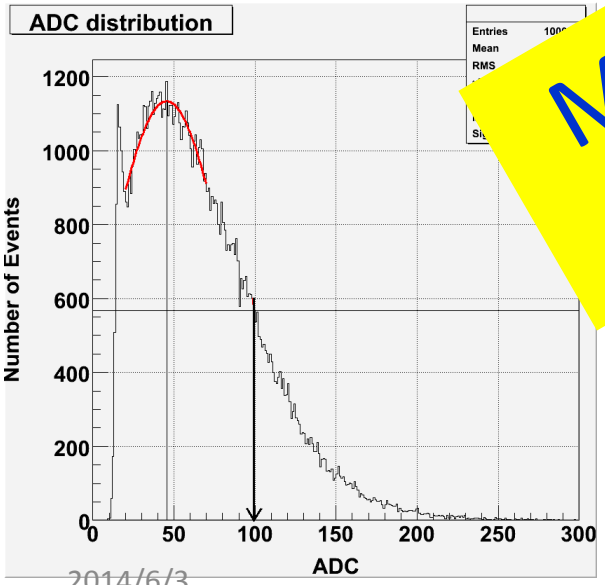
Inclination: 0.099



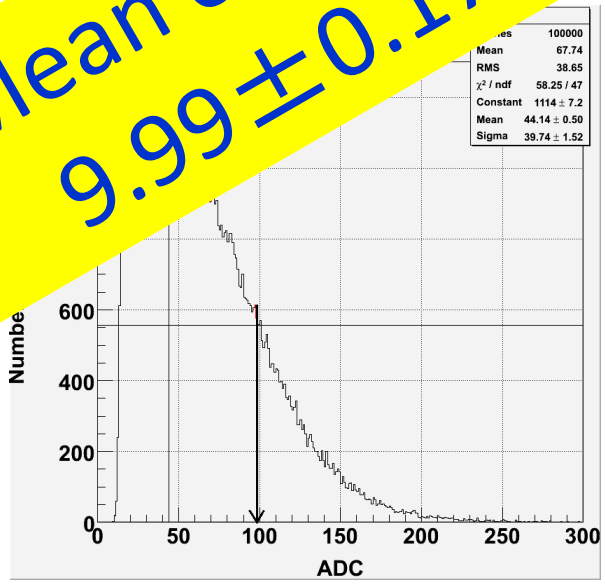


10.1[pe]

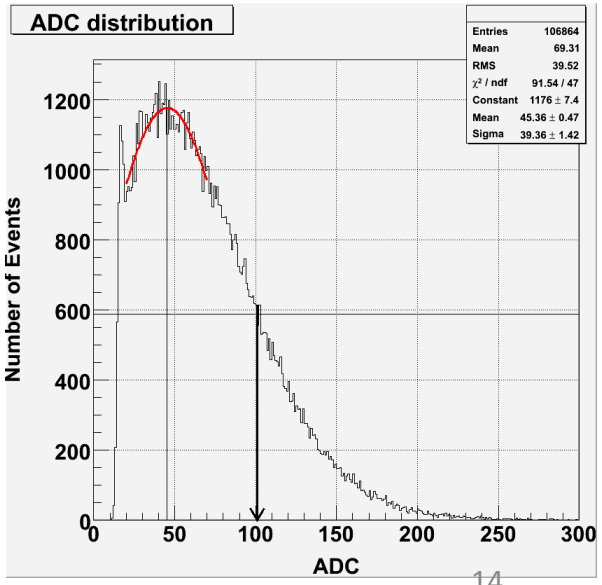
Mean of 5 samples
9.99±0.17 [pe]



9.88[pe]



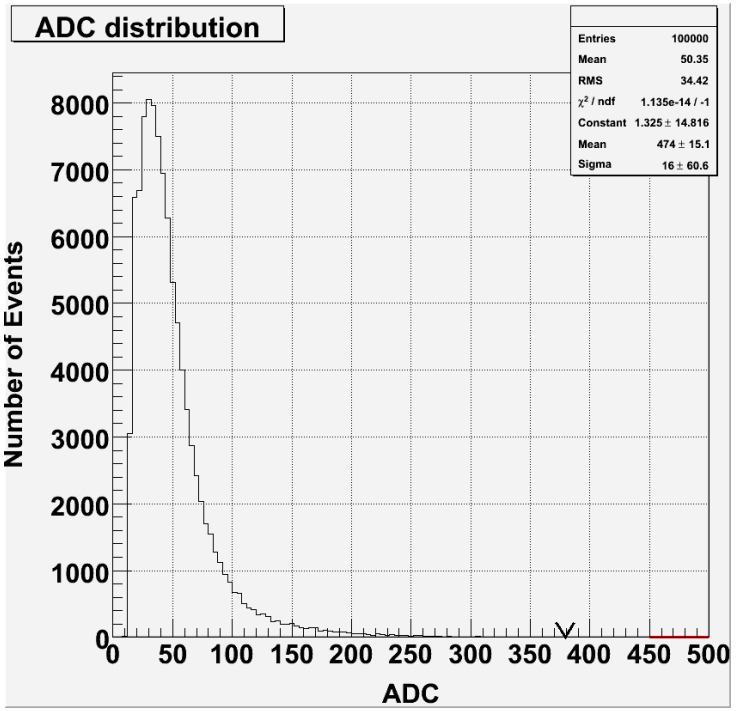
9.76[pe]



10.0[pe]

Aging measurement of 30%SDS+70%H_2O+PPO 30g/l(H_2O)

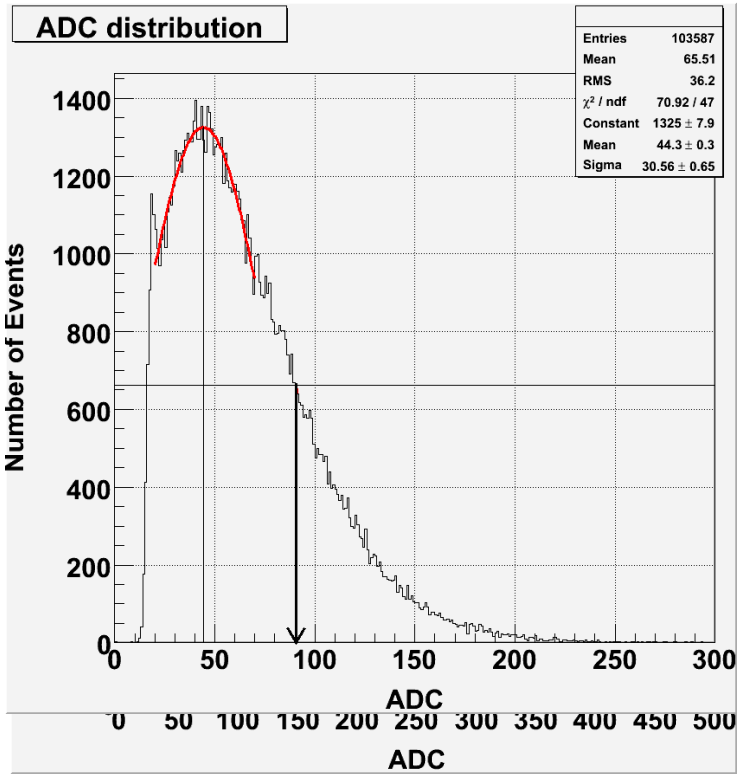
- Crystal formation after 1 year



No significant light yield

Aging measurement of 30%SDS+70%H_2O+PPO 30g/l(H_2O)

- It easily dissolved by shaking



9.18[pe]

(11.6 [pe] 1 year ago)

Next steps

(1) We tried a liquid detergent (35% fatty acid potassium+65% water) as a surfactant.

- Commercially available
- Safe and ecological

(2) Addition of Gd ($(Gd_2(SO_4)_2$)

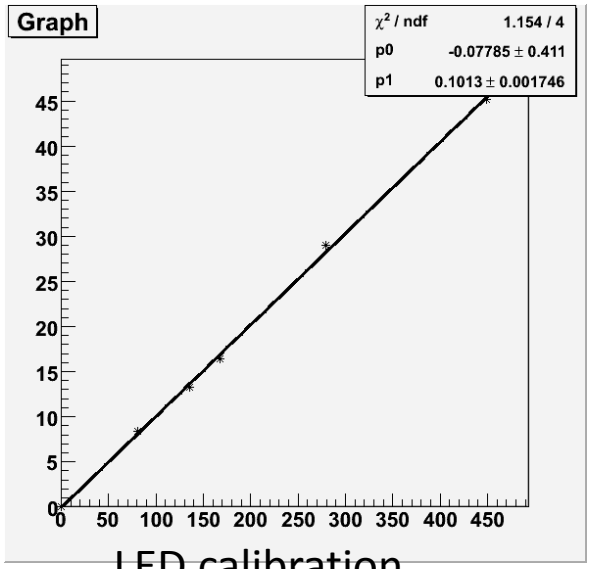
- Soluble ?

  target concentration: 0.2% weight ratio

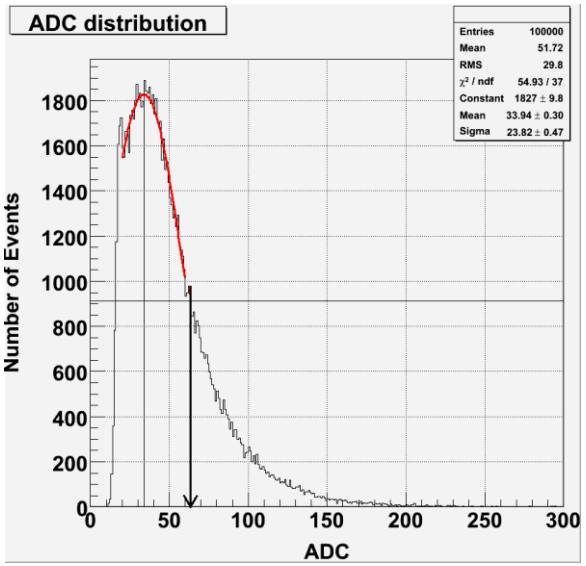
  (enough concentration for neutron capture measurement)

- How much light yield?

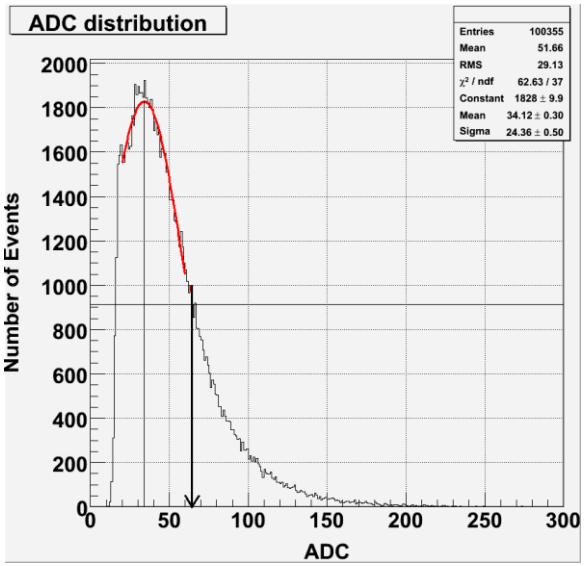
Light yield of 50% detergent+50%H_2O+PPO 30g/l(H_2O)



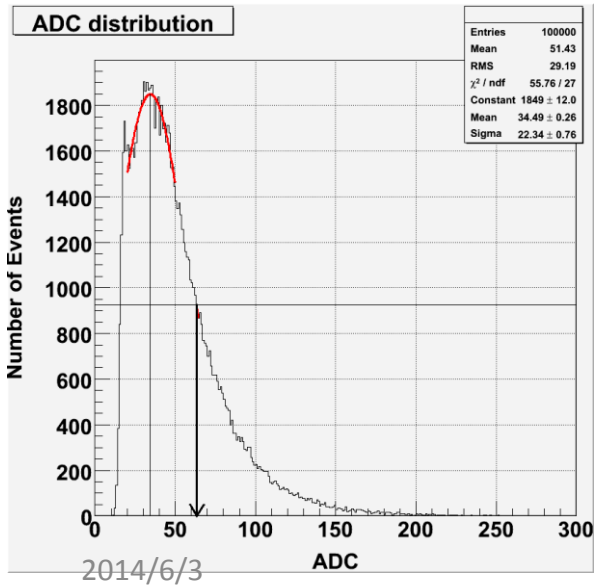
LED calibration
Inclination: 0.0994



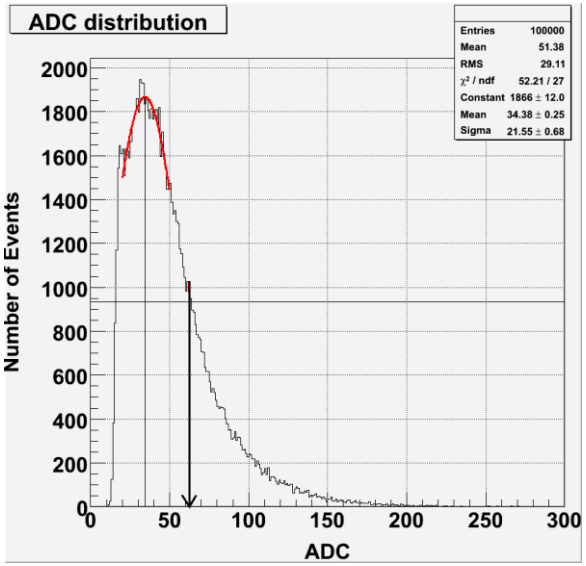
6.42[pe]



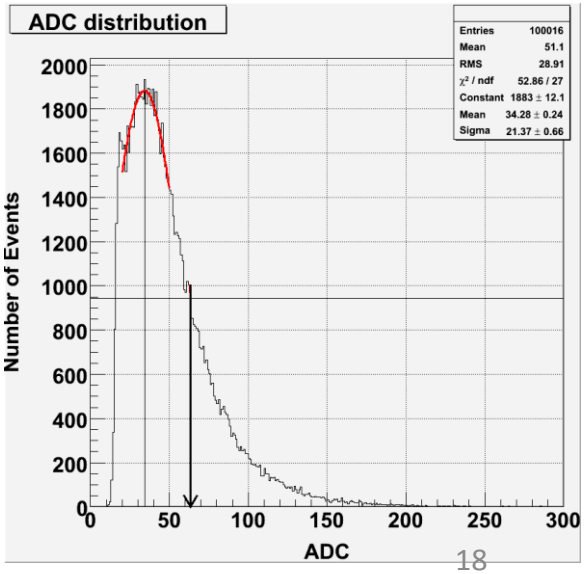
6.53[pe]



6.44[pe]

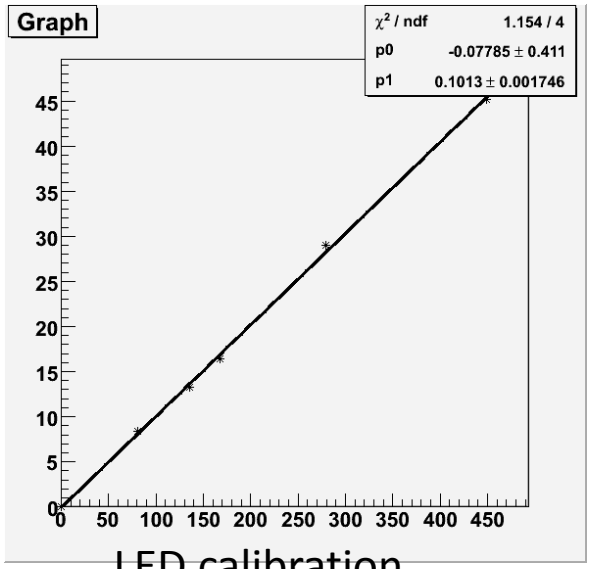


6.32[pe]



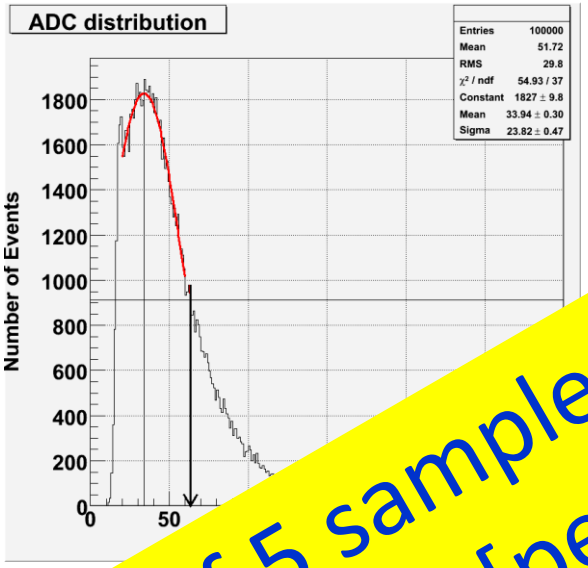
6.43[pe]

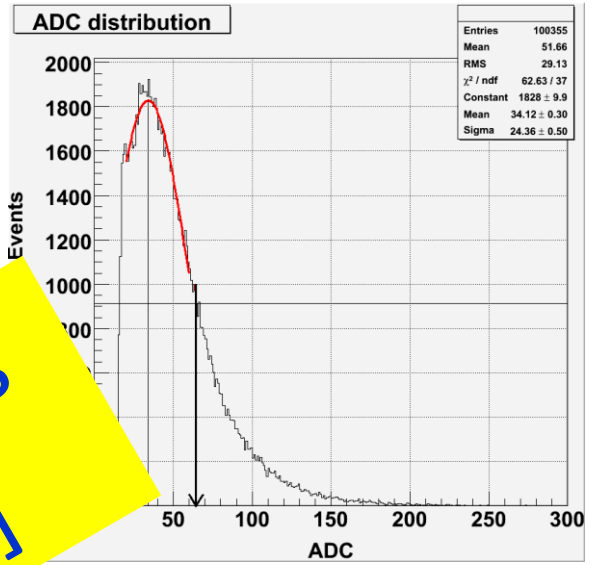
Light yield of 50% detergent+50%H_2O+PPO 30g/l(H_2O)



LED calibration

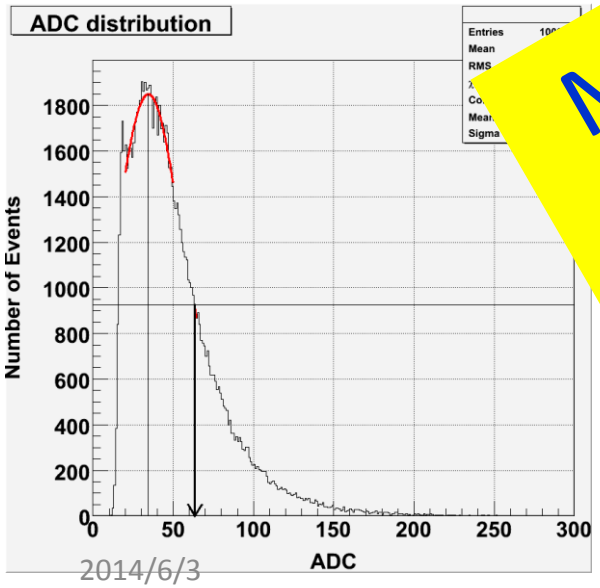
Inclination: 0.0994



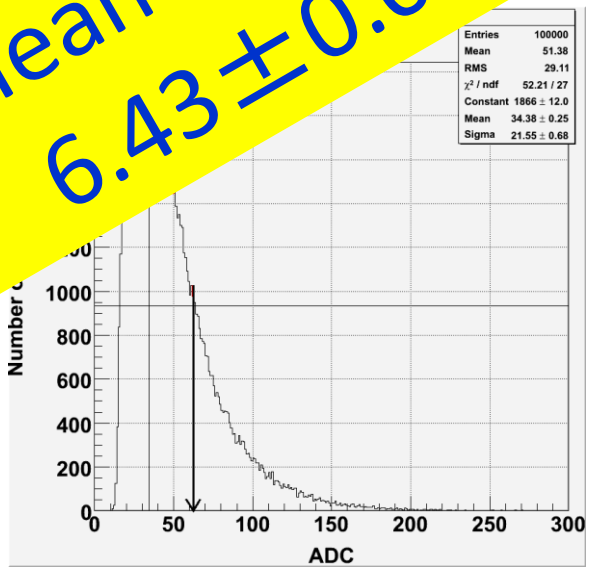


6.53[pe]

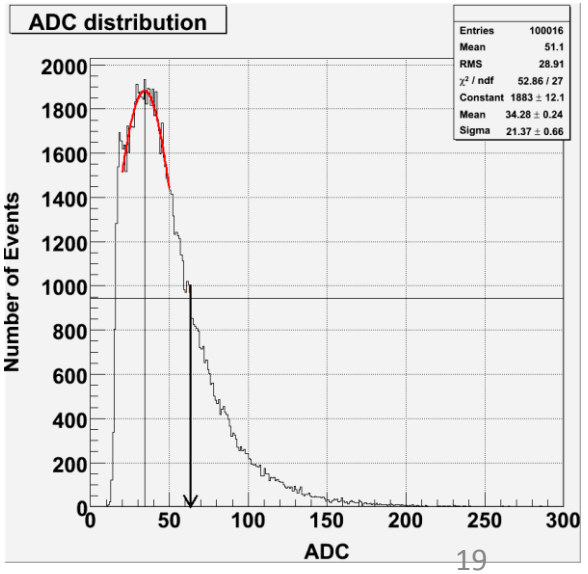
Mean of 5 samples
6.43±0.07 [pe]



6.44[pe]



6.32[pe]



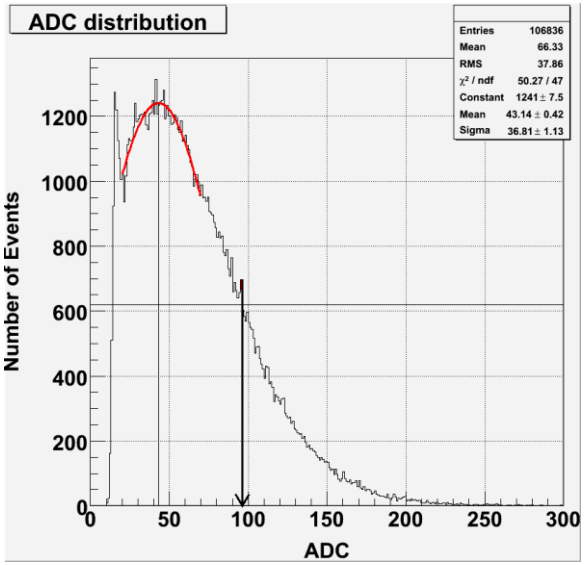
6.43[pe]

Light yield of 30%SDS+70%H_2O+PPO 30g/l(H_2O)+0.2%Gd

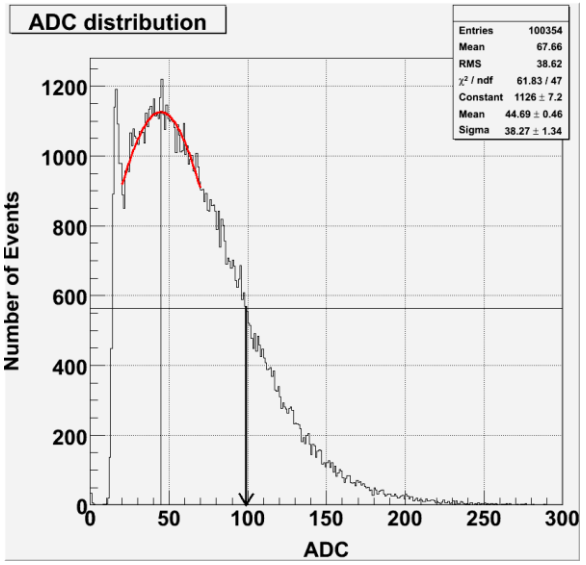
Gd:soluble

9.55±0.38[pe]

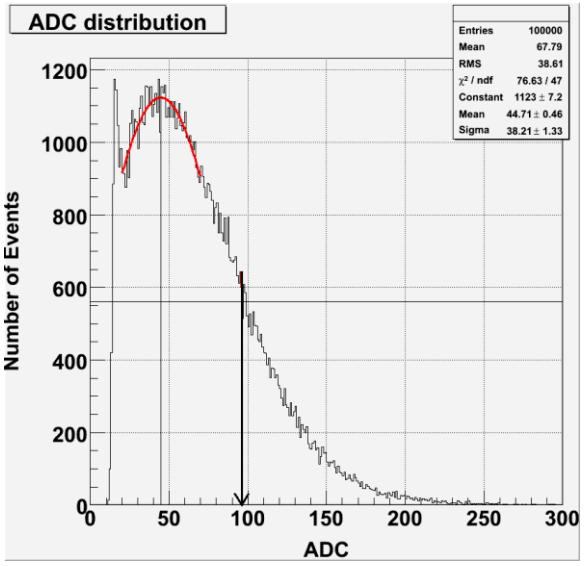
Same light yield as no Gd one (9.99±0.17 [pe])



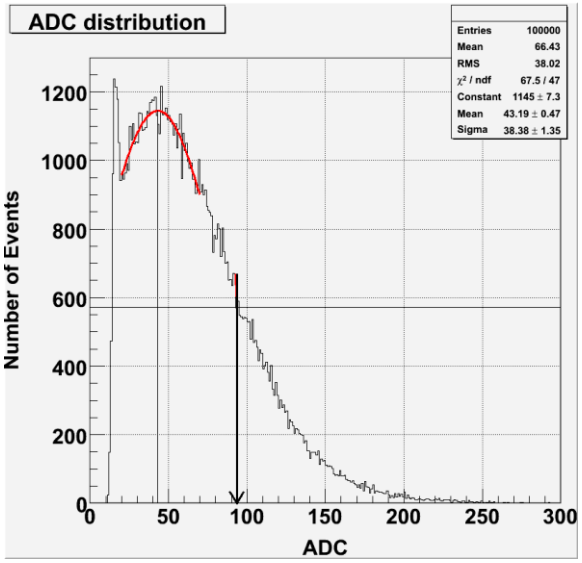
9.01[pe]



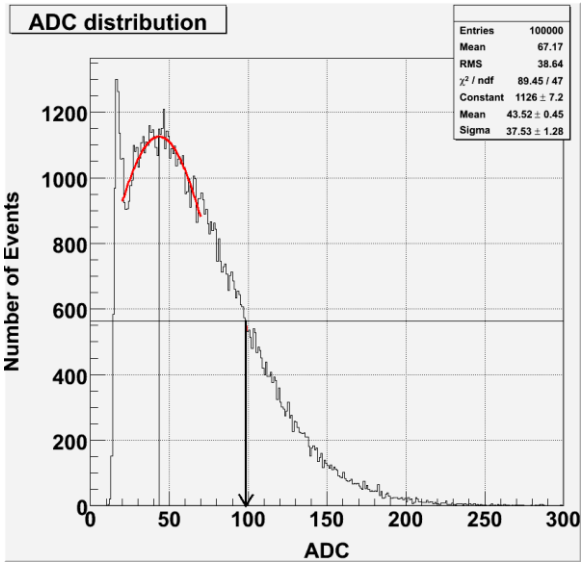
9.83[pe]



9.55[pe]



9.29[pe]



9.79[pe]

Summary

- We are developing water-based liquid scintillator.
- SDS (surfactant) + water (solvent)+PPO (luminescent agent)
  light yield: ～10 [pe]（1/25 of conventional scintillator）
  Aging：no significant or small deterioration for 1 year
  Gd($Gd_2(SO_4)_3$) ：soluble, the same light yield (～10 pe)
- Commercially available detergent (surfactant)＋water (solvent)
  light yield ： ～6.5[pe]
  Gd($Gd_2(SO_4)_3$) ：insoluble

Future plans:

- Measurement of neutron capture by Gd
- Try the following materials:
  ① surfactants with benzene ring
  ② aromatic molecules with hydrophilic group
  ③ water-soluble luminescent agents

Light Emission Process of Liquid Scintillator

Organic solvent(ex：PC) is excited by absorbing the radiation energy.

max. absorption:269nm

mean:290nm,　max:293nm

Organic solvent → water or flammable solvent

First solute (ex：PPO) absorbs the energy from the solvent and emits light.

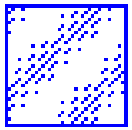
max absorption:303nm

emission mean:370nm,　max:364nm

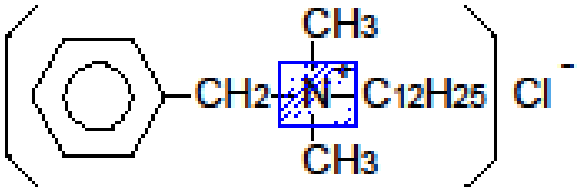
Second solute (ex：Bis-MSB) makes the wavelength longer to prevent reabsorption by the solvent.

max absorption:347nm

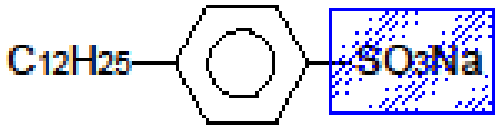
emission mean:422nm,　max:412nm



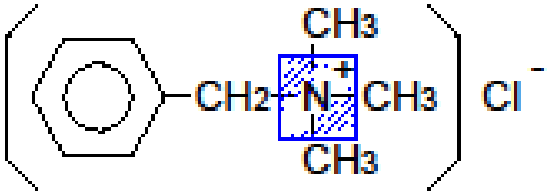
Hydrophilic group



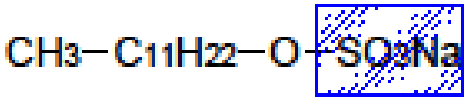
Benzalkonium chloride



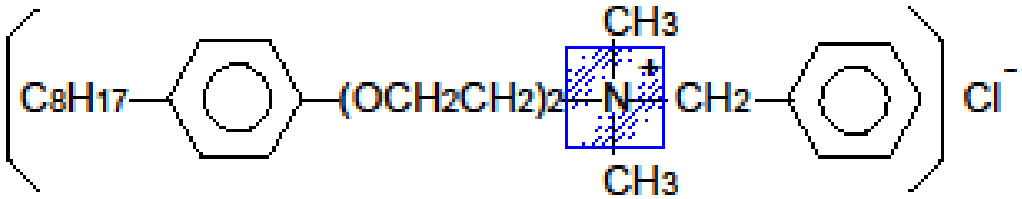
Dodecyl benzene sulfonic acid (ABS)



Benzyl chloride trimethyl ammonium



Sodium dodecyl sulfate (SDS)



Benzethonium chloride

Surfactants

Liquid scintillator so far (example)

- KamLAND(1200m^3): PC(20%)+dodecane(80%)+PPO(0.2%)
- PaloVerde(~10m^3): PC(36%)+mineral oil（60%）
  +alcohol(4%)＋PPO+bis-MSB+BHT(antioxidant)
- Borexino(300m^3)：PC(100%)+PPO(0.2%)
- DCHOOZ (~10m^3): PXE(20%) + $C_{12}H_{26}$(80%) + 0.1% Gd
  + PPO(6g/ℓ) + Bis-MSB(20mg/ℓ)

Nonvolatile material with high flash point

Solvent～20%, diluted solution～80%, and solute～several times 0.1%

Water

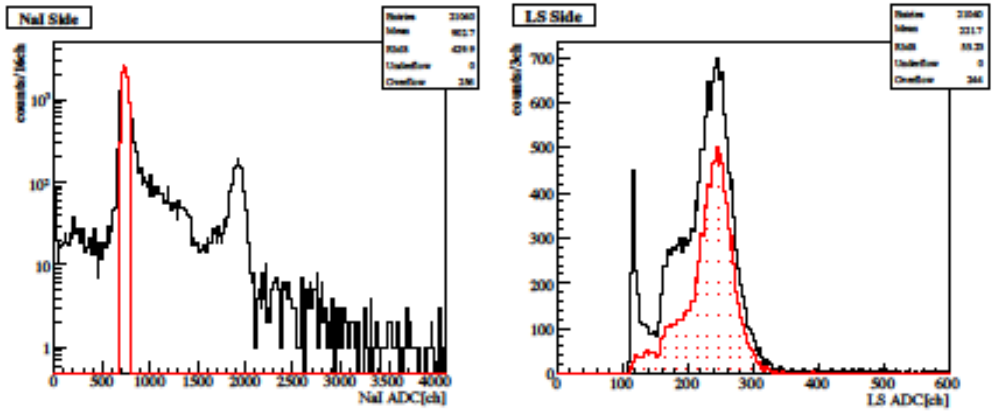


図 5.2: 後方散乱のスペクトル：左図は NaI のエネルギースペクトルでピンク色の部分でカットした。右図は PMT 側のエネルギースペクトルで NaI のカットによりピンク色の部分が得られた。

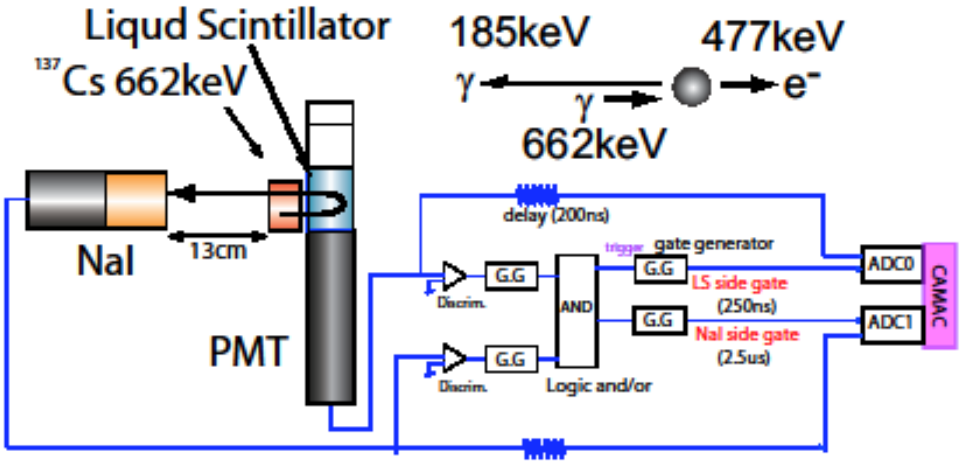


図 5.3: 発光量測定の装置と後方散乱の回路

修士論文：小川桃世
「KamLANDにおける太陽ニュートリノ観測に向けた液体シンチレーターの純化」
東北大学2006年(平成17年度)

Number of Cherenkov Photons

$$N = 2\pi\alpha l z^2 \left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1} \right) \left(1 - \frac{1}{n^2 \beta^2} \right)$$

N:number Cherenkov photons

α: fine structure constant

l: path length

z: charge

λ_1, λ_2: max. and min. wave lengths observed

When l=5mm, E = 1.5 MeV, λ_1=400 nm, λ_2=600 nm,

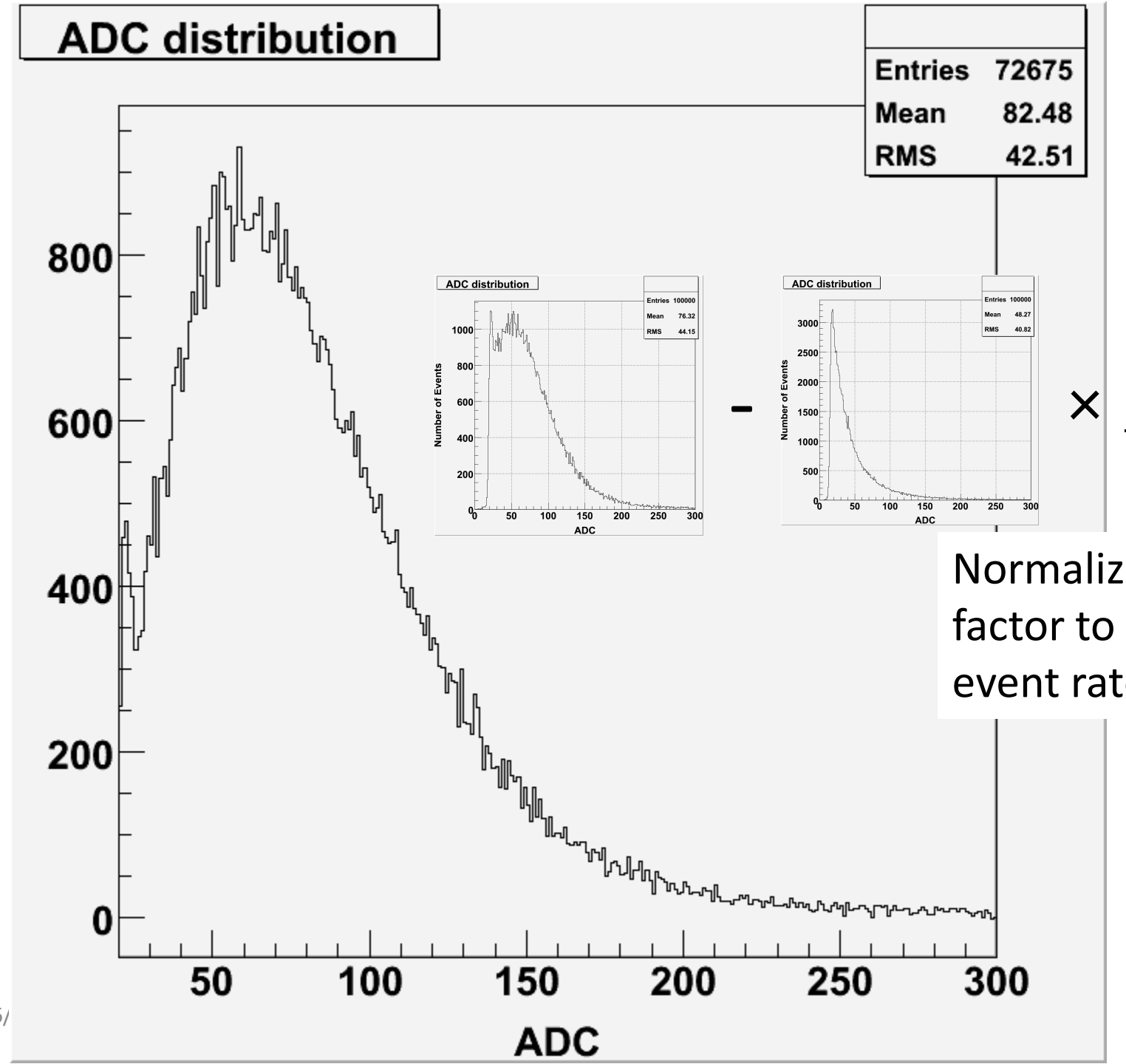
$N \approx 70$

Number of pe's obtained = 70 ×

0.2 (QE of PMT) ×

0.5 (acceptance ?)

= 7



$\times \frac{0.25}{\downarrow}$

Normalization factor to the event rate