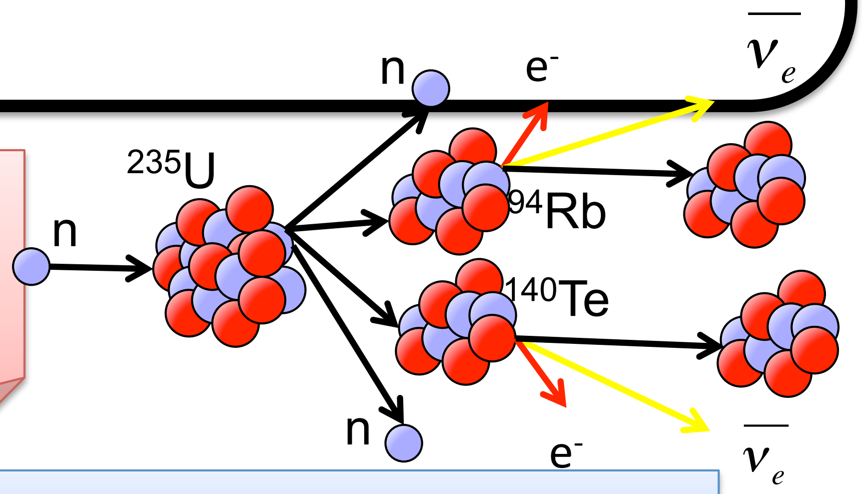
Study of plastic scintillator based reactor neutrino detector

AAP 2010 meeting @ Tohoku
Aug. 02-05 2010

H. Ono (Nippon Dental Univ.)
H. Miyata, K. Takahashi (Niigata Univ.)
Louie Murcia T. (MSUIIT)

Reactor monitoring system

• Nuclear power plant (1GW electric power) produces about 10^{19} anti-neutrinos/s.
• ~5000 neutrinos/day will be observed with 1ton ($1m^3$) detector placed very closely (20m) to the reactor core
→Possibility to monitor the reactor power output with anti-neutrino at the ground



Need to consider the reactor safety to place the detector very closely to the core.

Detector components should be considered carefully

Reactor monitor material

Flammable oil base

Common reactor neutrino detector is based on the **liquid scintillator** to achieve the large volume as neutrino target (ex. KamLand, DC)

From a safety point of view, **liquid scintillator based detector** has difficulty to place **closely to the reactor core** (or even in the nuclear power plant)

Flame-resistant, Solid

Plastic scintillator is based on the frame-resistant solid material
→Remain a possibility to place the detectors closely to the reactor

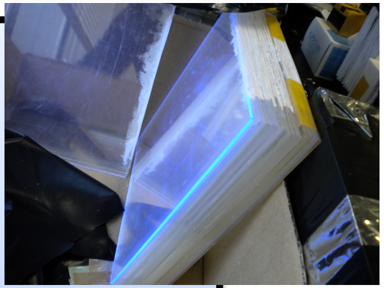
By using plastic scintillator based reactor monitor

- Large neutrino flux gain to place closely with fire safety.

→Possibility to measure at the ground level

- Need to keep compact size to place closely and cost issue

→Use gadolinium to achieve better neutron capture efficiency

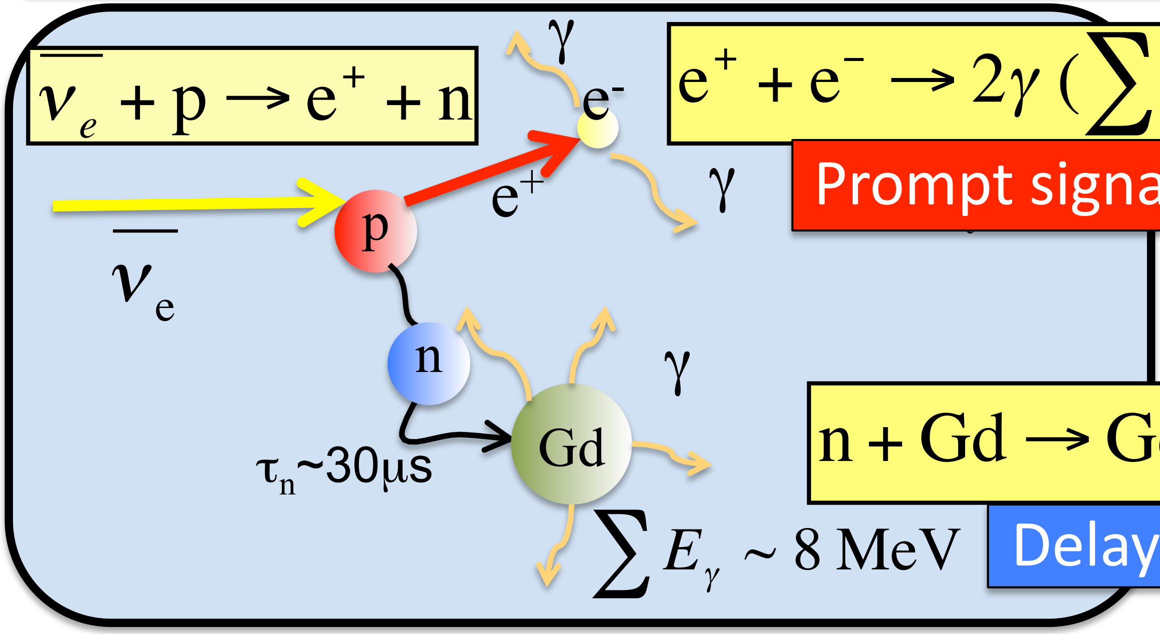


Gadolinium doped neutrino detector

Detection method : Neutrino inverse β decay $\bar{\nu}_e + p \rightarrow e^+ + n$

Gadolinium (Gd) has largest cross section for the **thermal neutron**

Gd Advantage : Shorter neutron capture time, large E_γ output



$e^+ + e^- \rightarrow 2\gamma\ (\sum E_\gamma = 1.02\ \text{MeV})$

Prompt signal

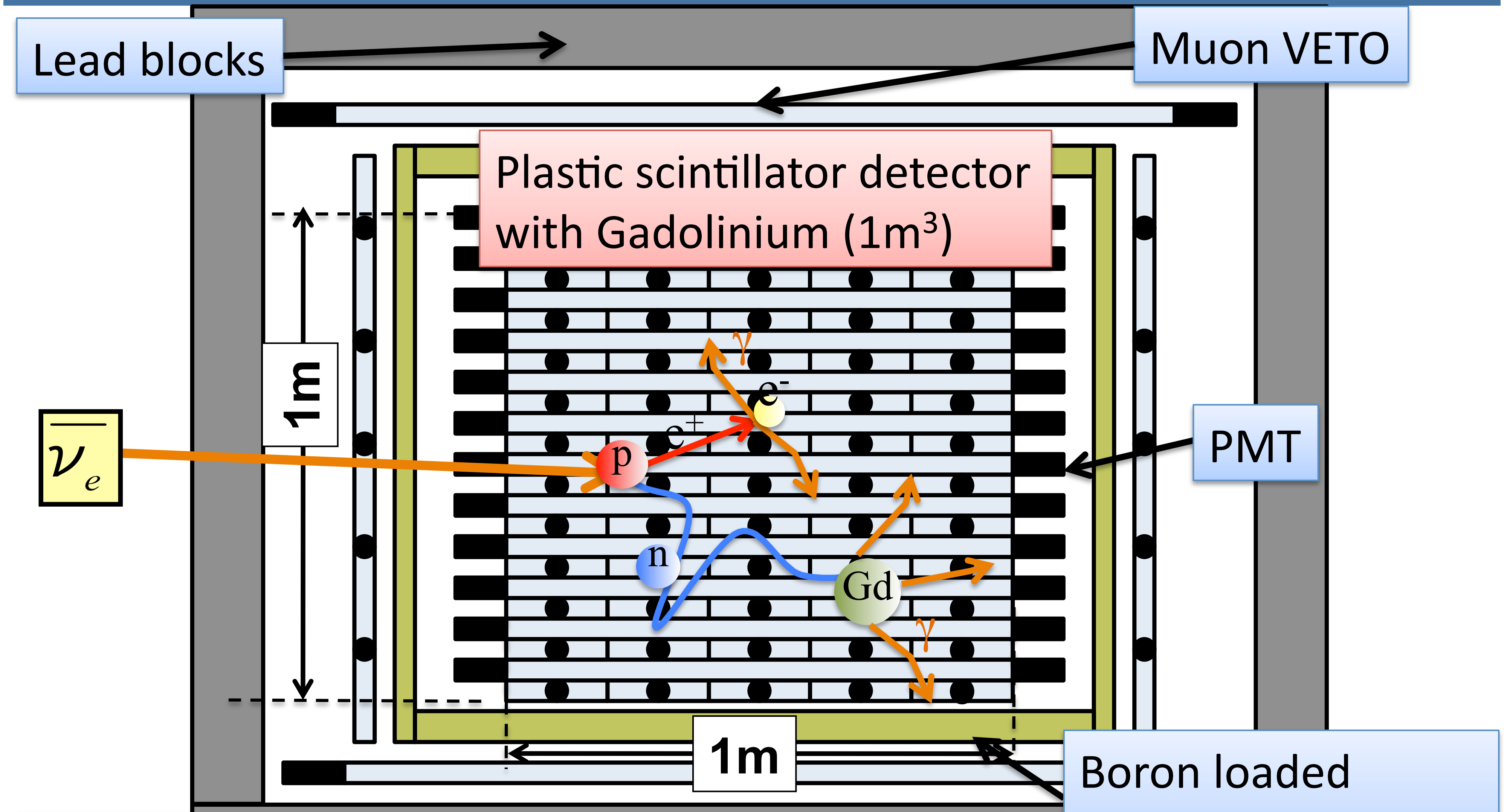
$n + Gd \rightarrow Gd' + \gamma\ (\sum E_\gamma \sim 8\ \text{MeV})$

Delayed signal

Many experiments adopt the Gd doped liquid scintillator as neutrino target

No commercial Gd loaded plastic scintillator exists for now!

Design of reactor neutrino monitor



1m³ size (1 ton), Closely placed to the reactor core (20m)

Prototype detector development

- Gd loaded plastic scintillator detector (Rod type)
  - Test sample of Gd loaded plastic scintillator produced by company.
- Layer aligned detector (Layer type)
  - Plastic scintillator and Gd painted sheet are aligned alternately.

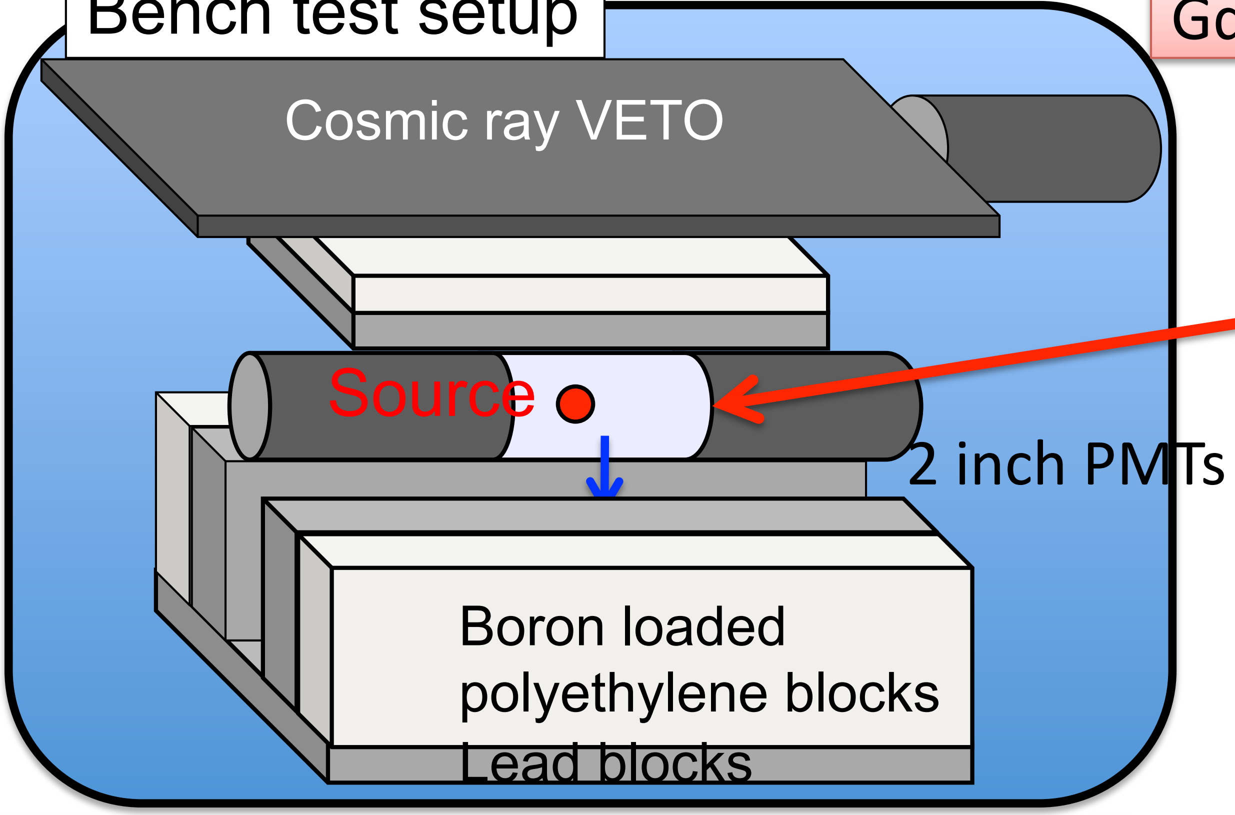
Each prototype detector is tested with
Pseudo neutrino event by ^{241}Am/Be neutron source

Evaluate the Gd effect with neutron capture time τ

Gd loaded plastic scintillator prototype (Rod type)

Gd loaded detector setup

Bench test setup

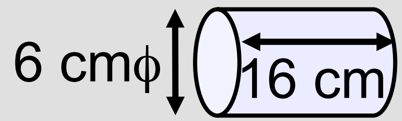


Gd loaded plastic scintillator

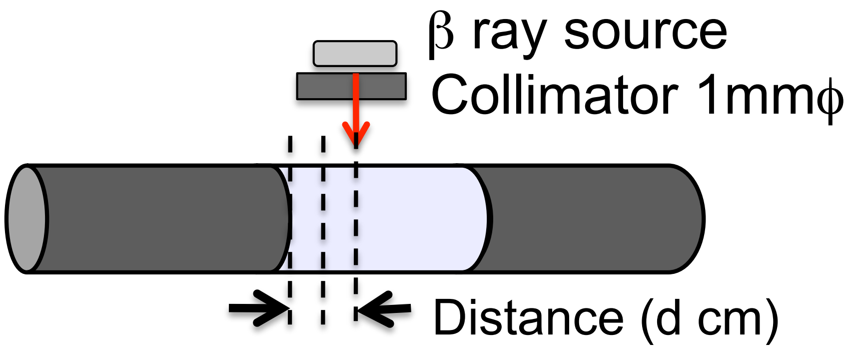
Sample is produced by "Kuraray (JP company)"
Gd doping : 0.1% /w

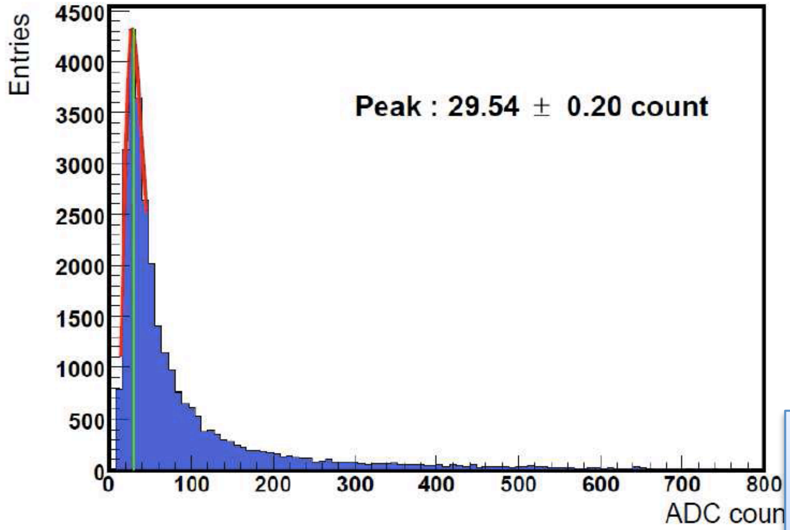
Lead blocks
Natural radiation protection
Boron loaded Polyethylene blocks
Natural environmental neutron protection

Reference : no-doping scintillator



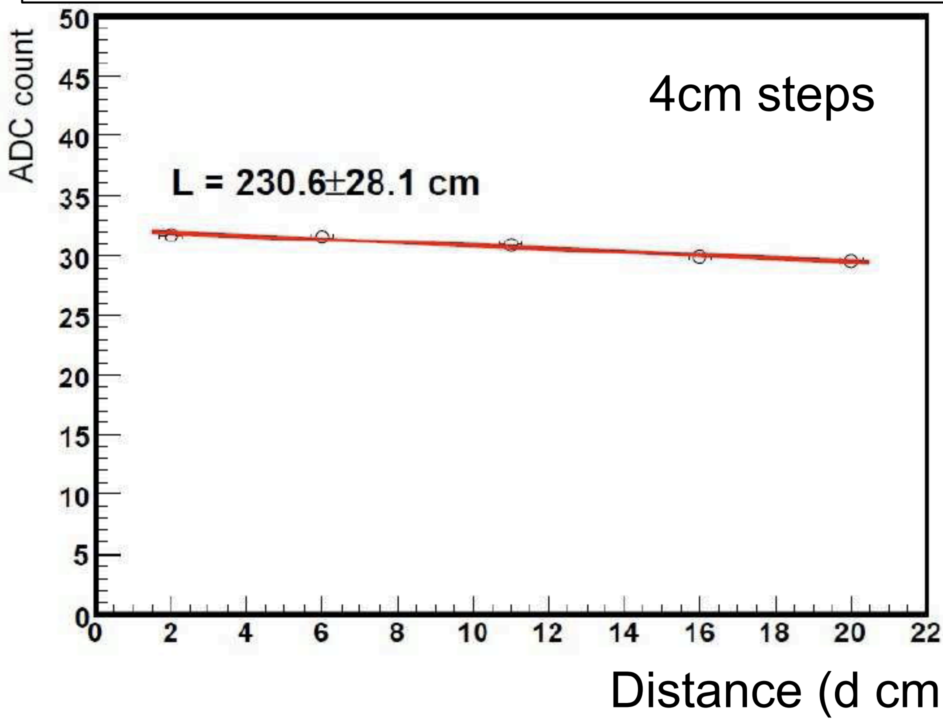
Attenuation length measurement





ADC distribution fitted with Landau function

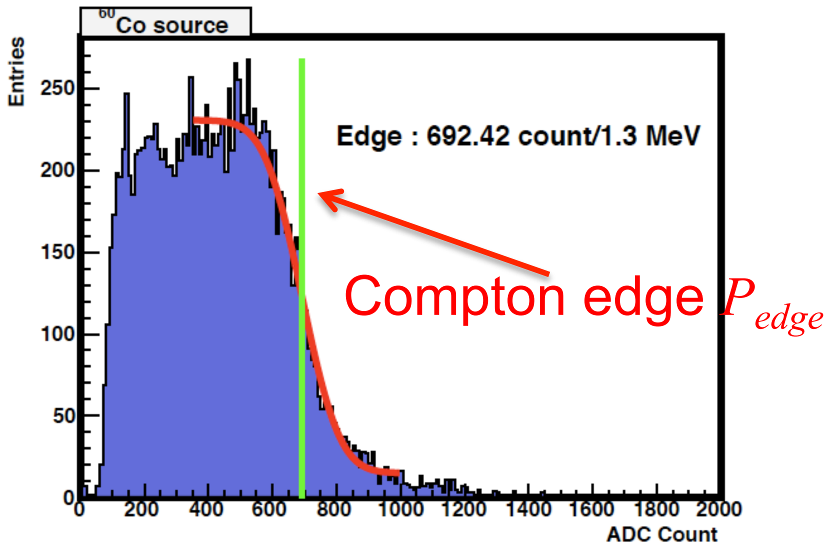
Attenuation length measurement



Attenuation length
L=230.6 ± 28.1 (cm)
Reasonable attenuation length is obtained

Calibration with ^{60}Co γ-ray source

Energy calibration of the detector is performed with ^{60}Co (E_γ=1.1, 1.3 MeV, mean=1.25 MeV) γ-ray source



Because of the small detector size, γ-rays escape from the detector

γ-rays energy distribution forms **Compton scattering edge**

Use Compton edge as energy calibration corresponds to Eγ=1.25 MeV

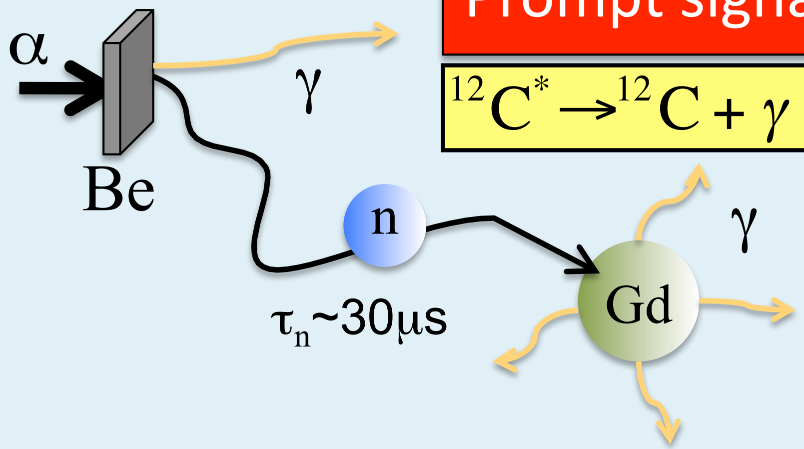
Compton edge is defined by fitting with Error function

$$f = p_0 \,\mathrm{Erf}\left(p_1\left(x - p_{edge}\right)\right) + p_2$$

Pseudo neutrino event with ^{241}Am/Be

Pseudo neutrino signal

$$^{241}\mathrm{Am} \rightarrow {}^{237}\mathrm{Np} + \alpha$$



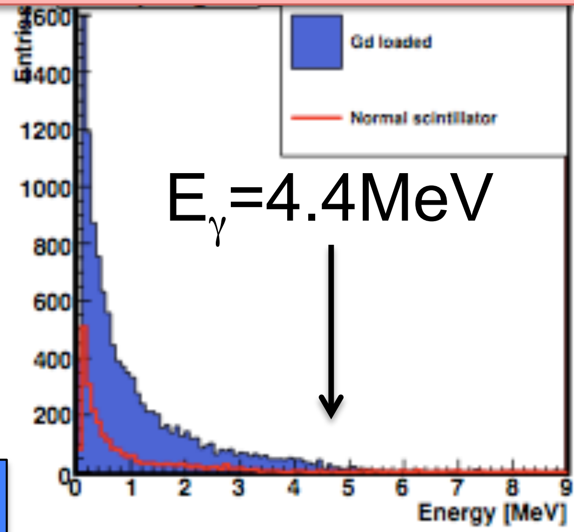
Prompt signal

$$^{12}\mathrm{C}^{*} \rightarrow {}^{12}\mathrm{C} + \gamma \ (4.43\ \mathrm{MeV})$$

Delayed signal

$$\mathrm{n} + \mathrm{Gd} \rightarrow \mathrm{Gd}' + \gamma \ (\sum E_{\gamma} \sim 8\ \mathrm{MeV})$$

Prompt signal distribution

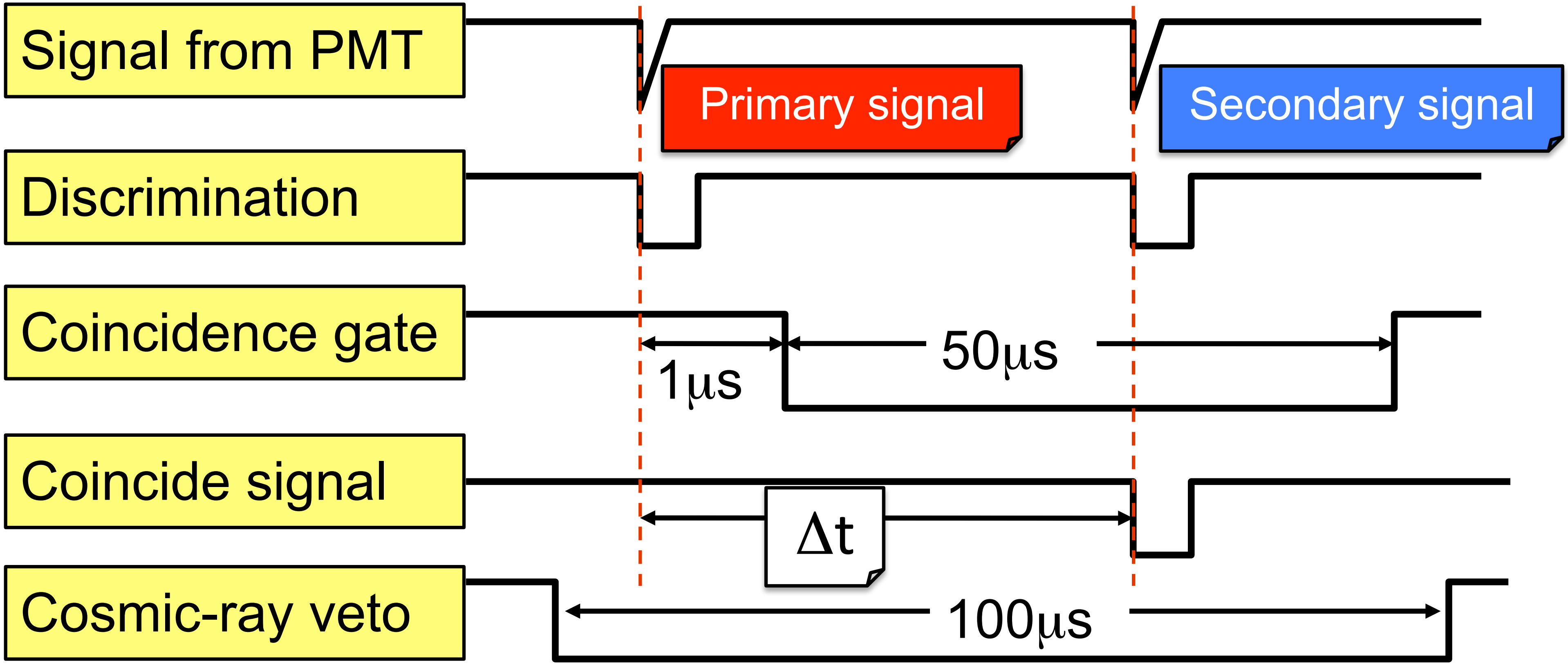


Faster neutron capture time will be achieved with Gd loaded plastic scintillator
→ Compare with no-dope plastic scintillator

Neutron capture (liquid scinti.)
Gd doped (0.1%/W) $\tau \sim 30\mu s$
No Gd dope $\tau \sim 180\mu s$

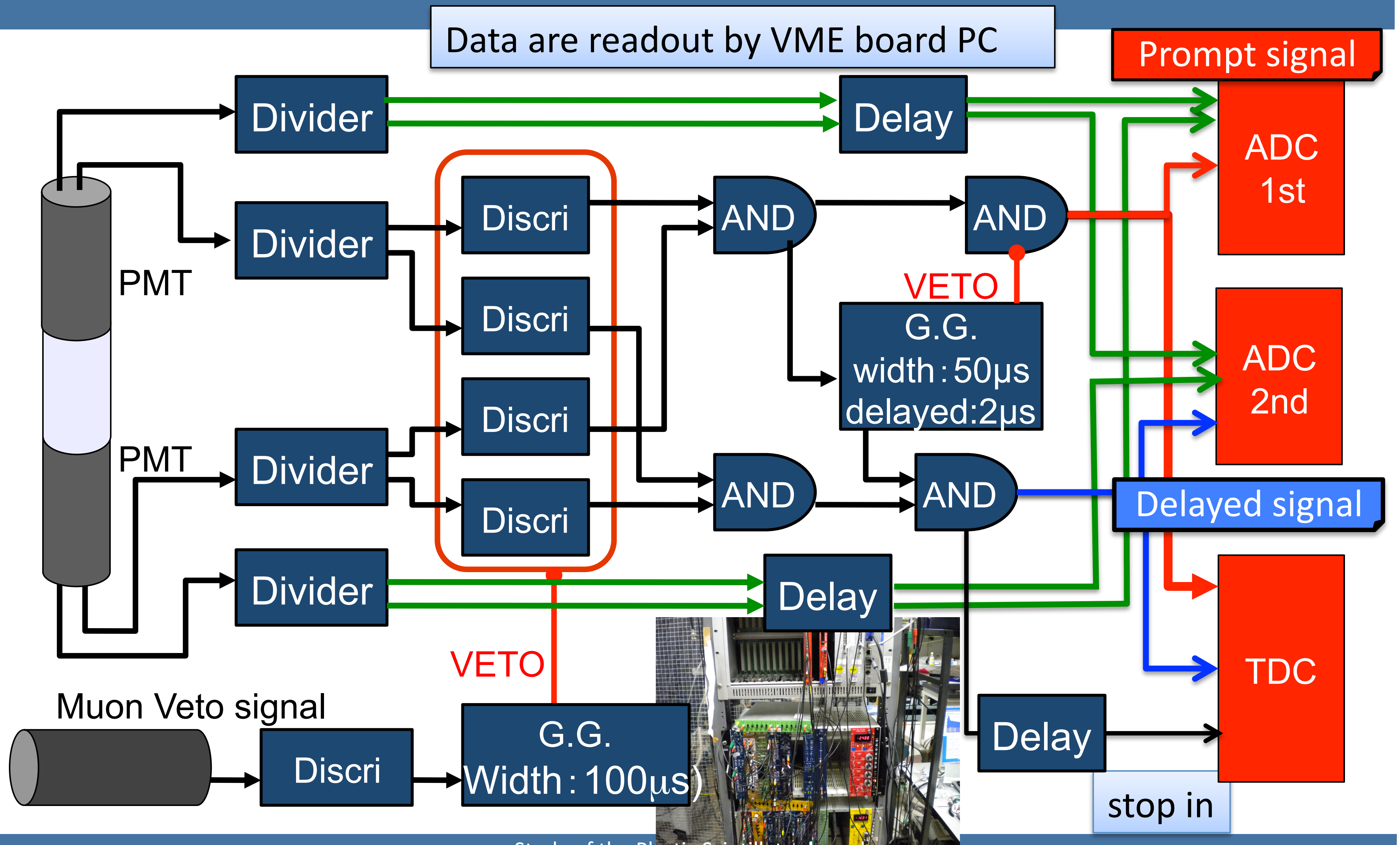
Ref : Chooz experiment (Eur. Phys. J. C 27, 331–374 (2003))

Data taking time chart



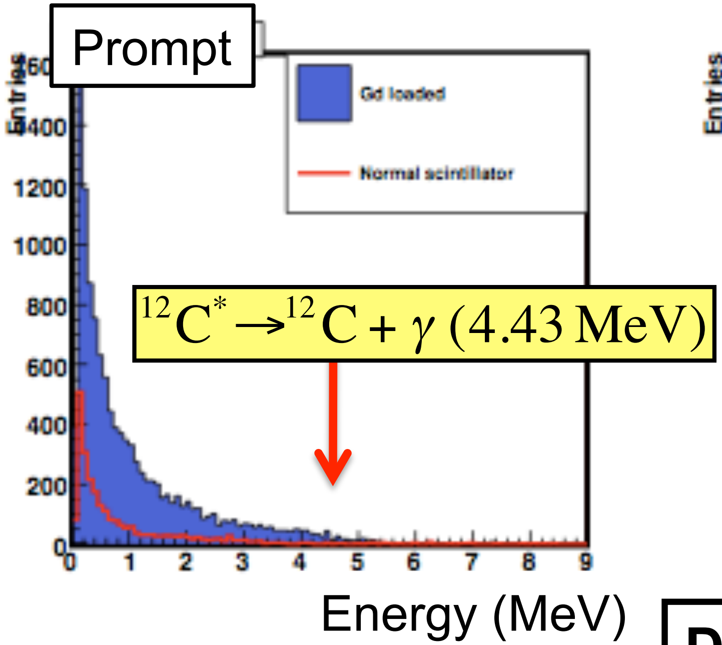
Time difference between the prompt and delayed signal (Δt) is recorded by TDC with 50μs time window (programmed)

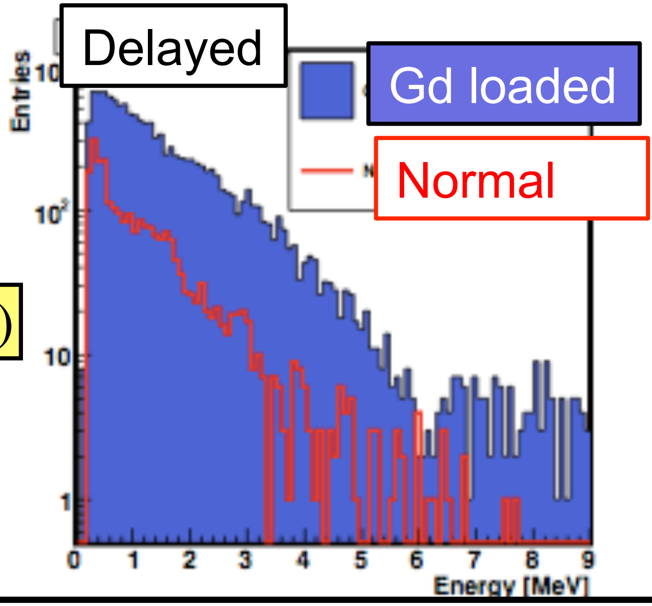
Delayed coincidence data taking logic

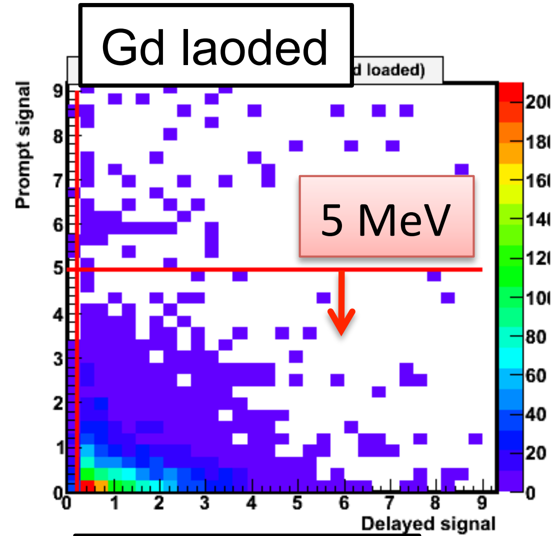


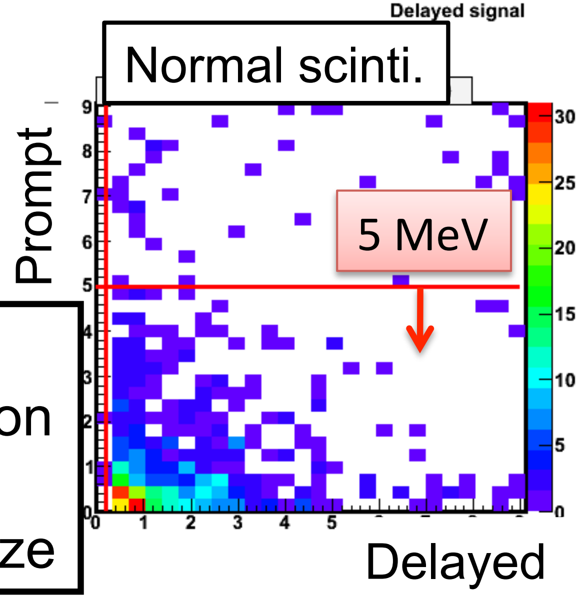
Energy distribution (prompt, delayed)

HV : -1700V (Gd loaded), -1600V (Normal)
Measurement : 24h
Threshold : Th_1=-40mV, Th_2=-100mV









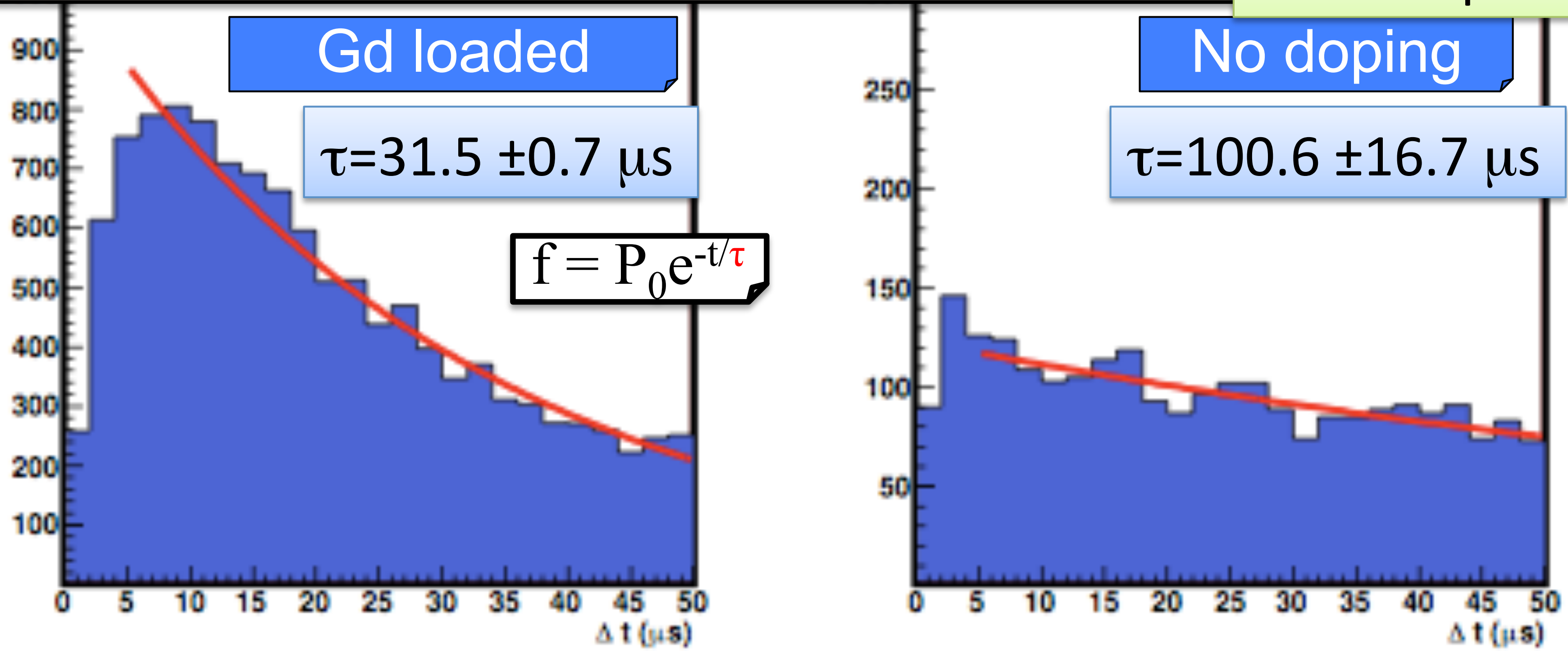
Prompt signal
Eγ=4.43 MeV
Compton edge is observed

Delayed signal
8MeV total neutron absorption peak can not observe because of small detector size

Comparison of neutron capture time

Mean neutron capture time (τ) is obtained from the time difference between prompt and delayed signal (Δt)

24h comparison



Neutron capture time becomes shorter by doping Gd τ=31.5±0.7
Pseudo neutrino event can be observed by Gd doped scintillator

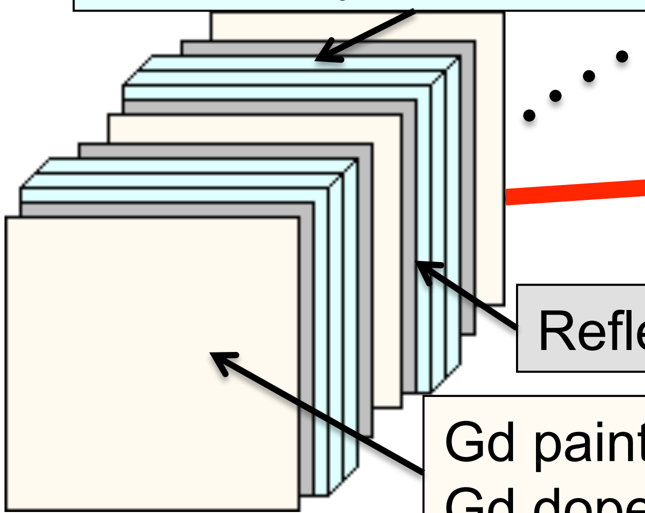
Layer aligned prototype detector (Layer type)

Layer aligned prototype

Sandwich structure of plastic scintillator+Gd paint sheet
Gd painted sheet : 0.1 mm-thick
Plastic scintillator : 2mm-thick x 2 layers

Size : 18x18cm^2 x 2mm (30 layers)

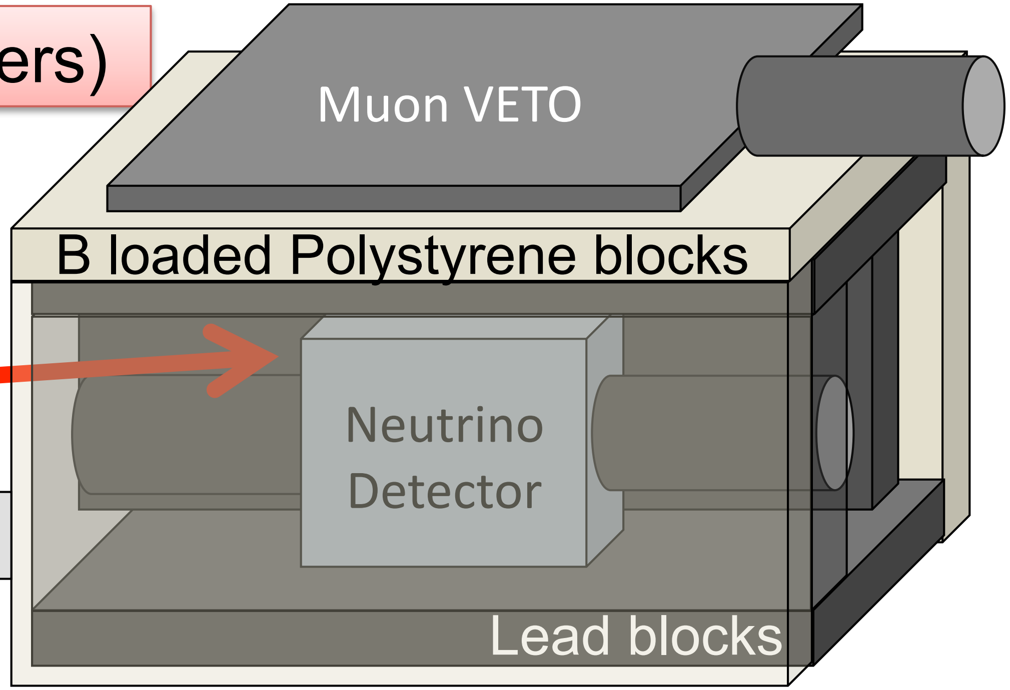
2mm, 2 layers scintillators



Reflective sheet

Gd painted sheet
Gd dope : 1.5%/W

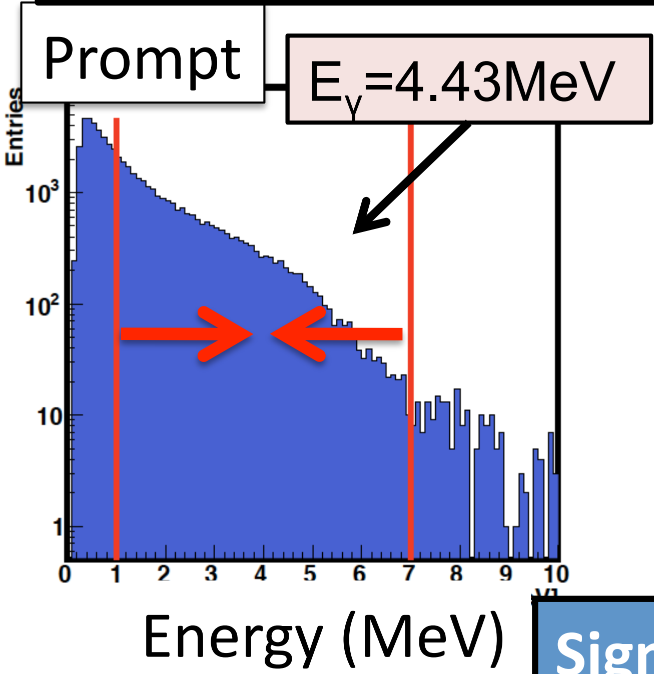
Readout by 2 inch PMTs

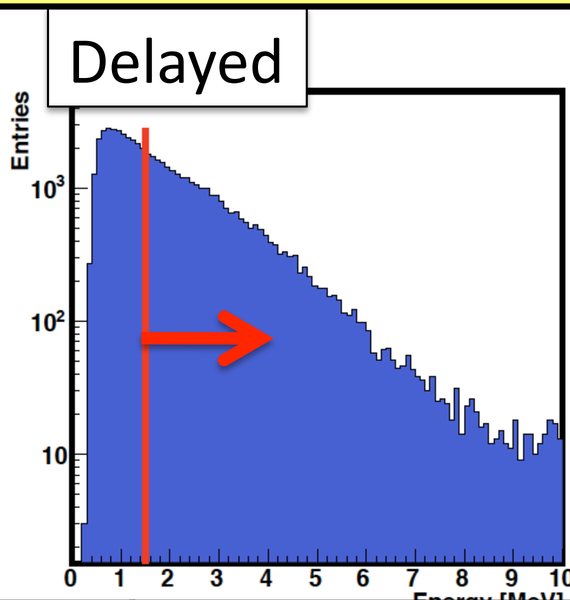


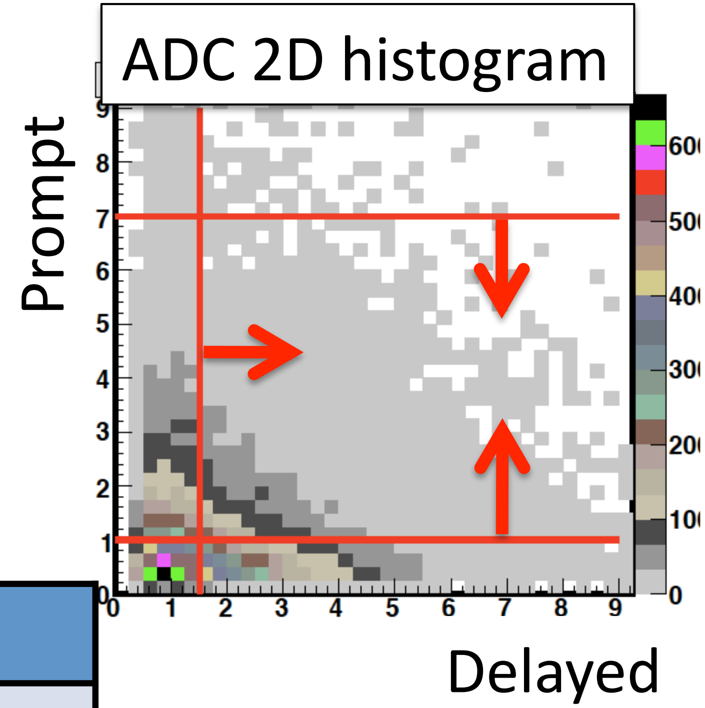
Detector is covered by lead blocks and boron loaded polystyrene blocks

^{241}Am/Be Pseudo event measurement

PMT HV = -2350V calibrated with Co gamma-ray signal
threshold_(Prompt, Delayed) = (-30mV, -60mV)
Measurement time: 12h



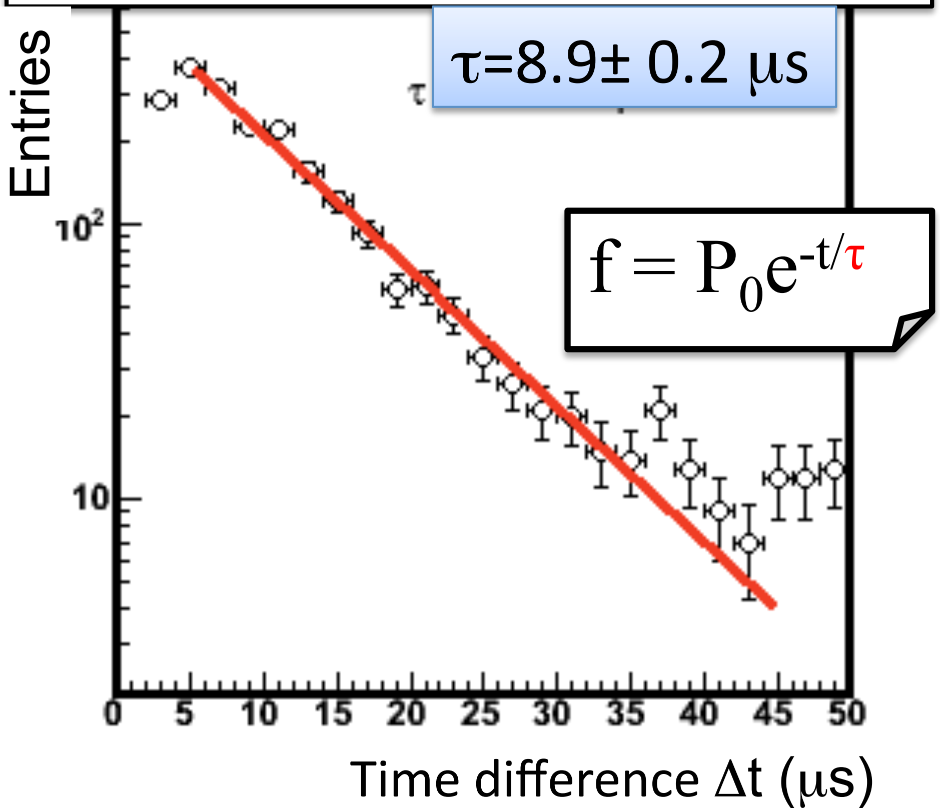




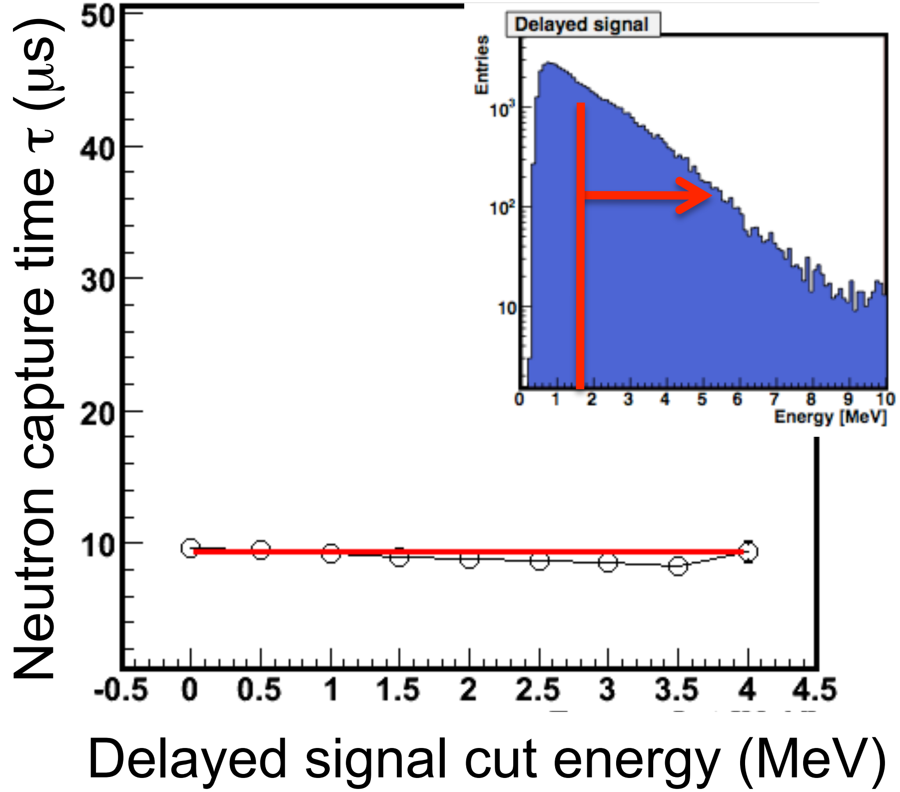
Signal	Cut region
Prompt	1.0 < Eγ < 7.0 MeV
Delayed	Eγ>1.5 MeV

Mean neutron capture time

Time difference (Δt) distribution



Delayed signal cut value dependence

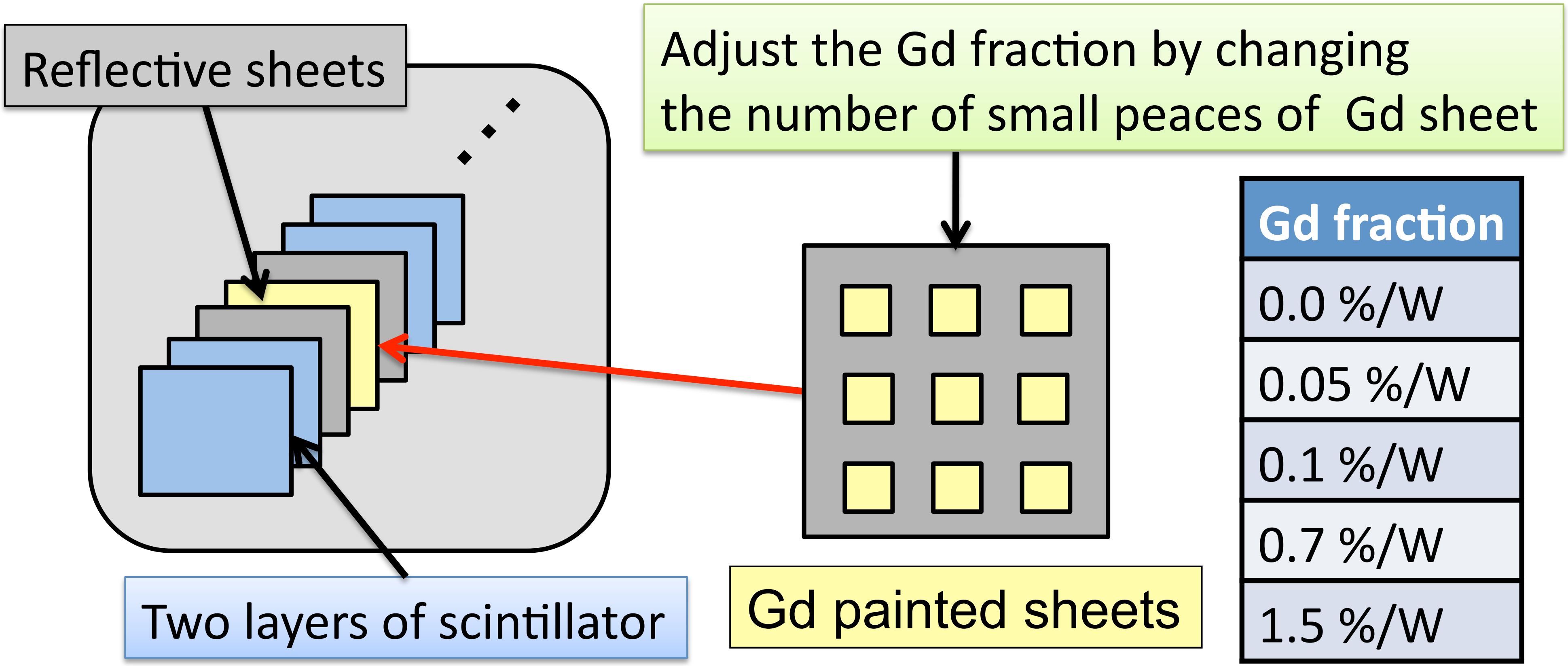


Gd fraction 1.5%/W makes neutron capture time shorter.

Higher energy output must be caused from neutron capture signal

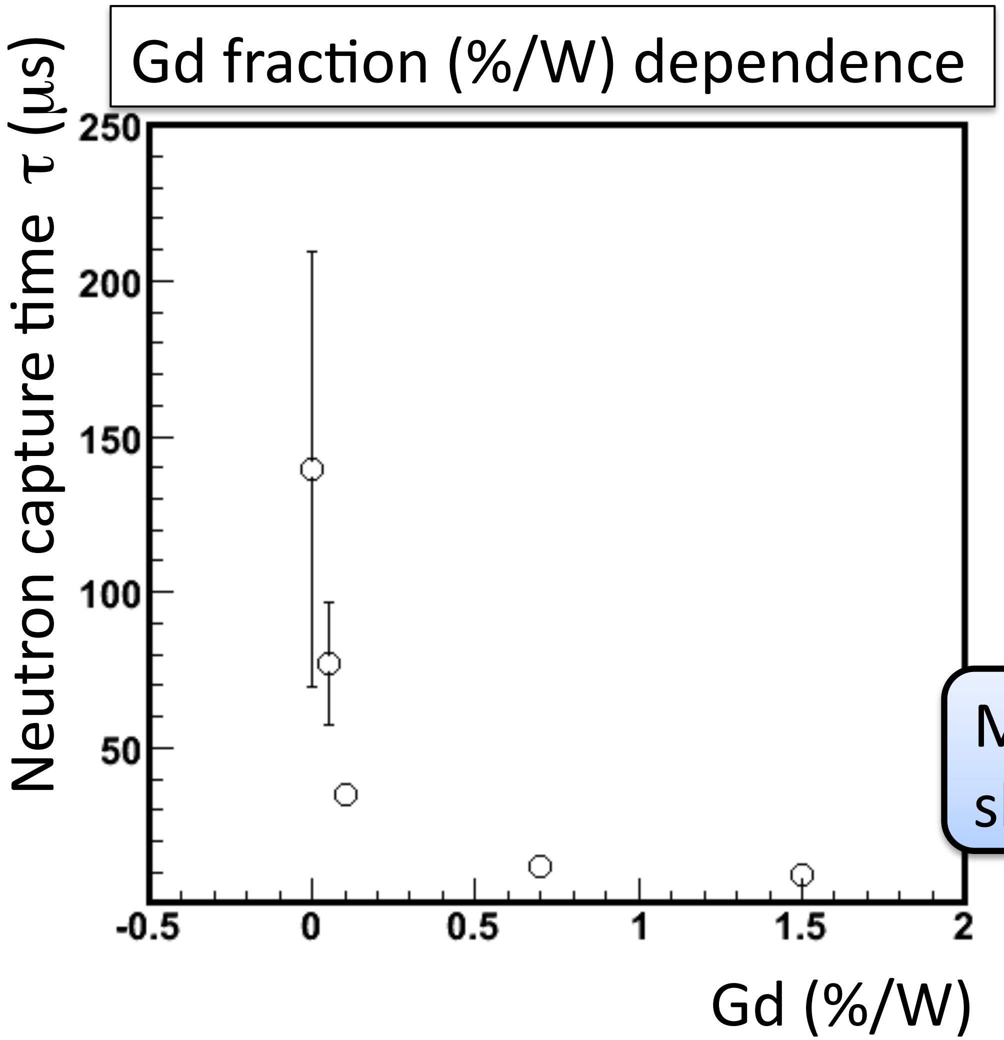
Gd content fraction effect

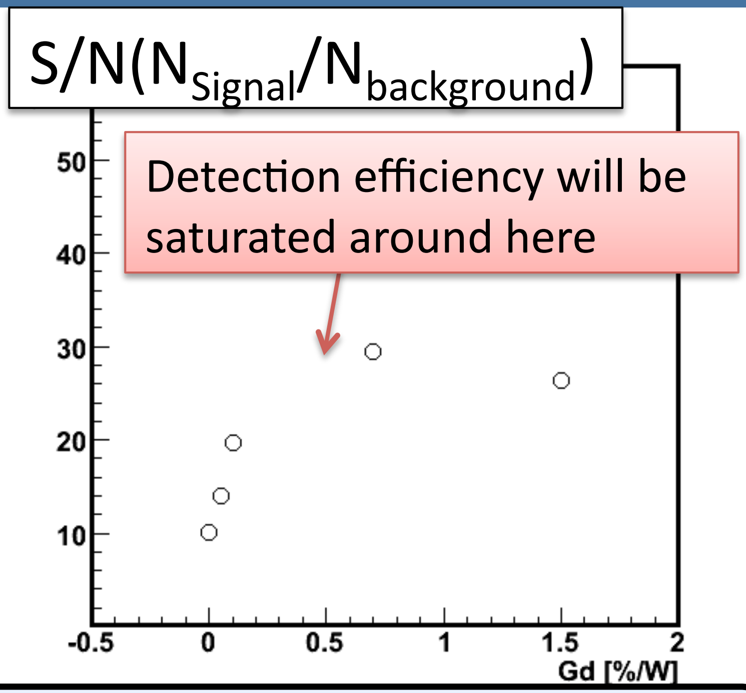
To check the effect of Gd fraction to the neutron capture time, several Gd fraction samples are prepared



Gd fraction
0.0 %/W
0.05 %/W
0.1 %/W
0.7 %/W
1.5 %/W

Dependence of Gd content fraction





Mean capture time becomes shorter with increasing Gd fraction

Dependence of Gd fraction is observed experimentally.

Need to confirm with simulation : next step

Conclusion and next steps

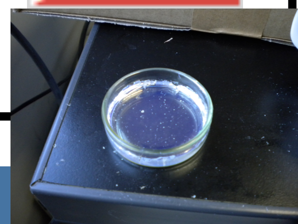
Conclusion

Two types of plastic scintillator based neutrino detectors are tested with ^{241}Am/Be pseudo neutrino event

- Neutron capture signals are observed with both prototype.
- Gd fraction dependence can be observed.

Next steps

- Geant4 simulation should be applied to confirm the effect of Gd fraction dependence.
- Upgrade the detector size
  - Upgrade prototype size with 2mm thick legacy scintillators.
  - Gd doped plastic scintillator has tried to produce by Philippine's collaborator.
  - Hopefully produce much cheaper price in Philippine



Backup

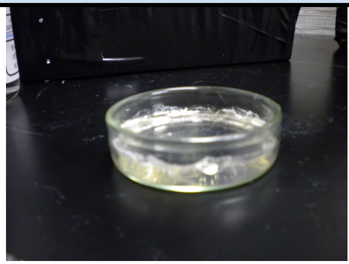
Future view for the large detector

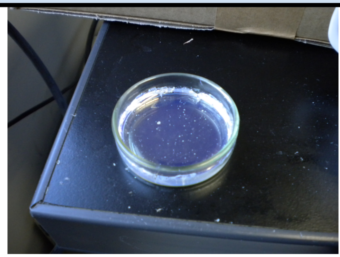
Plastic scintillator is manufactured in laboratory
Philippines collaborator try to make Gd/Boron loaded plastic scintillator

Base materials of scintillator

- Polystyrene pellet
- PPO (1st wave length shifter)
- POPOP (2nd wave length shifter)

Mix all the materials
and stair on the hot plate
Melt around 300°C then slowly cool down





Test samples made in Lab.

Further more,
Gadolinium or **Boron** will be doped for efficient neutron detection scintillator

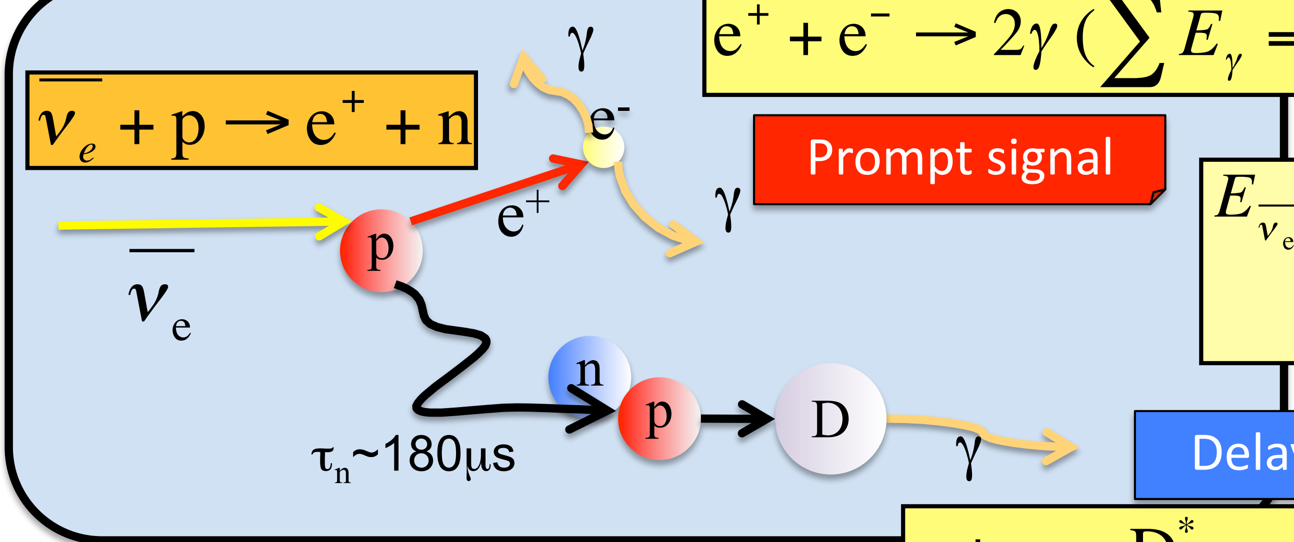
Large amount of plastic scintillator might be produced in Philippines much cheaper price.

Reactor neutrino detection method

Amount of anti neutrinos are produced from nuclear fission in reactor
Neutrino detection : **Inverse beta decay** in scintillator detector

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

$$e^+ + e^- \rightarrow 2\gamma \; (\sum E_\gamma = 1.02 \text{ MeV})$$



KamLAND experiment method

Prompt signal

$$E_{\overline{\nu}_e} \sim E_{e^+} + 1.8 \text{ MeV}$$
$$= E_{vis} + 2E_\gamma + 0.78 \text{ MeV}$$

Delayed signal

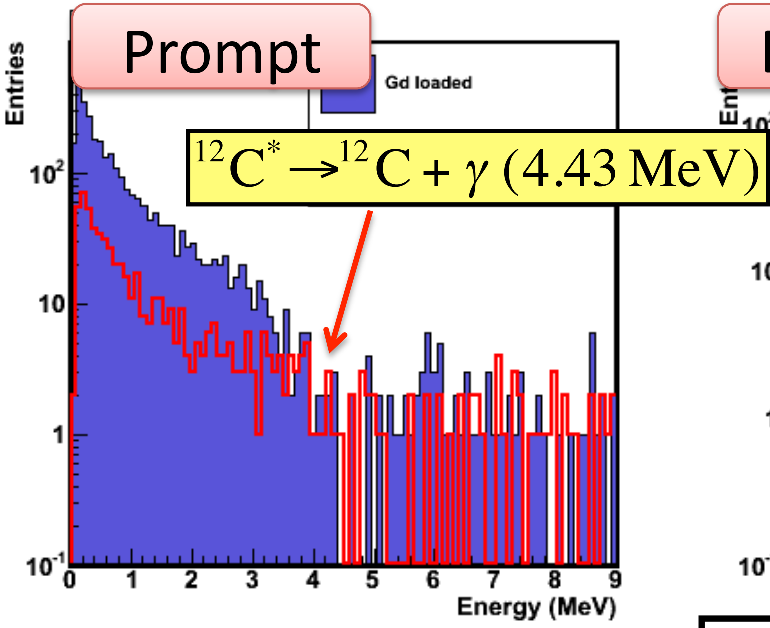
$$n + p \rightarrow D^* \rightarrow D + \gamma \; (E_\gamma = 2.2 \text{ MeV})$$

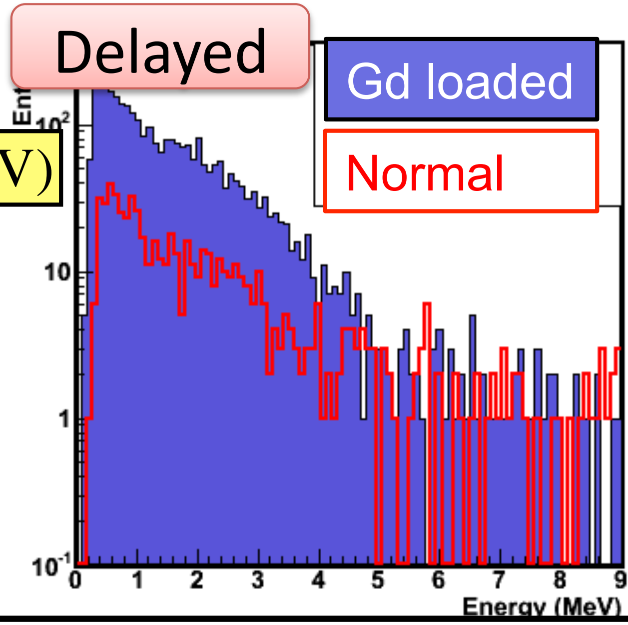
Coincidence of **prompt** and **delayed** signal makes drastic background reduction

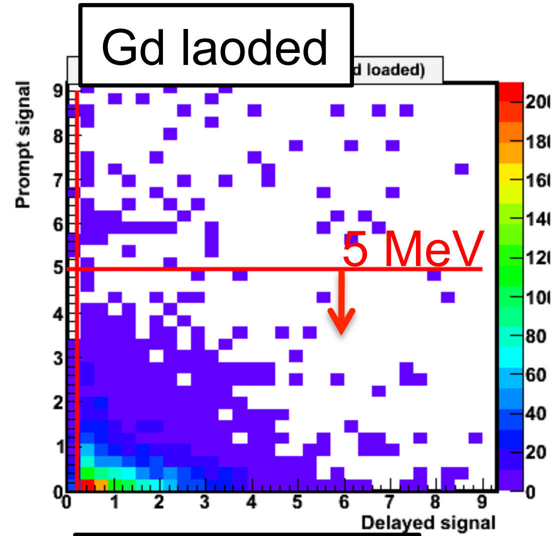
Energy distribution (Prompt, Delayed)

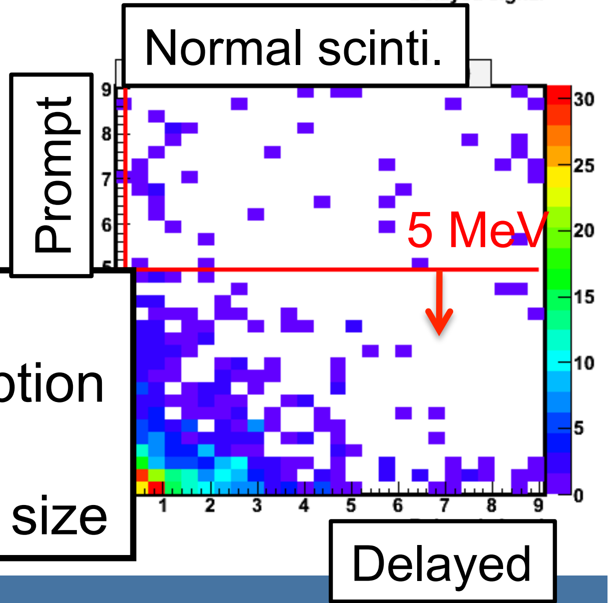
Measurement : 6h

Threshold : Th_1=-40mV, Th_2=-100mV





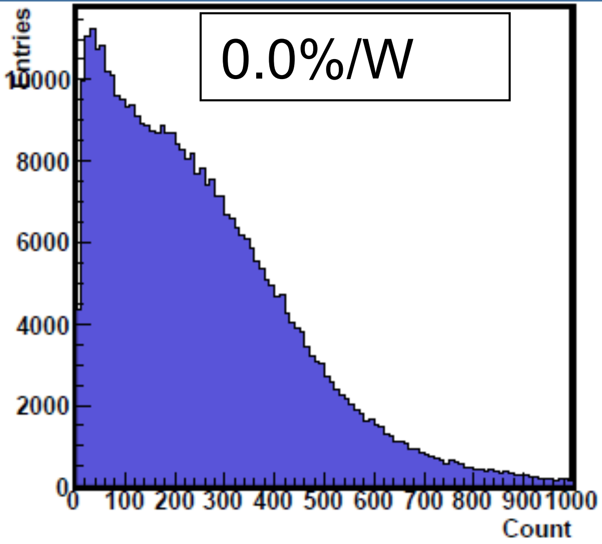


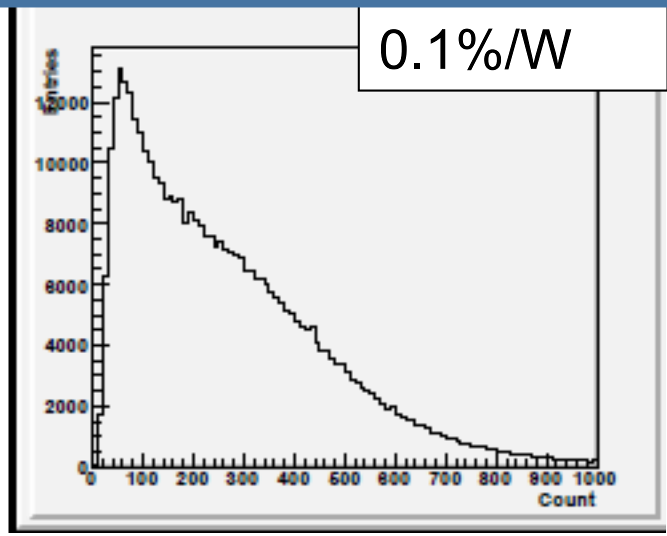


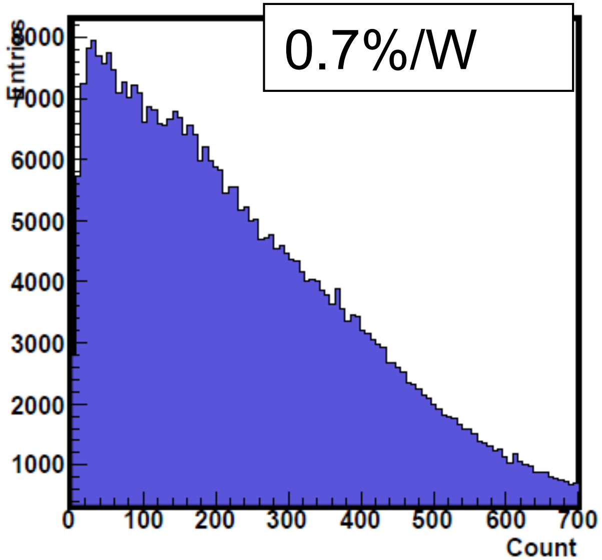
Prompt signal
Eγ=4.43 MeV
Compton edge is observed

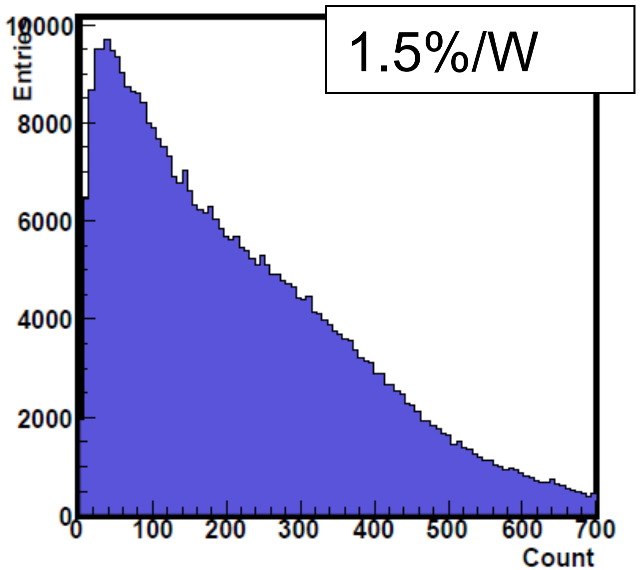
Delayed signal
8MeV total neutron absorption peak can not observe because of small detector size

^{60}Co gamma-ray energy distribution

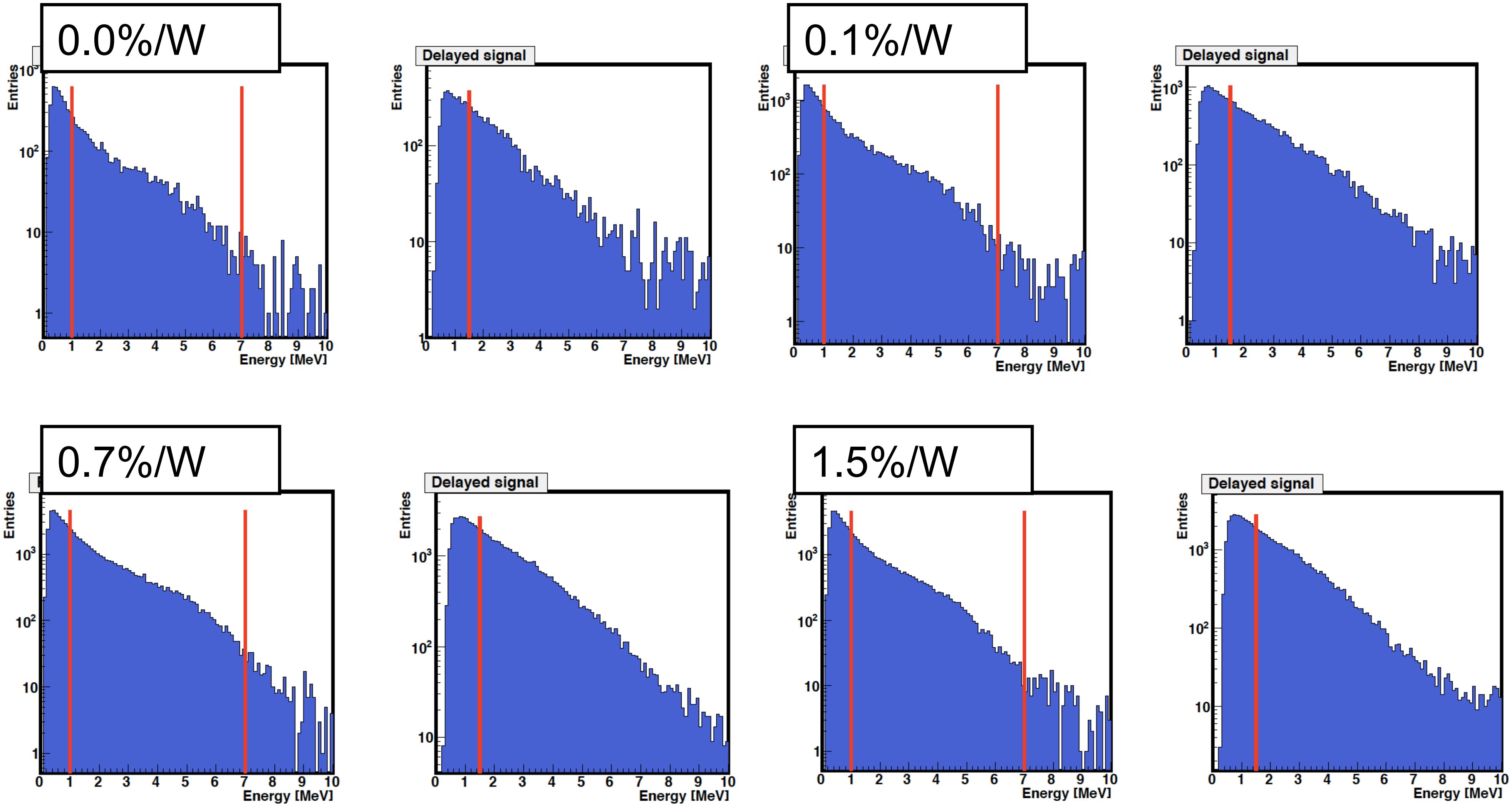




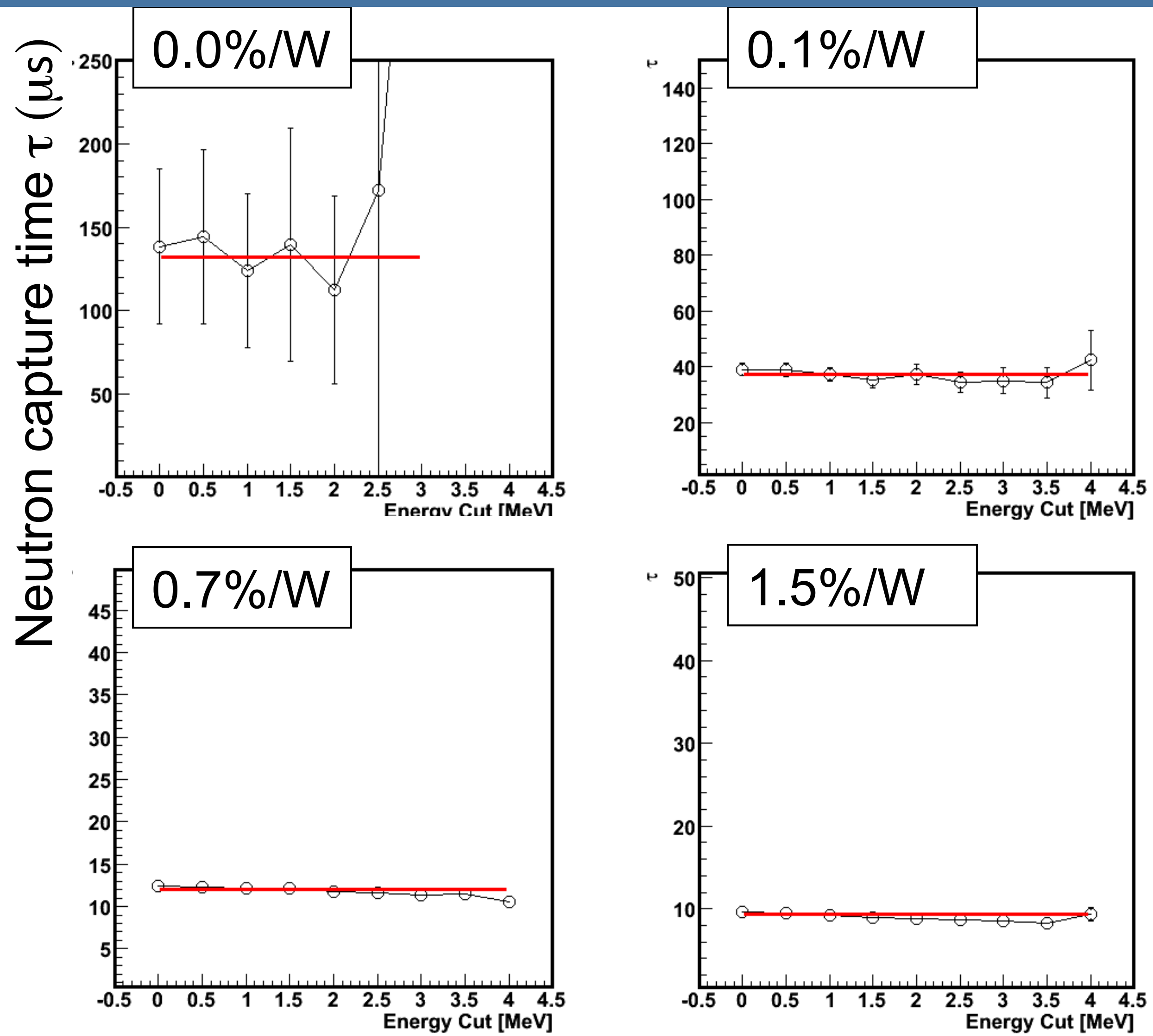


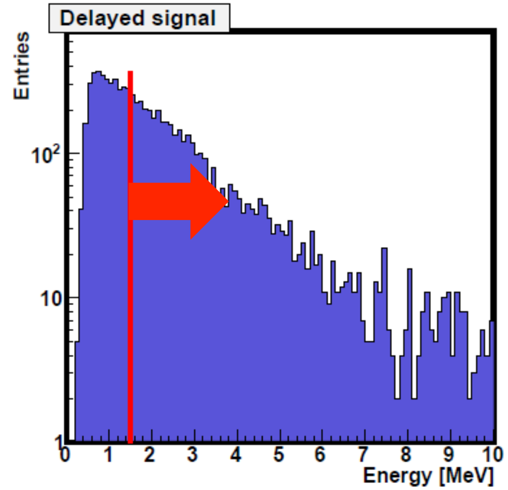


Energy distribution with Gd fraction



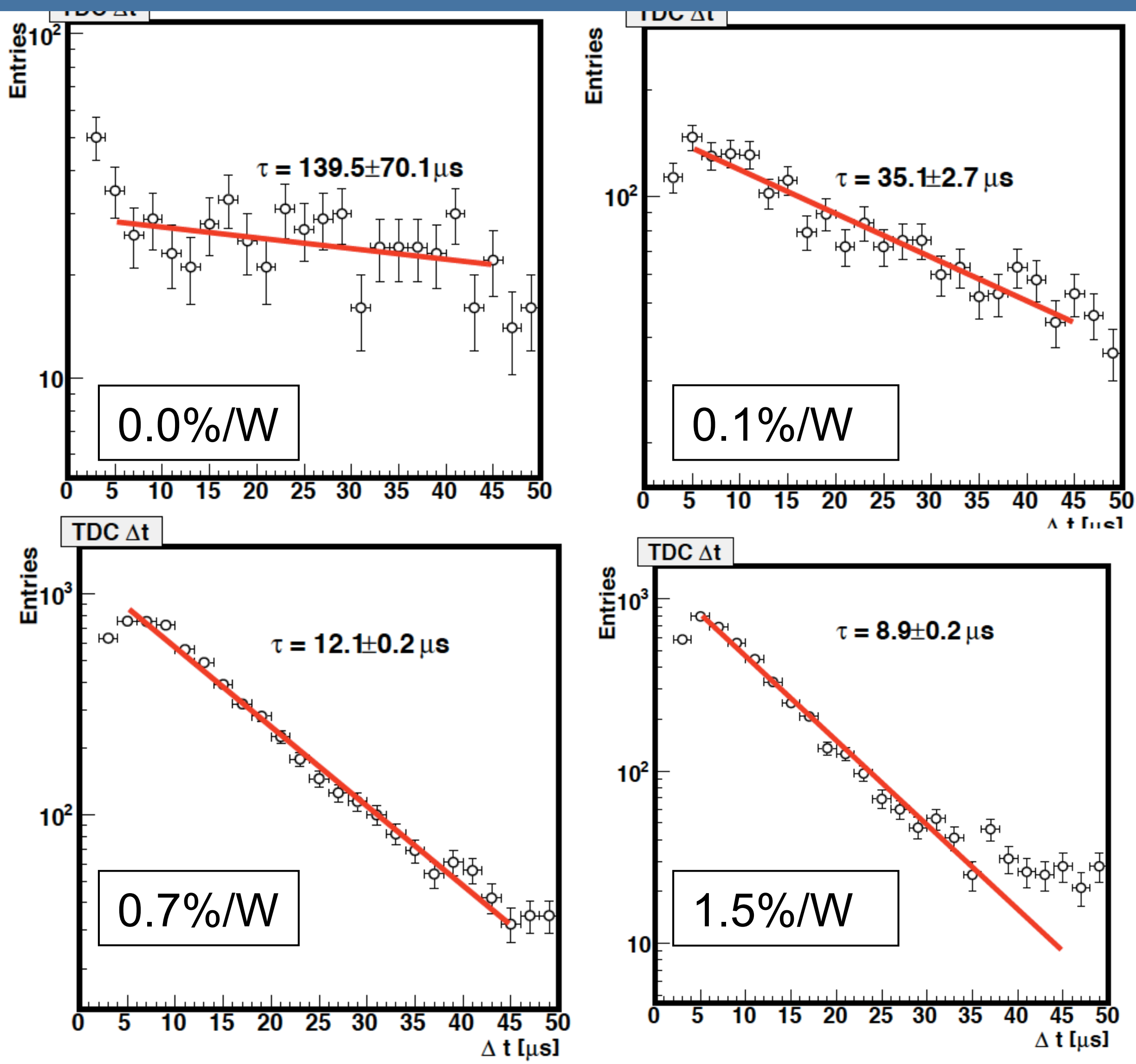
Stability check with energy cut





Energy cut value for delayed signal

Time difference Δt distribution



Delayed coincidence test setup

- Use VME multi-hit TDC and ADCs are used for the delayed coincidence measurement

- 16 ch multi-hit TDC (CAEN V1290N)
  - 51.2 μs dynamic range
  - Multi-hit event can be recorded

- 16 ch CS ADC (REPIC RPV-171)
  - 12bit (1000pC/4096 count=0.25 pC/count)