Observation of Reactor Antineutrinos at RENO

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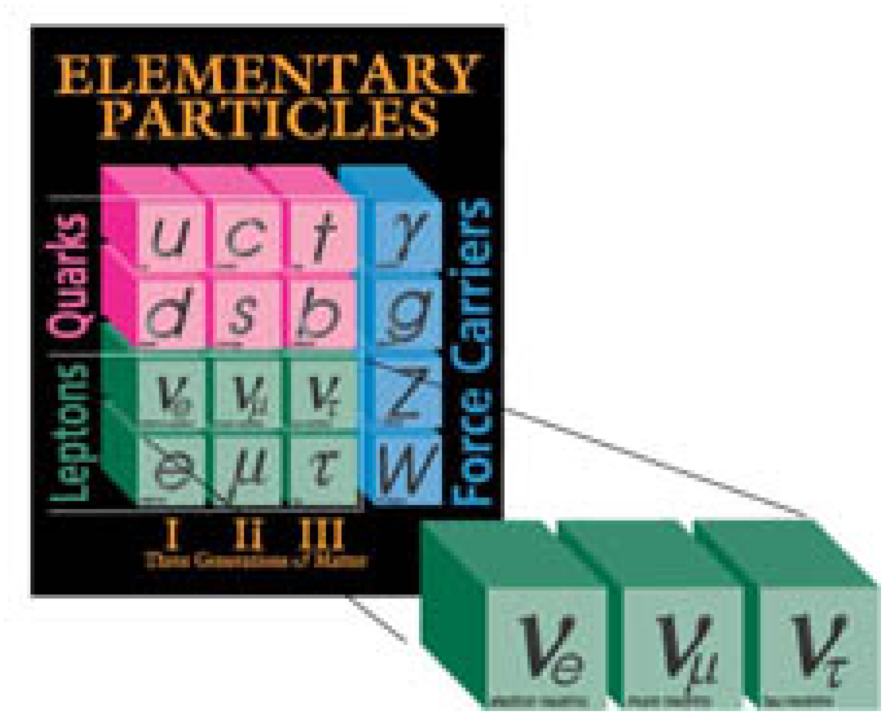
RENO ν θ_{13}

KNRC Korea Neutrino Research Center

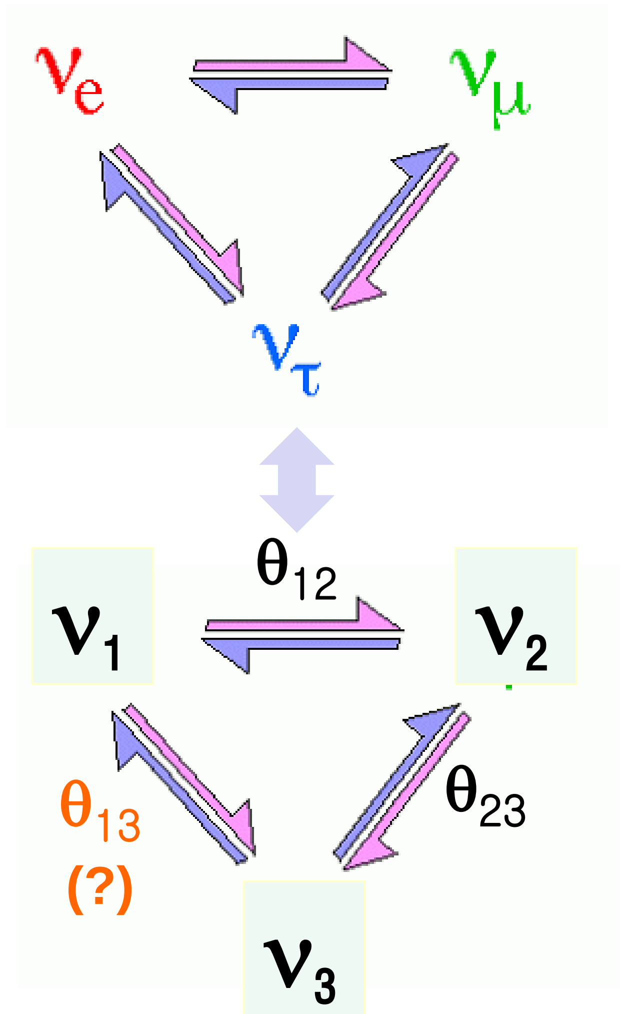
Outline

- Introduction
- Experimental setup & detector
- Data-taking & data set
- Calibration
- Event selection
- Efficiency & Background
- Reactor antineutrino prediction
- Results
- Systematic uncertainties
- Summary

Neutrino Oscillation



PMNS Neutrino Mixing Angles and CP Violation



Reactor Antineutrino Oscillation

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E_\nu}\right)$$

Past Efforts for Finding θ_{13}

- Chooz (2003) & Palo Verde (2000): No signal

$\sin^2(2\theta_{13}) < 0.12$ at 90% C.L.

- T2K : 2.5 σ excess (2011)

$0.03 < \sin^2(2\theta_{13}) < 0.28$ at 90% C.L. for N.H.

$0.04 < \sin^2(2\theta_{13}) < 0.34$ at 90% C.L. for I.H.

- MINOS : 1.7 σ excess (2011)

$0 < \sin^2(2\theta_{13}) < 0.12$ at 90% C.L. for N.H.

$0.04 < \sin^2(2\theta_{13}) < 0.19$ at 90% C.L. for I.H.

- Double Chooz : 1.7 σ measurement (2011)

$\sin^2(2\theta_{13}) = 0.086 \pm 0.041(\text{stat.}) \pm 0.030(\text{syst.})$

- Daya Bay (03. 08. 2012)

5.2 σ observation

$\sin^2(2\theta_{13}) = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$

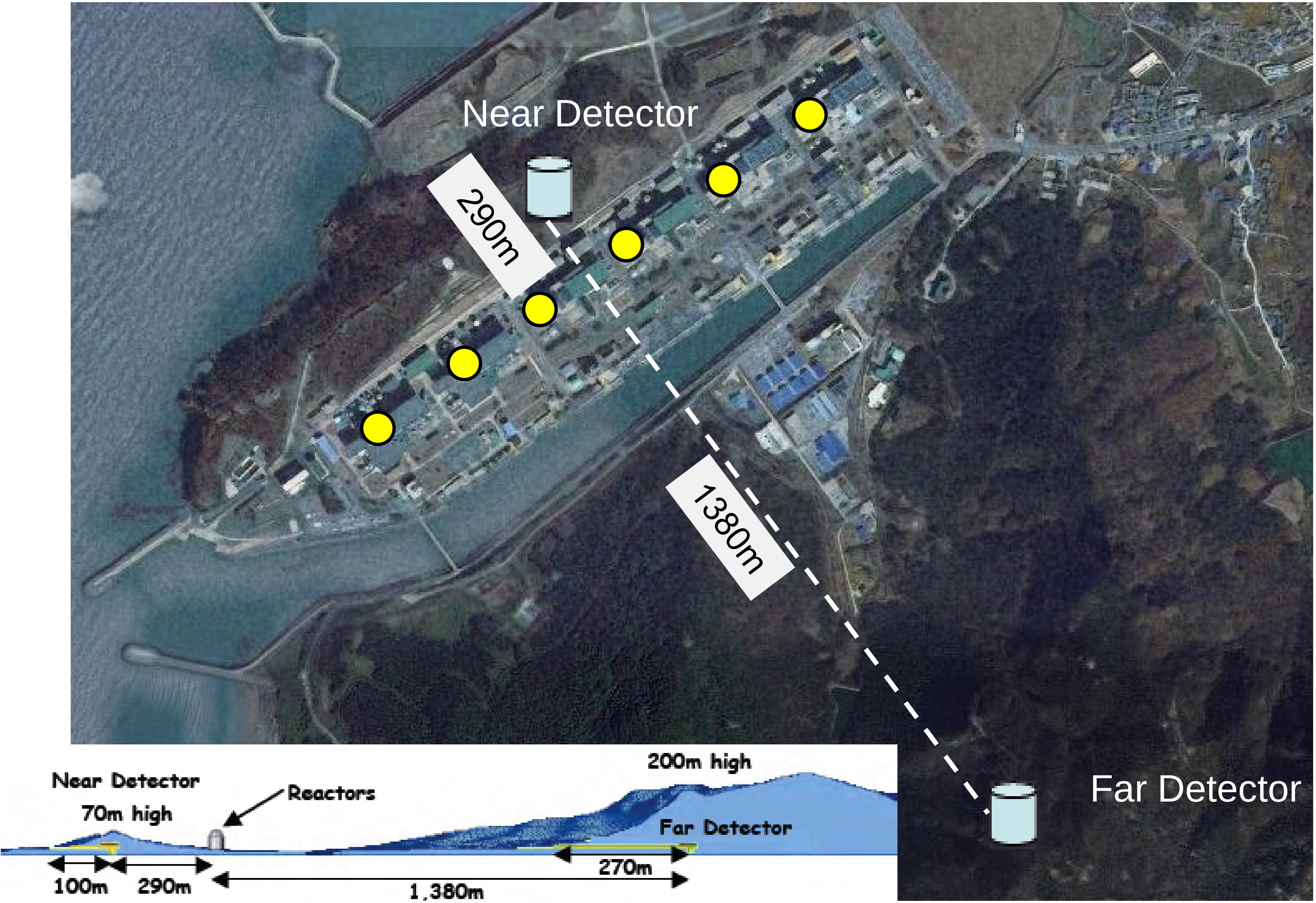
RENO Collaboration

(12 institutions and 40 physicists)

- Chonbuk National University
- Chonnam National University
- Chung-Ang University
- Dongshin University
- Gyeongsang National University
- Kyungpook National University
- Pusan National University
- Sejong University
- Seokyeong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

서울대 김수봉 교수가 이끄는 RENO 실험팀. 30여년간 관측에 실패한 마지막 중성미자 변환상수를 밝히기 위해 프랑스 중국과 치열한 경주를 벌이고 있다.

RENO Experimental Setup

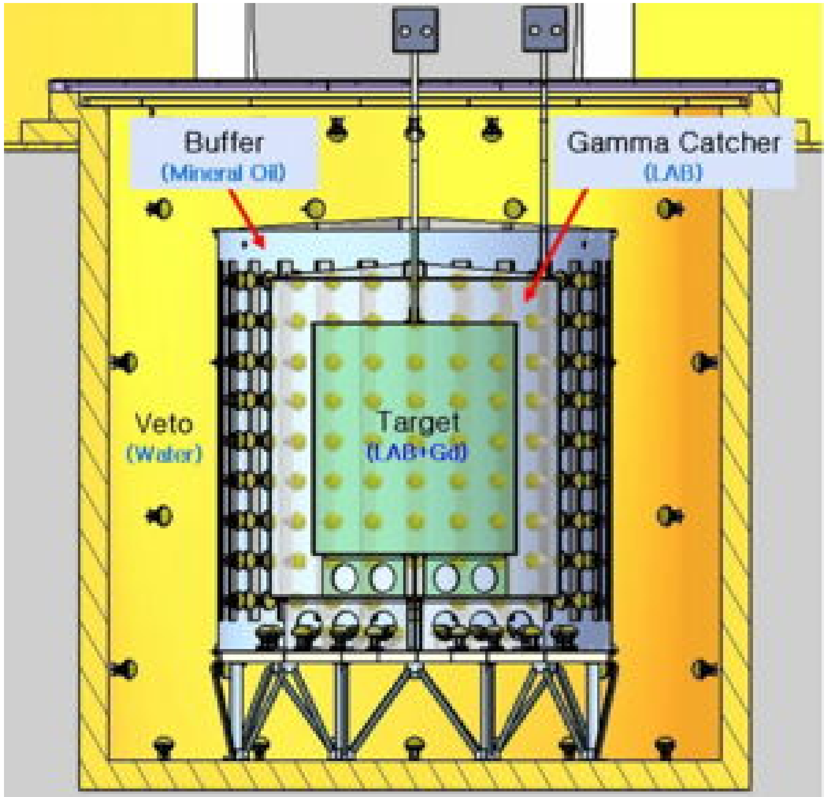


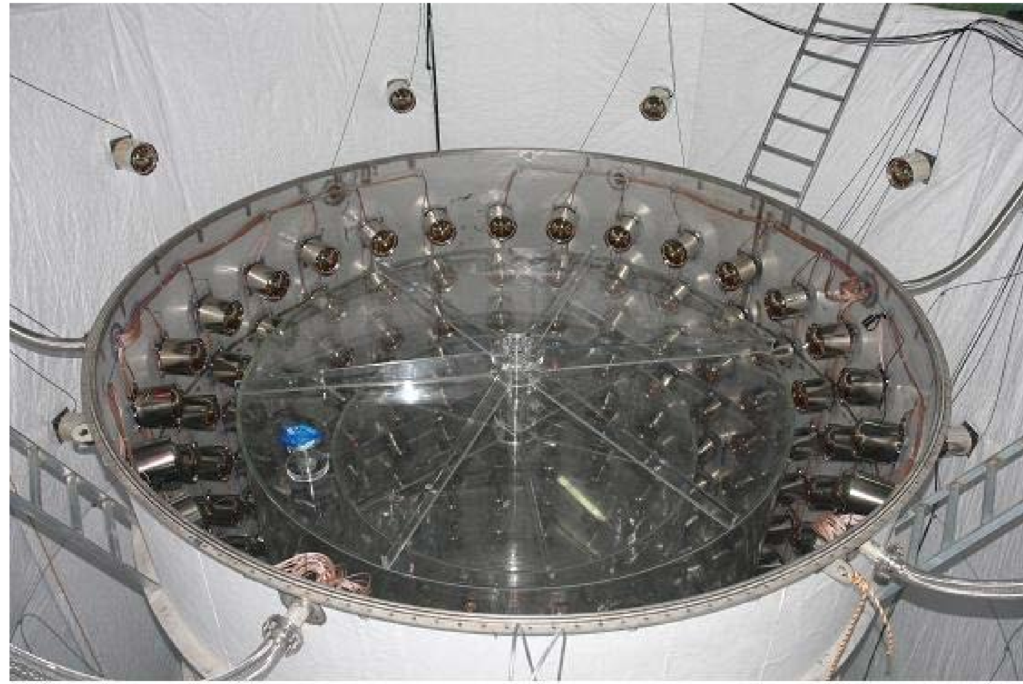
Contribution of Reactor to Neutrino Flux at Near & Far Detectors

Reactor #	Far (%)	Near (%)
1	13.73	6.78
2	15.74	14.93
3	18.09	34.19
4	18.56	27.01
5	17.80	11.50
6	16.08	5.58

- ❑ Accurate measurement of baseline distances to a precision of 10 cm using GPS and total station
- ❑ Accurate determination of reduction in the reactor neutrino fluxes after a baseline distance, much better than 0.1%

RENO Detector



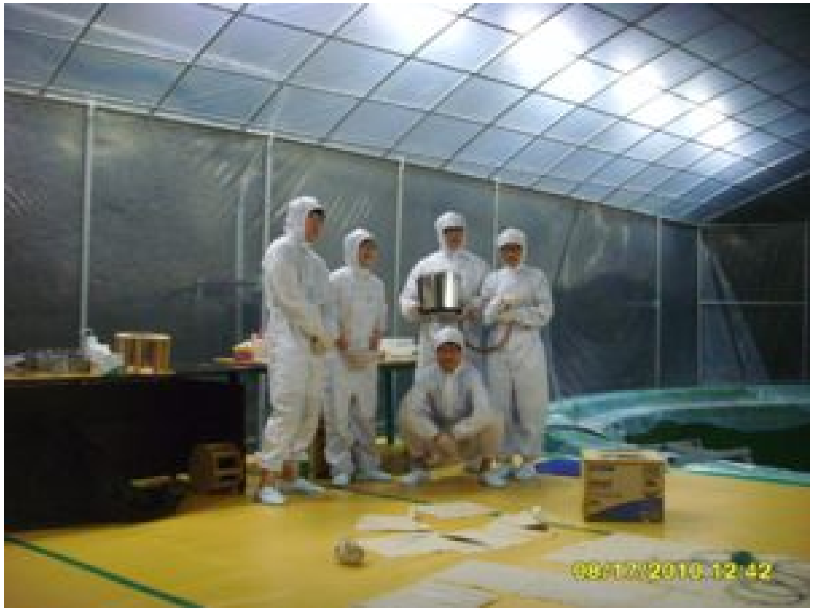


- 354 ID +67 OD 10” PMTs
- Target : 16.5 ton Gd-LS,   R=1.4m, H=3.2m
- Gamma Catcher : 30 ton LS,   R=2.0m, H=4.4m
- Buffer : 65 ton mineral oil,   R=2.7m, H=5.8m
- Veto : 350 ton water,   R=4.2m, H=8.8m

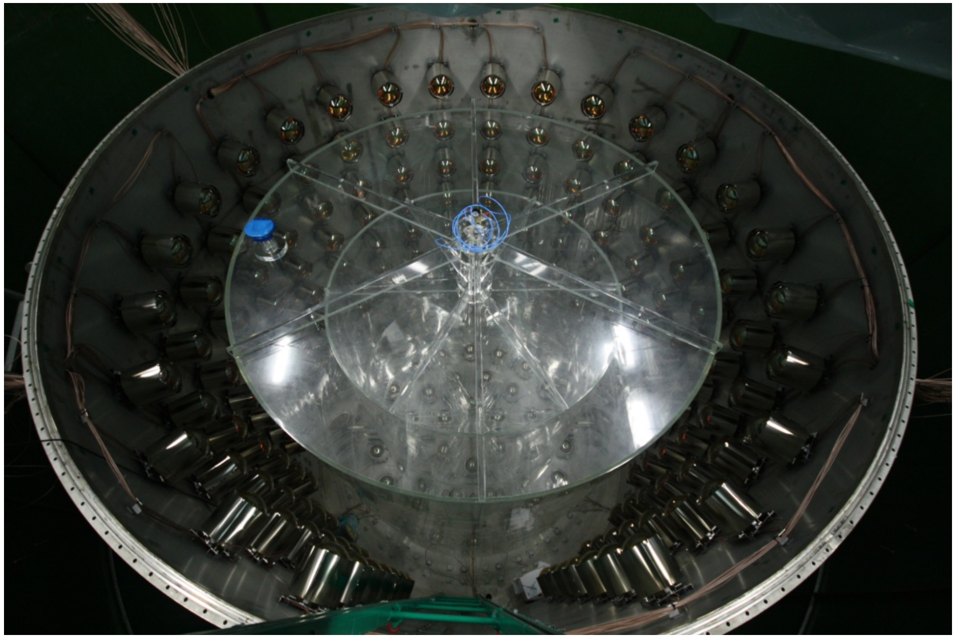
Summary of Detector Construction

- 2006. 03 : Start of the RENO project
- 2008. 06 ~ 2009. 03 : Civil construction including tunnel excavation
- 2008. 12 ~ 2009. 11 : Detector structure & buffer steel tanks completed
- 2010. 06 : Acrylic containers installed
- 2010. 06 ~ 2010. 12 : PMT test & installation
- 2011. 01 : Detector closing/ Electronics hut & control room built
- 2011. 02 : Installation of DAQ electronics and HV & cabling
- 2011. 03 ~ 06 : Dry run & DAQ debugging
- 2011. 05 ~ 07 : Liquid scintillator production & filling
- 2011. 07 : Detector operation & commissioning
- 2011. 08 : Start data-taking

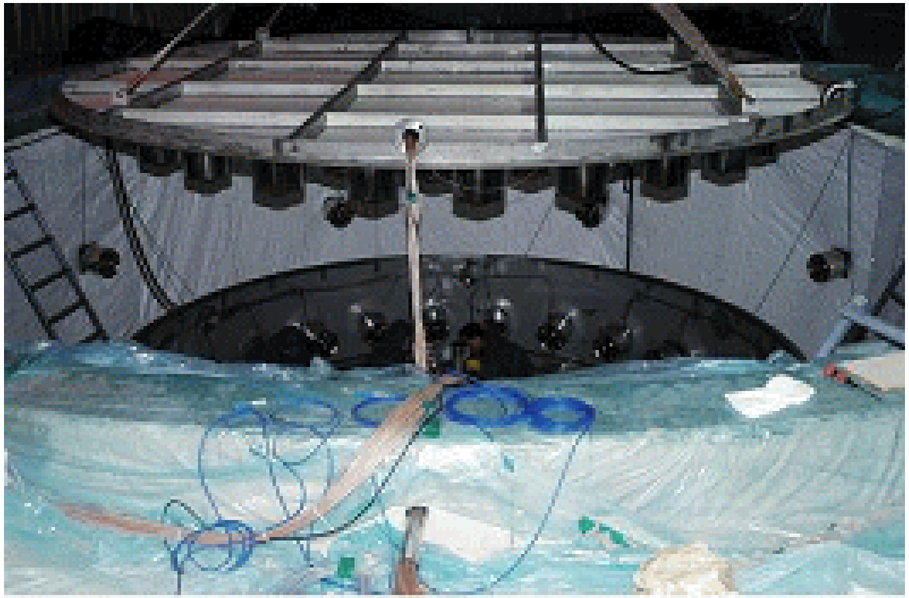
PMT Mounting (2010. 8~10)

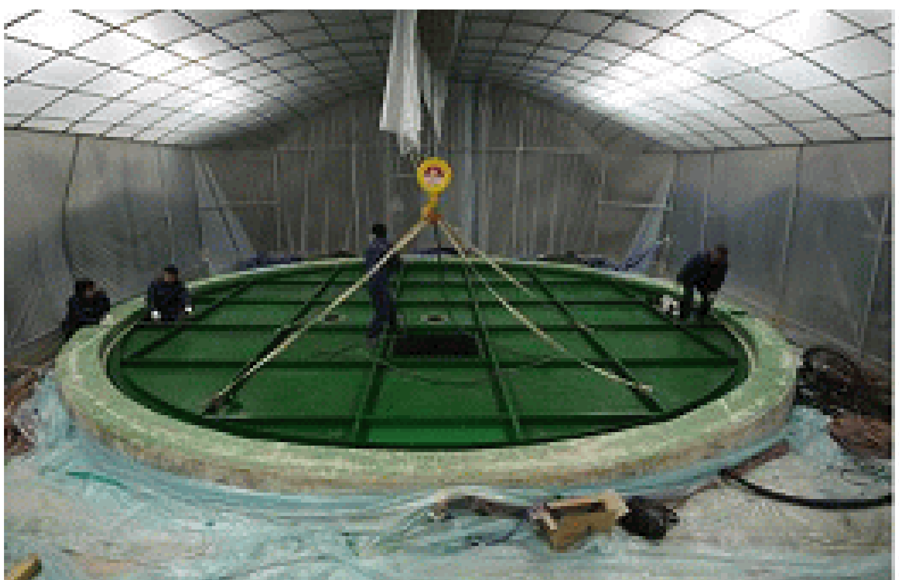


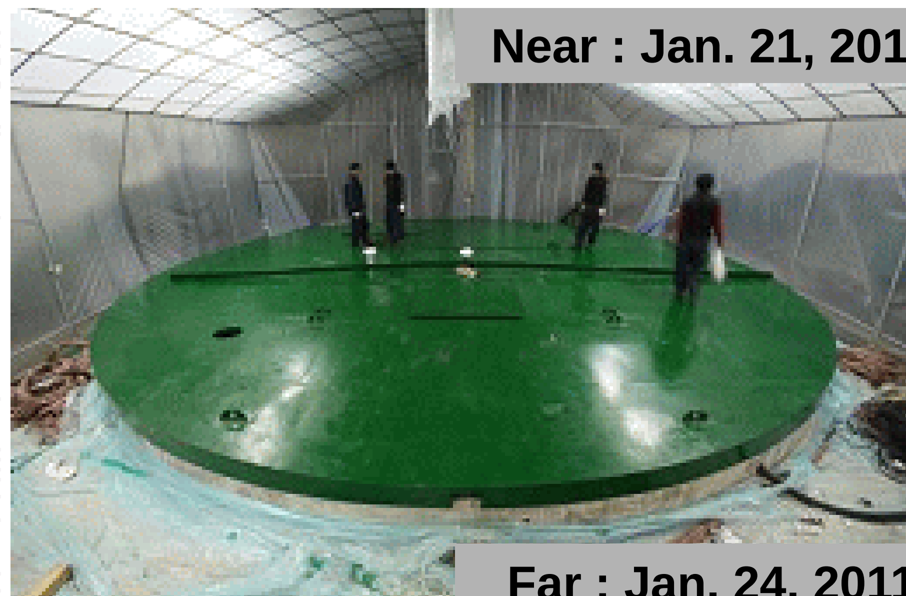
PMT Mounting (2010. 8~10)



Detector Closing (2011. 1)





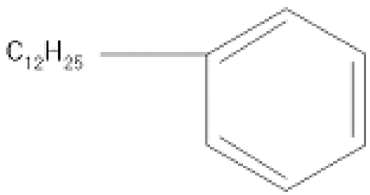


Near : Jan. 21, 2011

Far : Jan. 24, 2011

Detection of Reactor Antineutrinos

C_nH_{2n+1}-C_6H_5 (n=10~14)



Linear Alkyl Benzene (LAB)

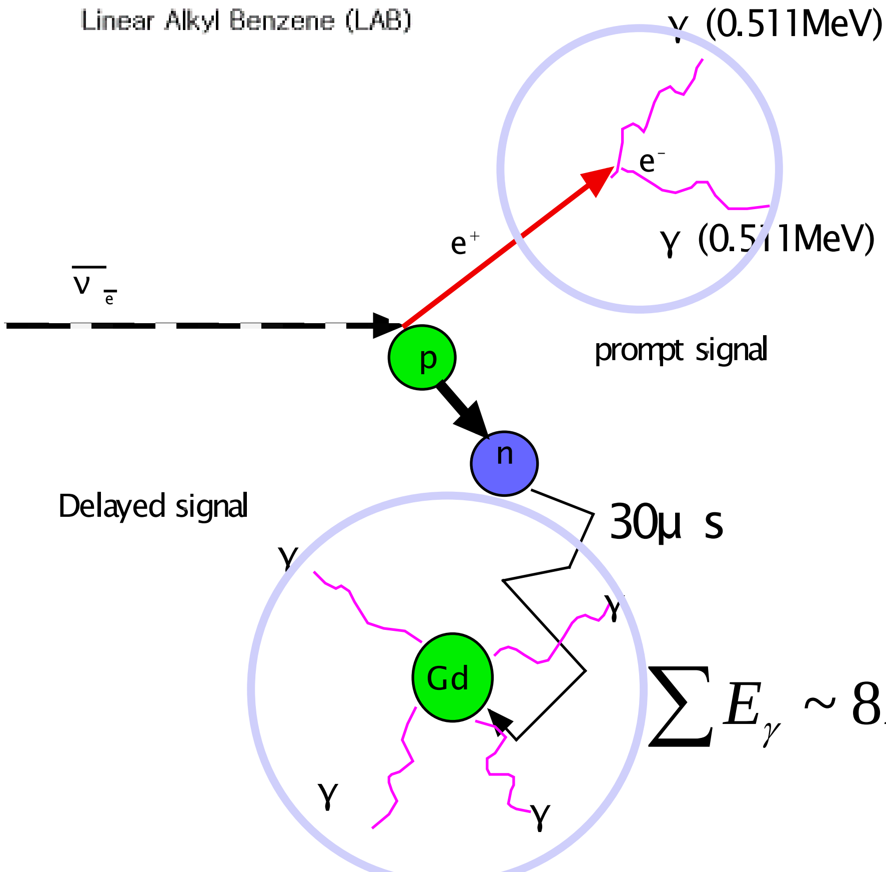
(prompt signal)

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

(delayed signal)

~180 μs: + p → D + γ (2.2 MeV)

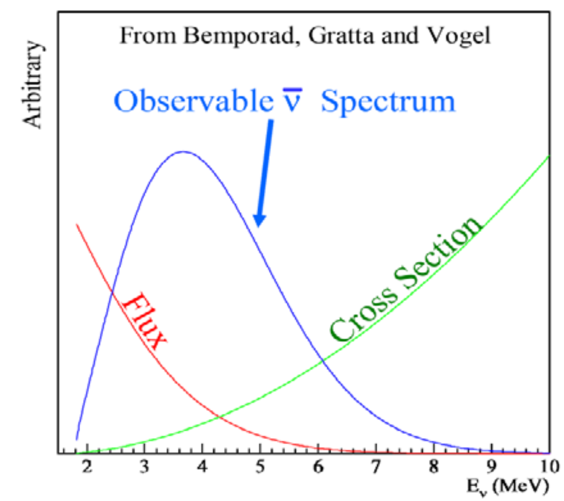
~28 μs (0.1% Gd): + Gd → Gd + γ's (8 MeV)



$$\sum E_\gamma \sim 8MeV$$

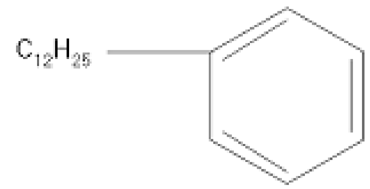
- **Neutrino energy measurement**

$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{10\text{-}40\ keV} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV}$$



Gd Loaded Liquid Scintillator

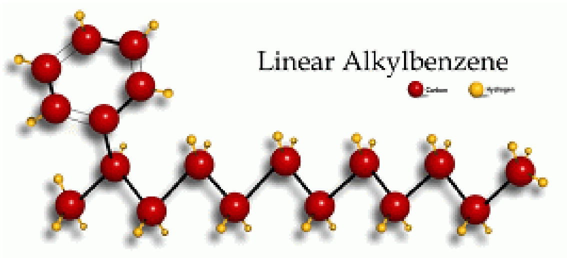
$C_nH_{2n+1}-C_6H_5$ (n=10~14)



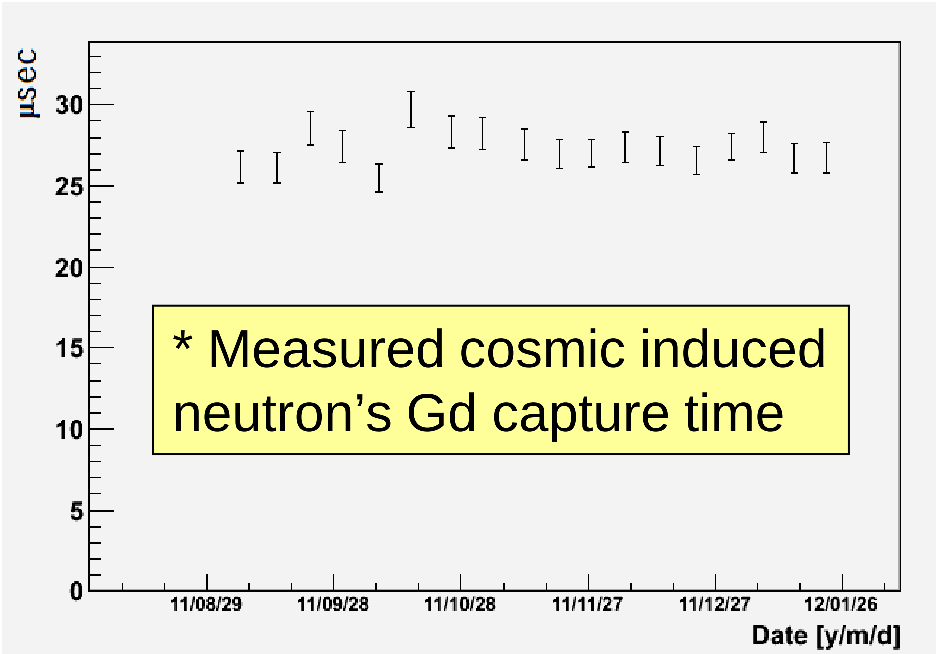
Linear Alkyl Benzene (LAB)

❑ Recipe of Liquid Scintillator

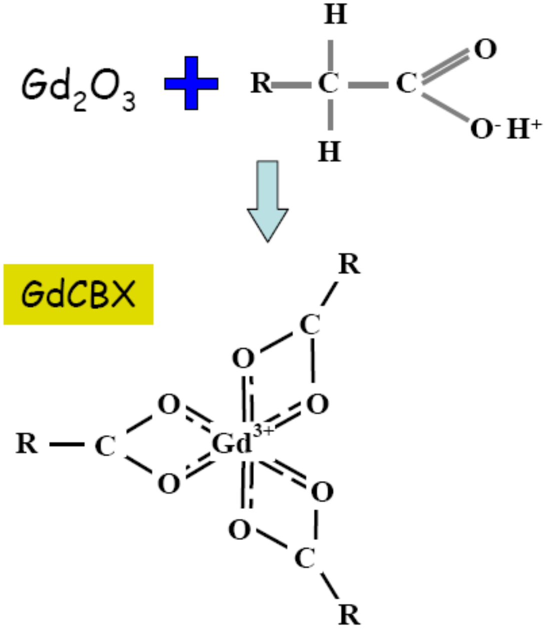
Aromatic Solvent & Flour	WLS	Gd−compound
LAB	PPO + Bis−MSB	0.1% Gd+(TMHA)^3 (trimethylhexanoic acid)



* Stable light yield over the time period : ~250 pe/MeV

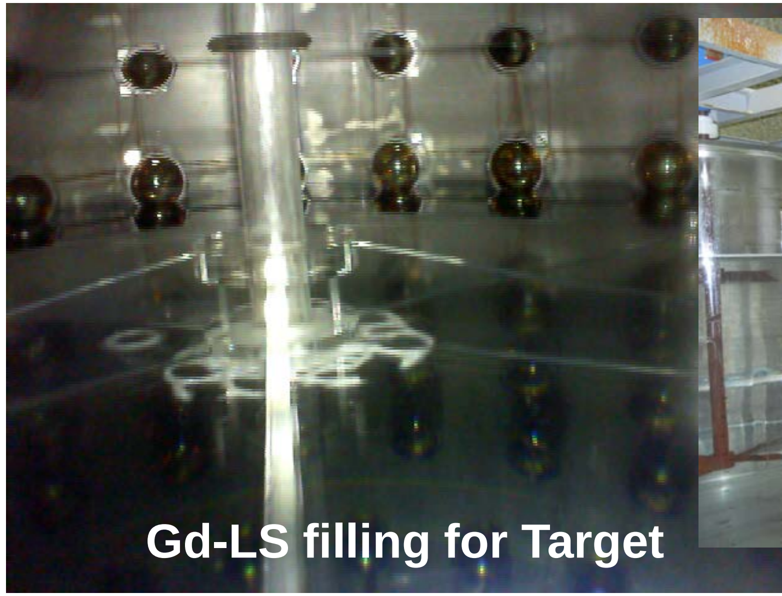


Carboxylic acids



Liquid(Gd-LS/LS/MO/Water) Production & Filling (May-July 2011)

Gd Loaded Liquid Scintillator

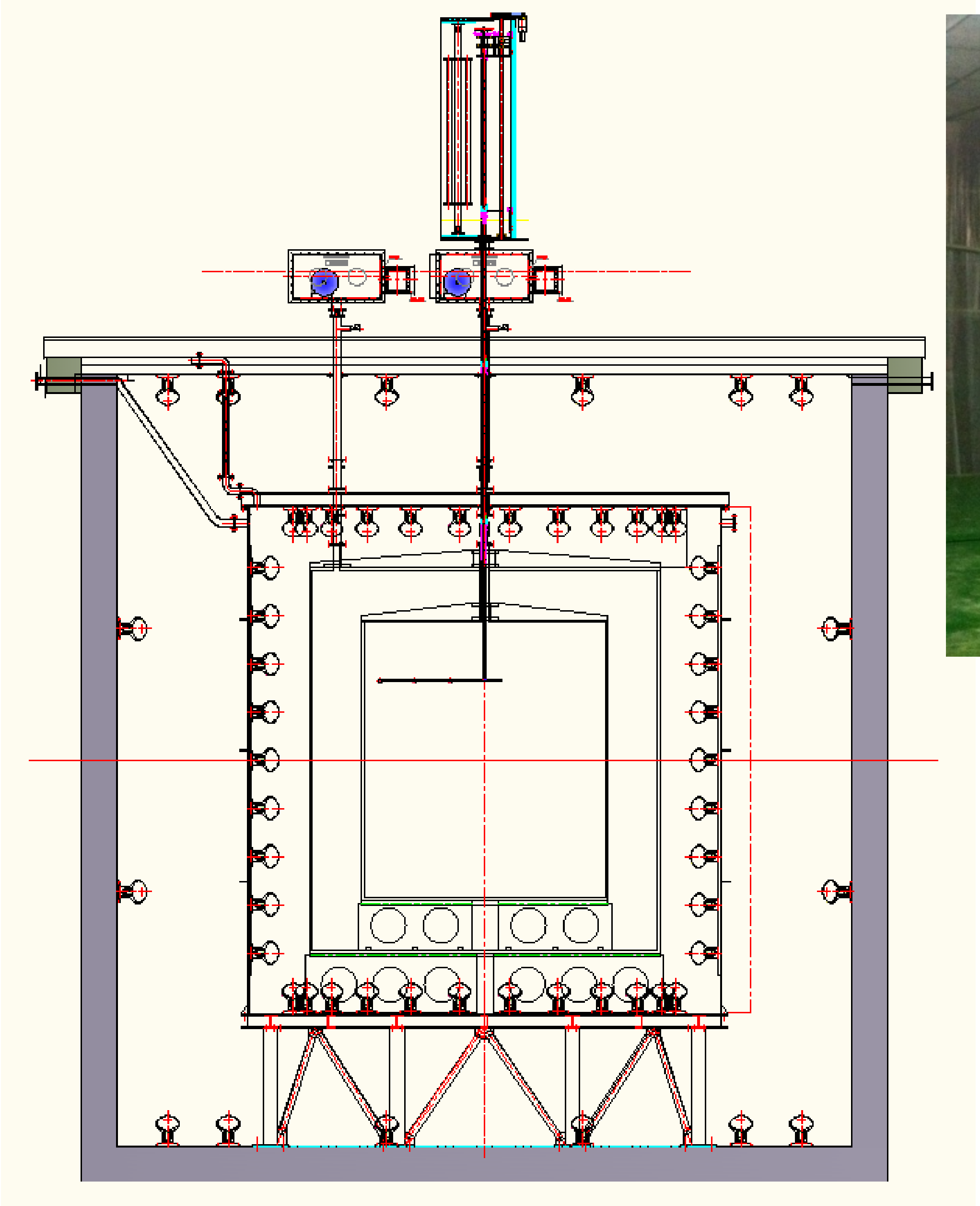


Gd-LS filling for Target

Water filling for Veto

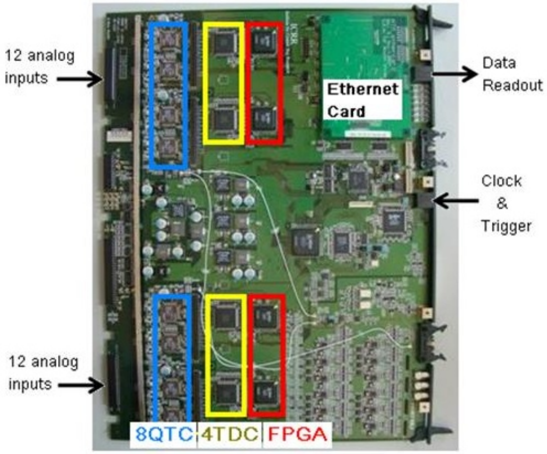
LS filling for Gamma Catcher

1D/3D Calibration System

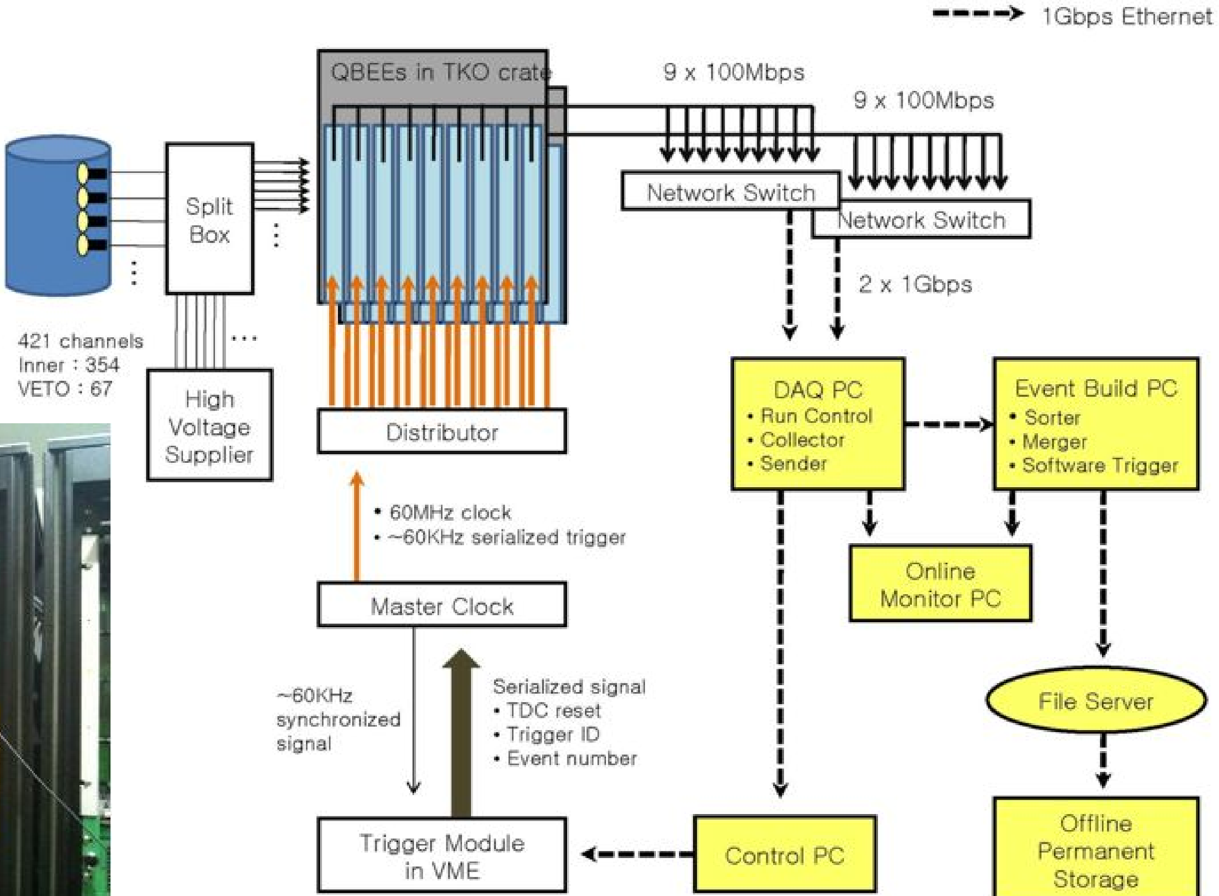


- ❑ Calibration system to deploy radioactive sources in 1D & 3D directions
- ❑ Radioactive sources : ^{137}Cs, ^{68}Ge, ^{60}Co, ^{252}Cf
- ❑ Laser injectors

Data Acquisition System



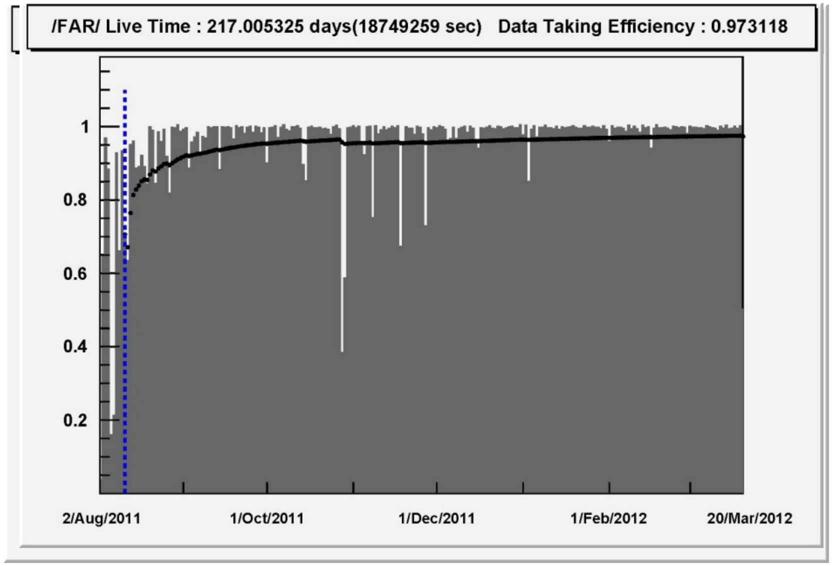
- 24 channel PMT input to ADC/TDC
- 0.1pC, 0.52nsec resolution
- ~2500pC/ch large dynamic range
- No dead time (w/o hardware trigger)
- Fast data transfer via Ethernet R/W

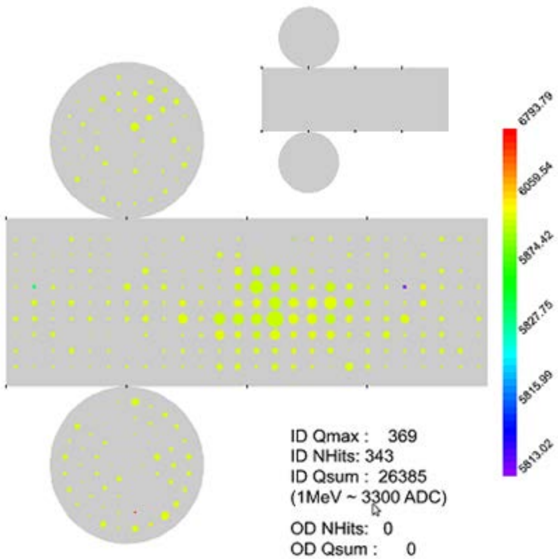


Data-Taking & Data Set

- Data taking began on Aug. 1, 2011 with both near and far detectors.
- Data-taking efficiency > 90%.
- Trigger rate at the threshold energy of 0.5~0.6 MeV : 80 Hz
- Data-taking period : 213 days
  Aug. 11, 2011 ~ Mar. 10, 2012

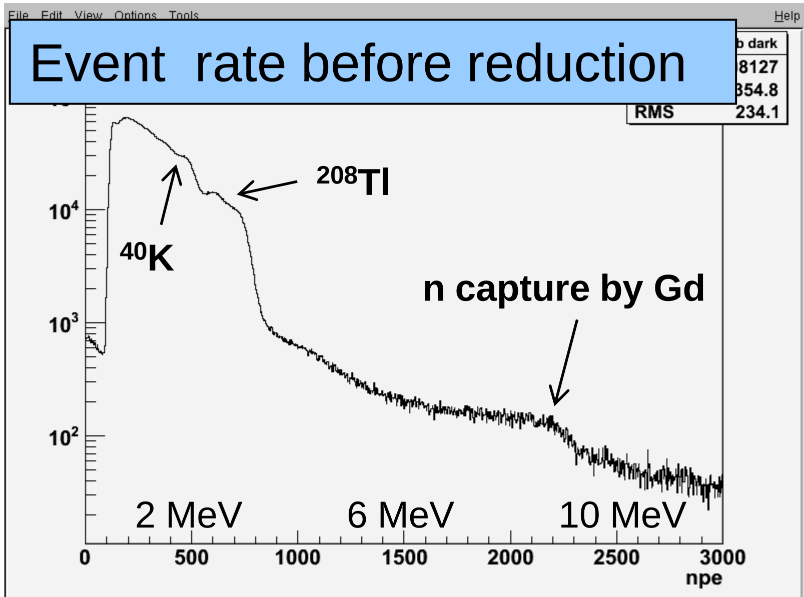
- Data-taking efficiency





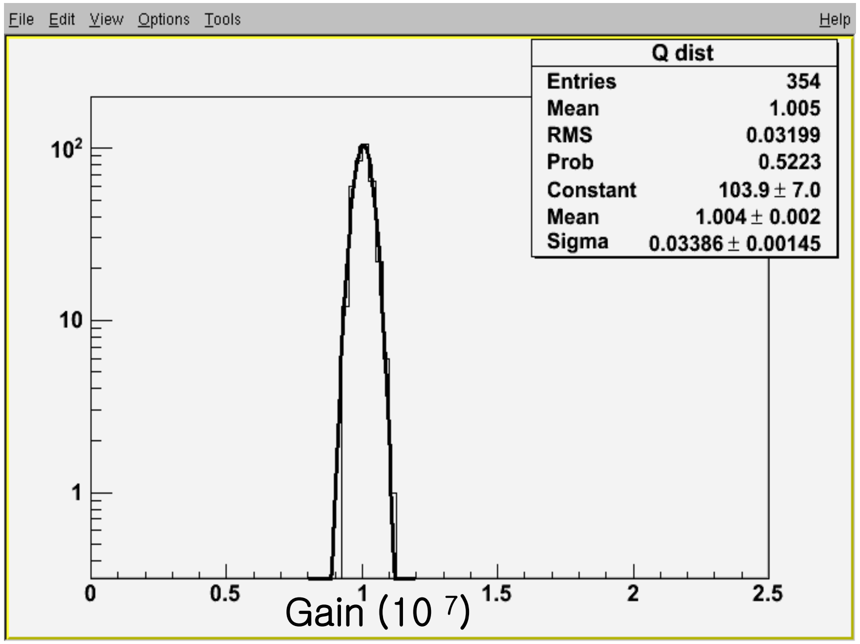
A candidate for a neutron capture by Gd

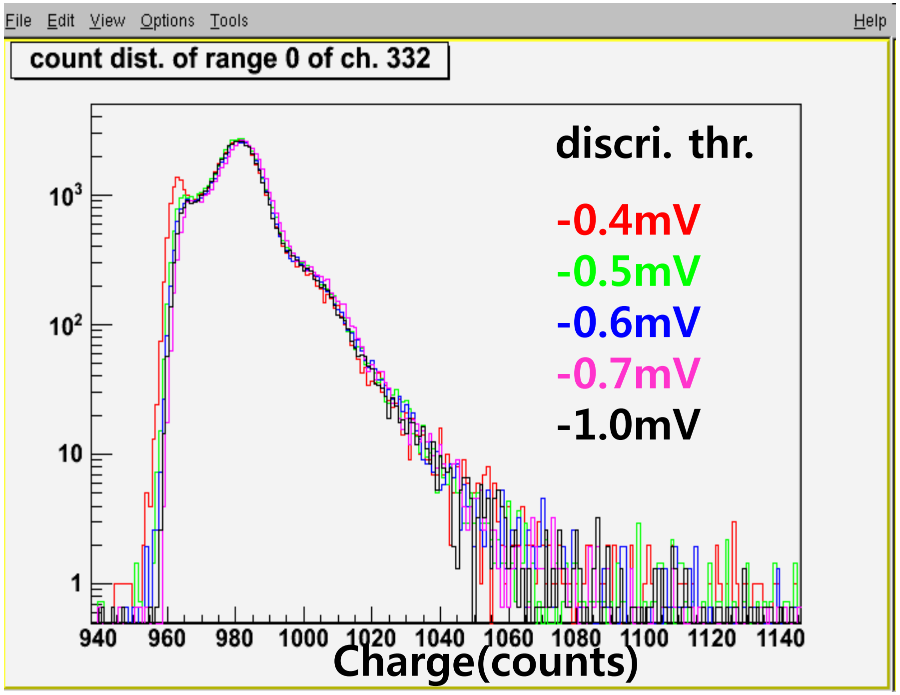
Event rate before reduction



PMT Threshold & Gain Matching

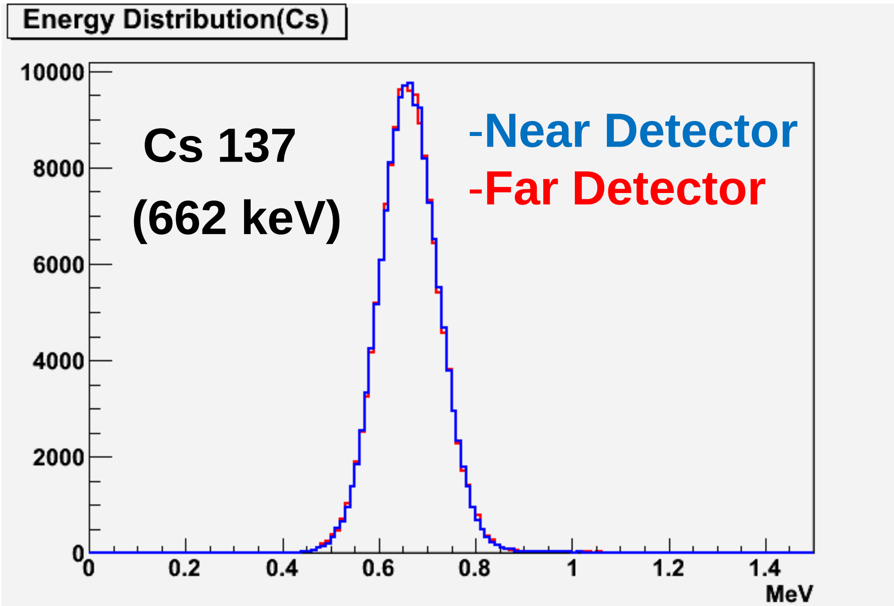
- PMT gain : set 1.0×10^7 using a Cs source at center
- Gain variation among PMTs : 3% for both detectors.

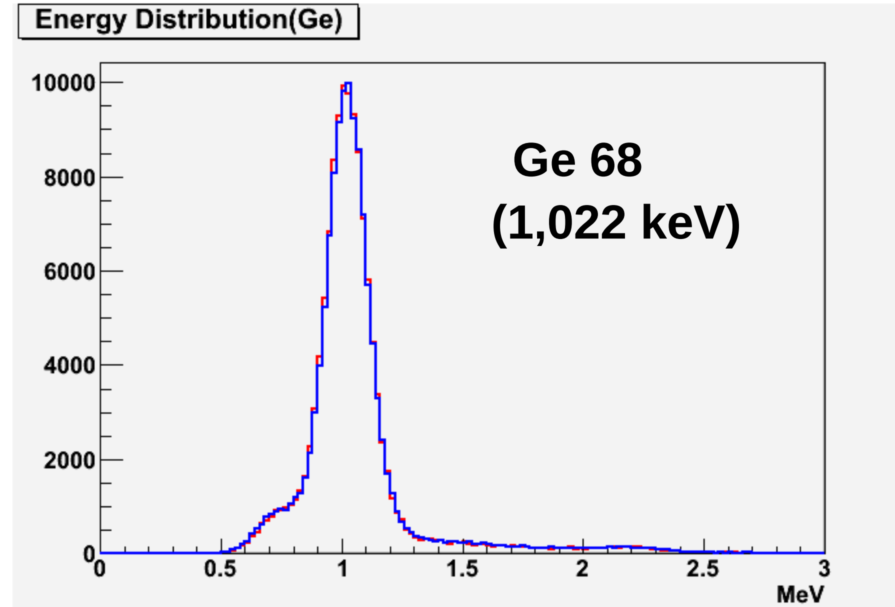


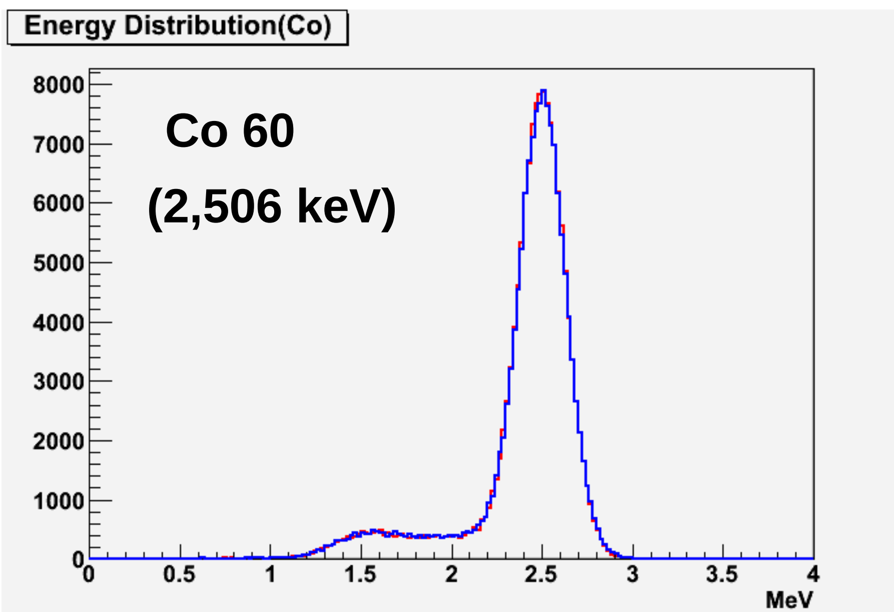


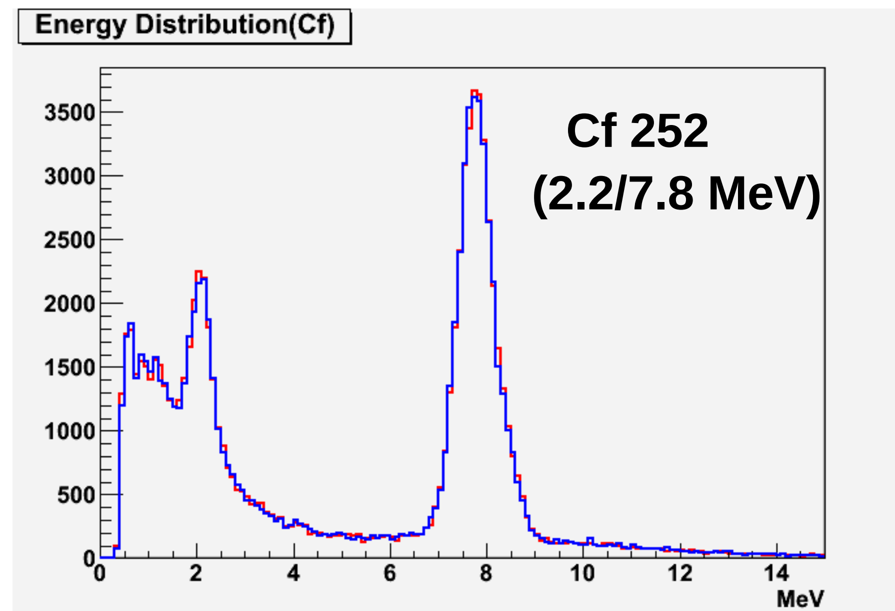
- PMT threshold : determined by a single photoelectron response using a Cs source at the center

Energy Calibration



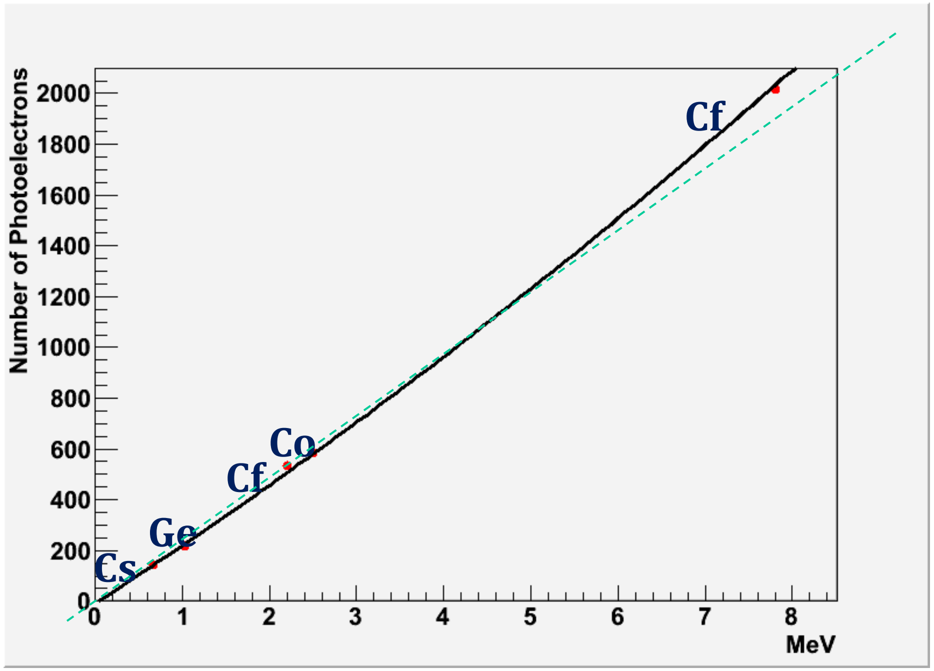




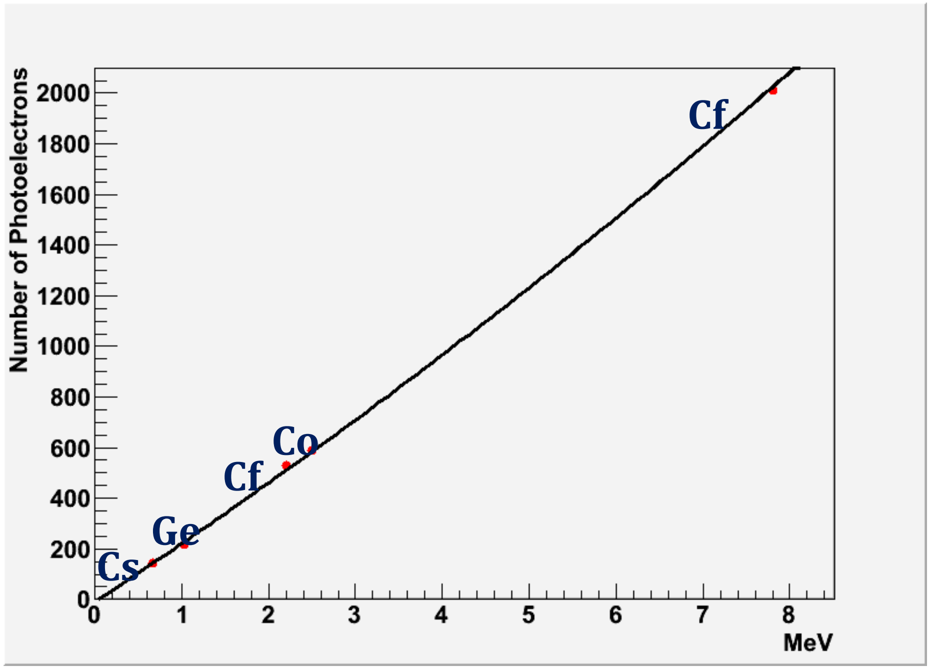


Energy Scale Calibration

Near Detector



Far Detector

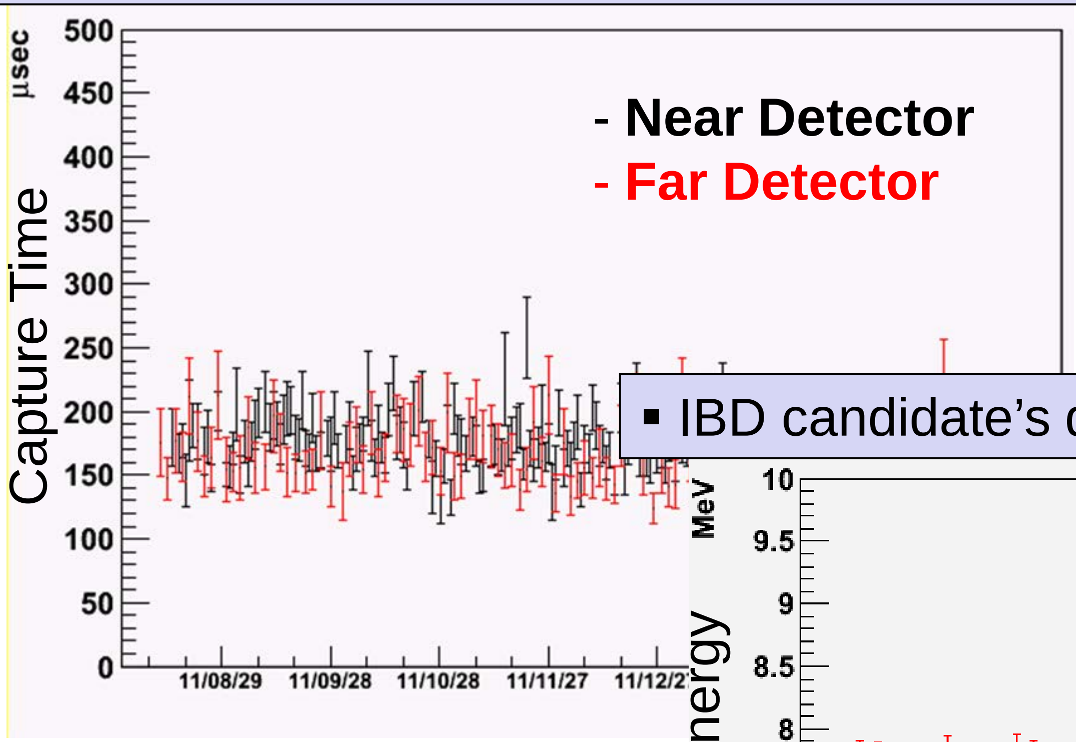


$$\delta E = \frac{5.9\%}{\sqrt{E(MeV)}} + 1.2\%$$

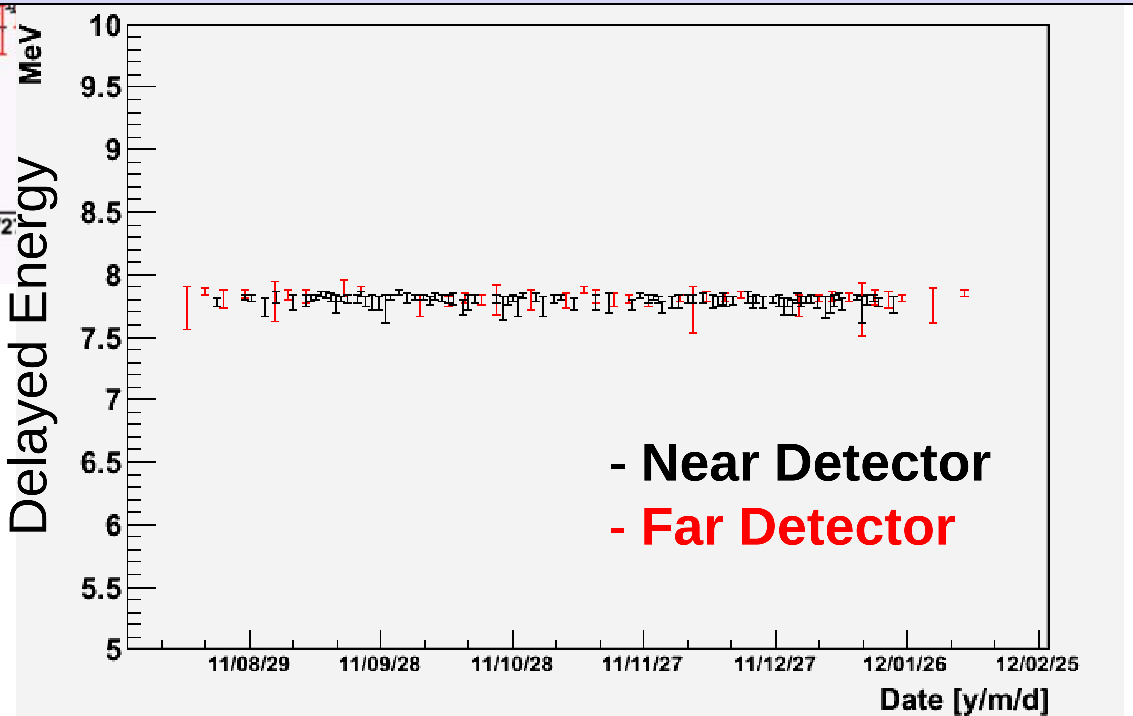
- ~ 250 pe/MeV (sources at center)
- Identical energy response (< 0.1%) of ND & FD
- Slight non-linearity observed

Detector Stability & Identity

- Cosmic muon induced neutron's capture by H



- IBD candidate's delayed signals (capture on Gd)

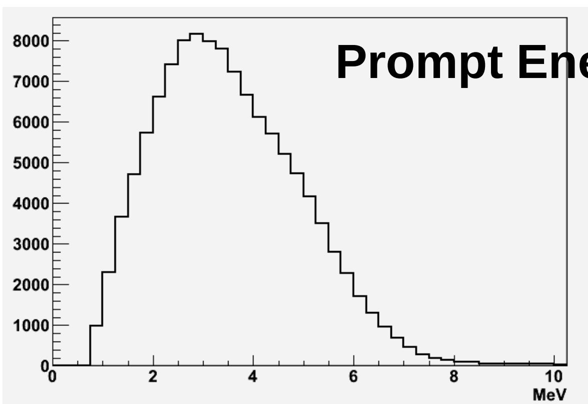


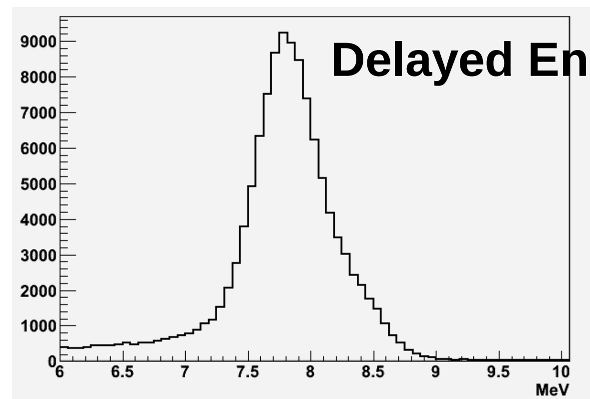
IBD Event Signature and Backgrounds

❑ IBD Event Signature

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

- Prompt signal (e^+) : 1 MeV 2γ's + e^+ kinetic energy (E = 1~10 MeV)
- Delayed signal (n) : 7.8 MeV γ's from neutron's capture by Gd
  ~28 μs (0.1% Gd) in LS





❑ Backgrounds

- Random coincidence between prompt and delayed signals (uncorrelated)
- $^{9}Li/^{8}He$ β-n followers produced by cosmic muon spallation
- Fast neutrons produced by muons, from surrounding rocks and inside detector (n scattering : prompt, n capture : delayed)

IBD Event Selection

- ❑ Reject flashers and external gamma rays : $Q_{max}/Q_{tot} < 0.03$
- ❑ Muon veto cuts : reject events after the following muons

  (1) 1 ms after an ID muon with E > 70 MeV, or with 20 < E < 70 MeV and OD NHIT > 50

  (2) 10 ms after an ID muon with E > 1.5 GeV
- ❑ Coincidence between prompt and delayed signals in 100 μs

  - E_{prompt} : 0.7 ~ 12.0 MeV, $E_{delayed}$: 6.0 ~ 12.0 MeV
  - coincidence : $2\ \mu s < \Delta t_{e+n} < 100\ \mu s$
- ❑ Multiplicity cut : reject pairs if there is a trigger in the preceding 100 ms window

Random Coincidence Backgrounds

❑ Calculation of accidental coincidence

$$N_{accidental} = N_{delayed} \times \left(1 - \exp^{[-R_{prompt}(Hz)\times\Delta T(s)]}\right) \pm \frac{N_{accidental}}{\sqrt{N_{delayed}}}$$

- ΔT = 100 ms time window
- Near detector :

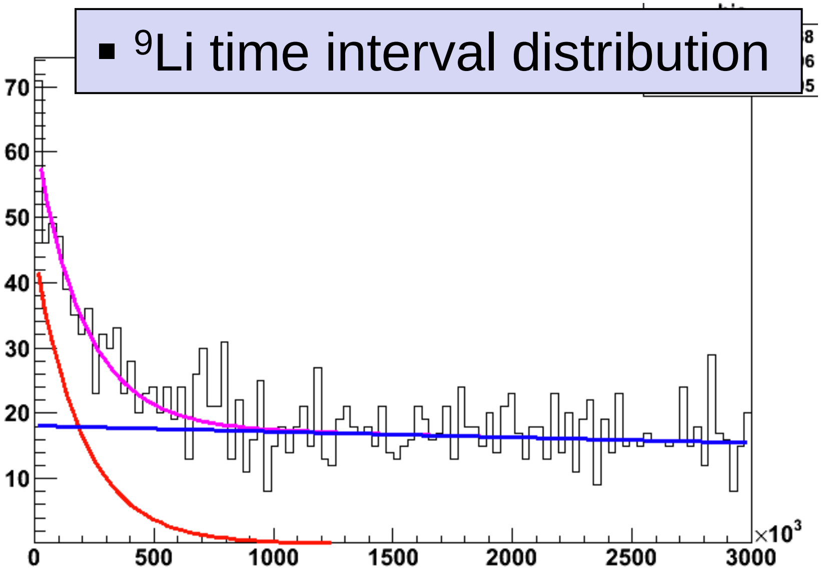
  R_{prompt} = 8.8 Hz, N_{delay} = 5100/day $\rightarrow$ $BG^{near}_{accidental} = 4.51 \pm 0.06 / day$
- Far detector :

  R_{prompt} = 10.7 Hz, N_{delay} = 674/day $\rightarrow$ $BG^{far}_{accidental} = 0.72 \pm 0.03 / day$

$^{9}Li/^{8}He$ β-n Backgrounds

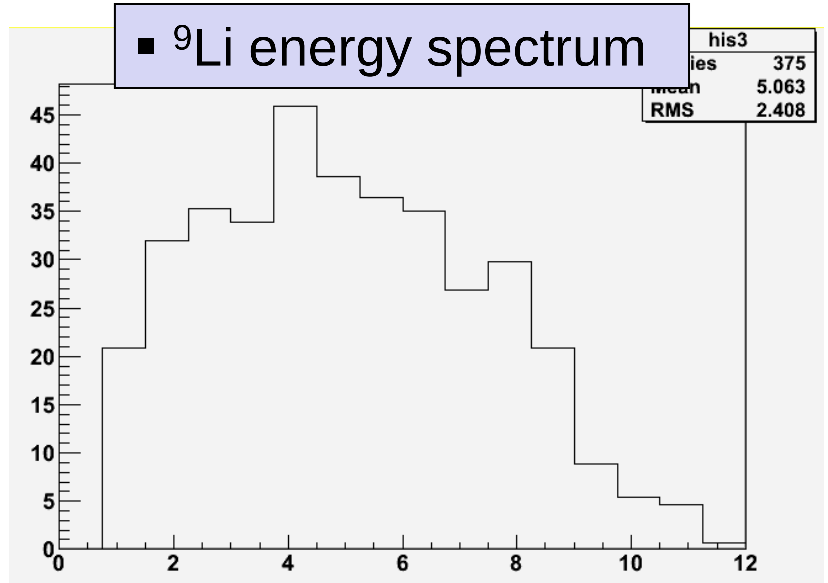
❑ Find prompt-delay pairs after muons, and obtain their time interval distribution with respect to the preceding muon.

▪ ^{9}Li time interval distribution



Time interval (ms)

▪ ^{9}Li energy spectrum



Energy (MeV)

▪ Near detector :

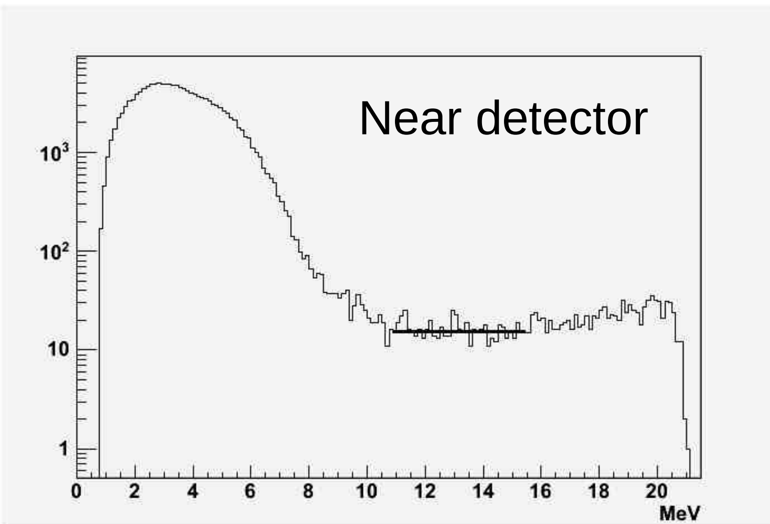
$$BG^{near}_{Li/He} = \pm \ / day$$

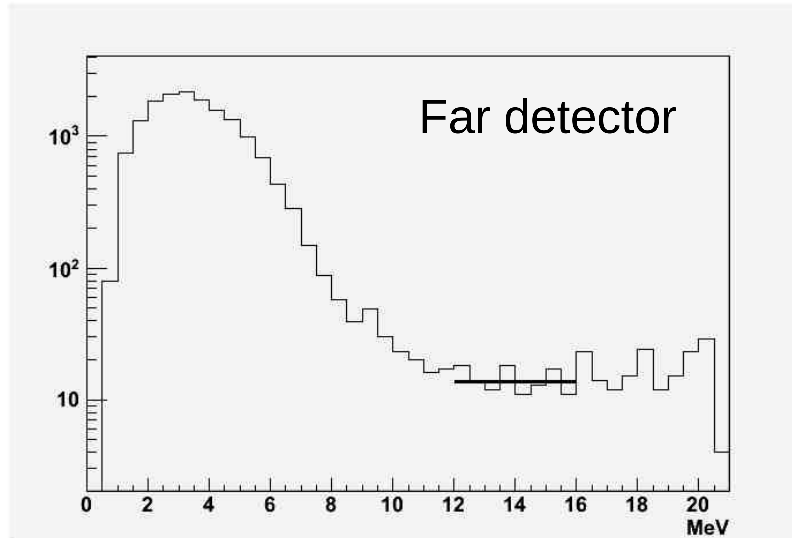
▪ Far detector :

$$BG^{far}_{Li/He} = \pm \ / day$$

Fast Neutron Backgrounds

❑ Obtain a flat spectrum of fast neutron's scattering with proton, above that of the prompt signal.

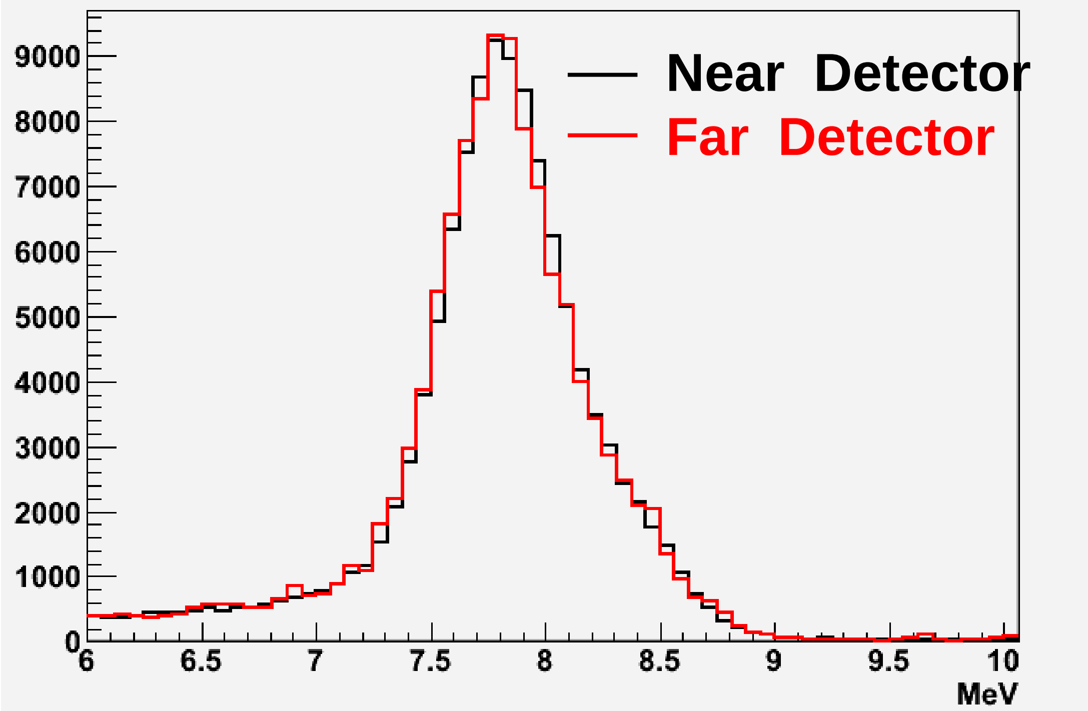




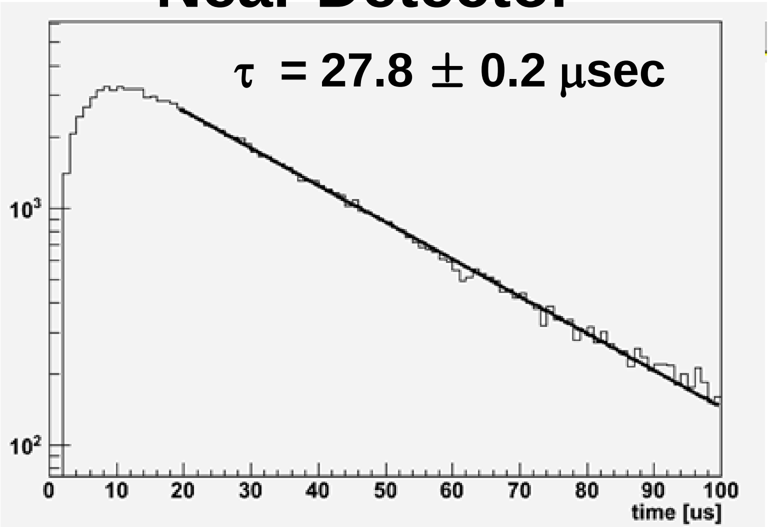
- Near detector : $BG^{near}_{neutron} = \quad \pm \quad / \, day$
- Far detector : $BG^{far}_{neutron} = \quad \pm \quad / \, day$

Spectra & Capture Time of Delayed Signals

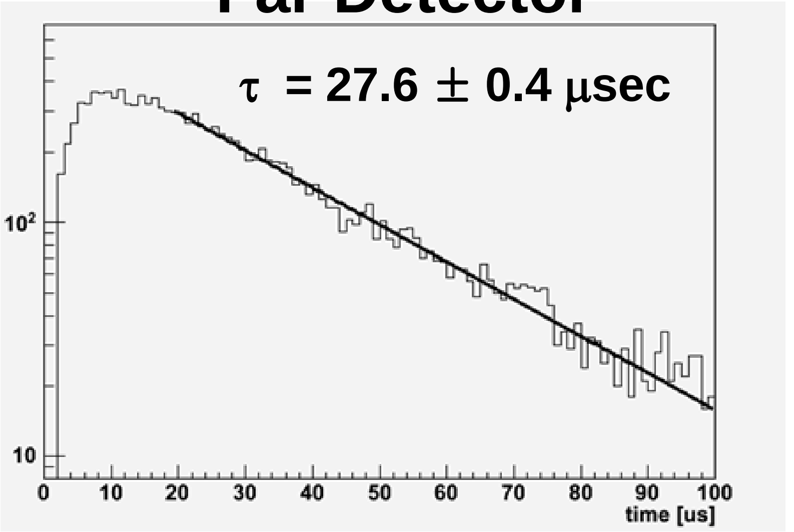
❑ Observed spectra of IBD delayed signals



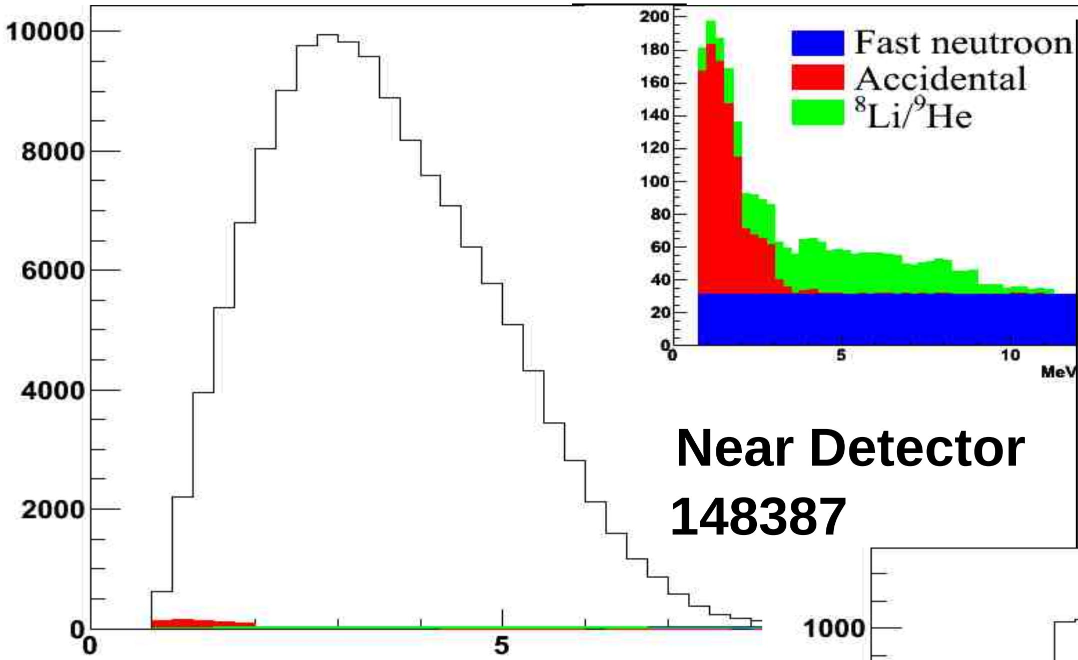
Near Detector

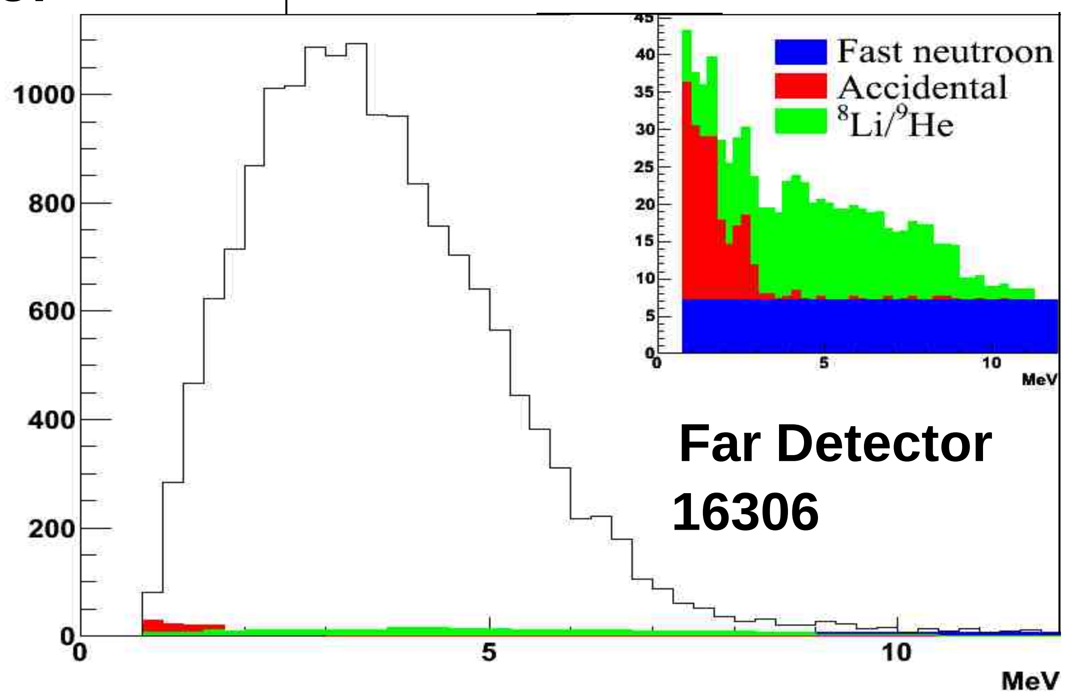


Far Detector



Measured Spectra of IBD Prompt Signal





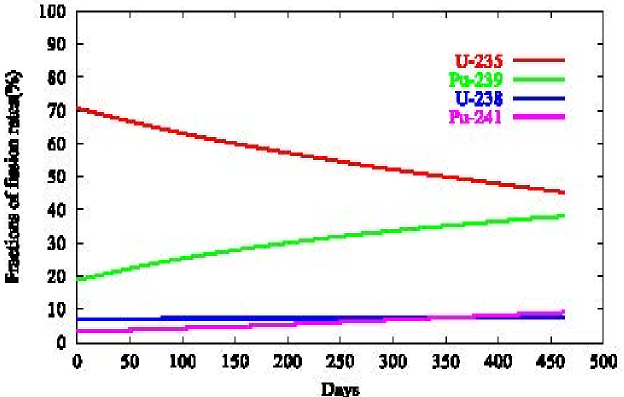
Expected Reactor Antineutrino Fluxes

- Reactor neutrino flux

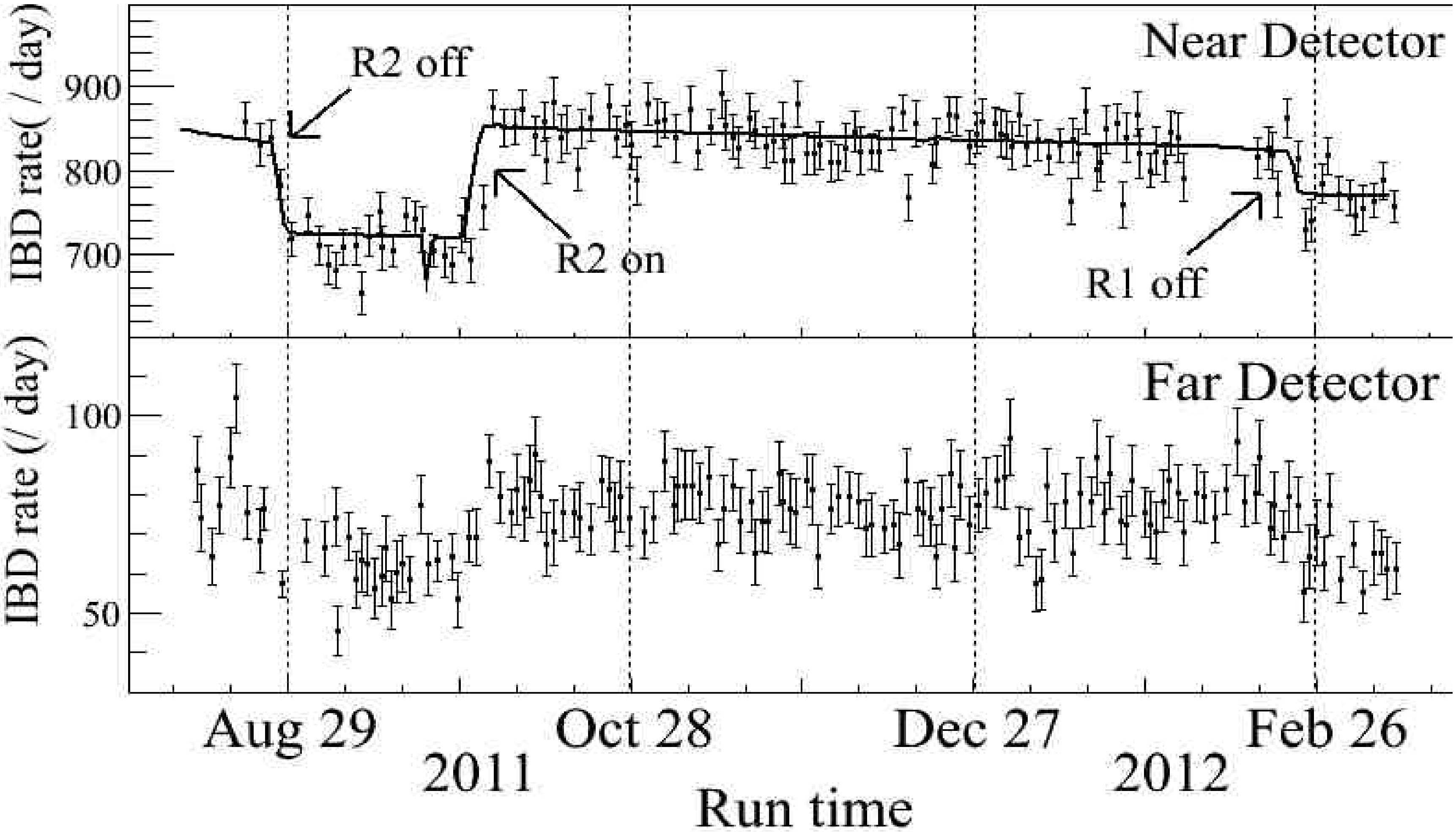
$$\Phi(E_\nu) = \frac{P_{th}}{\sum_i^{isotopes} f_i \cdot E_i} \sum_i^{isotopes} f_i \cdot \phi_i(E_\nu)$$

- P_{th} : Reactor thermal power provided by the YG nuclear power plant
- f_i : Fission fraction of each isotope determined by reactor core simulation of Westinghouse ANC
- $\phi_i(E_\nu)$: Neutrino spectrum of each fission isotope
  [* P. Huber, Phys. Rev. C84, 024617 (2011)
  T. Mueller *et al*., Phys. Rev. C83, 054615 (2011)]
- E_i : Energy released per fission
  [* V. Kopeikin *et al*., Phys. Atom. Nucl. 67, 1982 (2004)]

Isotopes	James	Kopeikin
^{235}U	201.7±0.6	201.92±0.46
^{238}U	205.0±0.9	205.52±0.96
^{239}Pu	210.0±0.9	209.99±0.60
^{241}Pu	212.4±1.0	213.60±0.65



Observed Daily Averaged IBD Rate



Reduction of Systematic Uncertainties

- **Detector related :**
  - **"Identical" near and far detectors**
  - **Careful calibration**
- **Reactor related :**
  - **Relative measurements with near and far detectors**

$$\frac{N^{\nu}_{far}}{N^{\nu}_{near}} = \left(\frac{L_{near}}{L_{far}}\right)^2 \left(\frac{N^{p}_{far}}{N^{p}_{near}}\right) \left(\frac{\epsilon_{far}}{\epsilon_{near}}\right) \left[\frac{P(\bar{\nu}_e \to \bar{\nu}_e; E, L_{far})}{P(\bar{\nu}_e \to \bar{\nu}_e; E, L_{near})}\right]$$

Neutrino flux	**$1/r^2$**	**Number of protons**	**Detection efficiency**	**Yield of $\sin^2(2\theta_{13})$**

Efficiency & Systematic Uncertainties

Prompt energy cut	
Flasher cut	
Gd capture fraction	
Delayed energy cut	
Time coincidence cut	
Spill-in	
Common	
Detector	
Muon veto loss ($\delta_{\mu-veto}$)	
Multiplicity cut loss (δ_{multi})	
Total	(6

Reactor		
	Uncorrelated	Correlated
Thermal power	0.5%	–
Fission fraction	0.7%	–
Fission reaction cross section	–	1.9%
Reference energy spectra	–	0.5%
Energy per fission	–	0.2%
Combined	0.9%	2.0%
Detection		
	Uncorrelated	Correlated
IBD cross section	–	0.2%
Target protons	0.1%	0.5%
Prompt energy cut	0.01%	0.1%
Flasher cut	0.01%	0.1%
Gd capture ratio	0.1%	0.7%
Delayed energy cut	0.05%	0.5%
Time coincidence cut	0.01%	0.5%
Spill-in	0.03%	1.0%
Muon veto cut	0.02%	0.1%
Multiplicity cut	0.02%	0.05%
Combined	0.2%	1.5%

Summary

- RENO started data taking with both near and far detectors from August 1, 2011..

- RENO will published their first result soon.
  - Rapid detector construction, data-taking & data-analysis
  - Satisfactory detector performance.
  - Detector calibration and comparison of ND & FD are performed.
  - IBD selection and background estimation completed.
  - Detection efficiency and systematic uncertainty understood.

- RENO started to get an oscillation signal from the late 2011, and has been under a sanity check and an accurate background estimation based on the reported schedules of the other experiments.

A bright future for the neutrino physics due to a large value of θ_{13} !!!