Simulation of the Neutron Detector Performance for LAMPS

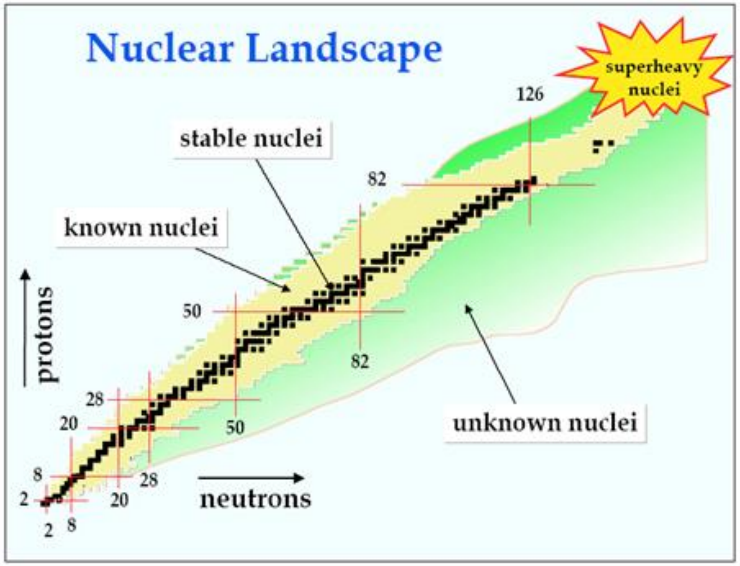
Korea Univ. Nuclear Physics Lab.
Beomgon Kim

Contents

Nucleosynthesis

- **Nucleosynthesis?**
  - Process that creates new atomic nuclei from pre-existing nucleons
- Light nuclei were produced by **Big Bang**.
  - H, He, Li, etc.
- **proton-proton chain reaction, CNO & HCNO cycle, s-process, p-process, etc.**
  - Nuclear fusion in stars
  - Can create elements up to Fe & Ni.
- **r-process, rp-process**
  - Nucleon capture in supernovae
  - Can create elements heavier than Fe.

Nucleosynthesis



- **Isospin?**
  - ➢ A quantum number related to the strong interaction
  - ➢ The proton & neutron are associated with different isospin projections $I_3 = +\frac{1}{2}$ & $I_3 = -\frac{1}{2}$
- Isospin asymmetric nuclear matter is far away from the stability line.
  - ➢ Neutron stars, etc.
- An understanding of the properties of isospin-rich nuclear matter is necessary for the advancement of both nuclear physics & astrophysics.

Equation of State & Symmetry Energy

- **Equation of State(EOS)**

$$E_A(\rho,\delta) = E(\rho,\delta=0) + E_S(\rho)\delta^2 + O(\delta^4)$$

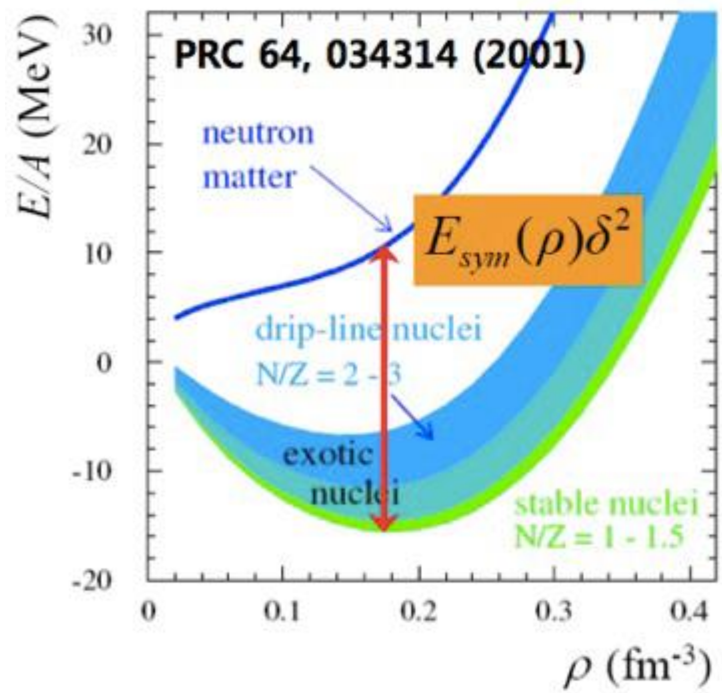
- E_A : **Energy per nucleon**

- **Symmetry Energy**

$$E_S = E_A(\rho,\delta=1) - E_A(\rho,\delta=0)$$

$$\rho = \rho_n + \rho_p$$
$$\delta = (\rho_n - \rho_p)/\rho$$

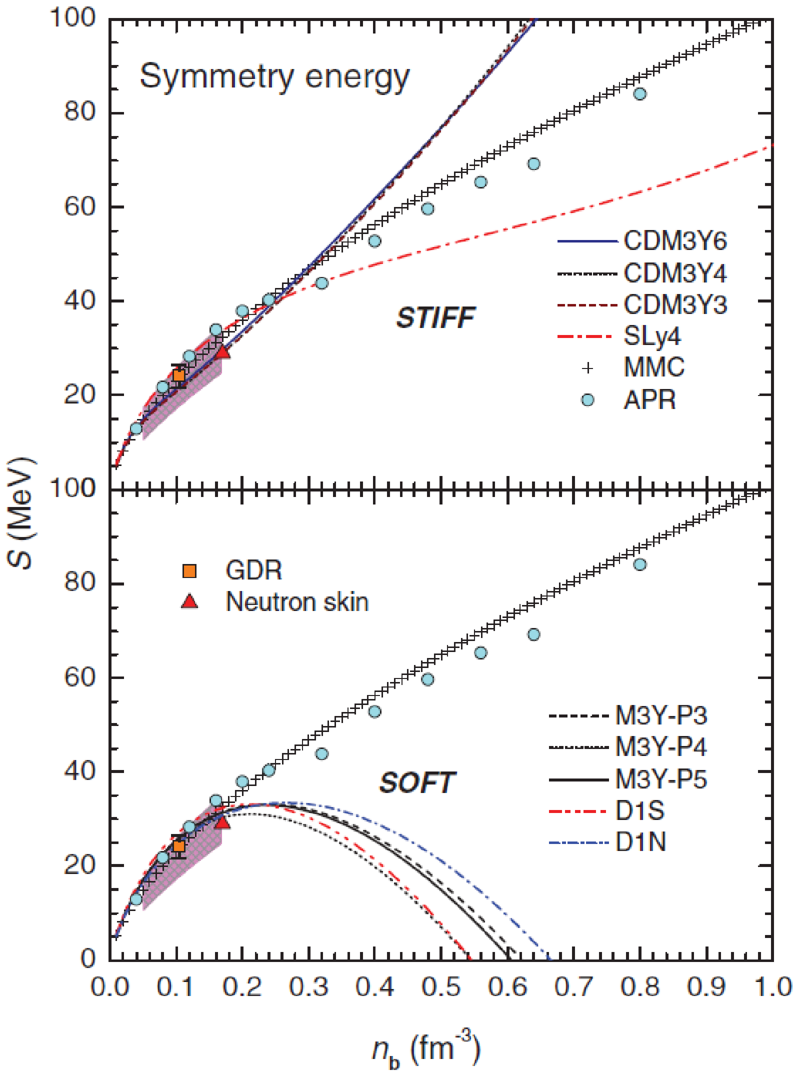
ρ_n : **Neutron density**
ρ_p : **Proton density**
ρ_0 : **saturation density**



CDR, FAIR (2001)

Equation of State & Symmetry Energy

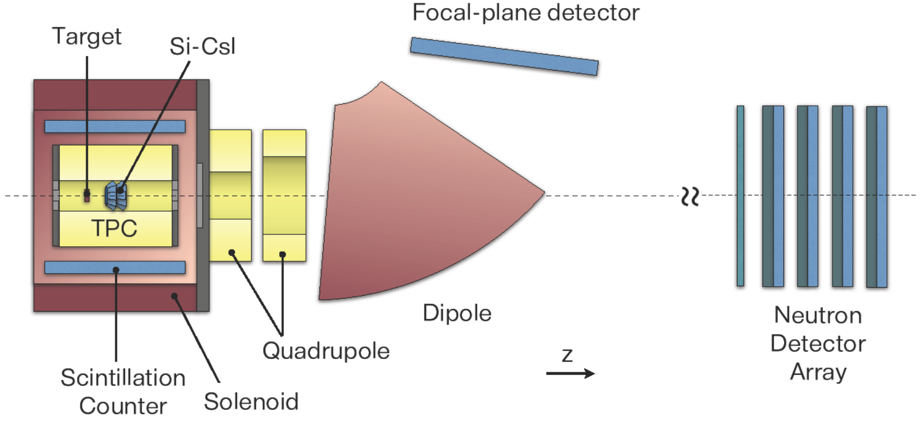
- **Different behaviors at high ρ**
  - **Stiff? or soft?**

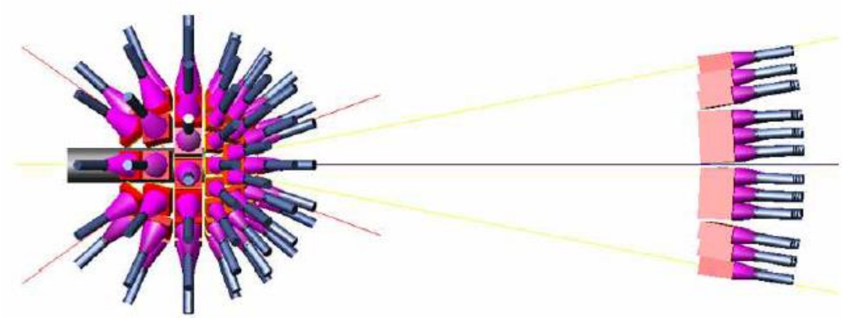


RAON

- **"RAON" – Korea Rare Isotope Accelerator at RISP**
  - ➢ So far, Korea have performed experiments using foreign accelerator facilities.
  - ➢ We expect independent research of basic science.
  - ➢ Many studies related with nuclear, atomic, molecular, material, and medical science can be conducted.

LAMPS





- **LAMPS(Large Acceptance Multi-Purpose Spectrometer)**
  - Primary purpose : Nuclear symmetry energy
  - Also useful for nuclear structure & nuclear astrophysics.

Neutron Detector

❖ Why We Detect Neutrons?

- Neutron's yields & energy spectra are strongly related to density dependent behavior of EOS & N/Z ratio of nuclear system.
  - **Neutron detection plays important role in symmetry energy research.**

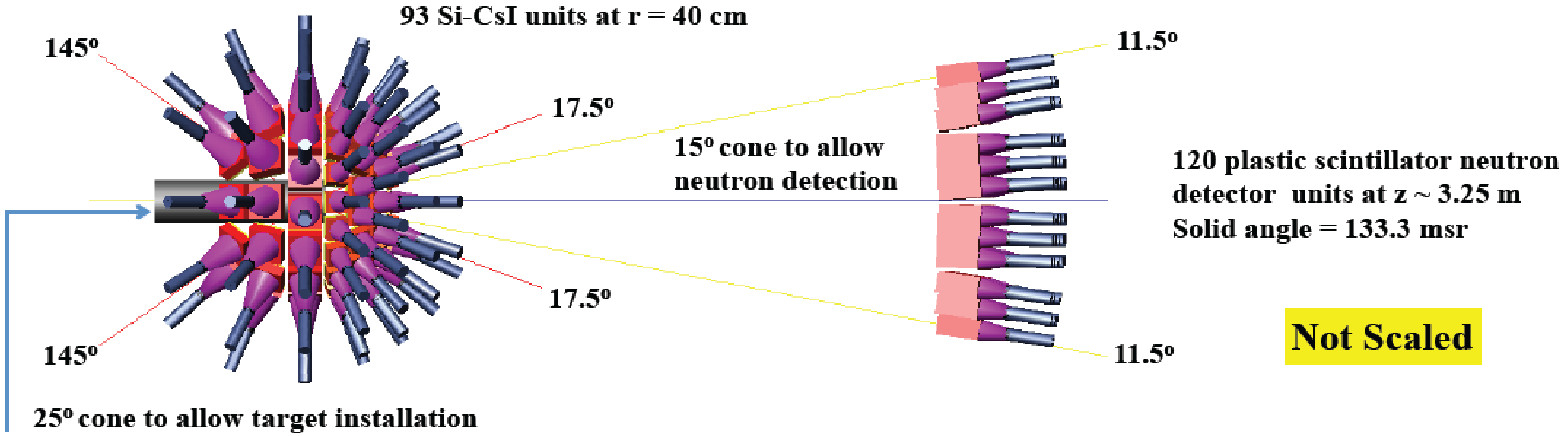
❖ How Can We Detect Neutrons?

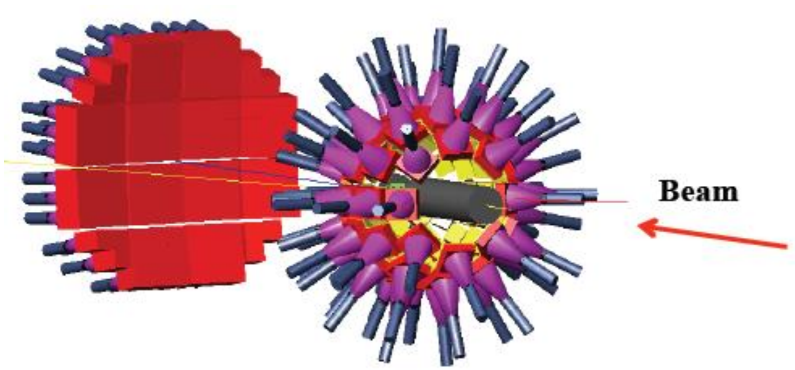
- **Collision with protons**
  - n-p scattering
  - n-^{12}C scattering
- **Neutron capture**
  - $n + p \rightarrow d + \gamma$
  - $n + {}^{12}C \rightarrow {}^{13}C + \gamma$

◆ Should cover from a few tens to a few hundreds MeV.

Neutron Detector

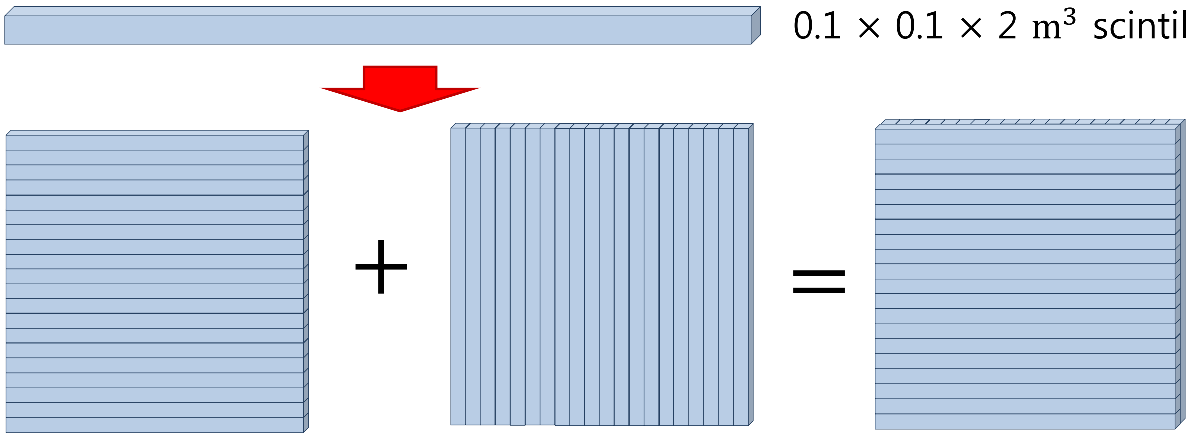
❖ Low-energy Neutron Detector





- $E_{beam} < 18.5A$ MeV
- Designed for GDR & PDR experiments

Neutron Detector



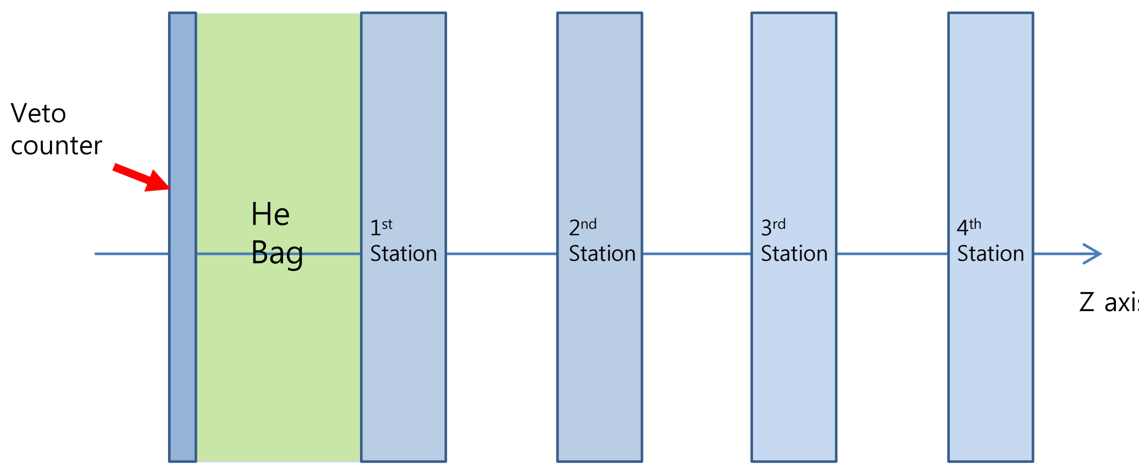
$0.1 \times 0.1 \times 2\ \mathrm{m}^3$ scintillator for 1 module

× 20 : Horizontal layer

× 20 : Vertical layer

× 40 : 1 Station

- 4 stations (8 layers)
- 40 cm gap between stations
- 20 module for 1 layer
- Veto counter & Helium bag in front of neutron detector



Motivation

❖ **Signal Generation**

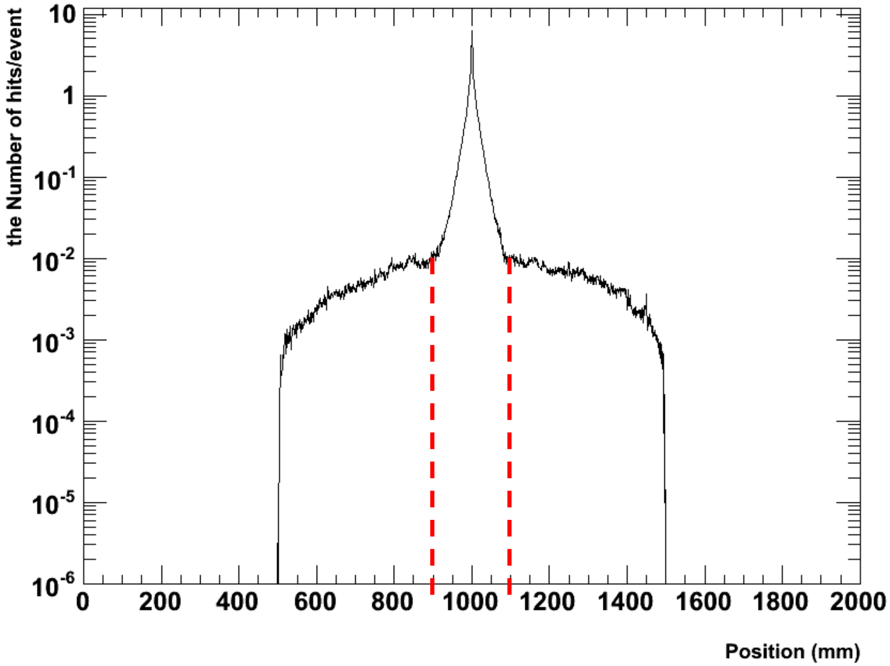
◆ **Why we should simulate the "signal"?**

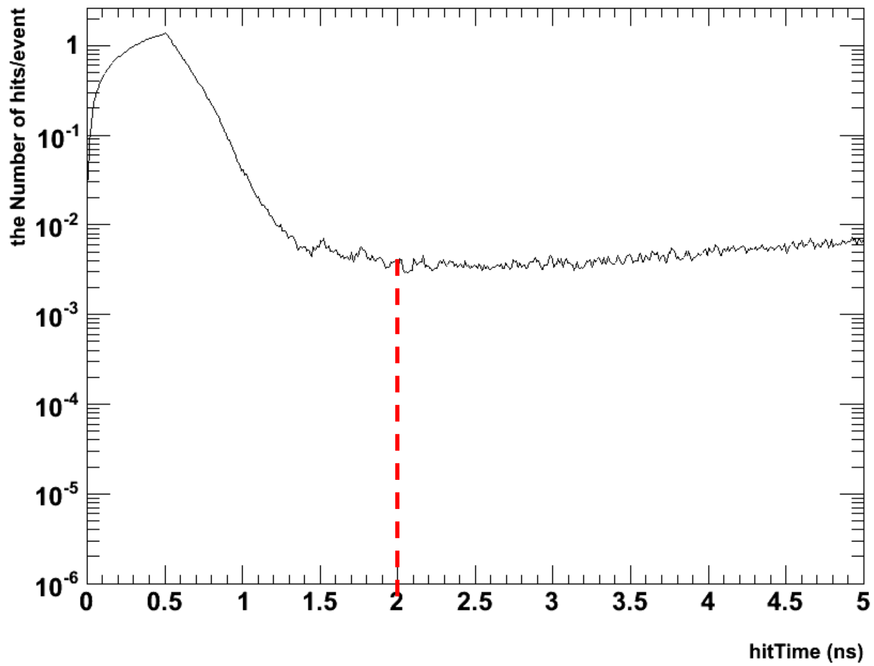
- Neutrons do not interact with electromagnetic force.
- In real experiment, neutrons can be detected only by the indirect methods which are collect information using electronics about photons that are generated by the collisions between the neutrons and nuclei inside detectors.
- The purpose of the Simulation : Using algorithm which is as same as possible with real experiment, design the most suitable setting of the experiment.
- If the algorithm of the electronics is included in simulation, the simulation will be more realistic.
- Therefore, I have tried to reproduce the pulse signal in the simulation.

Grouping of Hits

❖ Average Position & time distribution of the hits which are made when 300 MeV neutrons go through the center of the $0.1 \times 0.1 \times 2\ \mathrm{m}^3$ bar-type scintillator module

➢ To get condition of classifying Hits into "groups"





- 98 % of hits is exist within (neutron incident position) $\pm$ 100 mm.
- 98 % of hits is exist within (neutron incident time)+2 ns.

Grouping of Hits

- Within the gate time(= 150 ns), collect every hits which are made in the bar scintillator.

- For two or more signals inside a bar scintillator,
  - If the distance between signals is larger than **100 mm**,
  - Or if the difference of generation time is larger than **2 ns**,

  we will be able to distinguish them.
  Using these results, hits are classified into few groups.

- Apply Birks formula to the hits inside each group.

Birks Formula

❖ Birks Formula

$$\frac{dL}{dz} = \frac{SdE/dz}{1 + kBdE/dz + C(dE/dz)^2}$$

- Empirical formula for the **light yield per path length (dL/dz)** as a function of the **energy loss per path length (dE/dz)**.
- L : Scintillation response. ($\boldsymbol{L = E_{corr}}$)
- E : Specific energy lose at a depth z
- z : Path length
- S : Electronics response per specific energy loss at the non-quenching limit. Mostly, $\boldsymbol{S = 1}$
- kB : 1^{st} order parameter. From experiment, $\boldsymbol{kB = 0.977 \times 10^{-2}\ \mathrm{g\,cm^{-2}\,MeV^{-1}}}$
- C : 2^{nd} order parameter

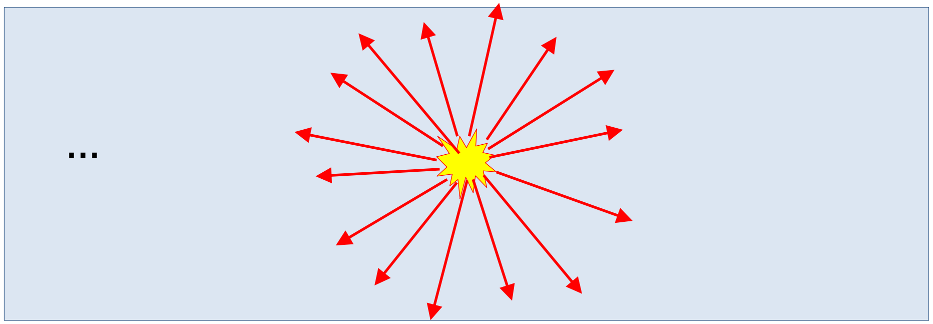
  It is expected strength is about two-order smaller than the one for kB.

  It becomes significant as the specific energy loss exceeds $50\ \mathrm{MeV\,g^{-1}\,cm^{2}}$.

  Therefore, it does not have to be considered for neutron event.

Photon Generation

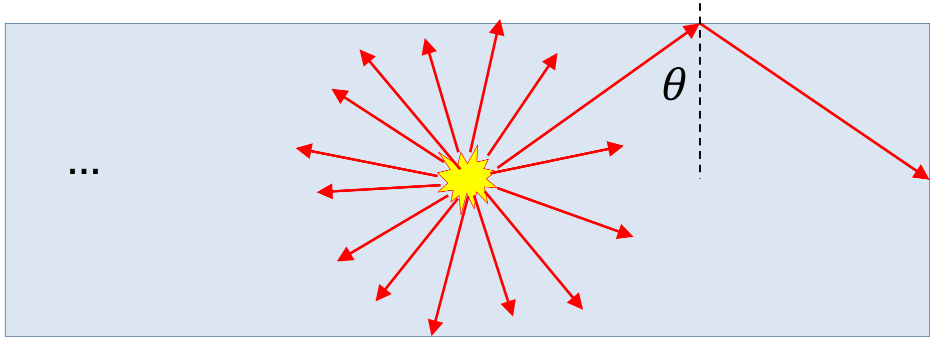
$$v_0 = \frac{c}{1.58} \approx 189.742 \text{ mm/ns}$$



- Inside BC-408, 7500 photons are generated per 1 MeV light energy.
  - ❖ Reference : A Comprehensive Technique for Determining the Intrinsic Light Yield of Scintillators, Joanna S. Salacka & Minesh K. Bacrania, IEEE Transactions on Nuclear Science, April 2010
- But, it takes too much time to consider 7500 photons per 1 MeV.
- Therefore, I considered only 750 photons per 1 MeV.
- Assume each photon has energy 1/750 MeV.
- Photons are randomly spread from a energy deposit position with spherical symmetry.

Propagation & Attenuation

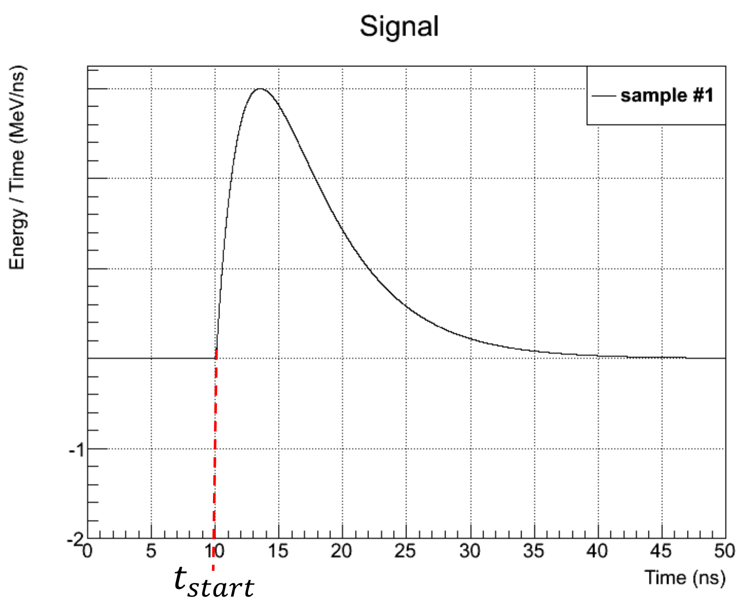
$$v_0 = \frac{c}{1.58} \approx 189.742 \text{ mm/ns} \qquad v = v_0 \sin\theta \sin\varphi$$



- Refractive index of BC-408 = 1.58
- Velocity inside BC-408 ≈ 189.742 mm/ns
- Critical angle θ_C = Arcsine (1/1.58) ≈ 39.27 ˚
- Velocity component which is parallel with bar scintillator is $v = v_0 \sin\theta \sin\varphi$ in spherical coordinates.
- Only if both θ and φ are larger than θ_C, photon will reach to the PMT.
- As the photon moves through scintillator, it loses its energy.
  - ➢ BC-408 bulk attenuation length = 3800 mm

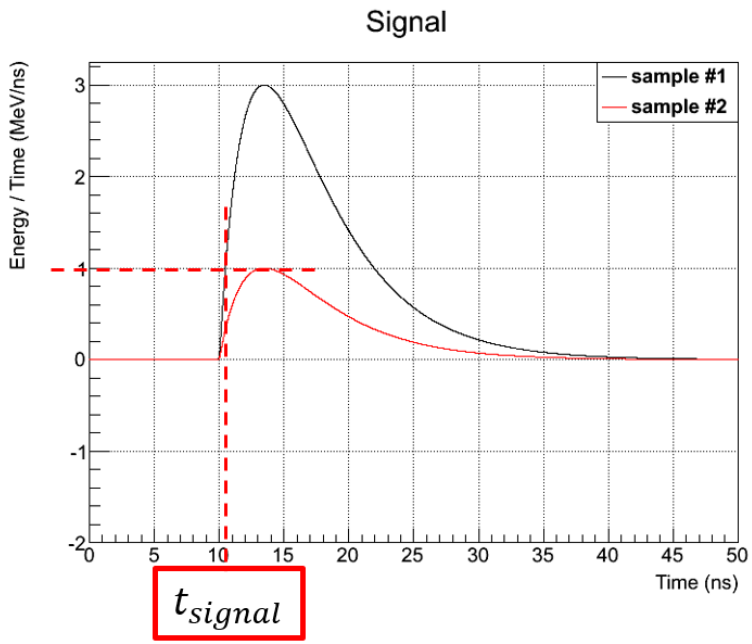
$$E_{PMT} = E_{photon} \exp[-\frac{l}{3800}]$$

Signal Generation



- Each photon makes small pulse right after arriving at the end of the scintillator.
  - ➢ Start time of small pulse : arrival time of photon
  - ➢ Area of small pulse : photon energy when it reaches to the end of the scintillator.
- These small pulses merge to form one large pulse.

Electron Equivalent Threshold & Signal HitTime



❖ **Electron Equivalent Threshold**

- ➢ Nonlinearity of detector response & neutron energy loss + Attenuation
- ➢ Measured deposit energy is smaller than real deposit energy.

- Generate electron equivalent threshold signal which has same start time with the signal.
- **(Time when the height of signal becomes same with max. height of the EET signal)**

= (Signal hitTime t_{signal} in the simulation)

≈ (Signal hitTime in real experiment)

Electron Equivalent Threshold & Signal HitTime

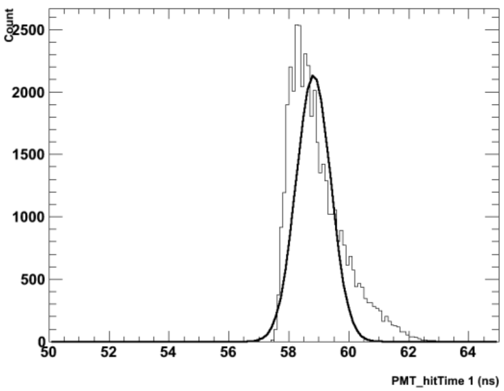
- This is an attempt to reproduce the **voltage threshold discriminator(VTD)** algorithm.

- Even if **the positions** where neutrons pass through the scintillator **are same**, depending on neutron deposit energy, propagation of photons & attenuation of their energies, **signal hitTime always can be different.**

- Only if **both of the signals** at each end of the scintillator **have larger value** than max. height of the EET signal, **the information is saved.**
  - Only if **both of the signal hitTimes are exist**, average value of the two signal hitTime**("true" signal hitTime)** $= \mathbf{0.5} \times (\boldsymbol{t_{signal\,1}} + \boldsymbol{t_{signal\,2}})$ is calculated and saved.

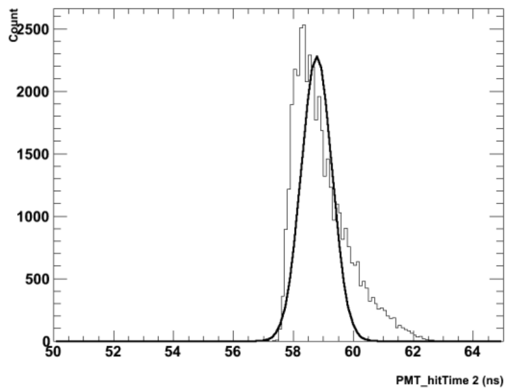
Result

- 300 MeV neutrons were fired to the center of 10 m away from $0.1 \times 0.1 \times 2\ \mathrm{m}^3$ bar-type scintillator module
  - Electro equivalent threshold = 2 MeV
  - 40000 events



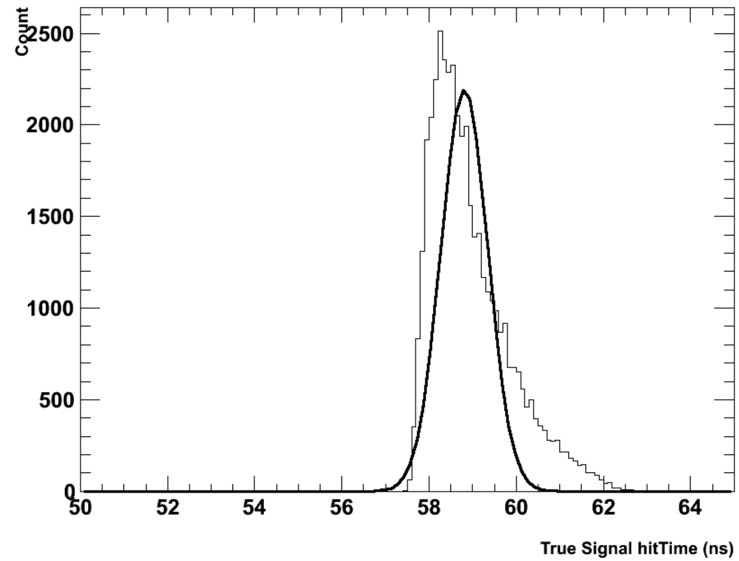
$m_{t1} = 58.817$ ns
$\sigma_{t1} = 0.566$ ns

$t_{signal1}$



$m_{t2} = 58.774$ ns
$\sigma_{t2} = 0.510$ ns

$t_{signal2}$

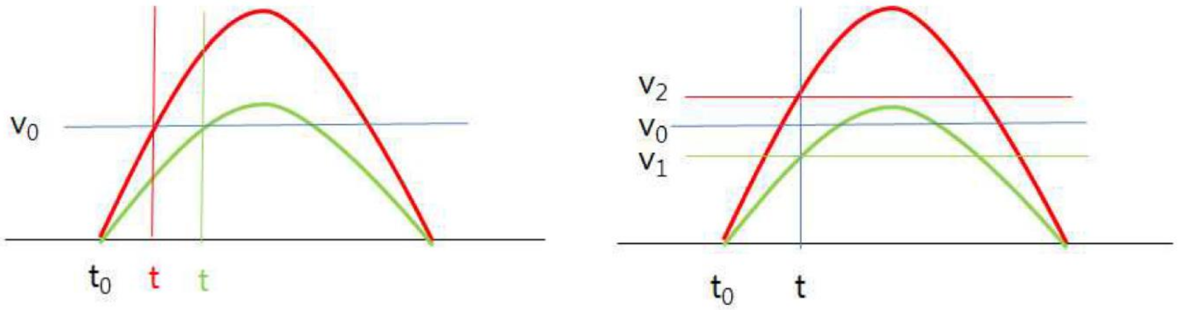


$m_{true} = 58.806$ ns
$\sigma_{true} = 0.524$ ns

$$t_{true} = 0.5 \times (t_{signal1} + t_{signal2})$$

Next Step

❖ **Constant Fraction Discriminator(CFD)**

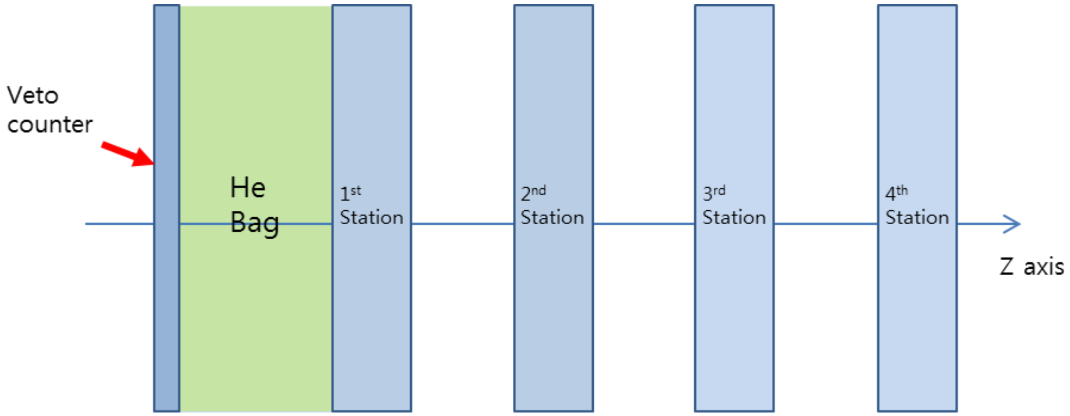


- VTD : If a pulse is larger than threshold voltage, it is considered the signal.
  - If the pulse has relatively large energy, the signal hitTime is shorter.
- CFD : Threshold voltage + time condition

  If a pulse is larger than threshold voltage **within a certain time**, it is considered the signal.
  - CFD has more advantageous than VTD.

Next Step

❖ **Full LAMPS High Energy Neutron Detector System Simulation**

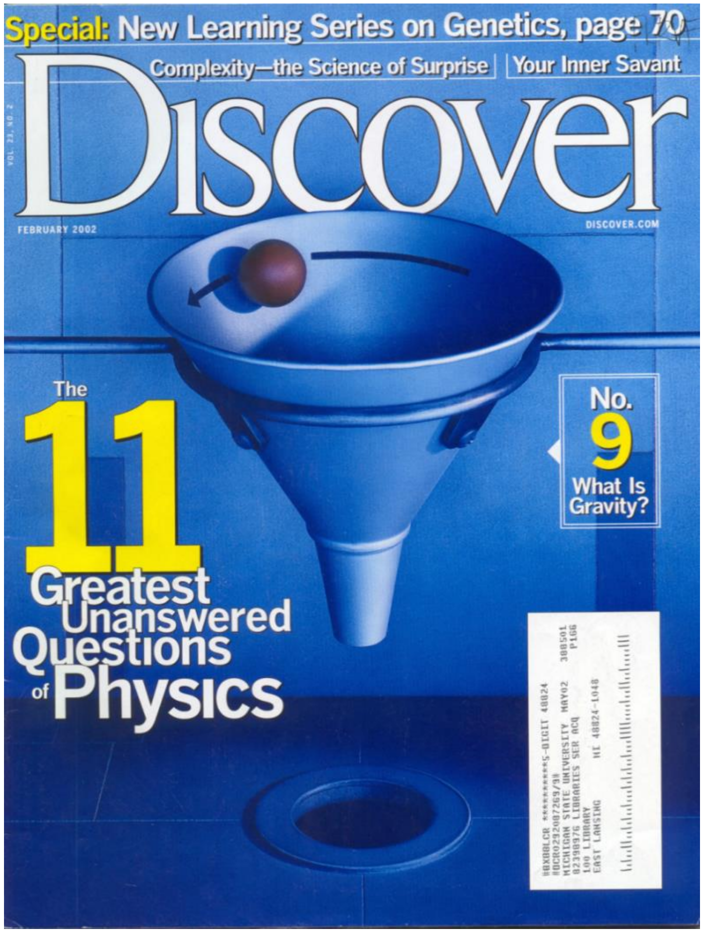


- The simulation should be applied to the full high energy neutron detector system.
- When two or more neutrons pass through the detector system, velocity condition is critical to classify the signals.
- Velocity condition is calculated by using the distance & **signal hitTime**

Summary

- RAON will be 1st rare isotope accelerator in Korea.
- LAMPS will play important role in research of symmetry energy
- The purpose of simulation is, using an algorithm as similar as possible with real experiment, design a most suitable setting of experiment.
- Therefore, if algorithm of the electronics can be contained in the simulation, more realistic simulation can be possible.
- For this reason, tried to reproduce pulse signal in simulation.
- Simulation result of the case which neutrons were fired to the center of 10 m away $0.1 \times 0.1 \times 2\ \mathrm{m}^3$ bar-type scintillator module
  - 300 MeV neutrons : time resolution $\approx 0{,}524\ \mathrm{ns} = 524\ \mathrm{ps}$
- CFD method simulation also should be done.
- The pulse signal simulation should be applied to the full neutron detector system simulation

Nucleosynthesis



Question #3 :

How were the heavy elements from iron to uranium made?

The Fermi Gas Model

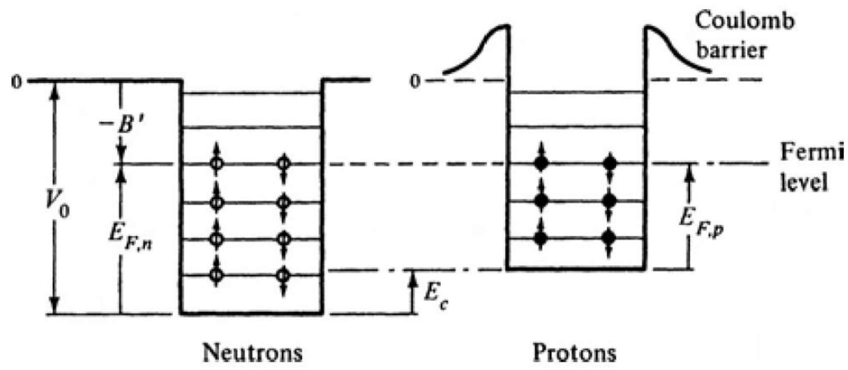


Figure 16.4: Nuclear square wells for neutrons and protons. The well parameters are adjusted to give the observed binding energy B'.

- Nucleon binding energies can be understood in terms of the Fermi gas model.
- The protons & neutrons that in the nucleus are considered as two independent systems of nucleons.
- They obey Fermi-Dirac statistics.
  - They comply with the Pauli Principle.
  - Nuclear force is short ranged. Therefore, they can move freely in a mean potential inside the entire nuclear volume.

Equation of State & Symmetry Energy

- **Expansion of Symmetry Energy in terms of ρ**

$$E_S(\rho) = E_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho}\right) + \frac{K}{18}\left(\frac{\rho-\rho_0}{\rho}\right)^2$$

- **Slope Parameter L**

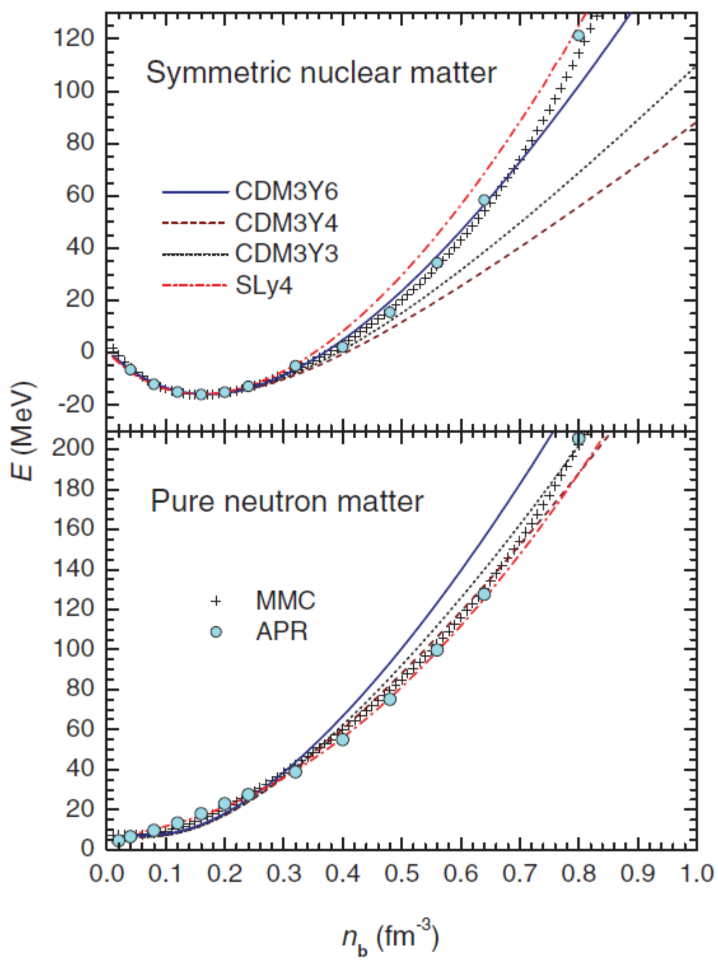
$$L = 3\rho_0 \frac{d}{d\rho}\left(\frac{E}{A}\right)$$

- **Incompressibility(or Curveture) K**

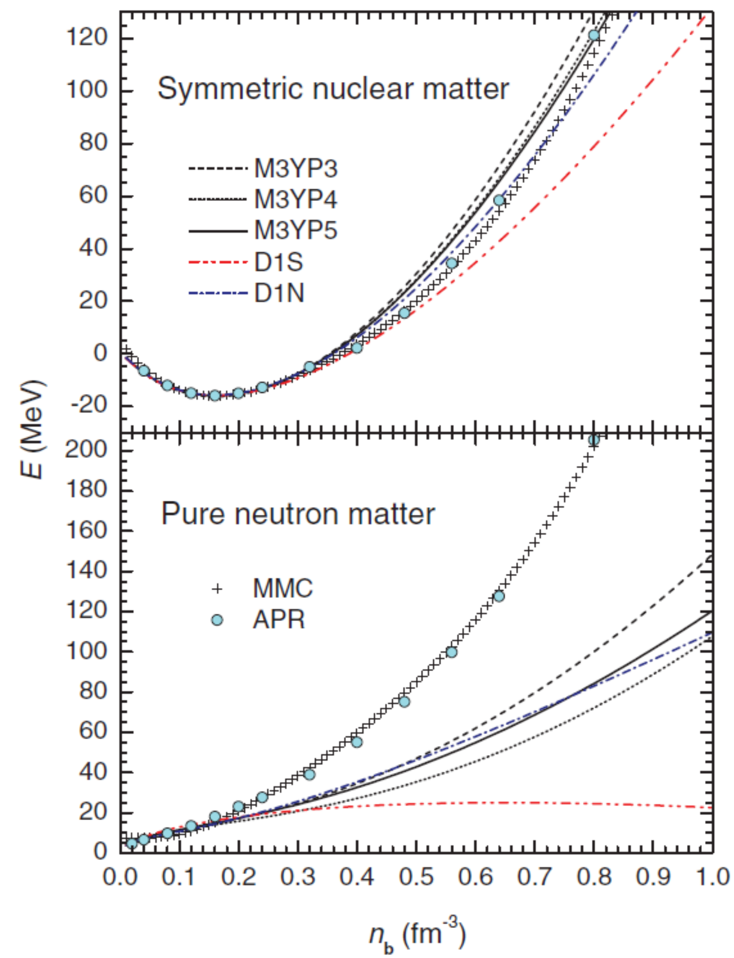
$$K = 9\rho_0^2 \frac{d^2}{d\rho^2}\left(\frac{E}{A}\right)$$

Equation of State & Symmetry Energy

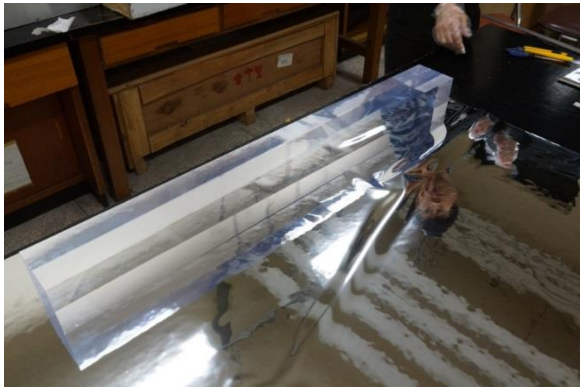
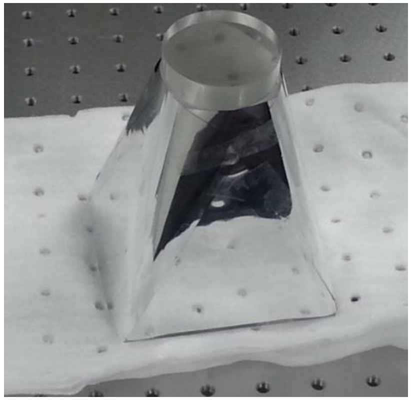
< Stiff Model >



< Soft Model >

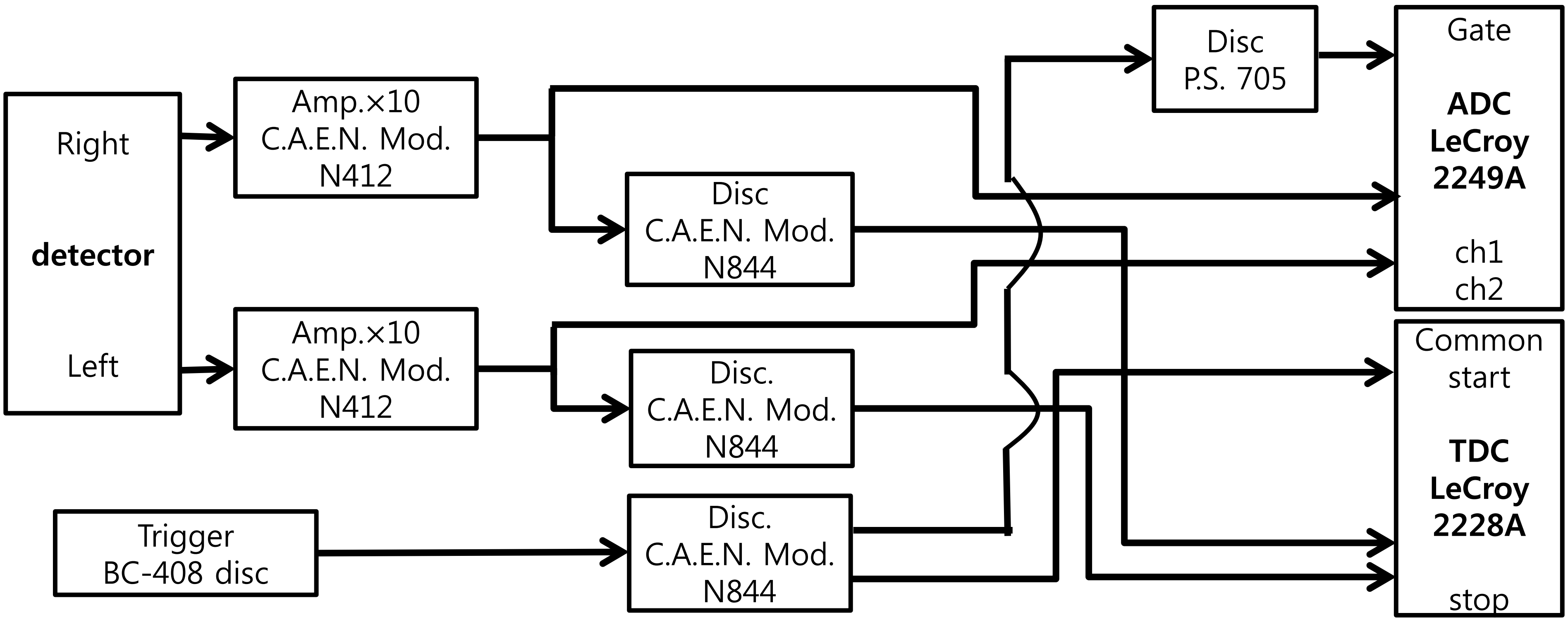


Components

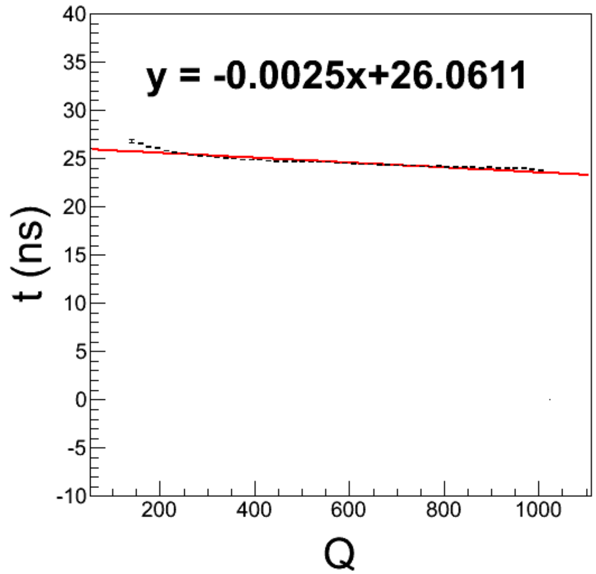
Scintillator	Light guide	PMT
		
Bicron BC-408 Decay constant: 2.1 ns Bulk light attenuation length: 380 cm Refractive index: 1.58 H:C ratio: 1.104 Density: 1.032 g/cm^3 Softening point: 70 ℃	**Arcrylic** Density: 1.18 g/cm^3 Refractive index: 1.4914	**H2431-50** Wavelength short: 300 nm Wavelength long: 650 nm Transit time: 16 ns Gain: 2.5×10^6

Circuit

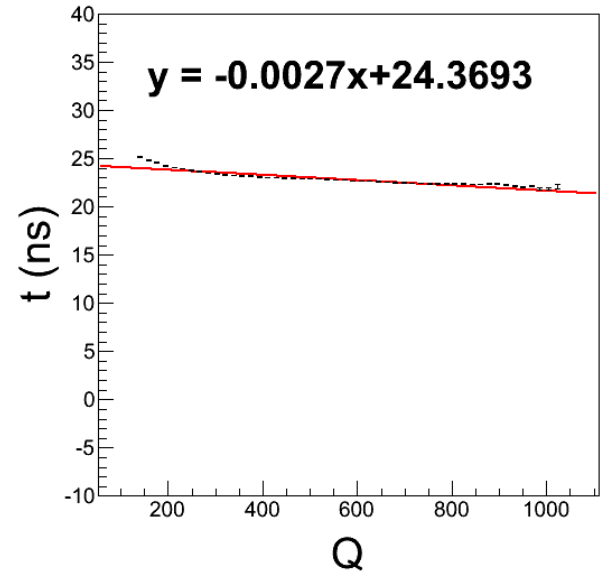
- Threshold : 180 mV
- Trigger threshold : 40 mV



1) Time Walk Correction



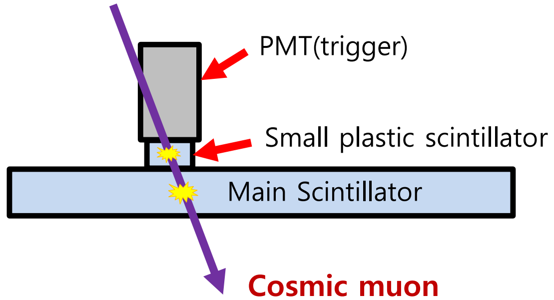
Left

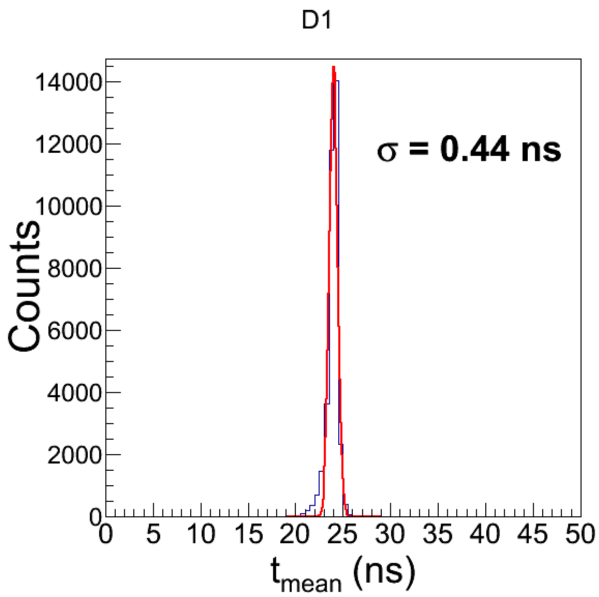


Right

- In this experiment, we have used VTD(Voltage Threshold Discriminator).
- So, When ADC value is high, TDC value(time) is low,
  ADC value is low, TDC value(time) is high.
- Therefore, TDC value should be corrected with Time Walk Correction.

2) Time Resolution



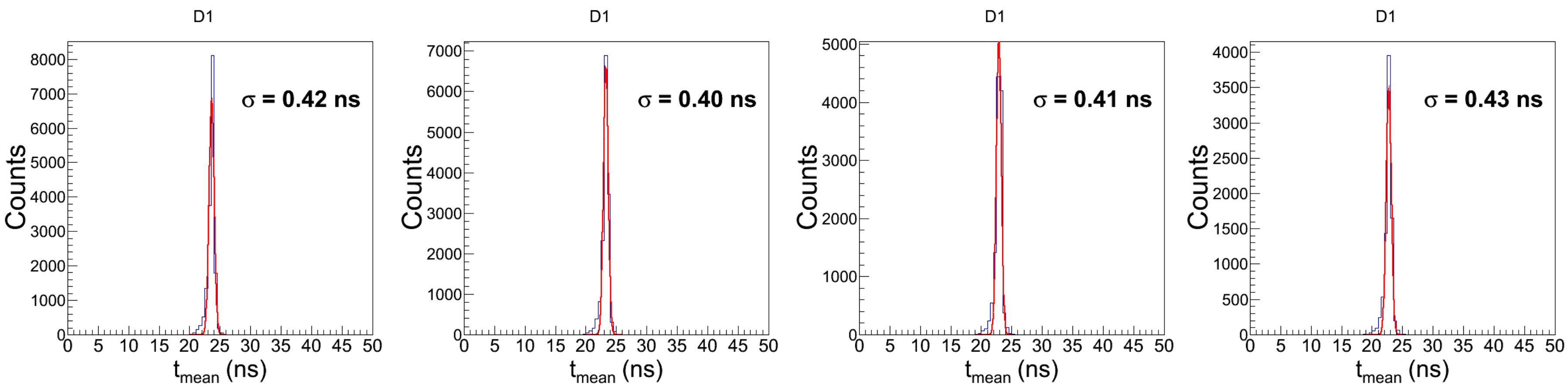


- Threshold : 150 mV, Thickness of small plastic scintillator : 2.5 cm
- Cosmic muon has high energy.
- We can get results similar to high energy neutron cases by using cosmic muons.
- Trigger time resolution $\sigma_{trigger}$ = 200 ps
- Measured time resolution $\sigma_{measured}$ = 440 ps
- Intrinsic time resolution $\sigma_{intrinsic} = \sqrt{\sigma_{measured}{}^2 - \sigma_{trigger}{}^2}$ = 392 ps

Cosmic Muon Test

3) Time resolution at higher PMT voltage

➢ Increasing both PMT voltages 50 V per 20000 events

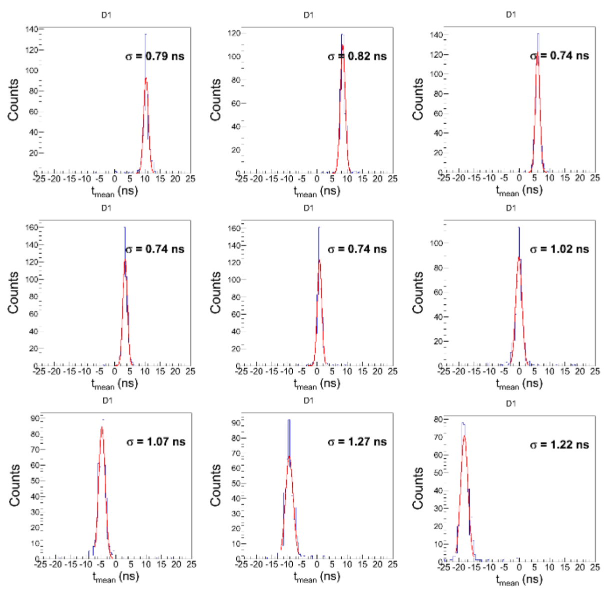


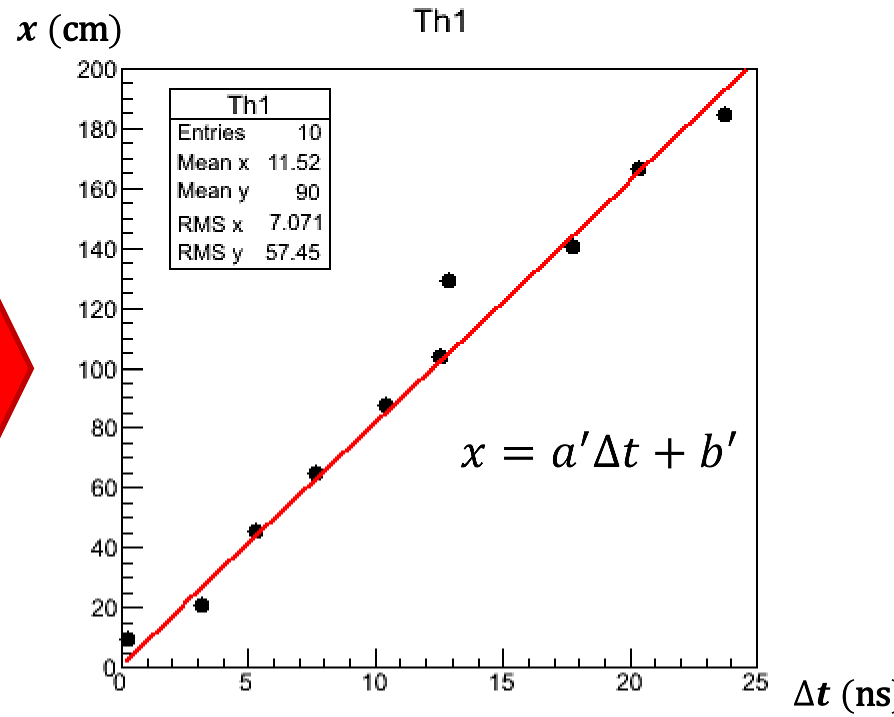
σ_t=0.288139 ns σ_t=0.260032 ns σ_t=0.264455 ns σ_t=0.296315 ns

Increasing voltage

Cosmic Muon Test

4) Position Resolution

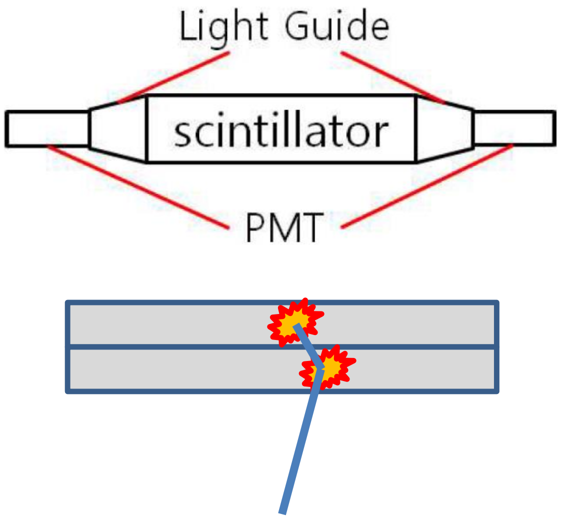


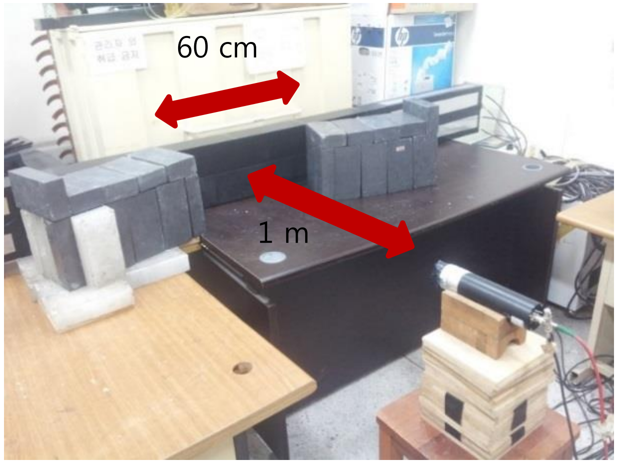


a′ (cm/ns)	b′ (cm)	σ_x (cm)
8.06 ± 0.30	1.30 ± 4.06	6.62

^{252}Cf Test

1) Time of Flight with ^{252}Cf

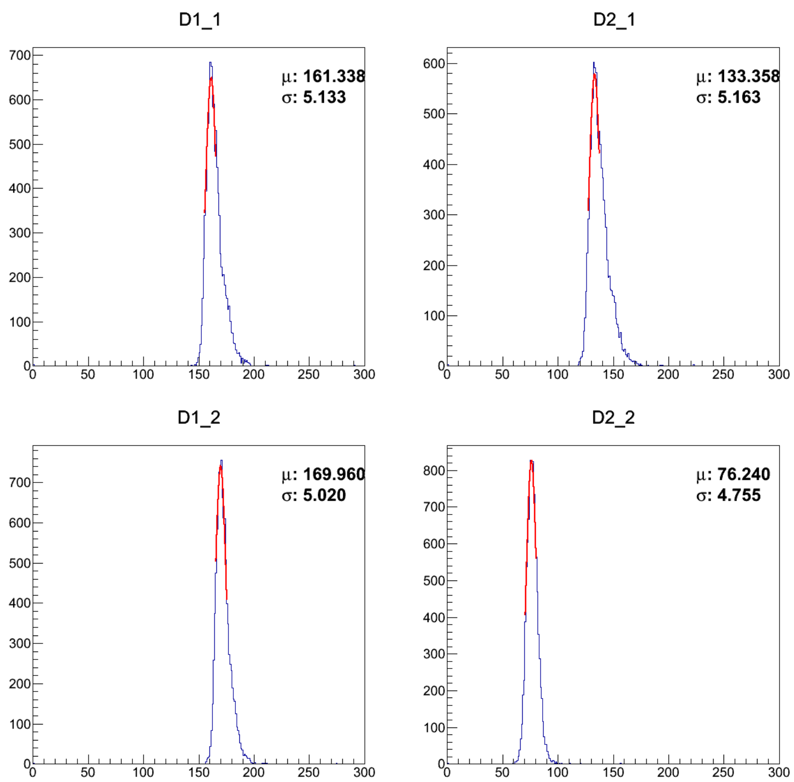




- Gamma & neutron are emitted by Californium 252.
- Gamma is used as reference of time.
- TOF method is used to calculate energy of neutron.
- Neutron can be detected in both detectors.
- Hit is ordered by its deposit timing in the each event.
- Only 1st hit will be used as real hit.

^{252}Cf Test

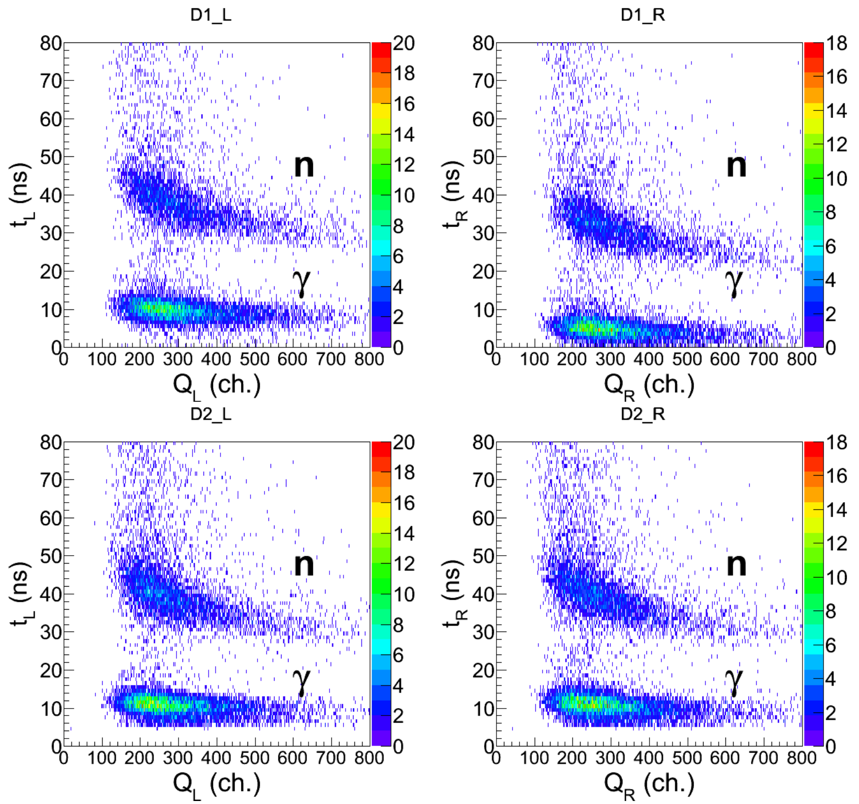
2) Pedestal Subtraction



- The electronics have basic charge value.
- This is called as "pedestal" and it must be subtracted to get real integrated charge value.

^{252}Cf Test

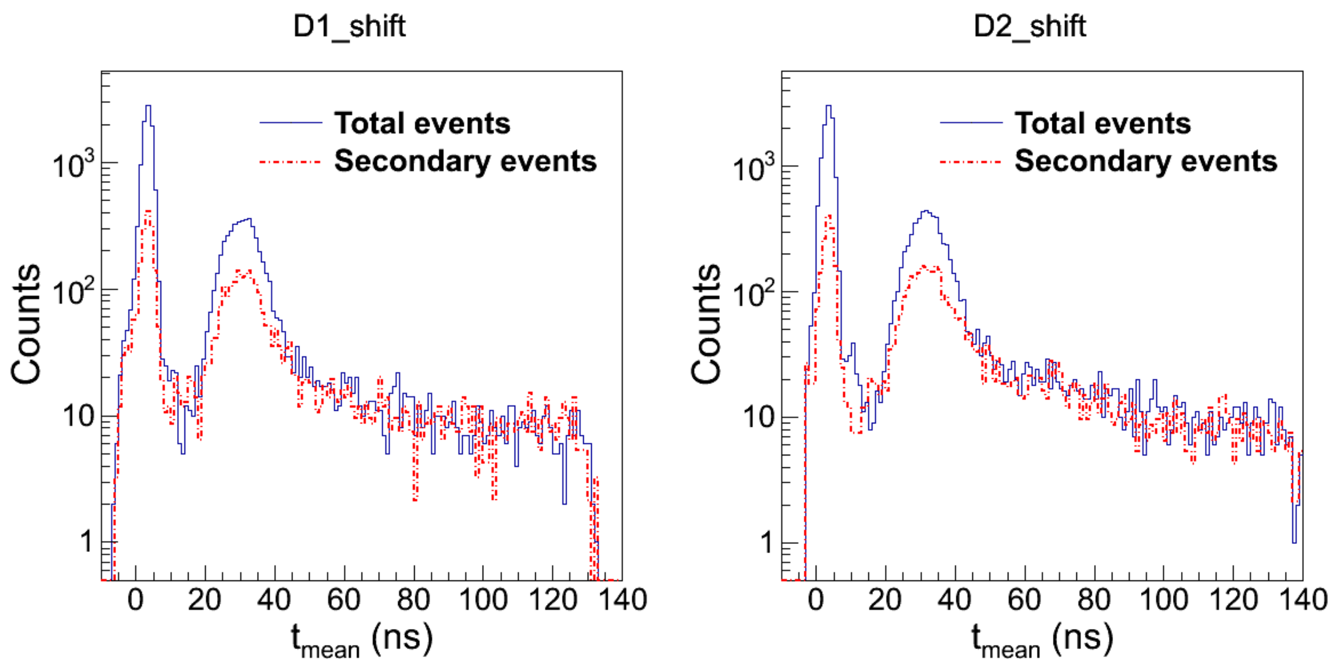
3) 2-D Plot



- Pedestal is subtracted.
- Neutron & gamma are well separated.
- There is ADC dependence of neutron energy.

^{252}Cf Test

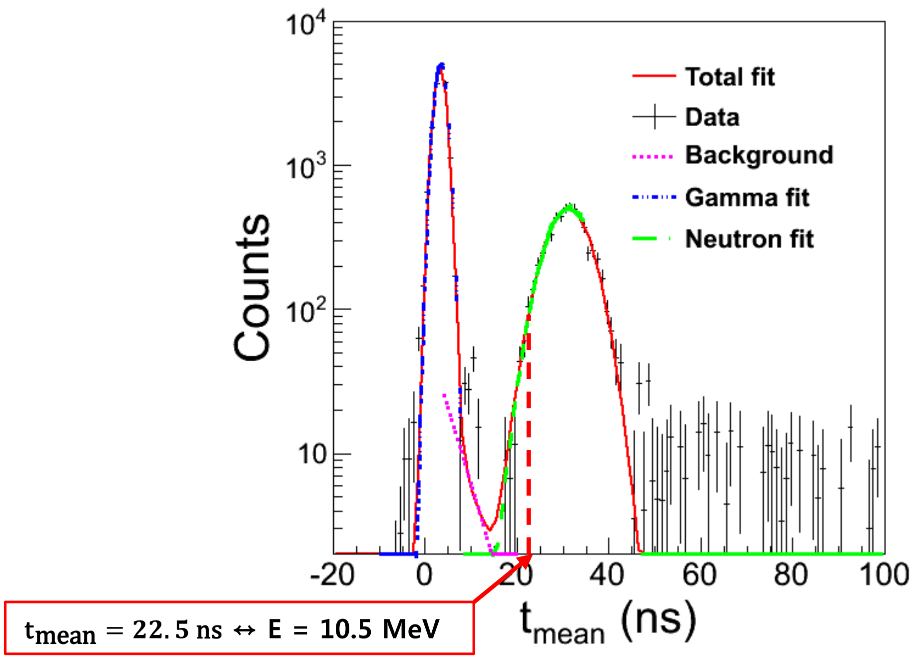
4) Time Distribution



- For each detector, time is the mean time of both side.
- Every points shifted to gamma value as 3.33 ns.

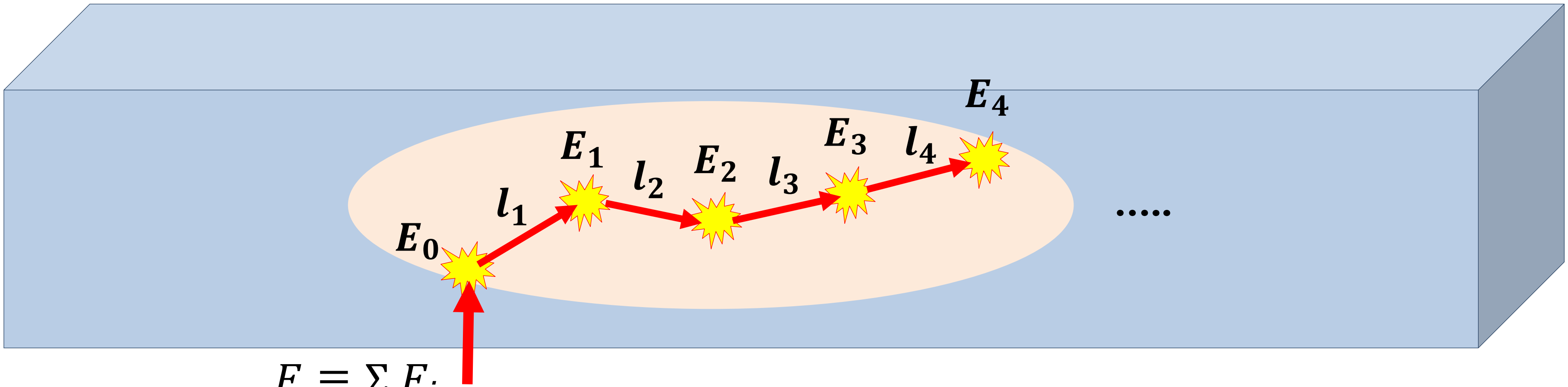
(3.33 ns = Gamma travel time of 1 m)

5) Accidental subtracted Time Distribution



- Accidental is the noise which electronics counts as signal when particle does not reaches to the detector.
- We must subtract this count of ratio.
- The plot is accidental subtracted time distribution when the hits are the first hit.

Birks Formula



$E \equiv \Sigma E_i$

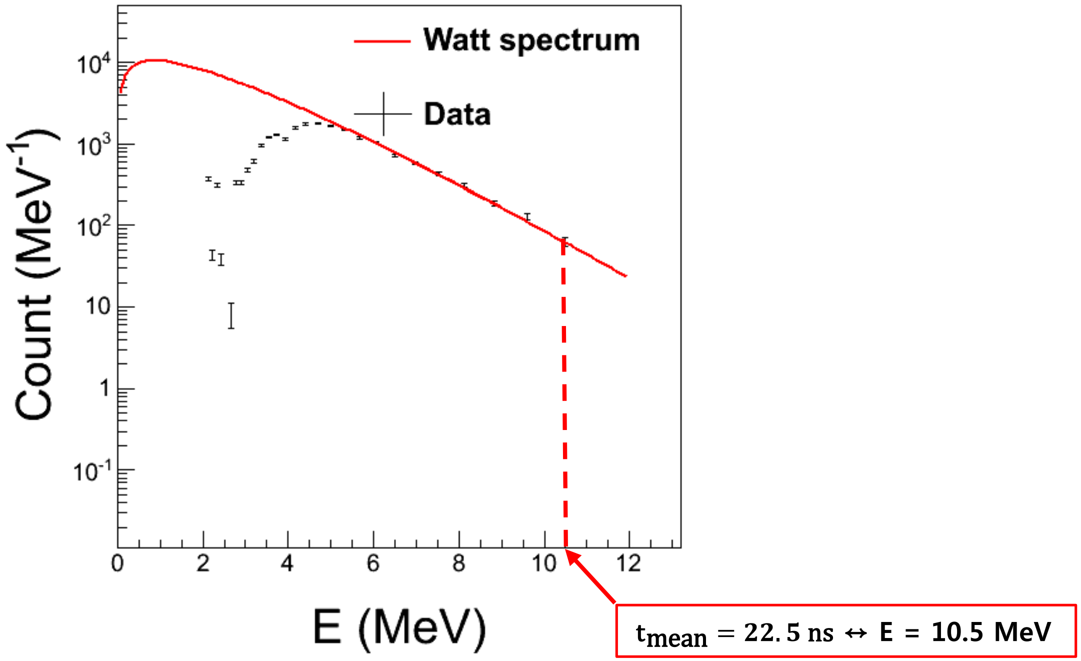
- Scintillator(BC-408) density $\rho = 1.032 \text{ g cm}^{-3}$
- Path length $z_i \equiv$ (density)*(distance between (i – 1)-th & i-th hit) $= \rho l_i$ (g cm^{-2})
- (i-th GEANT4 deposited energy) / $z_i \equiv E_i/z_i = E_i/\rho l_i$ ($\text{MeV g}^{-1}\text{ cm}^2$)
- (i-th corrected deposited energy) / z_i) / ((i-th GEANT4 deposited energy) / z_i)

$$= \frac{E_{corr-i}/z_i}{E_i/z_i} = \frac{1}{1 + kB(E_i/z_i)}$$

(Birks parameter $kB \approx 0.977 \times 10^{-2} \text{ g cm}^{-2}\text{MeV}^{-1}$)

- $E_{corr} \equiv \Sigma E_{corr-i}$: Scintillator-response-corrected total deposited energy

6) Watt Spectrum



- Using TOF method, neutron counts of each time can be converged to the counts of each energy.
- 2 m long bar-type detector can detect over than 5 MeV neutron.
- Watt spectrum : $y = 14067 \times e^{-0.88x} \times \sinh\sqrt{2x}$

RAON

Accelerator	Driver Linac		Post Acc.	Cyclotron
Particle	proton	U^{+79}	RI beam	proton
Beam energy	600 MeV	200 MeV/u	18.5 MeV/u	70 MeV
Beam current	660 μA	8.3 pμA	-	1 mA
Power on target	400 kW	400 kW	-	70 kW