High Flux Isotope Reactor Background Simulation Study with RENE Prototype Detector

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K-NEUTRINO SYMPOSIUM @ CNU

0. Contents

1. What is High flux isotope reactor (HFIR)?

2. Background simulation study.
   - [1]. Structure of RENE prototype detector (OLD).
   - [2]. Signal.
   - [3]. Backgrounds.
     - (1). Gamma background.
     - (2). Thermal neutron background.
     - (3). Fast neutron background.
     - (4). Muon background.
   - [4]. Several cuts.

3. Results.

4. References.

1. What is High flux isotope reactor?

High flux isotope reactor (HFIR).

- HFIR is a research reactor at Oak Ridge National Laboratory.

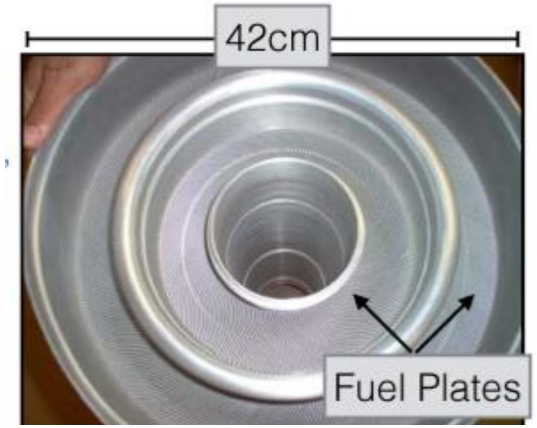
4 Primary Missions

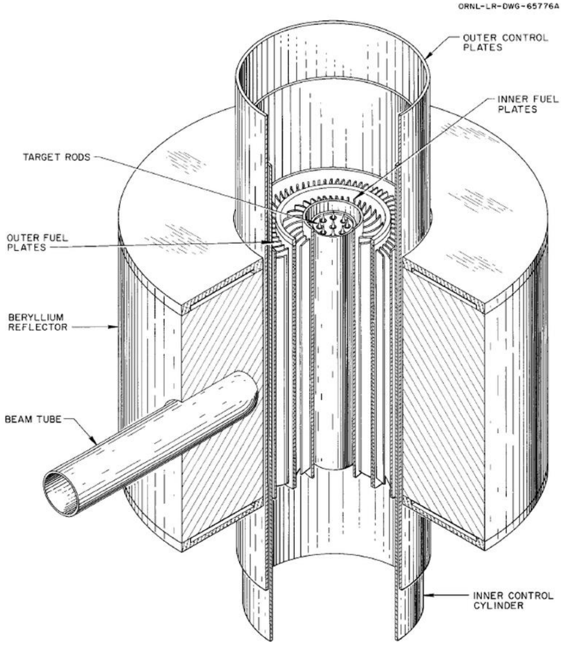
from HFIR brochure (right figure).

- **Neutron scattering**
  - To understand material properties on an atomic scale.
- **Isotope production**
  - To produce isotopes.
- **Irradiation materials testing**
  - To determine the effect of neutron irradiation on materials.
- **Neutron activation analysis**
  - To probe the elemental makeup of a wide variety of materials.

1. What is High flux isotope reactor?

High flux isotope reactor (HFIR).



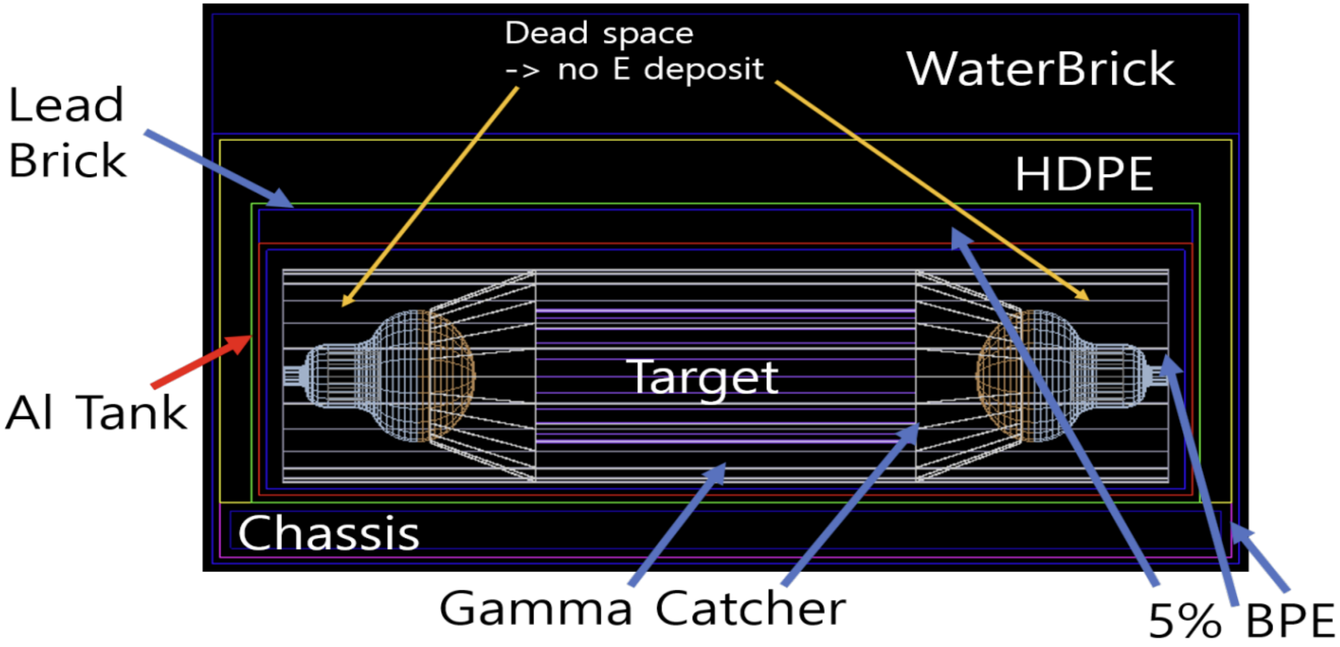


- From high enriched uranium (HEU) fuel, it produces anti-electron neutrino from 235U by more than 99%.
- Thermal power is **85 MW** at a period 21 to 23 days.
- Located on the Earth's surface and close to the reactor core (~ 8m from the experimental hall), the site is exposed to many background signals including neutrons, muons, etc.

[1]. Structure of RENE prototype detector (OLD).

Detector

- Target - 0.5 % Gd LS, radius: 254 mm, height: 1200 mm.
- Gamma catcher (GC) - LS, radius: 404 mm, height: 2800 mm.
- Target and GC are 3 mm thick CYLYNDRICAL containers.



*. LS: Liquid scintillator.

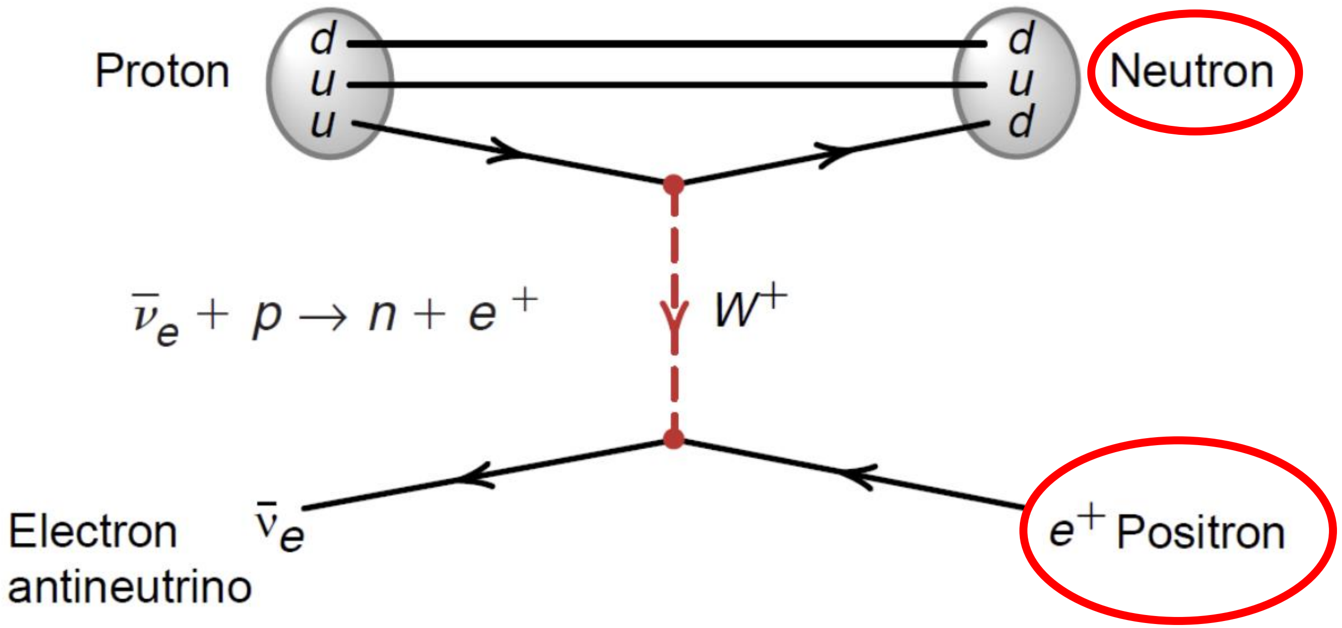
Shielding

From the inner part,

+ 25 mm thick 5% BPE.
+ 25 mm thick 5% BPE on the side.
+ 50 mm thick 5% BPE at the top.
+ 25 mm thick Al (container).
+ 75 mm thick 5% BPE at the top.
+ 25 mm thick Lead.
+ 100 mm thick HDPE on the side.
+ 241 mm thick HDPE at the top.
+ 70 mm thick Stainless steel at the bottom.
+ 25 mm thick 5% BPE.
+ 460 mm thick Water at the top.

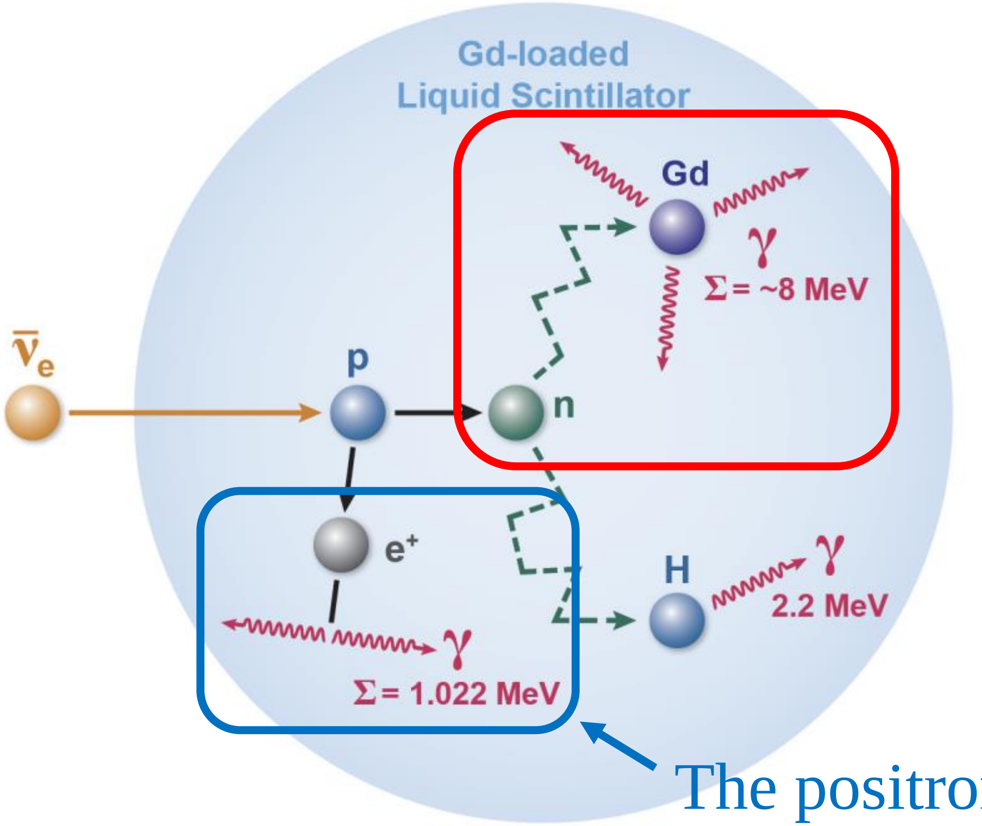
[2]. Signal.

- Electron-antineutrino ($\bar{\nu}_e$) interacts with a proton in the Target (inverse beta decay (IBD)), then a positron and a neutron are created in the process.



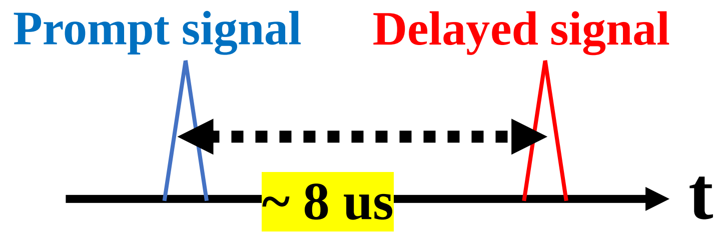
Neutrino physics @ the 2nd Asia-Europe-Pacific school of HEP, Z. Xing (2014).

[2]. Signal.



Physics with Reactor Neutrinos, X. Qian (2018).

About 8 us after the prompt signal, n-Gd emits ~ 8 MeV gamma rays (**delayed signal**).



- **With the signal pair, the neutrino interaction event can be distinguished.**

The positron leaves its energy promptly (**prompt signal**).

*. IBD: Inverse beta decay.

2. Background Simulation Study

[2]. Signal.

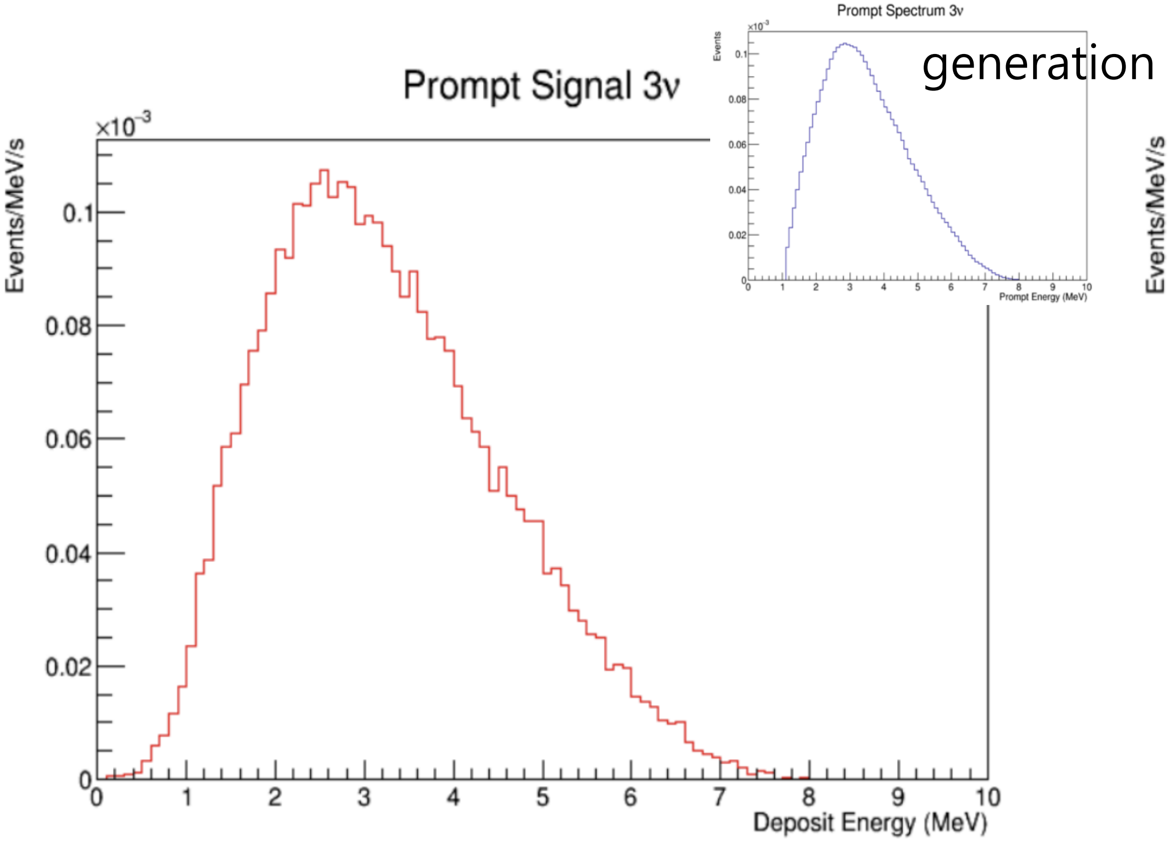
- Generate positrons and neutrons assuming that IBD interaction already happens.

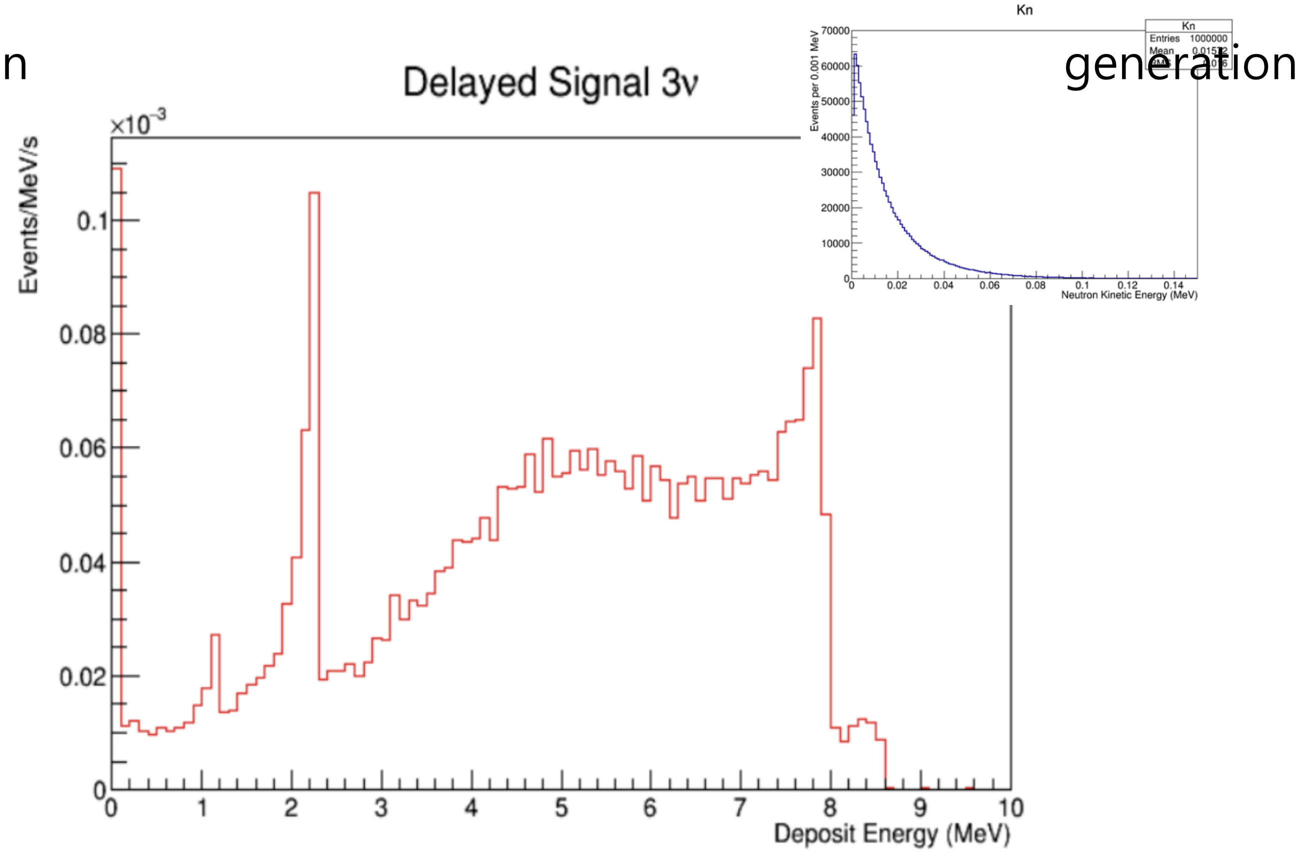
$$N_{IBD} = \frac{N_p}{4\pi} \int \epsilon \, \frac{N_{fis}}{L^2} \, \sigma_{IBD}(E) \, \Phi_{HM}(E) \, P_{\mathrm{osc}}(L, \; E) \, dE$$

N_{IBD}: the number of IBD interaction,
N_p: the number of protons,
ϵ: detection efficiency (assuming it is equal to 1.)
L: flight distance of neutrinos,
N_f: the number of fission for each isotope,
$\sigma_{IBD}(E)$: IBD cross-section,
$P_{osc}(\mathrm{L}, \mathrm{E})$: neutrino oscillation probability,
$\Phi_{HM}(E)$: reactor neutrino flux based on the Huber-Mueller model.

[2]. Signal.

Signal simulation result: <u>3.43mHz</u>





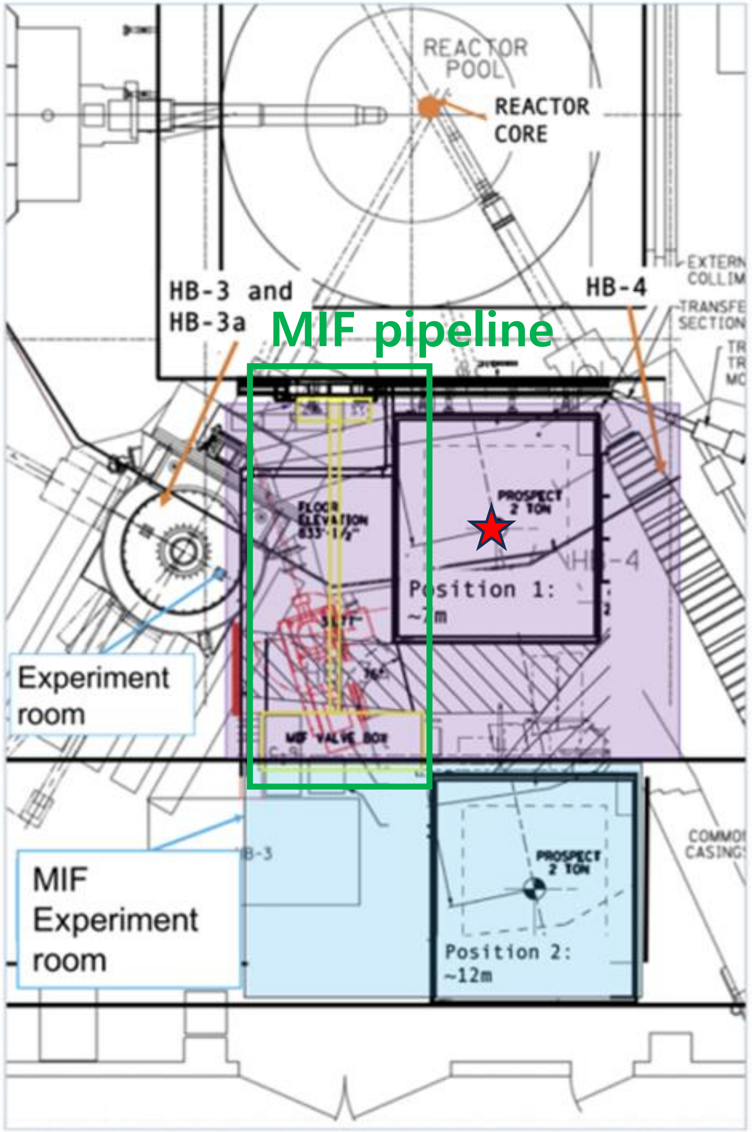
* Interaction rate: rate of particles that leave their energies in the active volume of the detector.

[3]. Backgrounds.

1. Gamma background
2. Thermal neutron background
3. Fast neutron background
4. Muon background

[3] - (1). Gamma background.

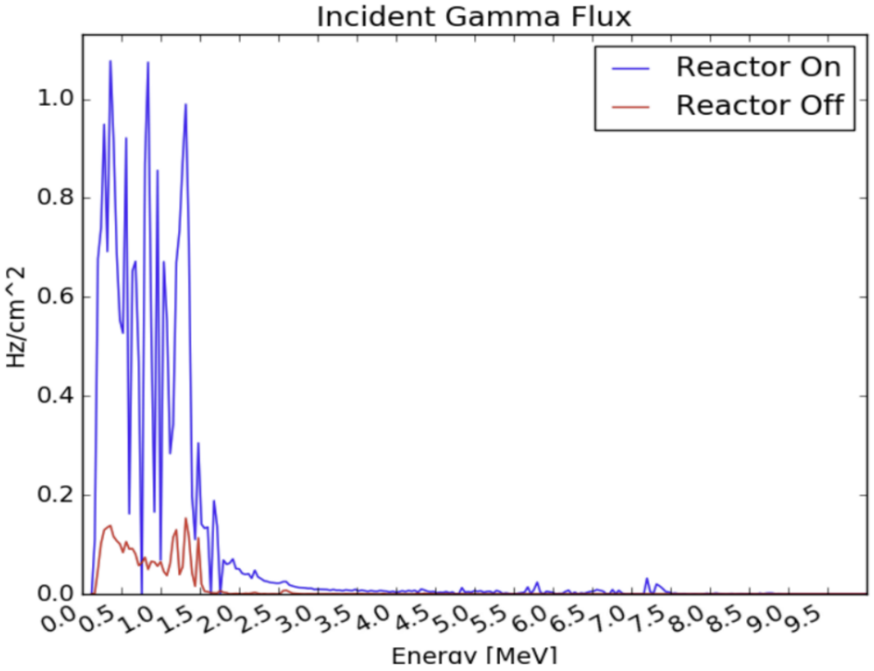
- 2 Types of gamma background:
  - Reactor On
  - Material Irradiation Facility (MIF) Pipeline
    - ✓ MIF is turned on when the reactor is on.



- In this study, consider **two cases**,
  - ✓ MIF turned off while the reactor is on.
  - ✓ MIF turned on while the reactor is on.

[3] - (1). Gamma background.

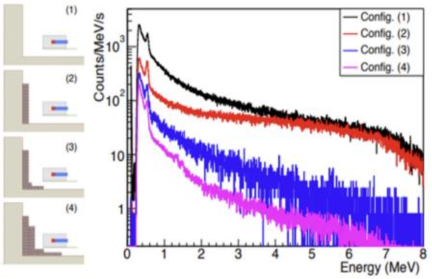
- 2 Types of gamma background:
  - <u>Reactor On</u>



(a) Reactor ON / OFF incident gamma background

[Fig 1]

[Fig 2]



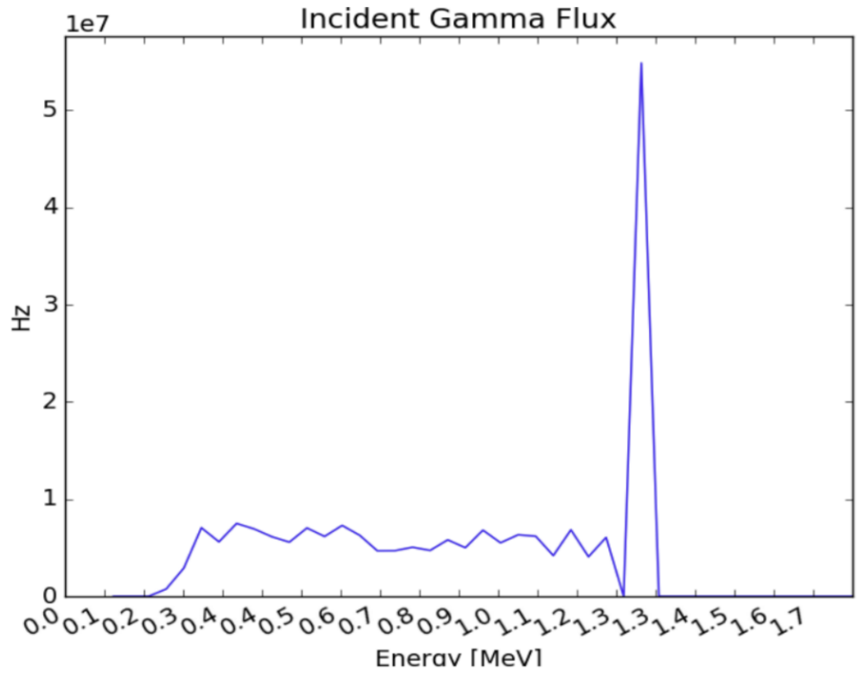
Configuration (dimensions in cm)	Rate (Hz) 1-3 MeV	Rate (Hz) 3-10 MeV
No Wall (1)	512.4	246.3
Add wall: 10 × 102 × 51 (2)	169.8	168.4
Add floor: 25 × 102 × 5 (3)	52.5	15.2
Add to floor: 25 × 102 × 10	32.2	10.5
Add to wall: 20 × 102 × 51	28.5	12.7
Extend floor: 30 × 20 × 5 (4)	15.5	3.0

[Fig 3]

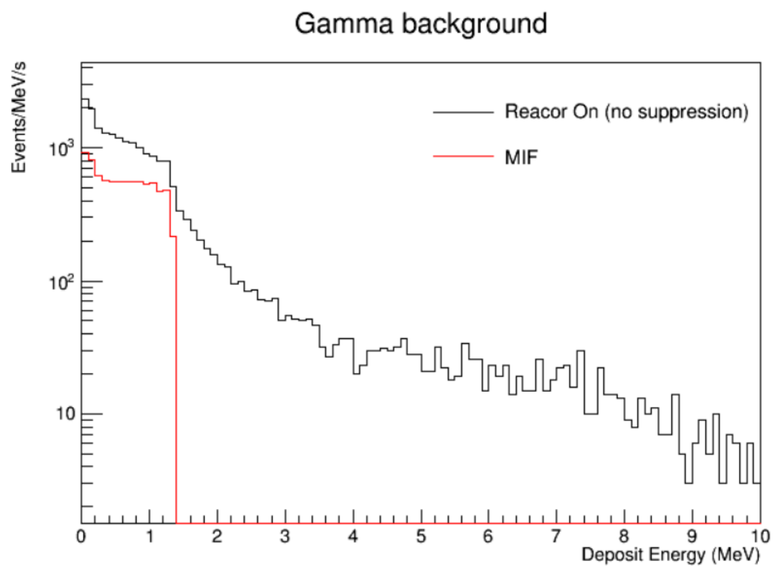
- The gamma background is generated based on the spectrum in Fig 1.
- Currently, lead bricks about 10 ~ 20 cm thick are placed on the wall facing the reactor (Fig 2).
- To reflect the structure, the gamma simulation result is corrected by the ratio of "No Wall" and "blue box" values (Fig 3).

[3] - (1). Gamma background.

- 2 Types of gamma background:
  - Material Irradiation Facility (MIF) Pipeline



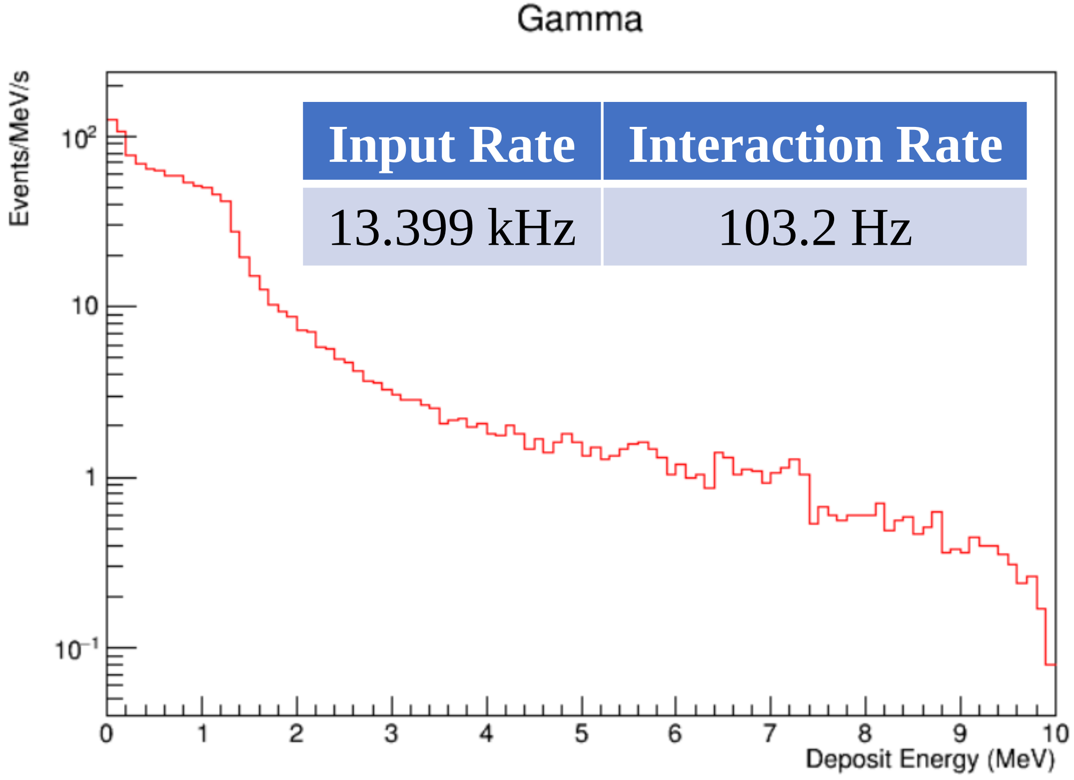
(b) Incident gamma background from MIF
[Fig 4]



- The rate of gamma from MIF is one half of the gamma at reactor-on in the range between 0.1 to 1.29 MeV (PROSPECT collaboration).
- The MIF gamma is made on the surfaces except the rear and upper faces of the detector based on the spectrum shown in Fig 4.
- In Fig 2, it is corrected by the above fact.

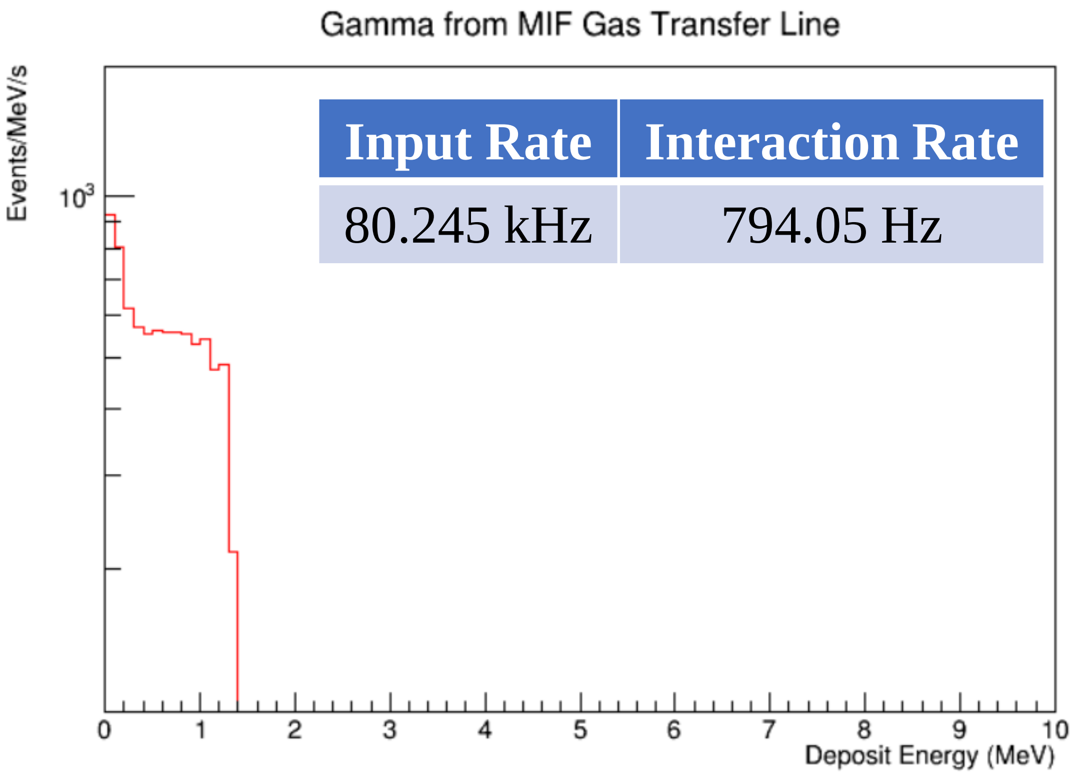
[3] - (1). Gamma background.

- Gamma BKG simulation results:
  - <u>Reactor On</u>



Input Rate	Interaction Rate
13.399 kHz	103.2 Hz

  - <u>Material Irradiation Facility (MIF) Pipeline</u>

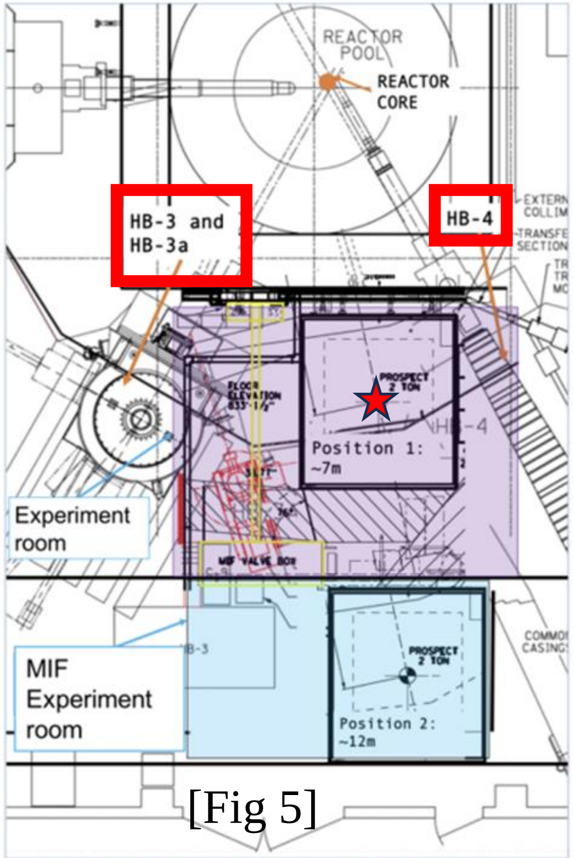


Input Rate	Interaction Rate
80.245 kHz	794.05 Hz

* Interaction rate: rate of particles that leave their energies in the active volume of the detector.

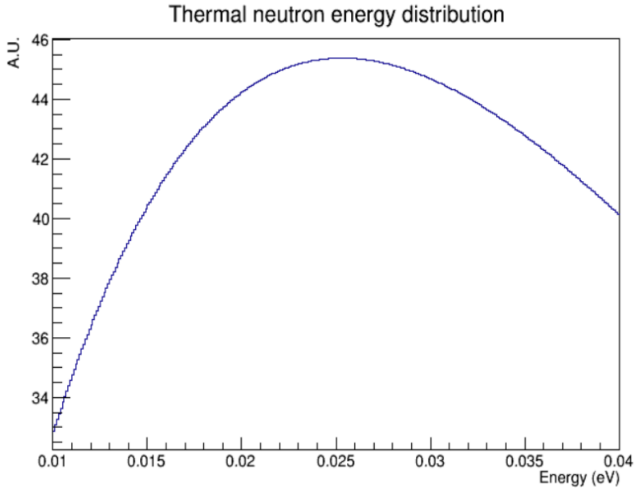
[3] - (2). Thermal neutron background.

- From the measurement, $2/cm^2/s$ rate is reported from the PROSPECT collaboration.
- Thermal neutron comes mainly from neutron beam lines shown in Fig 5.



[Fig 5]

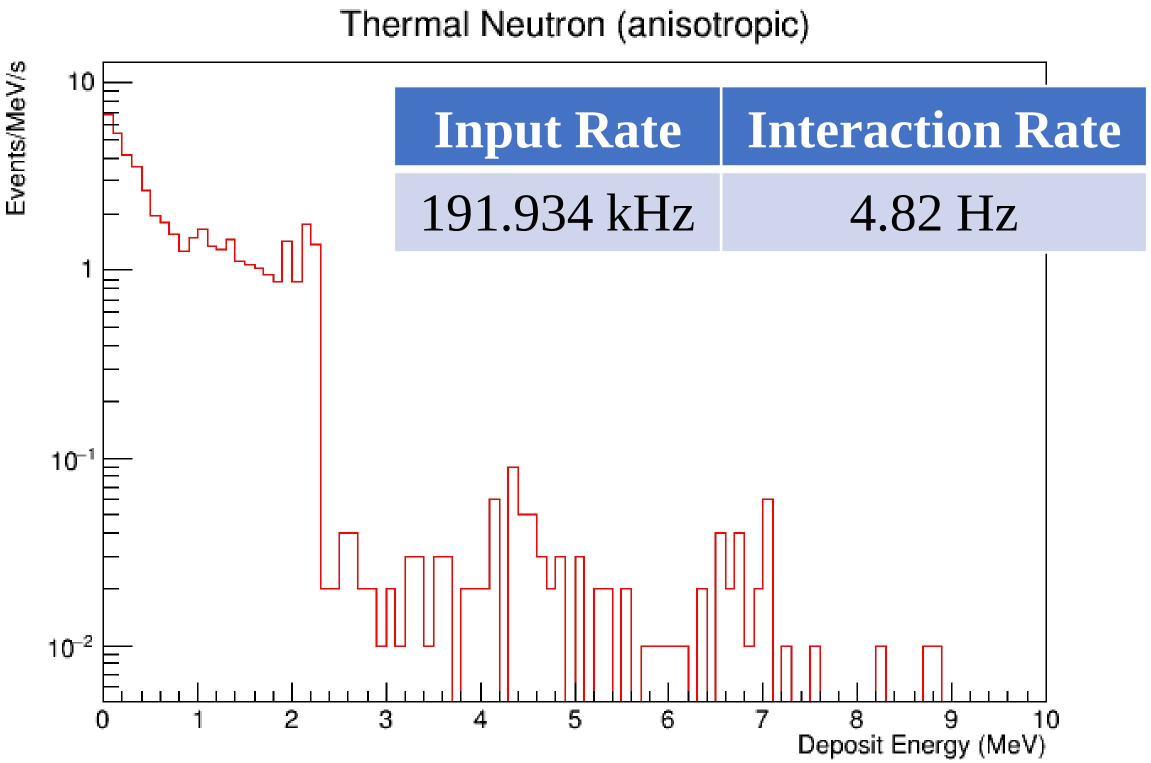
- Thermal neutrons are generated with the rate and the Maxwell - Boltzmann distribution with the room temperature.



- Their directions are considered in two ways.
  1. Only from the neutron beam line; "anisotropic case".
     - ✓ Generated on two sides and bottom side.
  2. From all directions; "isotropic case".

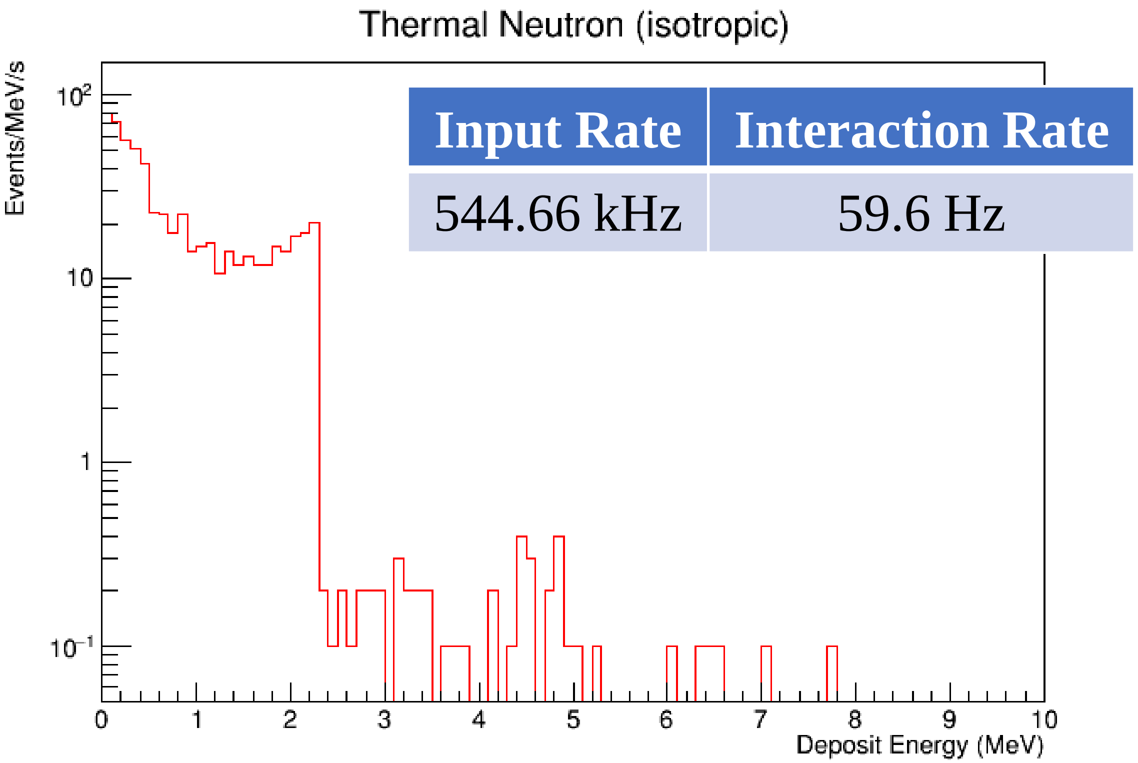
[3] - (2). Thermal neutron background.

- Thermal neutron BKG simulation results:
    - <u>Anisotropic generation</u>



Input Rate	Interaction Rate
191.934 kHz	4.82 Hz

    - <u>Isotropic generation</u>



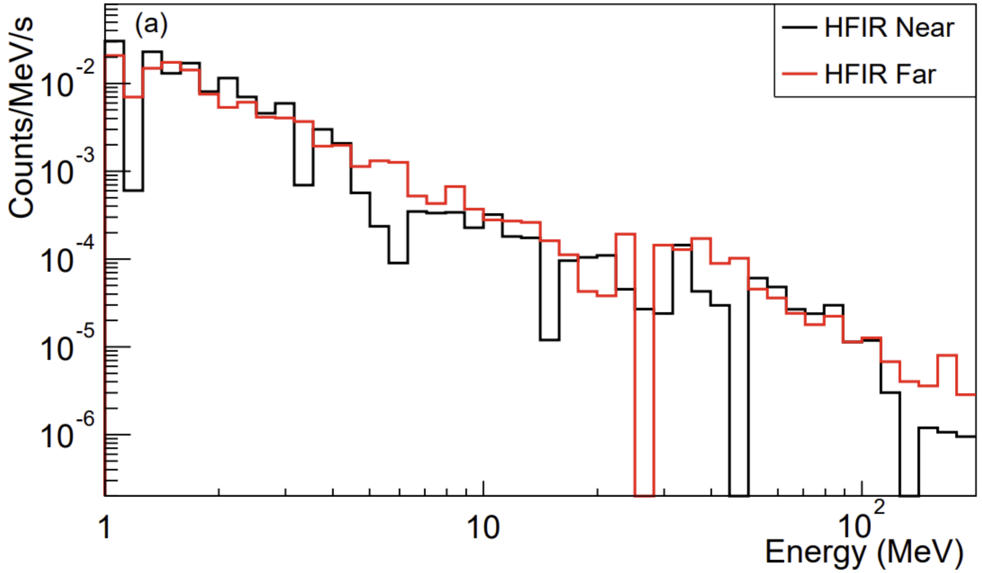
Input Rate	Interaction Rate
544.66 kHz	59.6 Hz

* Interaction rate: rate of particles that leave their energies in the active volume of the detector.

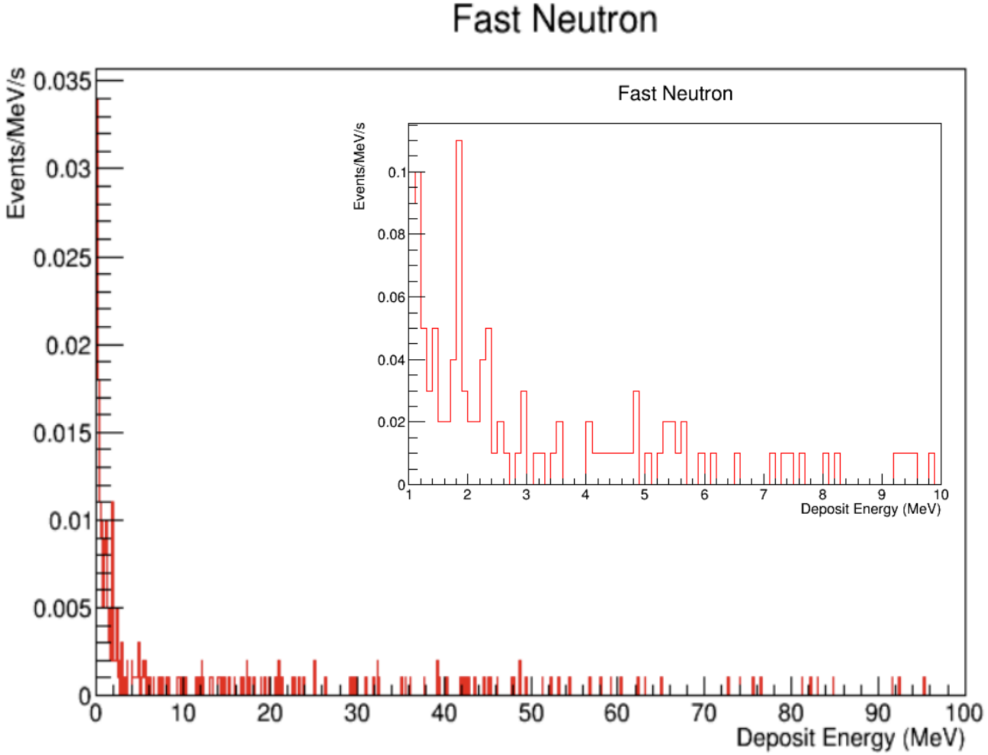
[3] - (3). Fast neutron background.

- Using the measurement from the PROSPECT collaboration, neutrons are simply generated on the top of the shielding.

Location	Exposure (h)	Flux ($E_n > 1$MeV)
HFIR near	12	$(4.1 \pm 0.3) \times 10^{-3} [cm^2 s^{-1}]$



- Fast neutron BKG simulation results:

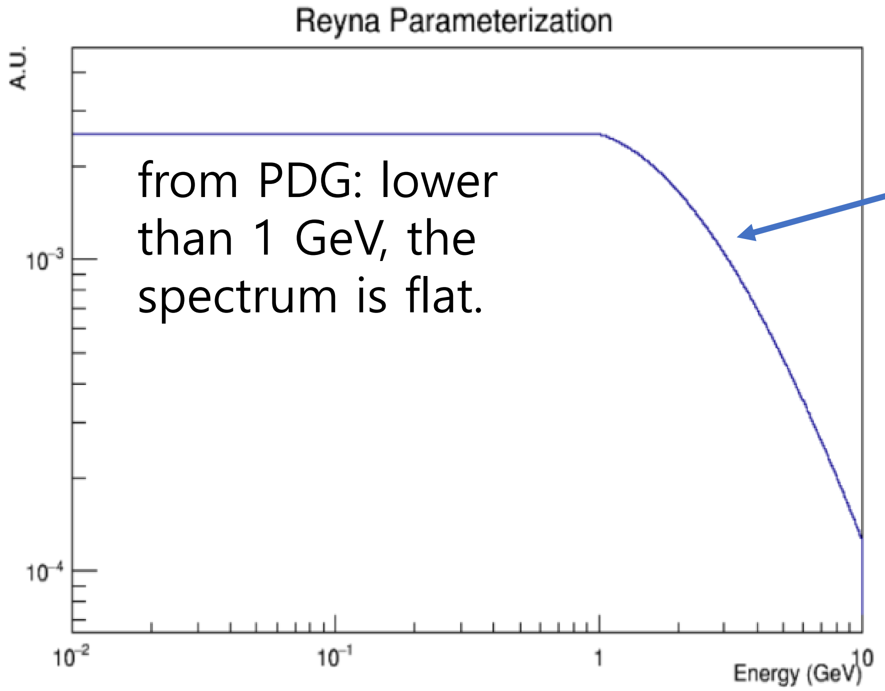


Input Rate	Interaction Rate
168.7 Hz	0.347 Hz

* Interaction rate: rate of particles that leave their energies in the active volume of the detector.

[3] - (4). Muon background.

- With the Reyna parametrization and the measurement from PROSPECT collaboration, muons are simply generated on the top of the shielding structure.



$$I_\mu(E_\mu,\,\theta) \;=\; (cos^3\theta)\, I_\nu(E_\mu)$$

$$,\,where\;\; I_\nu(E_\mu) \;=\; c_1 E_\mu^{-(c_2+c_3\log_{10}(E\mu)+c_4\log^2_{10}(E\mu)+c_5\log^3_{10}(E_\mu))}.$$

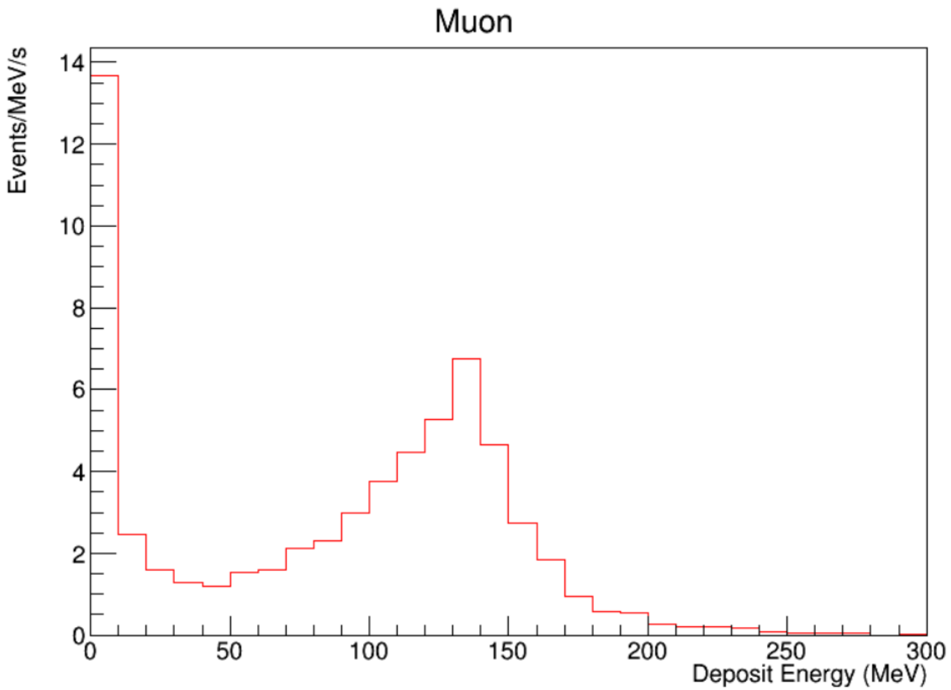
상수는 $c_1 = 0.00253,\; c_2 = 0.2455,\; c_3 = 1.288,\; c_4 = -0.2555,\; c_5 = 0.0209$

Reactor	Rate ($m^{-2}sr^{-1}s^{-1}$)
HFIR	84.9

Table 3: Cosmic muon background의 flux를 나타내었다 [2].

[3] - (4). Muon background.

- Muon BKG simulation results:



Input Rate	Interaction Rate
1.67 kHz	640.81 Hz

* Interaction rate: rate of particles that leave their energies in the active volume of the detector.

2. Background Simulation Study

[3] - (*). Summary of background simulation results.

Type	Input (Hz)	Interaction Rate (Hz)	$1 - 10\text{MeV}\ E_{deposit}$ Range (Hz)
IBD Signal	4.63×10^{16}	3.43×10^{-3}	3.38×10^{-3}
Gamma (Rx On)	13.399×10^{3}	103.2	37.302
Gamma (MIF)	80.245×10^{3}	794.05	171.28
Fast n	168.7	0.347	0.115
Thermal n (anisotropic)	191.934×10^{3}	4.82	1.74
Thermal n (isotropic)	544.66×10^{3}	59.6	19.44
Muon	1.67×10^{3}	640.81	-

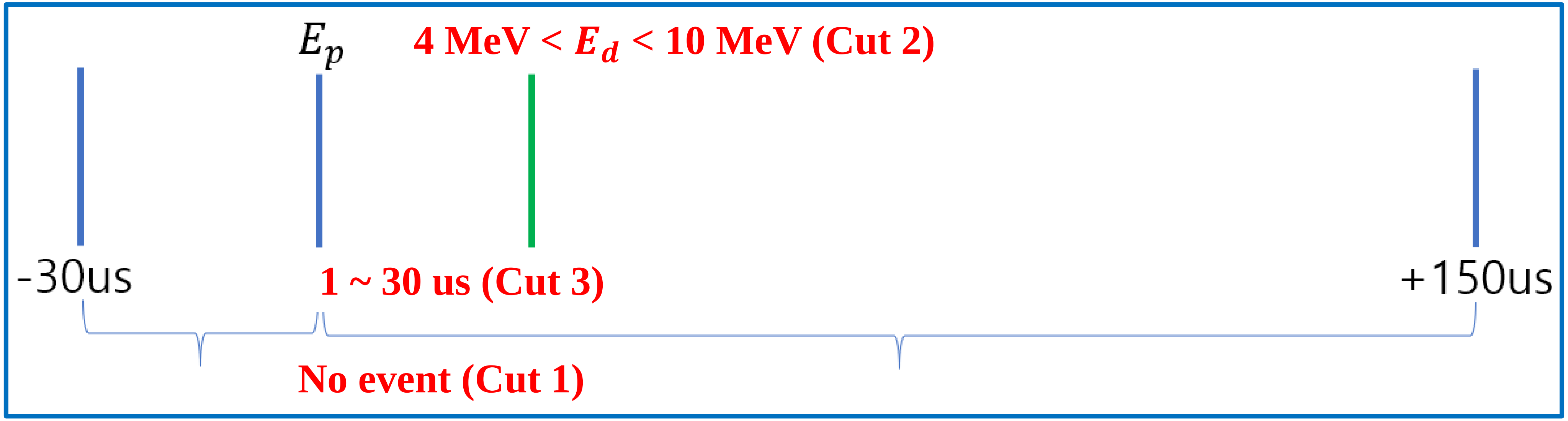
- Among the backgrounds, gamma is dominant, especially those from MIF.
- The shielding structure reduces backgrounds by more than 99%, except muon.
- Muon background is reduced by about 62%.

*. IBD signal input value is calculated based on the HM model.

[4]. Several cuts.

- Using cuts among NEOS event selection cuts.

1. No event before 30μs and after 150μs from a prompt.
2. 1MeV < Ep < 10MeV and 4MeV < E_d < 10MeV.
3. Time coincidence between prompt and delayed 1μs ~ 30μs.

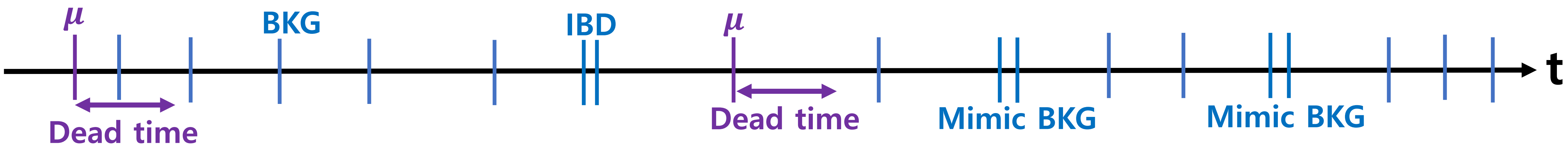


4. ~~PSD. (Not prepared.)~~
5. After muon event, all events are vetoed in 150μs window (Muon veto).

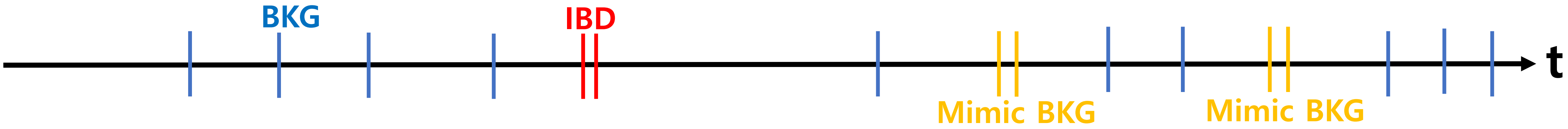
[4]. Several cuts.

- How to apply the cuts.

1. The number of IBD and background signals is determined by rates and spectra from the simulation results in the 1 ~ 10 MeV range (for muon, all energy range used).
2. A time between 0 to 100,000 seconds is randomly assigned to each IBD and background signal, and then arranged in ascending order.



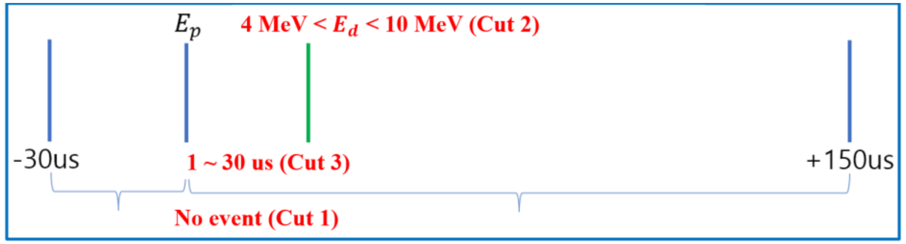
3. Deadtime is calculated by the 150 us veto window after the muon leaves its energy to the detector and any event is removed when it is in the veto window.
4. The selection cuts are applied for the case with or without 1 us event window.

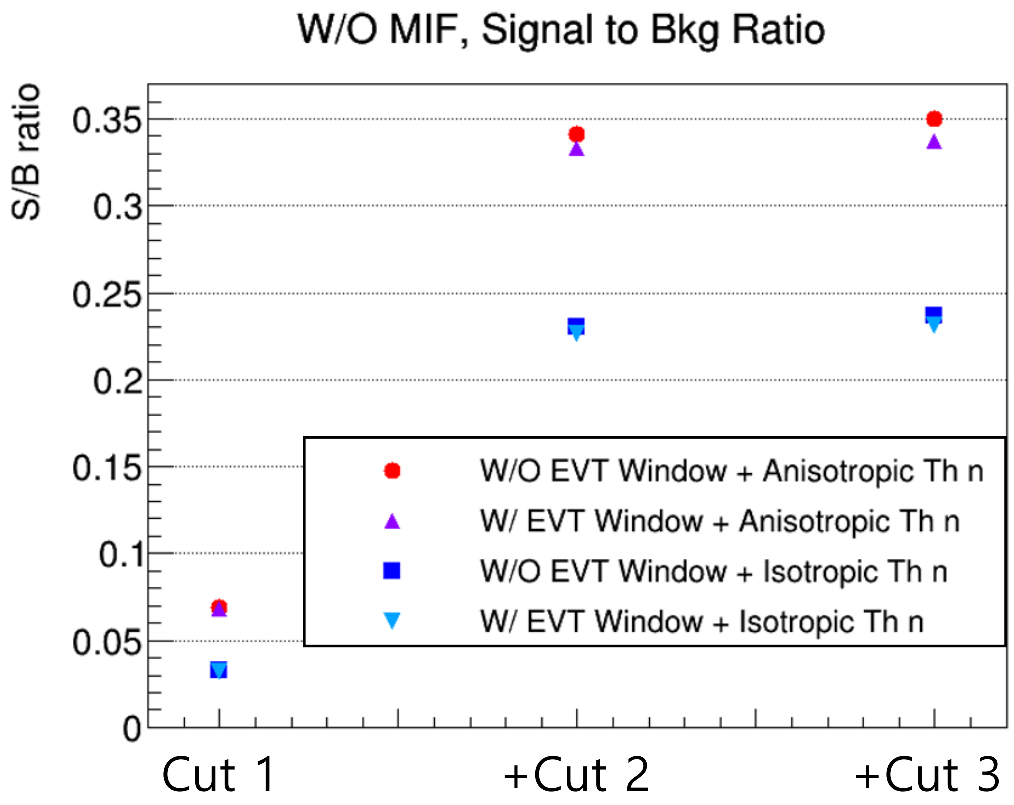


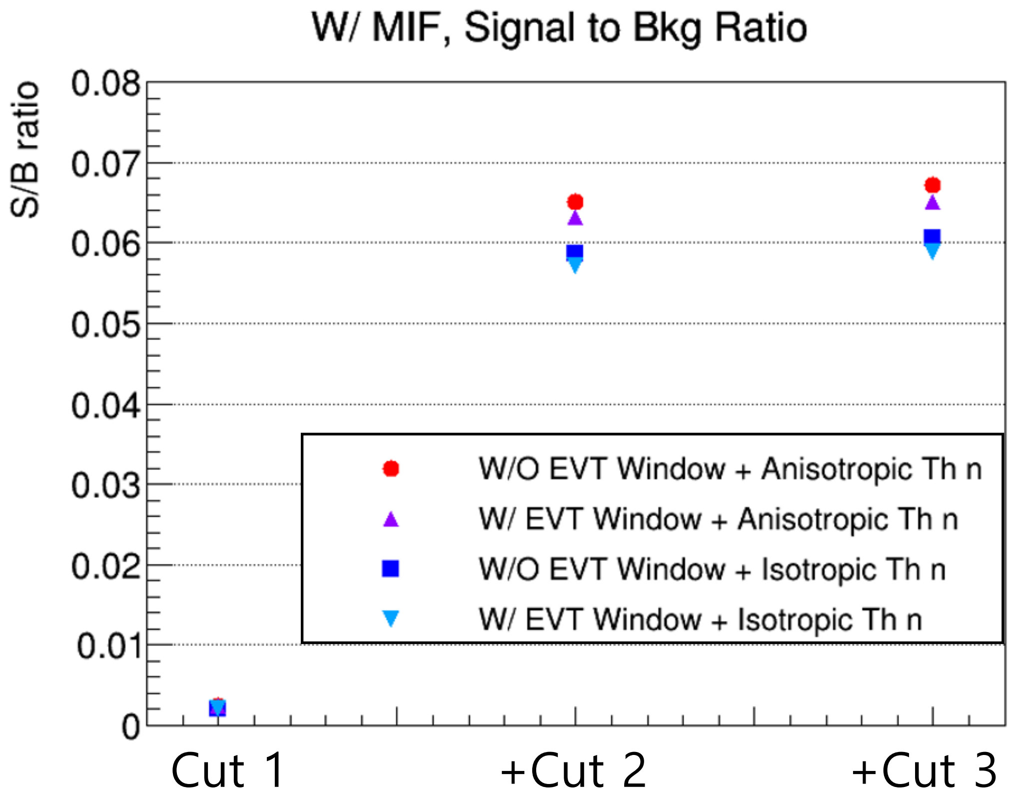
3. Results

Results: Assume that the detector is exposed with 100,000 seconds.

	w/o event window	w/ event window
DEADTIME	8768.70s	8822.38s







3. Results

Results: Signal to background ratio (S/B).

- Default cut: 1MeV < Ep < 10MeV
- Cut 1; No event before 30μs and after 150μs from a prompt

	w/o MIF		w/ MIF	
	Anisotropic	Isotropic	Anisotropic	Isotropic
w/o evt window	0.0691	0.0329	0.00245	0.00209
w/ evt window	0.0678	0.0322	0.00240	0.00205

- + Cut 2; 4MeV < Ed < 10MeV

	w/o MIF		w/ MIF	
	Anisotropic	Isotropic	Anisotropic	Isotropic
w/o evt window	0.341	0.230	0.0651	0.0587
w/ evt window	0.333	0.226	0.0632	0.0571

- + Cut 3; Time coincidence between prompt and delayed 1μs ~ 30μs

	w/o MIF		w/ MIF	
	Anisotropic	Isotropic	Anisotropic	Isotropic
w/o evt window	0.350	0.237	0.0671	0.0605
w/ evt window	**0.337**	**0.231**	**0.0651**	**0.0589**

Conclusion.

- S/B ratio is estimated to be about 0.231 to 0.337 when MIF is turned off.
- It is necessary to cut back on the gamma background.
- The optimization of the detector and the shielding structure is required.
- A more elaborate study including the optimization of the experimental setup will be reported in the near future.

4. References

HFIR introduction.

- https://neutrons.ornl.gov/hfir
- D. Norcini, “First search for ev-scale sterile neutrinos and precision measurement of the 235U antineutrino spectrum with the prospect experiment.”, PhD thesis (Yale University, 2019).

Signal generation.

- P. Huber, “Determination of antineutrino spectra from nuclear reactors”, Phys. Rev. C 84, 024617 (2011).
- P. Vogel and J. F. Beacom, “Angular distribution of neutron inverse beta decay, $\overline{\nu_e} + p \rightarrow e^+ + n$”, Phys. Rev. D 60, 053003 (1999).

Background generation.

- B. A. Heffron, “Characterization of reactor background radiation at HFIR for the prospect experiment.”, MS thesis (University of Tennessee, 2017).
- B. Hackett, “Dang and the background characterisation of HFIR for prospect.”, MS thesis (University of Surrey, 2017).
- D. Norcini, “First search for ev-scale sterile neutrinos and precision measurement of the 235U antineutrino spectrum with the prospect experiment.”, PhD thesis (Yale University, 2019).
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- J. Ashenfelter et al. (PROSPECT), “Background Radiation Measurements at High Power Research Reactors”, Nucl. Instrum. Meth. A 806, 401–419 (2016).
- D. Reyna, A simple parameterization of the cosmic-ray muon momentum spectra at the surface as a function of zenith angle, arXiv:hep-ph/0604145v2 (2006).
- R. L. Workman et al. (Particle Data Group), “Review of Particle Physics”, PTEP 2022, 083C01 (2022).

Thank you.

Backup pages.

BKG Simulation @ HFIR

- **Simulation - Thermal neutron**

Simulation 결과 (비등방적)

Input Rate	Interaction Rate
191.934 kHz	4.82 Hz

Simulation 결과 (등방적)

Input Rate	Interaction Rate
544.66 kHz	59.6 Hz

✓ *Input rate는 약 2.8배 늘었지만 interaction rate가 약 12.3배 늘었다.*

WHY?

❖ **최외곽의 실딩이 BPE니까 2MeV γ를 기준으로 뚫고 들어오는 양 추정. (n-capture gamma)**
  - 바닥 면은 7cm steel chassis. *λ~3cm.*
  - 옆, 앞, 뒤 면은 chassis 구조 대신 10cm HDPE, 윗 면은 chassis 구조 대신 24.1cm HDPE. *λ~20cm.*

➢ **뚫고 들어오는 정도는 아래와 같다.**
  - Ratio (위/바닥): 24.1cm HDPE / 7cm chassis ~ 윗 면에서 대략 3배 정도 더 뚫고 들어옴.
  - Ratio (옆,앞,뒤/바닥): 10cm HDPE / 7cm chassis ~ 옆, 앞, 뒤 면에서 대략 6배 정도 더 뚫고 들어옴.

➢ **Thermal n bkg를 동일한 양으로 보정하고, 각 면들의 이벤트 개수의 기여를 보자.**
  - 방향성 고려: 바닥 ~ 62%, 옆(L,R) ~ 38%. || 방향성 고려 X: 바닥 ~ 15%, 위 ~ 15%, 옆(L,R),앞,뒤 ~ 70%.

➢ **기여도에 맞게 이벤트 기여를 비등방적인 경우에서 등방적인 경우로 바꾸자.**
  - 바닥->위: ¼ of 62% ~ 15%.
  - 바닥->옆,앞,뒤: ½ of 62% ~ 30%.
  - Ex) (비등방)100개 이벤트 -> (등방)400개 이벤트: 바닥->위=75개, 바닥->옆,앞,뒤=300개, 바닥->바닥=25개.

BKG Simulation @ HFIR

- **Backup – Steel/Iron**

"A comparative study of empirical formulas for gamma-ray dose build-up factor in iron and lead materials"

Table 3. The gamma attenuation coefficient and mean free path in iron and lead.

$E\gamma$	Iron			Lead		
/MeV	μ/ρ_{Fe} /$10^{-2}cm^2/g$	μ /cm^{-1}	λ /cm	μ/ρ_{Pb} /$10^{-2}cm^2/g$	μ /cm^{-1}	λ /cm
0.5	8.414	0.656	1.524	16.14	1.83	0.546
1	5.995	0.468	2.139	7.102	0.805	1.242
2	4.265	0.333	3.006	4.606	0.522	1.915
3	3.621	0.282	3.541	4.234	0.48	2.083
4	3.312	0.258	3.871	4.197	0.476	2.101
6	3.057	0.238	4.194	4.391	0.498	2.008
8	2.991	0.233	4.286	4.675	0.53	1.886
10	2.994	0.234	4.282	4.972	0.564	1.774

BKG Simulation @ HFIR

- **Backup – PE/BPE**

"Calculation of gamma-ray attenuation parameters for locally developed shielding material: Polyboron"

Table 3 – The theoretical and X-Com values (with coherent scattering) of mass attenuation coefficients, μ_m (cm^2/g) for different shielding materials.

Photon energy (MeV)	Polyboron		Ordinary concrete		Pure polyethylene		Borated polyethylene		Water	
	Theoretical value	X-Com value	Theoretical value	X-Com value	Theoretical value	X-Com value	Theoretical value	X-Com value	Theoretical value	X-Com value
1.00E-03	2.434E+03	2.434E+03	3.428E+03	3.445E+03	1.894E+03	1.894E+03	1.714E+03	1.723E+03	4.077E+03	4.077E+03
1.50E-03	7.919E+02	7.920E+02	1.229E+03	1.235E+03	5.999E+02	6.001E+02	5.394E+02	5.425E+02	1.376E+03	1.376E+03
2.00E-03	3.479E+02	3.479E+02	1.448E+03	1.455E+03	2.593E+02	2.592E+02	2.333E+02	2.345E+02	6.172E+02	6.173E+02
3.00E-03	1.061E+02	1.060E+02	4.952E+02	4.977E+02	7.743E+01	7.743E+01	6.945E+01	6.982E+01	1.929E+02	1.928E+02
4.00E-03	4.491E+01	4.491E+01	2.409E+02	2.421E+02	3.242E+01	3.242E+01	2.902E+01	2.918E+01	8.277E+01	8.277E+01
5.00E-03	2.292E+01	2.292E+01	1.737E+02	1.745E+02	1.643E+01	1.643E+01	1.469E+01	1.477E+01	4.259E+01	4.259E+01
6.00E-03	1.321E+01	1.320E+01	1.048E+02	1.053E+02	9.435E+00	9.431E+00	8.431E+00	8.474E+00	2.464E+01	2.464E+01
8.00E-03	5.561E+00	5.561E+00	4.987E+01	5.013E+01	3.975E+00	3.975E+00	3.662E+00	3.682E+00	1.037E+01	1.037E+01
1.00E-02	2.890E+00	2.890E+00	2.646E+01	2.659E+01	2.087E+00	2.087E+00	1.931E+00	1.942E+00	5.329E+00	5.330E+00
1.50E-02	9.730E-01	9.732E-01	8.268E+00	8.308E+00	7.452E-01	7.455E-01	6.942E-01	6.982E-01	1.673E+00	1.672E+00
2.00E-02	5.228E-01	5.229E-01	3.639E+00	3.657E+00	4.316E-01	4.316E-01	4.029E-01	4.050E-01	8.096E-01	8.098E-01
3.00E-02	2.940E-01	2.940E-01	1.210E+00	1.216E+00	2.707E-01	2.707E-01	2.523E-01	2.537E-01	3.755E-01	3.756E-01
4.00E-02	2.350E-01	2.350E-01	6.100E-01	6.130E-01	2.275E-01	2.275E-01	2.117E-01	2.129E-01	2.683E-01	2.683E-01
5.00E-02	2.104E-01	2.104E-01	3.928E-01	3.948E-01	2.084E-01	2.084E-01	1.937E-01	1.948E-01	2.269E-01	2.269E-01
6.00E-02	1.966E-01	1.967E-01	2.945E-01	2.959E-01	1.970E-01	1.970E-01	1.829E-01	1.840E-01	2.058E-01	2.059E-01
8.00E-02	1.802E-01	1.802E-01	2.115E-01	2.126E-01	1.823E-01	1.823E-01	1.692E-01	1.701E-01	1.836E-01	1.837E-01
1.00E-01	1.693E-01	1.693E-01	1.774E-01	1.784E-01	1.719E-01	1.719E-01	1.595E-01	1.604E-01	1.707E-01	1.707E-01
1.50E-01	1.507E-01	1.506E-01	1.427E-01	1.434E-01	1.534E-01	1.534E-01	1.423E-01	1.431E-01	1.505E-01	1.505E-01
2.00E-01	1.375E-01	1.375E-01	1.264E-01	1.270E-01	1.401E-01	1.402E-01	1.300E-01	1.307E-01	1.370E-01	1.370E-01
3.00E-01	1.192E-01	1.193E-01	1.077E-01	1.082E-01	1.216E-01	1.217E-01	1.128E-01	1.134E-01	1.187E-01	1.186E-01
4.00E-01	1.068E-01	1.068E-01	9.580E-02	9.628E-02	1.089E-01	1.089E-01	1.010E-01	1.016E-01	1.061E-01	1.061E-01
5.00E-01	9.748E-02	9.748E-02	8.724E-02	8.768E-02	9.947E-02	9.947E-02	9.224E-02	9.274E-02	9.687E-02	9.687E-02
6.00E-01	9.013E-02	9.014E-02	8.057E-02	8.098E-02	9.198E-02	9.198E-02	8.530E-02	8.576E-02	8.956E-02	8.956E-02
8.00E-01	7.916E-02	7.915E-02	7.068E-02	7.103E-02	8.078E-02	8.078E-02	7.490E-02	7.531E-02	7.866E-02	7.866E-02
1.00E+00	7.117E-02	7.117E-02	6.350E-02	6.382E-02	7.262E-02	7.262E-02	6.734E-02	6.772E-02	7.072E-02	7.072E-02
1.25E+00	6.364E-02	6.364E-02	5.678E-02	5.706E-02	6.495E-02	6.495E-02	6.022E-02	6.056E-02	6.323E-02	6.323E-02
1.50E+00	5.792E-02	5.791E-02	5.171E-02	5.197E-02	5.911E-02	5.910E-02	5.480E-02	5.510E-02	5.754E-02	5.754E-02
2.00E+00	4.965E-02	4.966E-02	4.460E-02	4.483E-02	5.064E-02	5.064E-02	4.697E-02	4.723E-02	4.941E-02	4.942E-02
3.00E+00	3.972E-02	3.972E-02	3.636E-02	3.654E-02	4.045E-02	4.045E-02	3.754E-02	3.774E-02	3.969E-02	3.969E-02
4.00E+00	3.388E-02	3.389E-02	3.174E-02	3.190E-02	3.443E-02	3.444E-02	3.198E-02	3.215E-02	3.403E-02	3.403E-02
5.00E+00	3.002E-02	3.002E-02	2.881E-02	2.895E-02	3.044E-02	3.045E-02	2.829E-02	2.845E-02	3.031E-02	3.031E-02
6.00E+00	2.728E-02	2.728E-02	2.683E-02	2.696E-02	2.761E-02	2.760E-02	2.567E-02	2.581E-02	2.770E-02	2.770E-02
8.00E+00	2.366E-02	2.366E-02	2.438E-02	2.450E-02	2.383E-02	2.383E-02	2.220E-02	2.232E-02	2.429E-02	2.429E-02
1.00E+01	2.139E-02	2.139E-02	2.300E-02	2.311E-02	2.145E-02	2.145E-02	2.001E-02	2.012E-02	2.219E-02	2.219E-02
1.50E+01	1.831E-02	1.831E-02	2.143E-02	2.154E-02	1.819E-02	1.819E-02	1.702E-02	1.712E-02	1.941E-02	1.941E-02
2.00E+01	1.681E-02	1.681E-02	2.095E-02	2.105E-02	1.658E-02	1.658E-02	1.556E-02	1.565E-02	1.813E-02	1.813E-02

- Density로 간단하게 1 g/cm-3 으로 계산함. (simulation에서 사용한 값은 pe=0.91와 bpe=1.04입니다.)
- 이 경우는 B의 농도가 30%인 경우입니다. (저희의 경우는 5%)

BKG Simulation @ HFIR

- **Result – Appling Cut 1**

$$R_{\mathrm{IBD\_mimic}} = \mathrm{R_{bkg}} \times \frac{\mathrm{R_{bkg}}\,\Delta \mathrm{t}}{1!}\,\mathrm{e}^{-\mathrm{R_{bkg}}\,\Delta \mathrm{t}} \times [1 - \{1 - \mathrm{e}^{-\mathrm{R_{bkg}}\,\mathrm{T}}\}]\,,$$
$$= \mathrm{R_{bkg}} \times \frac{\mathrm{R_{bkg}}\,\Delta \mathrm{t}}{1!}\,\mathrm{e}^{-\mathrm{R_{bkg}}\,\Delta \mathrm{t}} \times \mathrm{e}^{-\mathrm{R_{bkg}}\,\mathrm{T}}\,.$$

- R_{IBD_mimic} 는 IBD mimicking rate, R_{bkg} 는 background 이벤트 rate,
  Δt는 pair's time window, T는 첫 번째 컷의 time window이다.
- Thermal neutron background 를 비등방성으로 가정.
- MIF를 고려한 경우, R_{bkg}에 210.437 Hz, MIF를 고려하지 않은 경우에 39.157 Hz, Δt에 30 μs, T에 180 μs을 대입.
- MIF를 고려한 경우에 대략 1.27 Hz, MIF를 고려하지 않은 경우에 약 45.62 mHz의 값을 얻었음.
- Table 6의 결과와 비교하면 대략 1시그마 안에서 일치.
- [통계 에러: 약 3.56 × 10^{-3}, 6.756 × 10^{-4}) , 차이(결과-예상): 약 1 × 10^{-3}, 3 × 10^{-5}]

➢ 컷 코드는 문제없이 잘 동작한다고 판단.

BKG Simulation @ HFIR

- **Result – Appling Cut 1**
  - W/O Event Window

100,000초의 라이브 타임에서 데드 타임은 약 8.77% 인 8768.70초

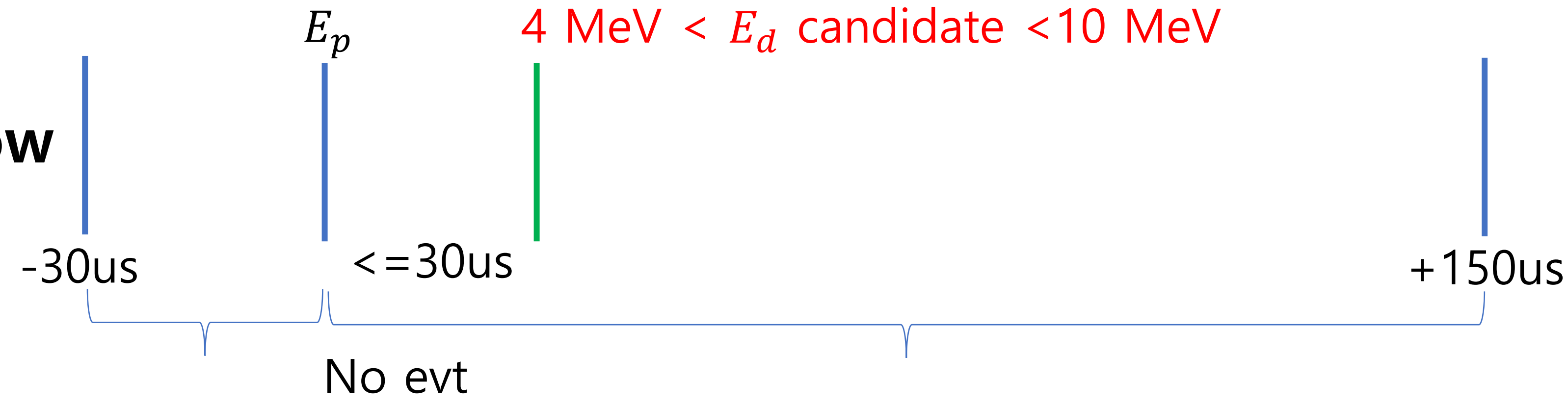
❖ S/B_{iso} = Isotropic thermal n, S/B_{aniso} = Anisotropic thermal n

	W/O MIF		W/ MIF	
Type	1 - 10 MeV	Selection Cut	1 - 10 MeV	Selection Cut
S	3.38 mHz	3.16 mHz	3.38 mHz	3.11 mHz
$B_{\rm aniso}$	39.16 Hz	45.65 mHz	210.44 Hz	1.27 Hz
$B_{\rm iso}$	56.86 Hz	95.9 mHz	228.14 Hz	1.48 Hz
$S/B_{\rm aniso}$	-	0.069	-	0.0024
$S/B_{\rm iso}$	-	0.033	-	0.0021

BKG Simulation @ HFIR

- **Result – Appling Cut 1+2**
  - W/O Event Window

100,000초의 라이브 타임에서 데드
타임은 약 8.77% 인 8768.70초



	W/O MIF		W/ MIF	
Type	1 - 10 MeV	Selection Cut	1 - 10 MeV	Selection Cut
S	3.38 mHz	2.34 mHz	3.38 mHz	2.31 mHz
B_{aniso}	39.16 Hz	6.84 mHz	210.44 Hz	35.54 mHz
B_{iso}	56.86 Hz	10.10 mHz	228.14 Hz	39.4 mHz
S/B_{aniso}	-	0.341	-	0.065
S/B_{iso}	-	0.230	-	0.059

- 1번 컷의 결과와 비교.
- MIF를 고려하지 않은 경우,

S/B_{aniso}와S/B_{iso}는 각각 약 5배, 약 7배 정도 개선.

- MIF를 고려한 경우,

S/B_{aniso}와S/B_{iso}는 각각 약 27배, 약 28배 정도 개선.

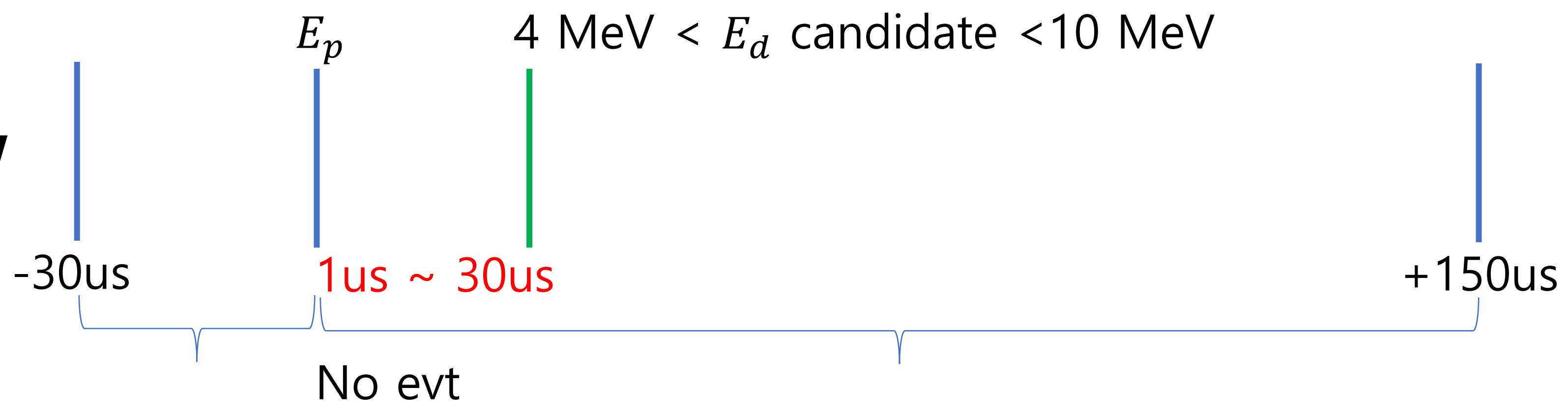
✓ 에너지 컷이 IBD를 흉내내는 background 를 많이 잘라내는데, 그 이유는 HFIR의 gamma background의 대부분이 약 3 MeV 이하 이기 때문이다.

✓ 구체적으로 HFIR의 gamma background가 RENE prototype 검출기의 main detection channel인 n-Gd capture에 의한 signal을 흉내내지 못하기 때문이다.

BKG Simulation @ HFIR

- **Result – Appling Cut 1+2+3**
  - W/O Event Window

100,000초의 라이브 타임에서 데드
타임은 약 8.77% 인 8768.70초



	W/O MIF		W/ MIF	
Type	1 - 10 MeV	Selection Cut	1 - 10 MeV	Selection Cut
S	3.38 mHz	2.32 mHz	3.38 mHz	2.30 mHz
B_{aniso}	39.16 Hz	6.63 mHz	210.44 Hz	34.31 mHz
B_{iso}	56.86 Hz	9.82 mHz	228.14 Hz	38.04 mHz
S/B_{aniso}	-	0.35	-	0.067
S/B_{iso}	-	0.237	-	0.06

- 1+2번 컷의 결과와 비교.
- MIF를 고려하지 않은 경우,

S/B_{aniso}와S/B_{iso}는 각각 약 2.6%, 3% 정도 개선.

- MIF를 고려한 경우,

S/B_{aniso}와S/B_{iso}는 각각 약 3%, 1.6% 정도 개선.

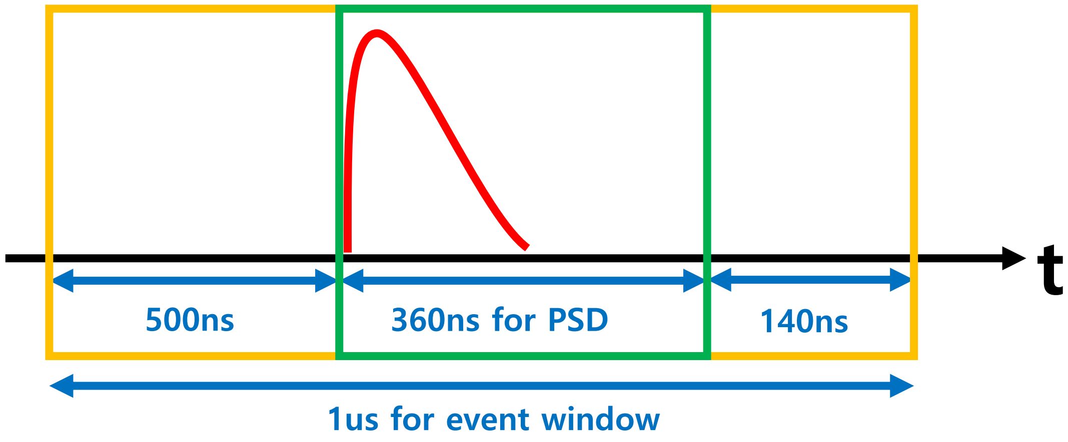
✓ Prompt – Delayed time coincidence: 1us이하인 경우는 굉장히 드물다. (RENE CDR)

BKG Simulation @ HFIR

- **Result 2 – With event window.**

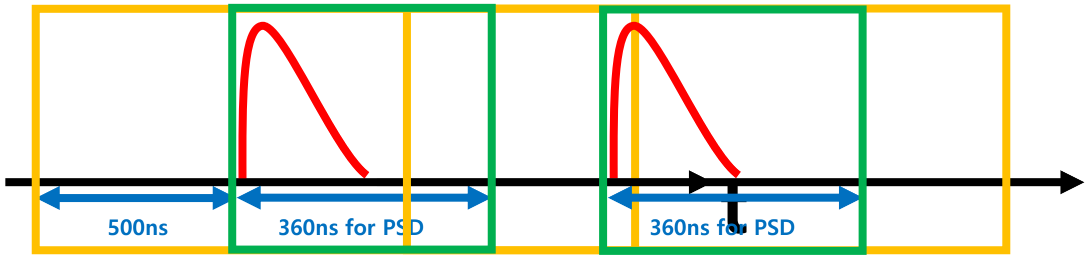
✓ **Event window를 1us 으로 설정함.**

➢ pre-trigger 를 500ns + NEOS의 PSD window가 360ns + 140ns.

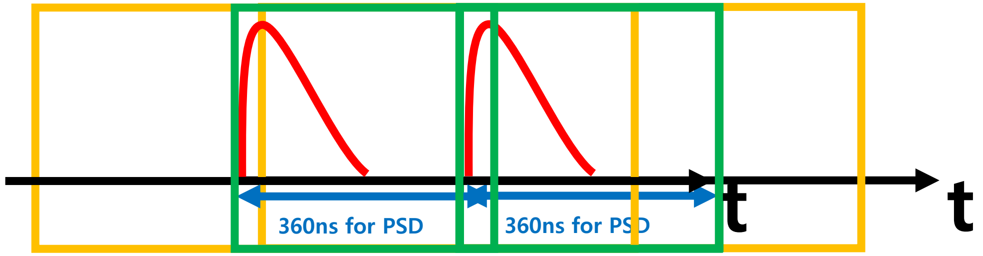


✓ **Event 분류.**

➢ Event time window가 겹친다고 해도 PSD window가 겹치지 않으면 두 개의 개별적인 event로 간주.



➢ PSD window 가 겹치면 하나의 event로 간주. (DT5730SB – overlap)

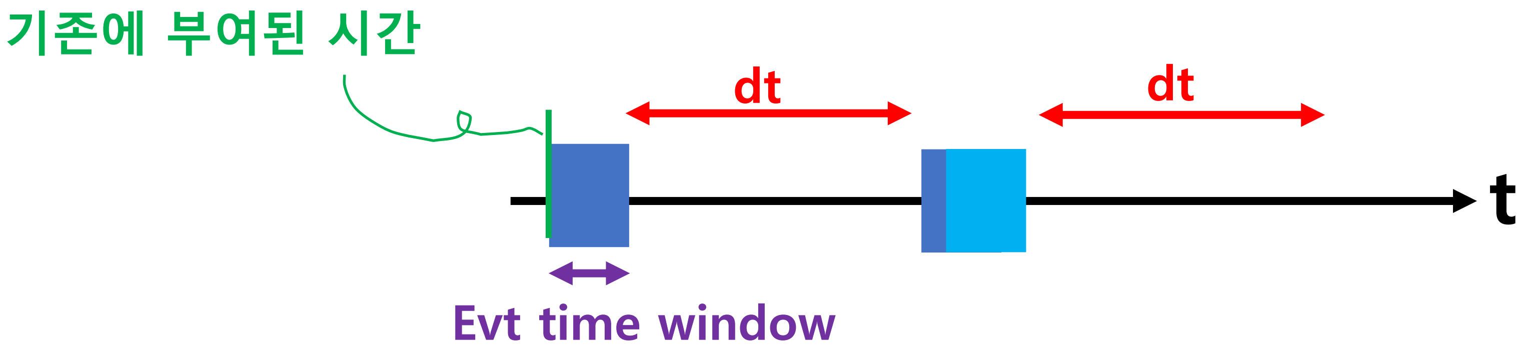


BKG Simulation @ HFIR

- **Result 2 – With event window.**

✓ **How to cut?**

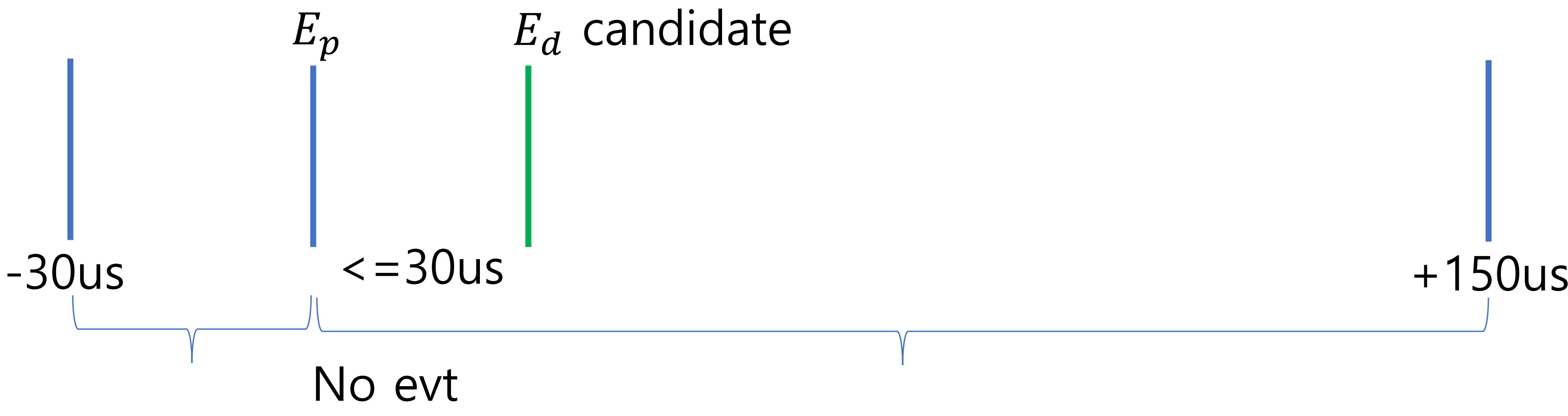
1. 이전에 언급한대로 event window를 적용하여 event를 정리.
2. 정리된 event에 muon deadtime cut을 적용.
3. Timing cut을 적용.
   - ➢ 컷을 할 때, 앞에 오는 event의 기존에 부여된 시간에서 event window 를 더한 시간과 뒤 event의 기존에 부여된 시간을 비교하여 timing cut을 적용.
   - ➢ 겹친 event의 경우에는 추가된 이벤트의 기존에 부여된 시간을 기준으로 event window 를 더하여 비교에 사용.



BKG Simulation @ HFIR

- **Result 2 – Appling Cut 1**
  - W/ Event Window

100,000초의 라이브 타임에서 데드 타임은 약 8.82% 인 8822.38초



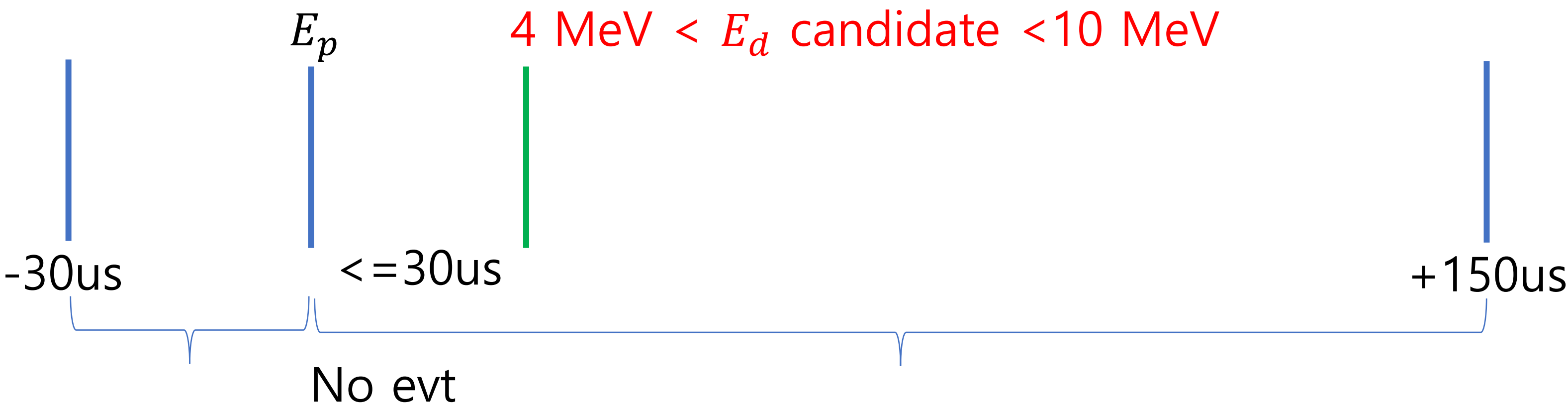
❖ S/B_{iso}= Isotropic thermal n, S/B_{aniso}= Anisotropic thermal n

	W/O MIF		W/ MIF	
Type	1 - 10 MeV	Selection Cut	1 - 10 MeV	Selection Cut
S	3.38 mHz	3.17 mHz	3.38 mHz	3.13 mHz
B_{aniso}	39.16 Hz	46.78 mHz	210.44 Hz	1.30 Hz
B_{iso}	56.86 Hz	98.36 mHz	228.14 Hz	1.52 Hz
S/B_{aniso}	-	0.0678	-	0.00240
S/B_{iso}	-	0.0322	-	0.00205

BKG Simulation @ HFIR

- **Result 2 – Appling Cut 1+2**
  - W/ Event Window

100,000초의 라이브 타임에서 데드 타임은 약 8.82% 인 8822.38초



	W/O MIF		W/ MIF	
Type	1 - 10 MeV	Selection Cut	1 - 10 MeV	Selection Cut
S	3.38 mHz	2.34 mHz	3.38 mHz	2.31 mHz
B_{aniso}	39.16 Hz	7.01 mHz	210.44 Hz	36.64 mHz
B_{iso}	56.86 Hz	10.34 mHz	228.14 Hz	40.55 mHz
S/B_{aniso}	-	0.333	-	0.0632
S/B_{iso}	-	0.226	-	0.0571

- 1번 컷의 결과와 비교.
- MIF를 고려하지 않은 경우,

S/B_{aniso}와S/B_{iso}는 각각 약 5배, 약 7배 정도 개선.

- MIF를 고려한 경우,

S/B_{aniso}와S/B_{iso}는 각각 약 26배, 약 28배 정도 개선.

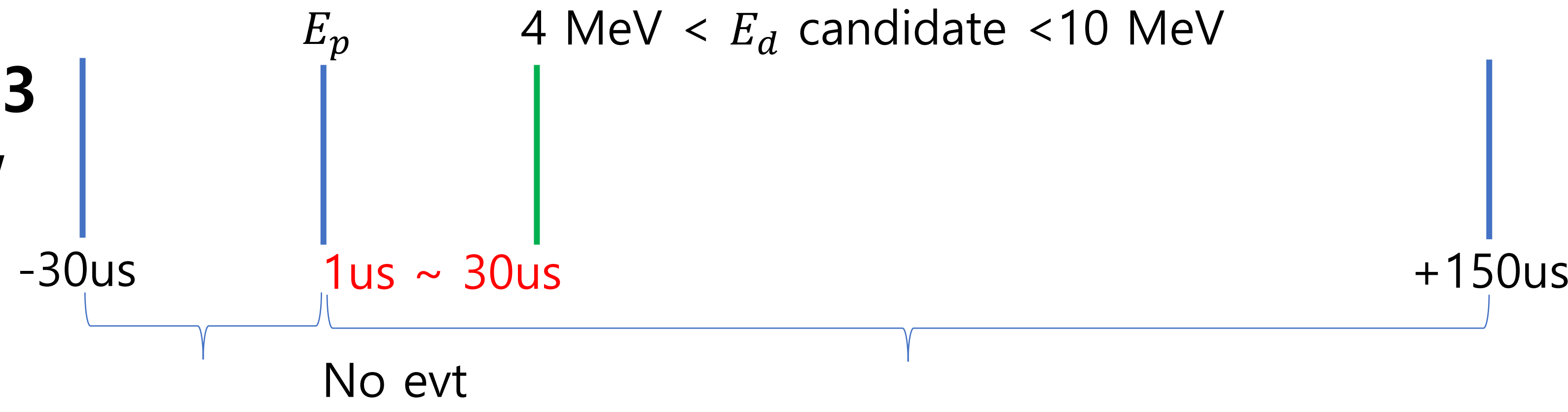
✓ 에너지 컷이 IBD를 흉내내는 background 를 많이 잘라내는데, 그 이유는 HFIR의 gamma background의 대부분이 약 3 MeV 이하 이기 때문이다.

✓ 구체적으로 HFIR의 gamma background가 RENE prototype 검출기의 main detection channel인 n-Gd capture에 의한 signal을 흉내내지 못하기 때문이다.

BKG Simulation @ HFIR

- **Result 2 – Appling Cut 1+2+3**
  - W/ Event Window

100,000초의 라이브 타임에서 데드 타임은 약 8.82% 인 8822.38초



	W/O MIF		W/ MIF	
Type	1 - 10 MeV	Selection Cut	1 - 10 MeV	Selection Cut
S	3.38 mHz	2.27 mHz	3.38 mHz	2.25 mHz
B_{aniso}	39.16 Hz	6.73 mHz	210.44 Hz	34.56 mHz
B_{iso}	56.86 Hz	9.84 mHz	228.14 Hz	38.18 mHz
S/B_{aniso}	-	0.337	-	0.0651
S/B_{iso}	-	0.231	-	0.0589

- 1+2번 컷의 결과와 비교.
- MIF를 고려하지 않은 경우, S/B_{aniso}와S/B_{iso}는 각각 약 1.2%, 2.2% 정도 개선.

- MIF를 고려한 경우, S/B_{aniso}와S/B_{iso}는 약 3% 정도 개선.

✓ Prompt – Delayed time coincidence: 1us이하인 경우는 굉장히 드물다. (RENE CDR)

BKG Simulation @ HFIR

- **Results – 세부 결과: W/O Event Window**
  - Cut 1

Anisotropic + W/O MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	41.76	0.13	1.68
S1	Fast n	0.11	0.00	0.00
S1	Thermal n	1.87	0.00	0.10

* Unit: mHz

Isotropic + W/O MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	41.62	0.13	21.97
S1	Fast n	0.11	0.00	0.00
S1	Thermal n	21.17	0.00	10.79

* Unit: mHz

Anisotropic + W/ MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	1.25×10^3	0.62	10.40
S1	Fast n	0.67	0.00	0.00
S1	Thermal n	9.94	0.00	0.10

* Unit: mHz

Isotropic + W/ MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	1.24×10^3	0.62	115.20
S1	Fast n	0.67	0.00	0.07
S1	Thermal n	115.50	0.07	10.47

* Unit: mHz

BKG Simulation @ HFIR

- **Results – 세부 결과: W/O Event Window**
  - Cut 1 + 2

Anisotropic + W/O MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	6.35	0.04	0.10
	Fast n	0.01	0.00	0.00
	Thermal n	0.33	0.00	0.01

* Unit: mHz

Isotropic + W/O MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	6.35	0.04	0.32
	Fast n	0.01	0.00	0.00
	Thermal n	3.33	0.00	0.11

* Unit: mHz

Anisotropic + W/ MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	34.59	0.19	0.42
	Fast n	0.01	0.00	0.00
	Thermal n	0.32	0.00	0.01

* Unit: mHz

Isotropic + W/ MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	34.46	0.19	1.44
	Fast n	0.01	0.00	0.00
	Thermal n	3.23	0.00	0.10

* Unit: mHz

BKG Simulation @ HFIR

- **Results – 세부 결과: W/O Event Window**
  - Cut 1 + 2 + 3

Anisotropic + W/O MIF

Mimic IBD		S2		
		Gamma	Fast n	Thermal n
S1	Gamma	6.16	0.04	0.10
	Fast n	0.01	0.00	0.00
	Thermal n	0.31	0.00	0.01

* Unit: mHz

Isotropic + W/O MIF

Mimic IBD		S2		
		Gamma	Fast n	Thermal n
S1	Gamma	6.14	0.04	0.30
	Fast n	0.01	0.00	0.00
	Thermal n	3.22	0.00	0.11

* Unit: mHz

Anisotropic + W/ MIF

Mimic IBD		S2		
		Gamma	Fast n	Thermal n
S1	Gamma	33.40	0.19	0.41
	Fast n	0.01	0.00	0.00
	Thermal n	0.30	0.00	0.01

* Unit: mHz

Isotropic + W/ MIF

Mimic IBD		S2		
		Gamma	Fast n	Thermal n
S1	Gamma	33.27	0.19	1.34
	Fast n	0.01	0.00	0.00
	Thermal n	3.13	0.00	0.10

* Unit: mHz

BKG Simulation @ HFIR

- **Results – 세부 결과: W/ Event Window**
  - Cut 1

Anisotropic + W/O MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	42.78	0.14	1.73
S1	Fast n	0.11	0.00	0.00
S1	Thermal n	1.92	0.00	0.10

* Unit: mHz

Isotropic + W/O MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	42.65	0.14	22.49
S1	Fast n	0.11	0.00	0.07
S1	Thermal n	21.75	0.07	11.08

* Unit: mHz

Anisotropic + W/ MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	1.28×10^3	0.64	10.59
S1	Fast n	0.68	0.00	0.00
S1	Thermal n	10.25	0.00	0.10

* Unit: mHz

Isotropic + W/ MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	1.27×10^3	0.64	118.90
S1	Fast n	0.68	0.00	0.07
S1	Thermal n	118.48	0.07	10.74

* Unit: mHz

BKG Simulation @ HFIR

- **Results – 세부 결과: W/ Event Window**
  - Cut 1 + 2

Anisotropic + W/O MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	6.49	0.05	0.10
	Fast n	0.01	0.00	0.00
	Thermal n	0.34	0.00	0.01

* Unit: mHz

Isotropic + W/O MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	6.47	0.05	0.32
	Fast n	0.01	0.00	0.00
	Thermal n	3.38	0.00	0.11

* Unit: mHz

Anisotropic + W/ MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	35.68	0.20	0.42
	Fast n	0.01	0.00	0.00
	Thermal n	0.33	0.00	0.01

* Unit: mHz

Isotropic + W/ MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	35.55	0.20	1.43
	Fast n	0.01	0.00	0.00
	Thermal n	3.27	0.00	0.10

* Unit: mHz

BKG Simulation @ HFIR

- **Results – 세부 결과: W/ Event Window**
  - Cut 1 + 2 + 3

Anisotropic + W/O MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	6.23	0.05	0.10
	Fast n	0.01	0.00	0.00
	Thermal n	0.33	0.00	0.01

* Unit: mHz

Isotropic + W/O MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	6.21	0.05	0.30
	Fast n	0.01	0.00	0.00
	Thermal n	3.16	0.00	0.11

* Unit: mHz

Anisotropic + W/ MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	33.64	0.19	0.39
	Fast n	0.01	0.00	0.00
	Thermal n	0.32	0.00	0.01

* Unit: mHz

Isotropic + W/ MIF

Mimic IBD		S2 Gamma	S2 Fast n	S2 Thermal n
S1	Gamma	33.51	0.19	1.31
	Fast n	0.01	0.00	0.00
	Thermal n	3.07	0.00	0.10

* Unit: mHz

BKG Simulation @ HFIR

- **Event window 코드 확인 – properly working.**

➢ 아래와 같이 PSD window에 겹치면 하나의 event로 간주하고, 에너지는 합친다.
➢ 그리고 dT는 하나의 event로 간주된 경우의 기존에 부여된 시간 차이로, 컷을 할 때 event의 시간 폭을 고려하기 위해 사용.
➢ (아래에서 시간 차이가 360ns안에 들어오면 하나의 event로 간주 & 확인을 위해 임의의 값을 넣음.)

Type	Time	Energy	pe
1	1	3124512	1249214
4	1000	23123214	1523513
1	1100	23123214	1523513
4	1600	23123214	15235135
7	1800	23123214	1523513
4	2700	23123214	1523513
5	5000	23123214	1523513
4	5200	23123214	1523513
4	7275	23123214	1523513
1	7400	1111	232134
3	10000	23123214	1523513
7	10111	23123214	1523513
5	15000	23123214	1523513
1	20000	23123214	1523513

Type	Time	Energy	pe	dT
1	1.000000	3124512.000000	1249214	0.000000
4	1000.000000	46246428.000000	3047026	100.000000
7	1600.000000	46246428.000000	16758648	200.000000
4	2700.000000	23123214.000000	1523513	0.000000
5	5000.000000	46246428.000000	3047026	200.000000
4	7275.000000	23124325.000000	1755647	125.000000
7	10000.000000	46246428.000000	3047026	111.000000
5	15000.000000	23123214.000000	1523513	0.000000
1	20000.000000	23123214.000000	1523513	0.000000

➢ 실제 코드 동작 일부:

종류	시간		에너지	
7	18281355500	[redacted]	114.703539	289311
4	18282311270	[redacted]	1.118996	1681
7	18282311270	[redacted]	38.537892	59672
7	18282467266	[redacted]	102.484852	154864

종류	시간		에너지	pe	dT
7	18281355500	[redacted]	114.703539	289311	0.000000
7	18282311270	[redacted]	39.656888	61353	0.000000
7	18282467266	[redacted]	102.484852	154864	0.000000
7	18284715479	[redacted]	39.845431	62603	0.000000

종류	시간		에너지	
7	21790880942	[redacted]	147.040101	230009
7	21794996690	[redacted]	11.893596	0
7	21796803455	[redacted]	0.026205	32
7	21796803455	[redacted]	122.807212	185329
7	21796854911	[redacted]	139.693693	212166

종류	시간		에너지	pe	dT
7	21794996690	[redacted]	11.893596	0	0.000000
7	21796803455	[redacted]	122.833417	185361	0.000000
7	21796854911	[redacted]	139.693693	212166	0.000000
7	21798190893	[redacted]	145.971442	219247	0.000000
7	21798940608	[redacted]	144.336299	290431	0.000000