RADSAGA seminar: Friday 6th October, 16:00-16:45, building 6 -2 -024 BE auditorium Meyrin

Neutron measurements at CHARM

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 - High energy accelerator research organization (KEK)

on behalf of CHARM/CSBF experimental group
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T. Kajimoto (Hiroshima-U), N. Nakao (Shimizu-Co),
E.J Lee, N. Shigyo (Kyushu-U), H. Yashima (Kyoto-U),
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Contents

- Neutron

Discovered by J.Chadwick on 1932
Baryon: udd
Mass : 1.674927.. x 10^{-27} kg
Mean life : 886.7 sec
Uncharged

  - Nuclear interaction is required to shield and detect

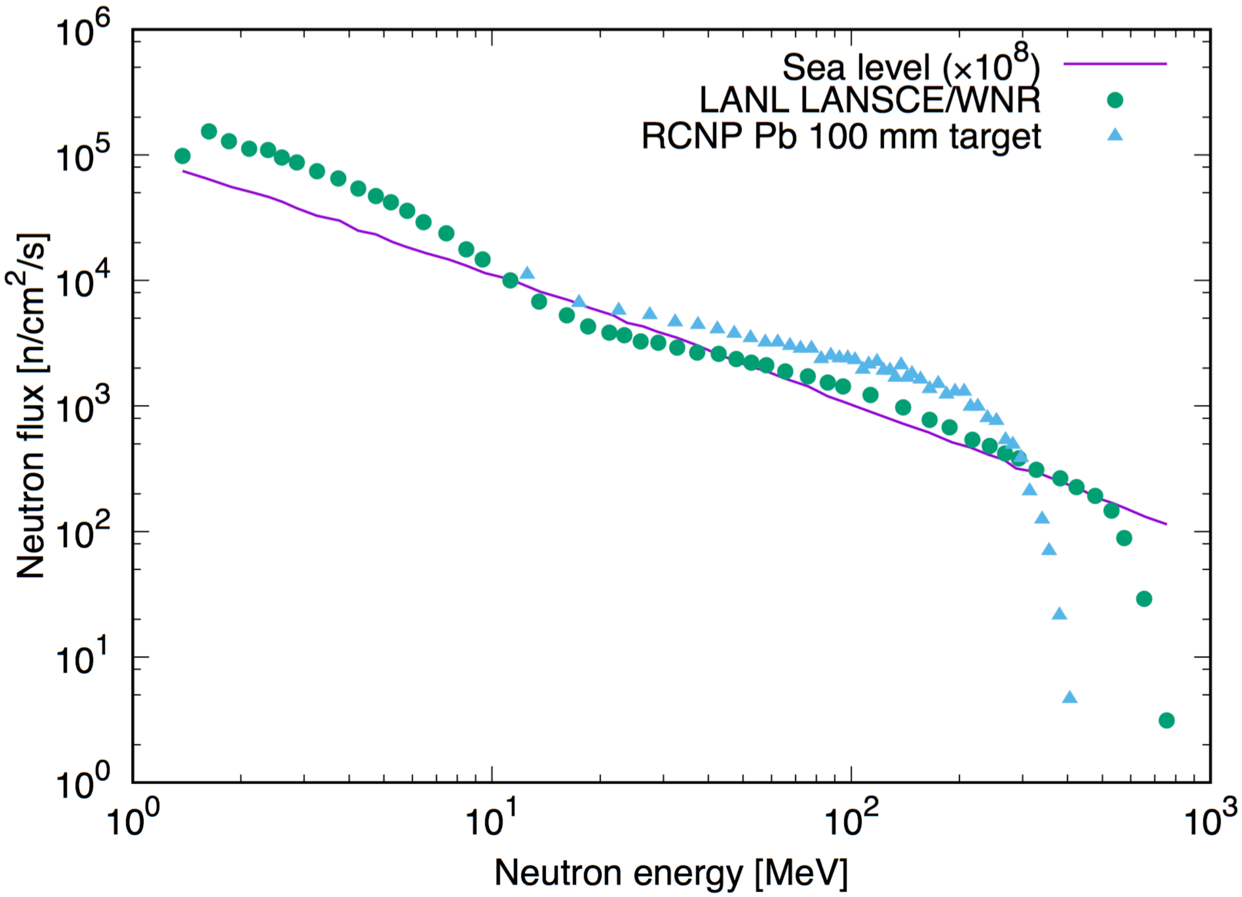
- In this talk

  - General features of neutron field, spectrum, simulation, attenuation length and measurement

  - Introduce an activity of neutron spectrum measurement at CERN CHARM facility

High energy neutron field

- Sea level environmental neutron spectrum
- White neutron can be produced by proton on thick metal target, LANSCE, RCNP, etc
- Testing devices
- Quasi-mono energetic by $^{7}Li(p,n)$ reaction



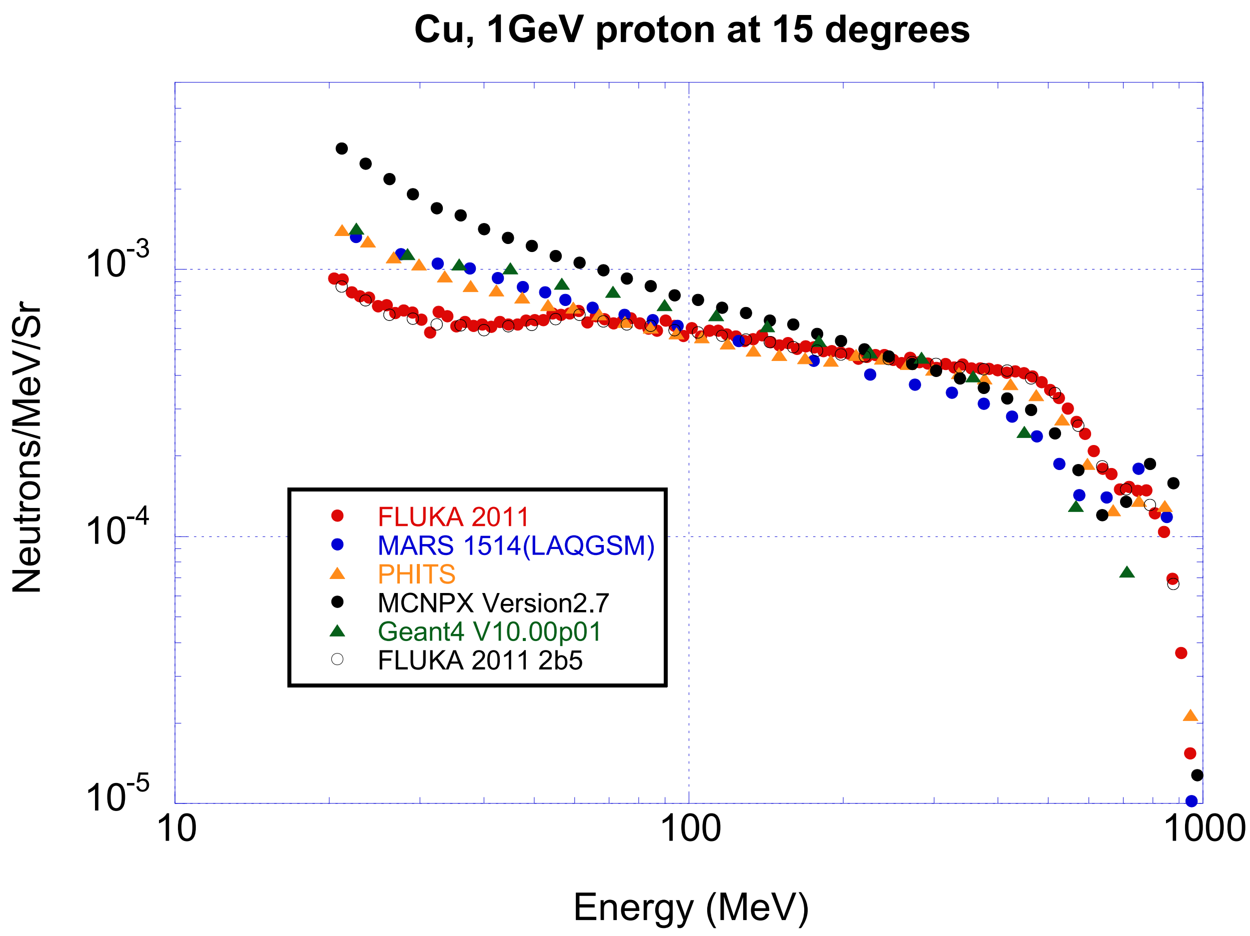
http://www.rcnp.osaka-u.ac.jp/Divisions/np1-a/RCF/RCNPCF-WNt.html

http://lansce.lanl.gov/facilities/wnr/flight-paths/ice-house/about.php

The neutron spectra of the fields are experimentally confirmed

Simulation codes

- Cross comparison among simulation codes
- Proton 10 GeV on Cu
  Target : 8.63 g/cm3
  16cmL-1.6cmD
- Neutron spectrum at 500 cm, ±0.5 degrees



H.Hirayama and T.sanami at SATIF13 10-12 Oct. 2016 at Dresden

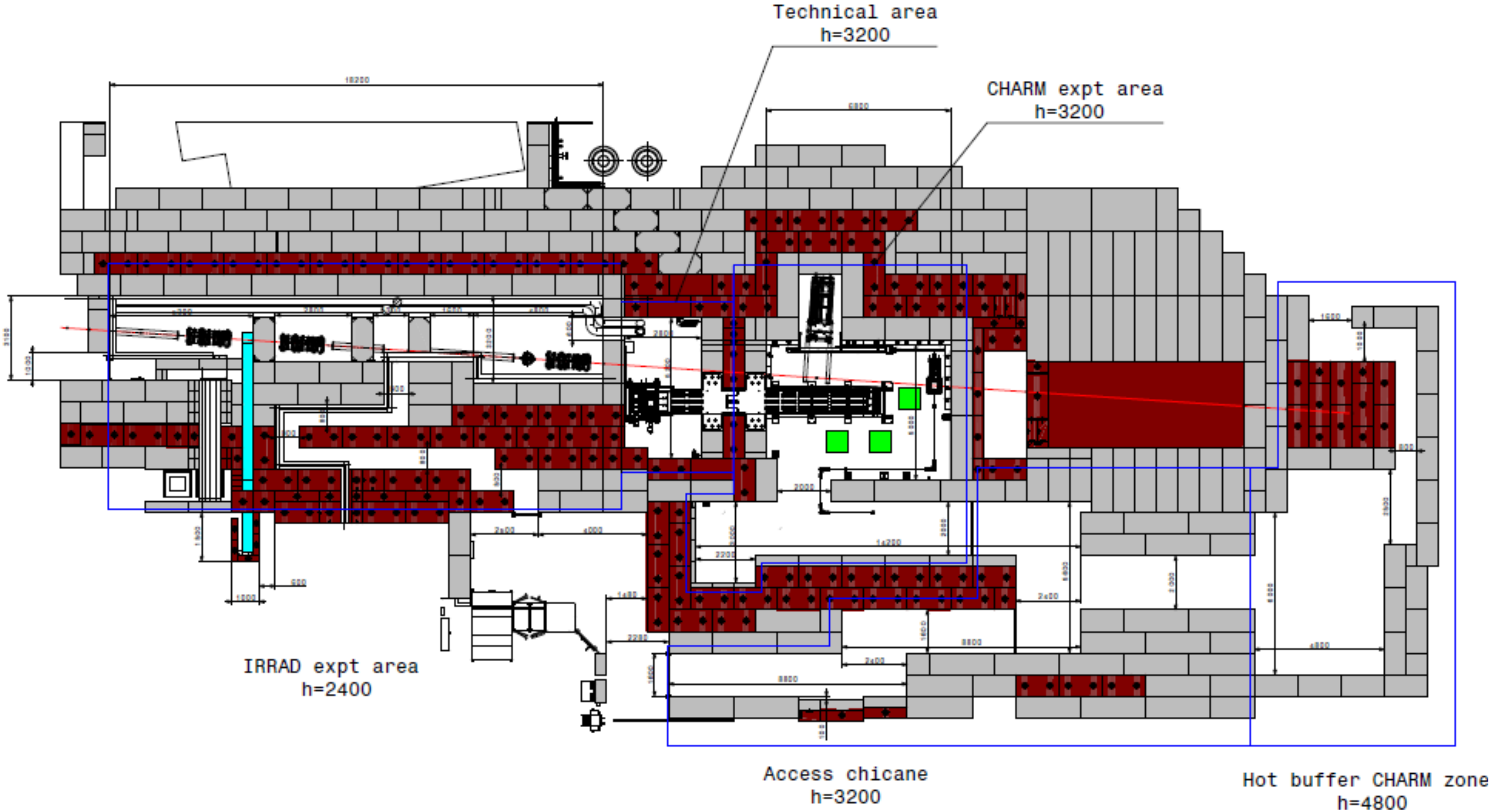
Results of calculation should be confirmed through experiment

Facility for neutron (mixed) field at CERN

- CERN also has the field in east hall

CHARM

- 24 GeV/c proton on target
  - Many of unique features instead of one disadvantage

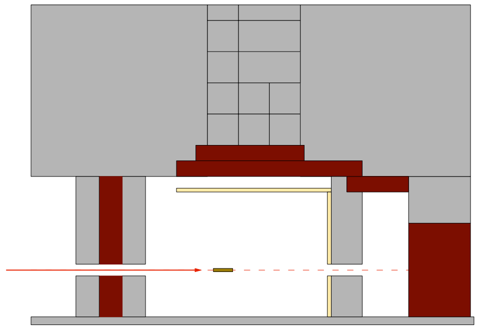


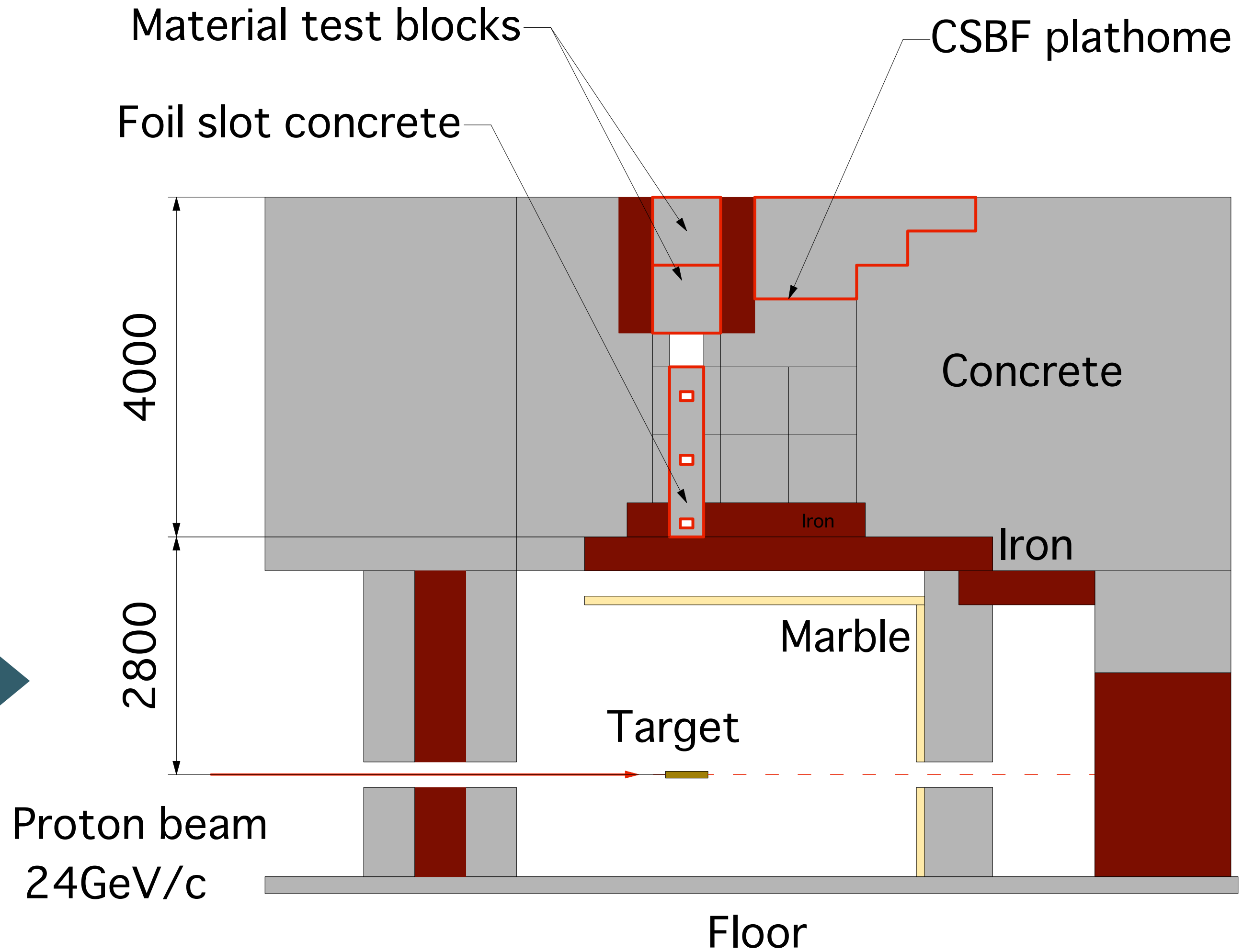
CHARM

- Intense, high energy beam makes high energy mixed field
- Change energy spectrum and charged/non-charged ratio by changing the position, sliding wall and target
- Well designed shielding structure and air ventilation system
- But, no pulse beam. TOF is not applicable.
    - Measure neutron spectrum with another technique
- Difficult to measure neutron inside simply putting detector because too intense, highly activated and mixed field
- Start measurement from outside, then become closer.

CERN Shielding Benchmark Facility (CSBF)

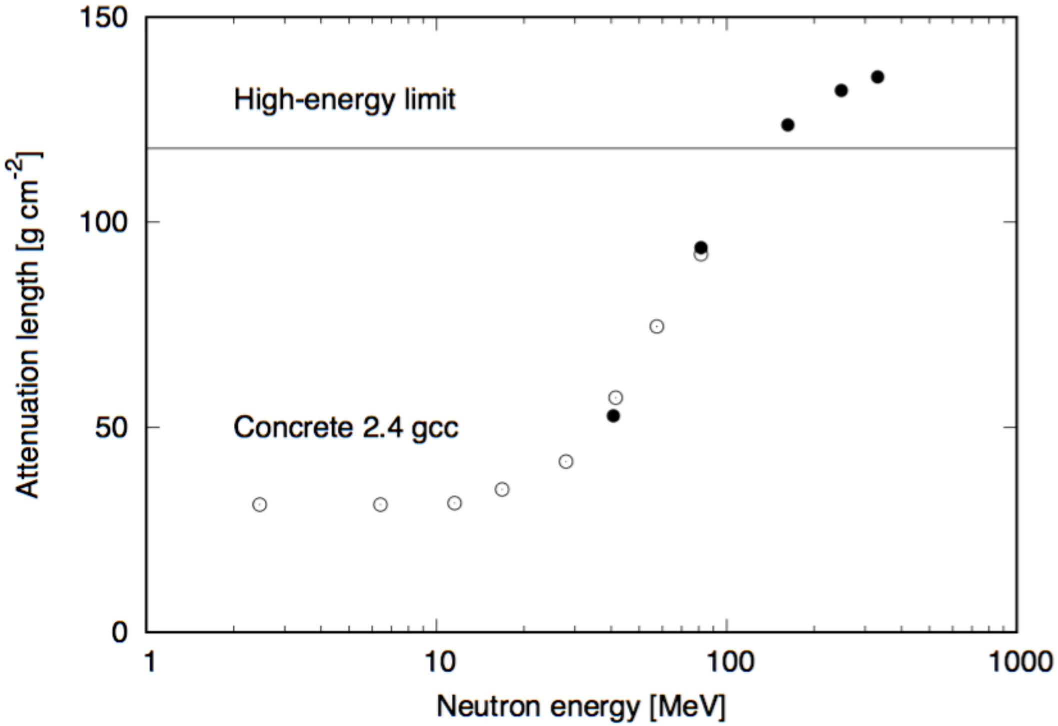
- Target : Cu, Al, Low density Al, Blank
- 24 GeV/c, 0.2 ～50 × 10^{10} p/spill, 6× 10^{10} p/sec (230W)
- Foil slot
- Material test blocks





CSBF

- Neutron transport in material depends on their energy (spectrum)
- Attenuation length is widely used for bulk shielding design



Taken from handbook of spallation research

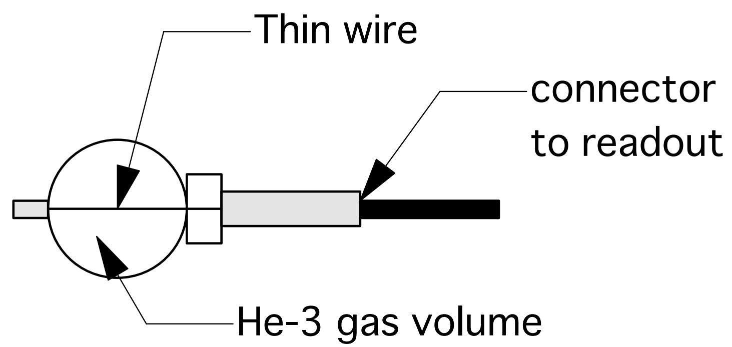
- Attenuation length, neutron energy spectra can be obtained for various materials
- Quick sample extraction for short lived nuclei measurement
- High energy irradiation field for dosimeter calibration

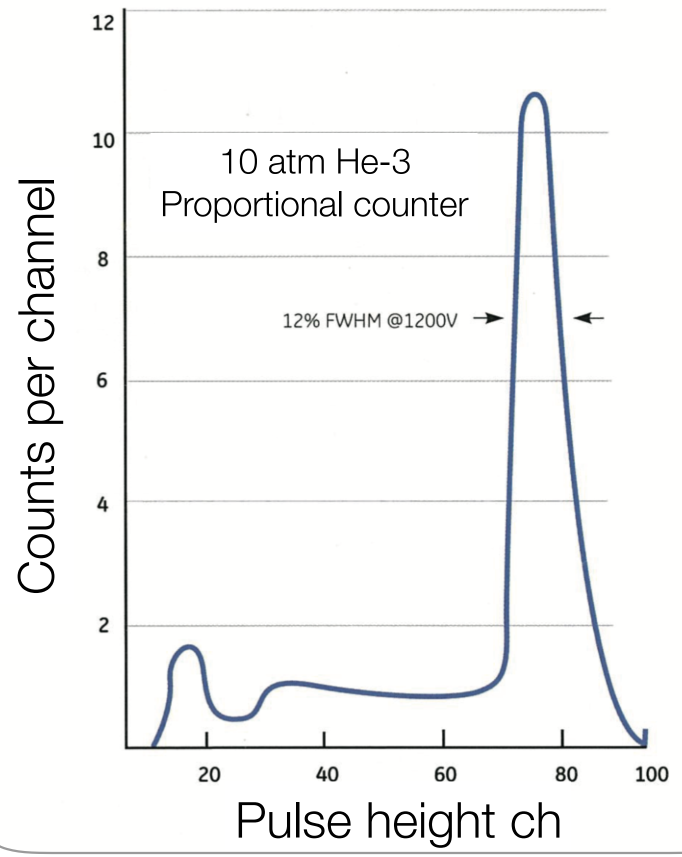
Experiment

- FY2015
  - Activation (Bi/Al) and unfolding method on top roof and corridor with nominal intensity beam (50×10^{10} p/spill)
- FY2016
  - Activation (Bi/Al/In) and unfolding method on top roof with revised geometry with down to 10×10^{10} p/spill beam
- FY2017
  - Activation (Bi/Al/In/C) and unfolding method on top roof with revised geometry with down to 0.2×10^{10} p/spill beam, and activation test (Au/Bi/Al) inside the cave

He-3 neutron counter

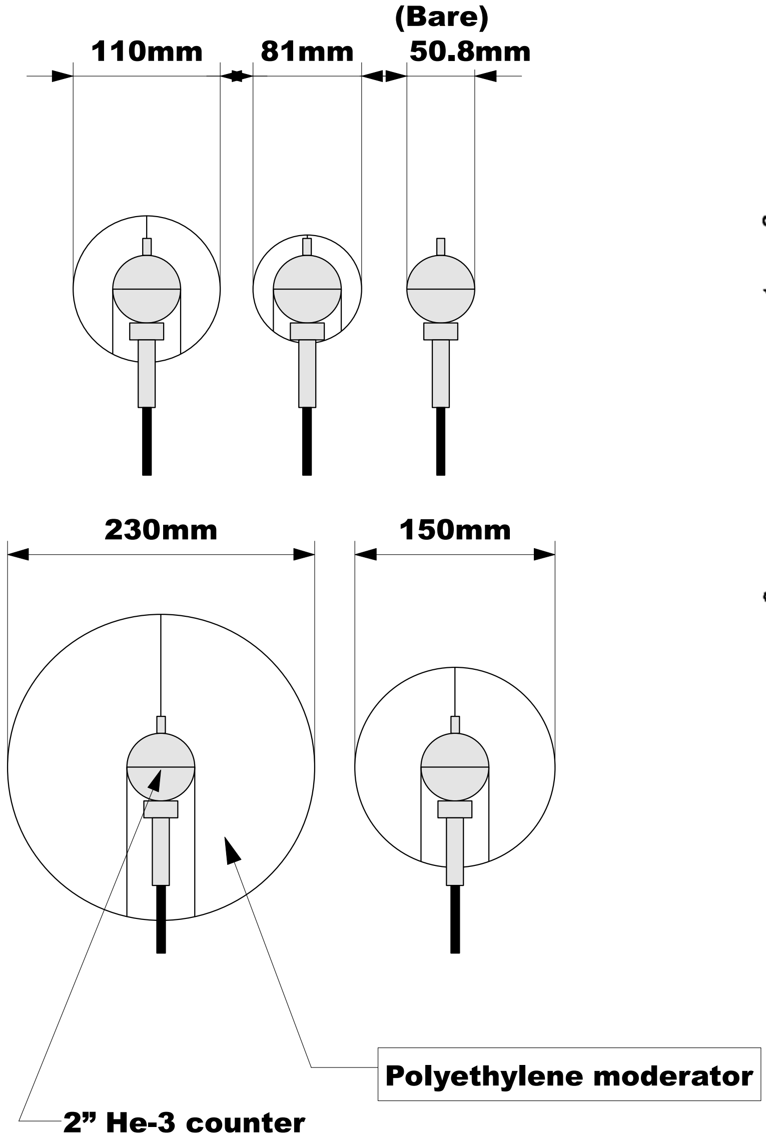
- ^{3}He spherical gas proportional counter
  - ^{3}He(n,p)t Q=0.765 MeV
  - E_p=0.574 MeV, E_t=0.191 MeV
  - 5330 barn for thermal neutron
- High sensitivity for thermal neutron
- The high Q-value helps to distinguish neutron events form gamma and noise

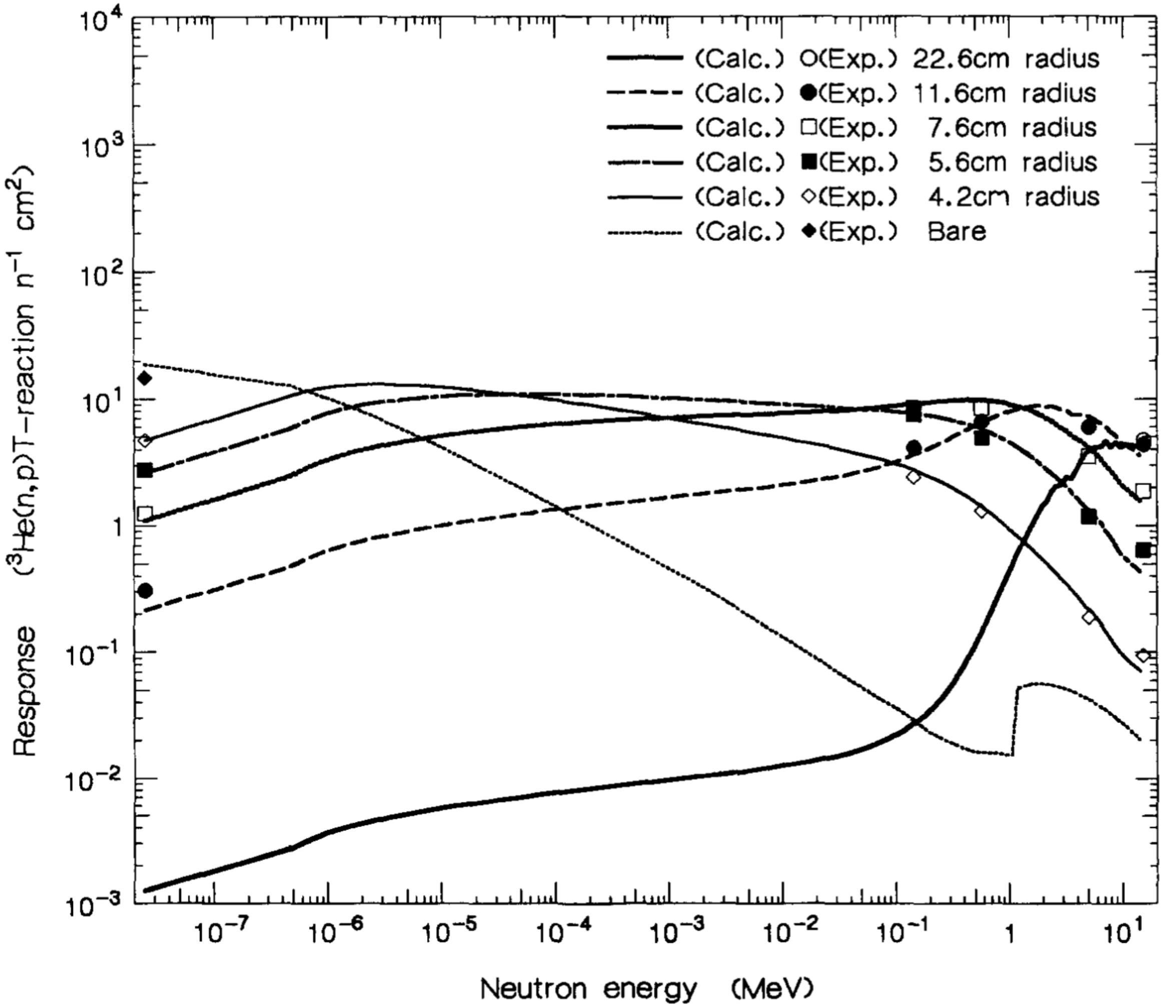




Bonner sphere

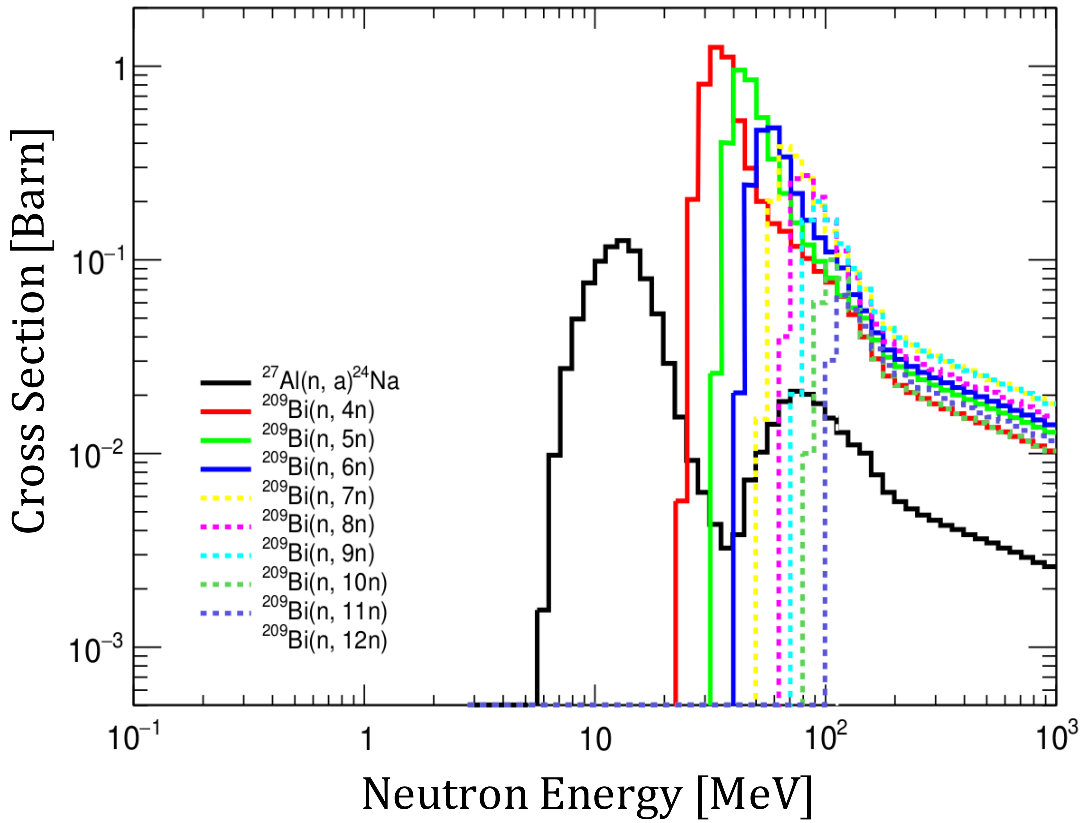
- ^{3}He spherical gas proportional counter and several moderators





Activation

- Threshold activation

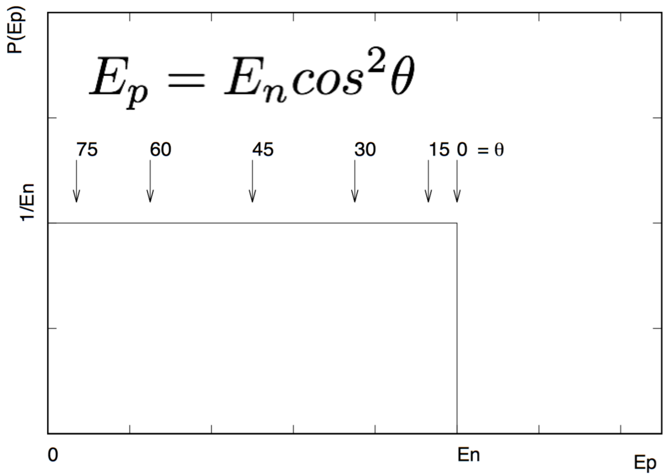


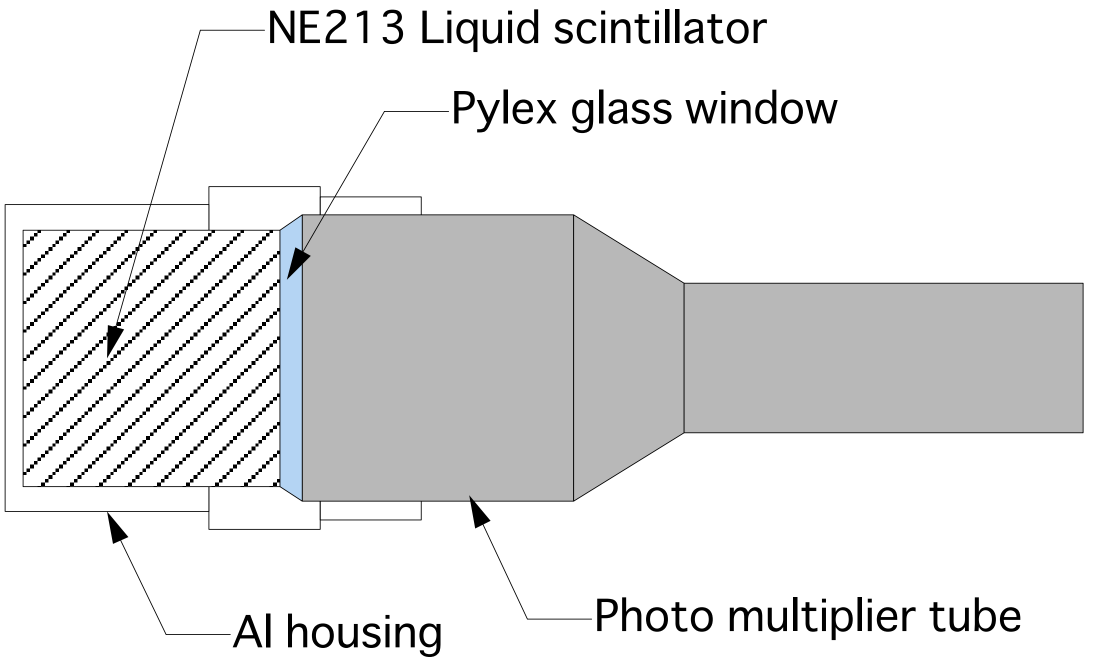
F. Maekawa et al., "Production of a Dosimetry Cross Section Set Up to 50 MeV", Proc. 10th International Symposium on Reactor Dosimetry, Sep. 12-17, 1999, Osaka, Japan p.417, American Society for Testing and Materials (2001).

Reaction	Half life	Threshold [MeV]
$^{12}C(n,2n)^{11}C$	20.4 min	20.4
$^{27}Al(n,\alpha)^{24}Na$	14.997 hrs	3.247
$^{209}Bi(n,10n)^{200}Bi$	36.4 min	70.89
$^{209}Bi(n,9n)^{201}Bi$	1.77 hrs	61.69
$^{209}Bi(n,8n)^{202}Bi$	1.67 hrs	54.24
$^{209}Bi(n,7n)^{203}Bi$	11.76 hrs	45.17
$^{209}Bi(n,6n)^{204}Bi$	11.22 hrs	38.13
$^{155}In(n,\gamma)^{116m}In$	54.1 min	Thermal

Unfolding

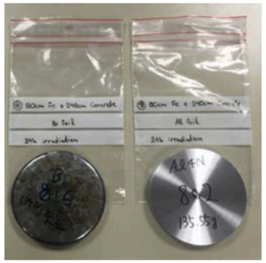
- NE213 liquid scintillator
  - Fast timing [less than 10 ns rise time]
  - neutron gamma separation
  - High detection efficiency
  - Unfolding capability





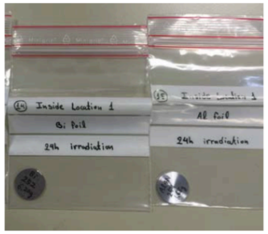
Measurement (Activation)

- Activation

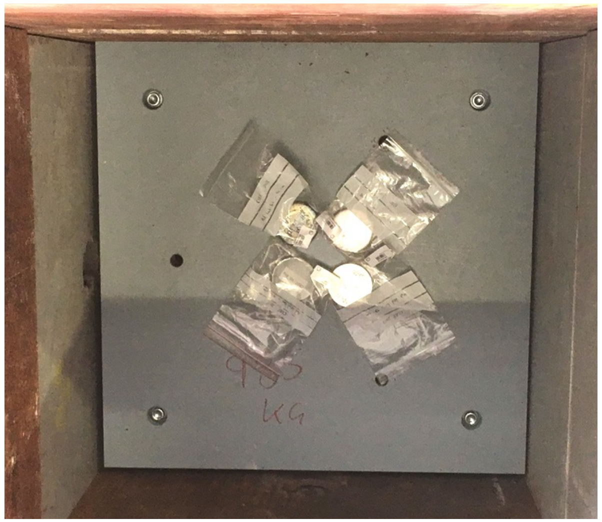


Φ8cm x 1cm厚
Bi: 500g
Al: 135g

Φ4cm x 0.4cm厚
Bi: 50g
Al: 13.3g



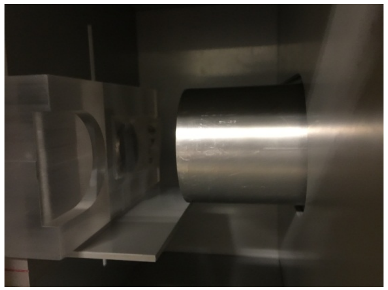
Φ2cm x 0.2cm厚
Bi: 6.2g
Al: 1.7g

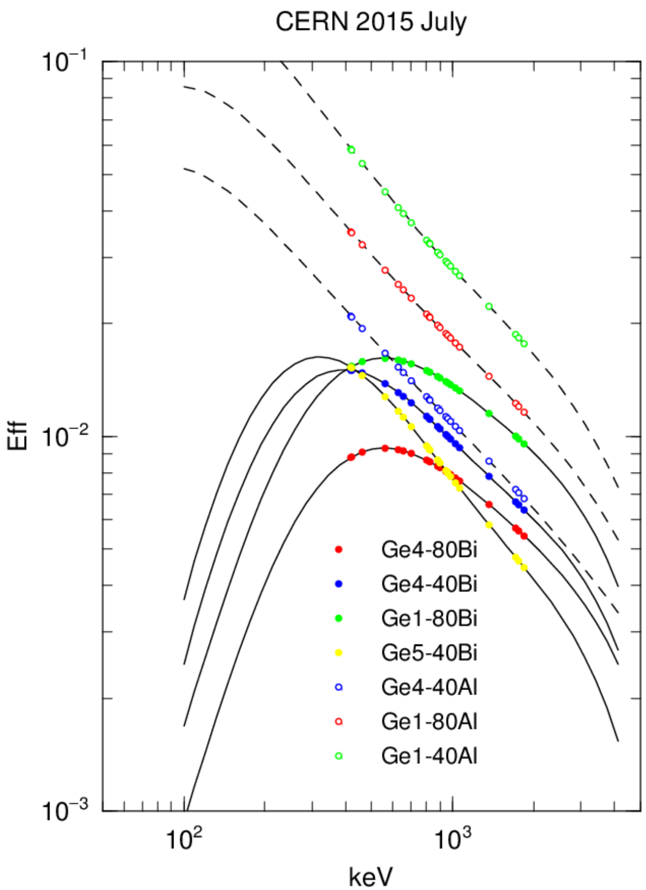


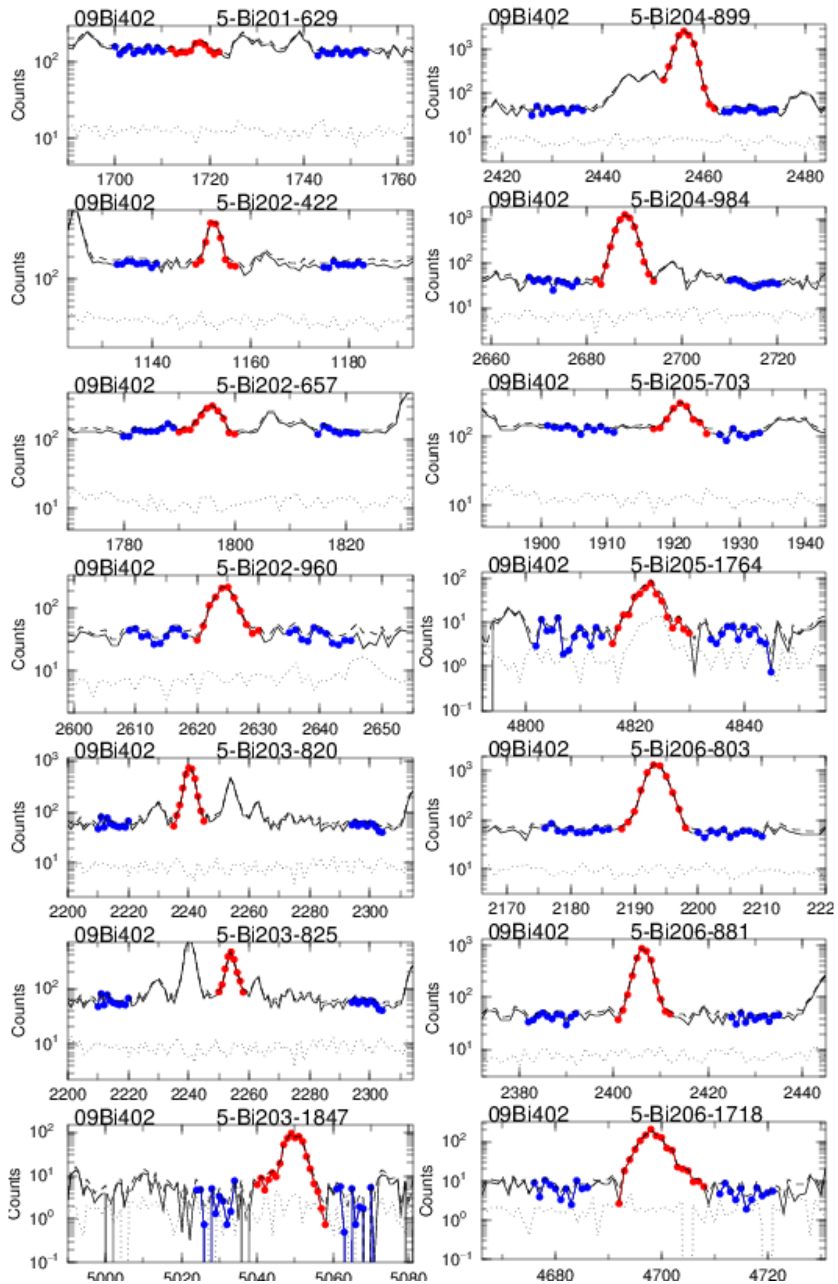
Data analysis (Activation)

- Gamma spectrometry
  - Determine induced activity through photon counting

Ge-4 (60%)

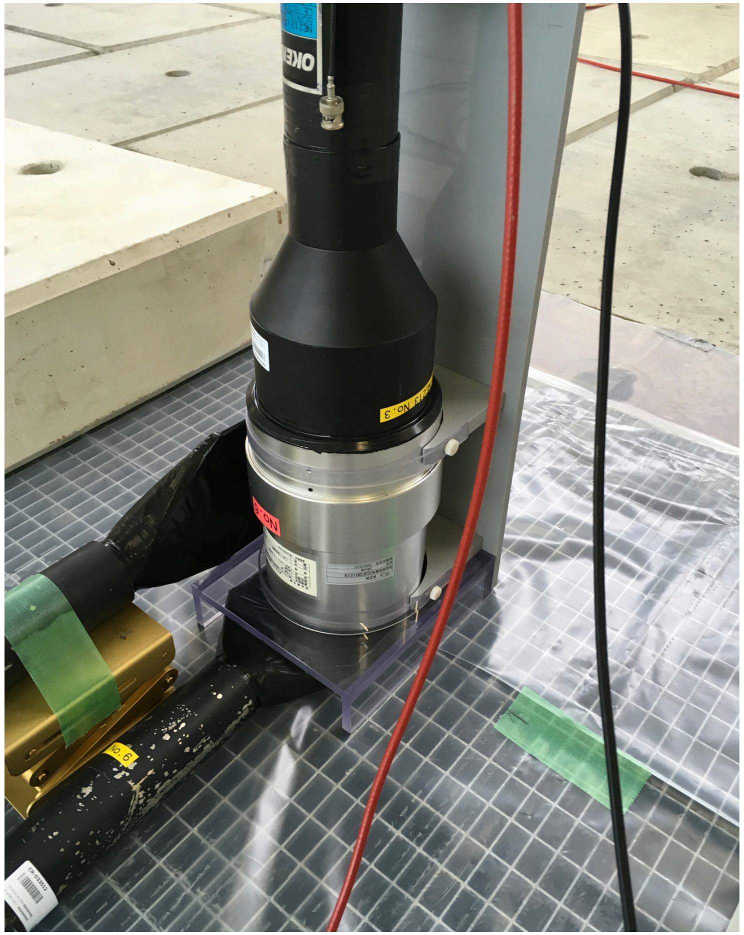


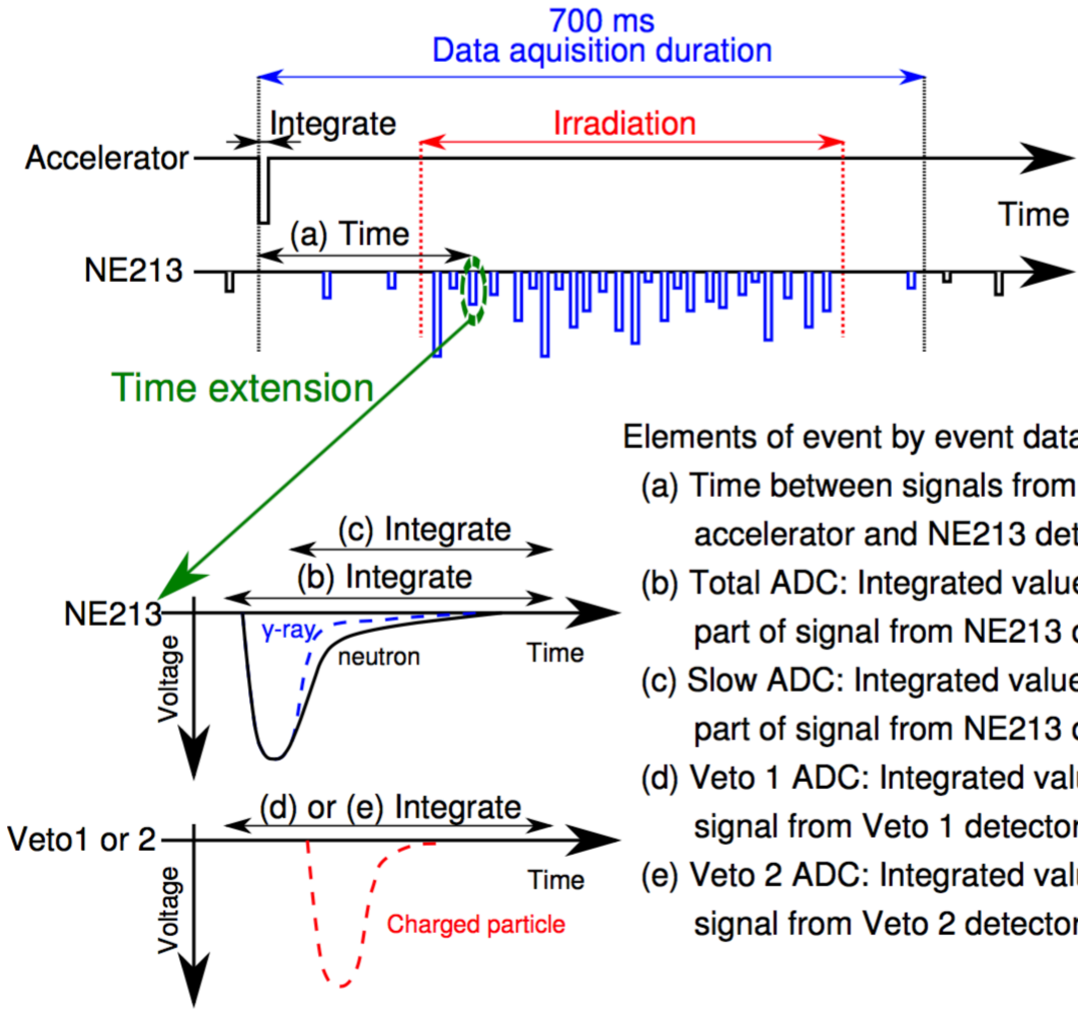




Measurement (Unfolding)

- NE213

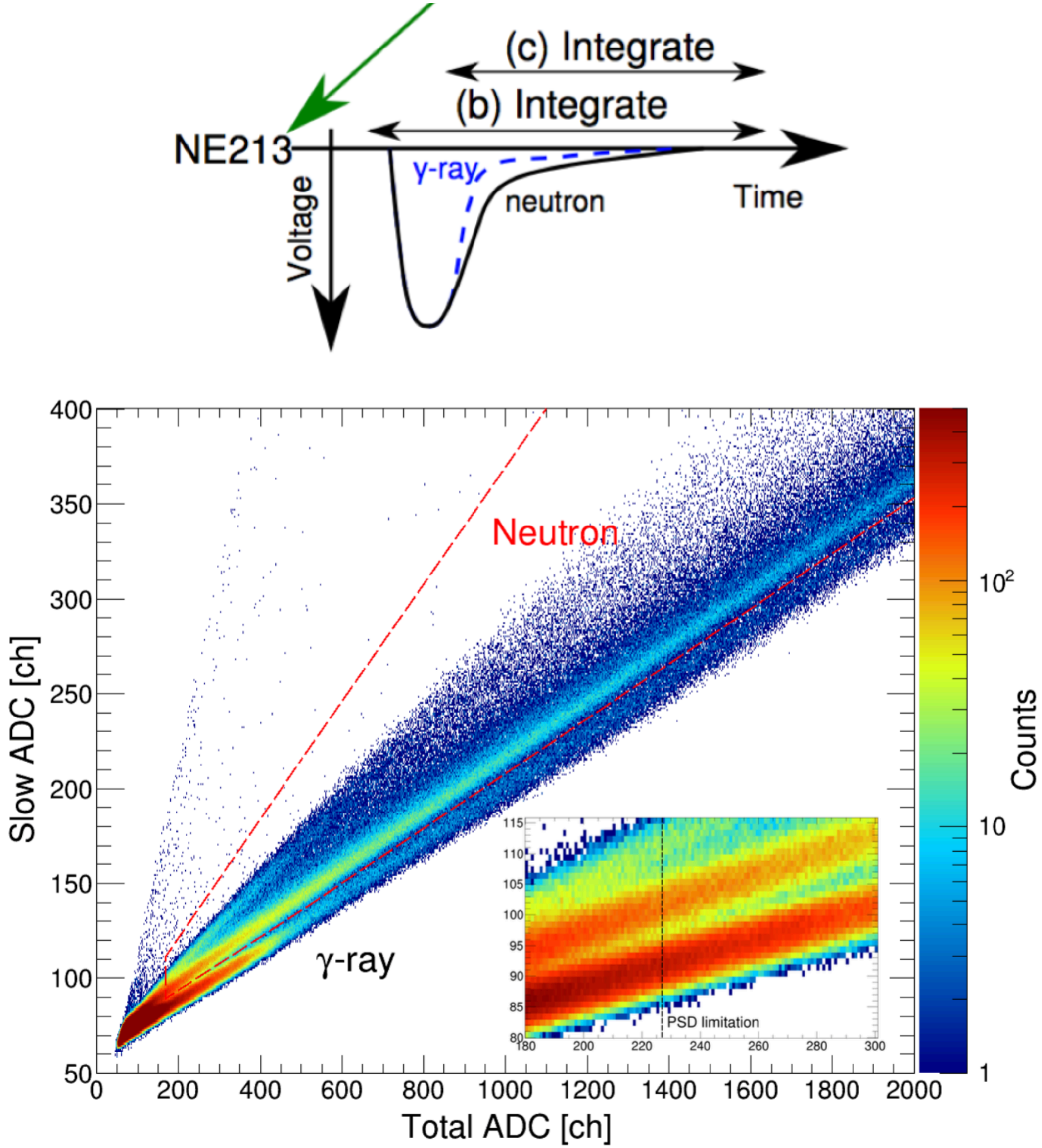


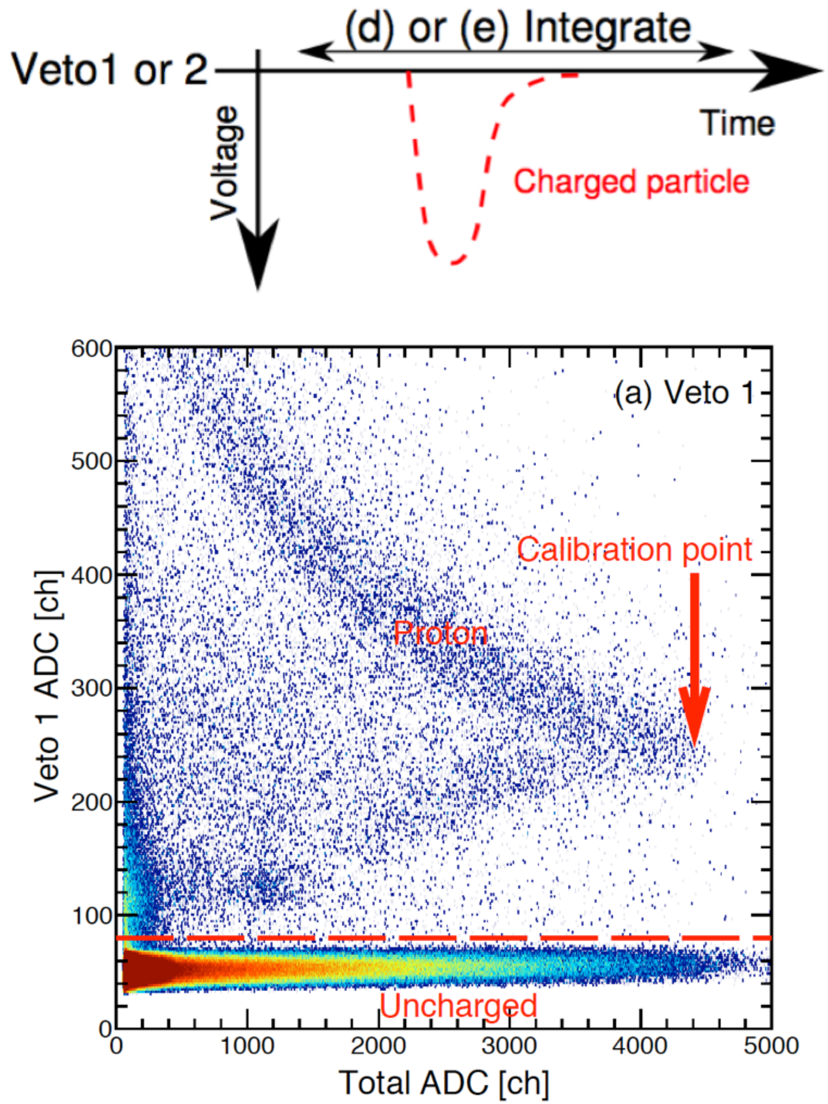


Elements of event by event data
(a) Time between signals from accelerator and NE213 detector
(b) Total ADC: Integrated value of total part of signal from NE213 detector
(c) Slow ADC: Integrated value of slow part of signal from NE213 detector
(d) Veto 1 ADC: Integrated value of signal from Veto 1 detector
(e) Veto 2 ADC: Integrated value of signal from Veto 2 detector

Data analysis (Unfolding)

- n-gamma discrimination, Charged particle rejection

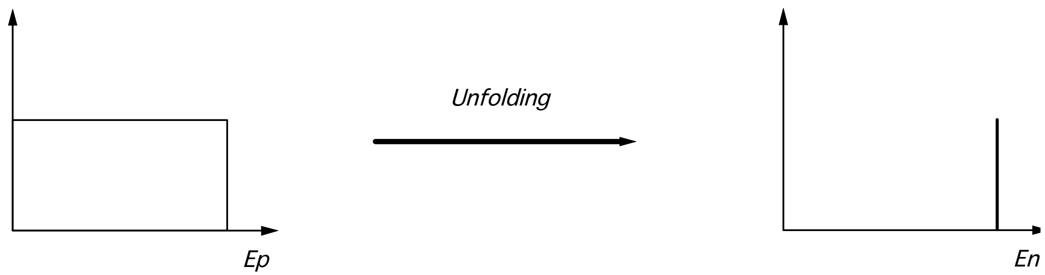




Unfolding

- **Unfolding**
  - Neutron energy spectrum is deduced from pulse height distribution
  - Responses for mono-energetic neutrons are obtained by calculation code or experiment
  - RooUnfold code is used

$$C_i = \sum_{j=1}^{M} R_{ij}\Phi(j) \qquad j = 1,2,\dots,N$$



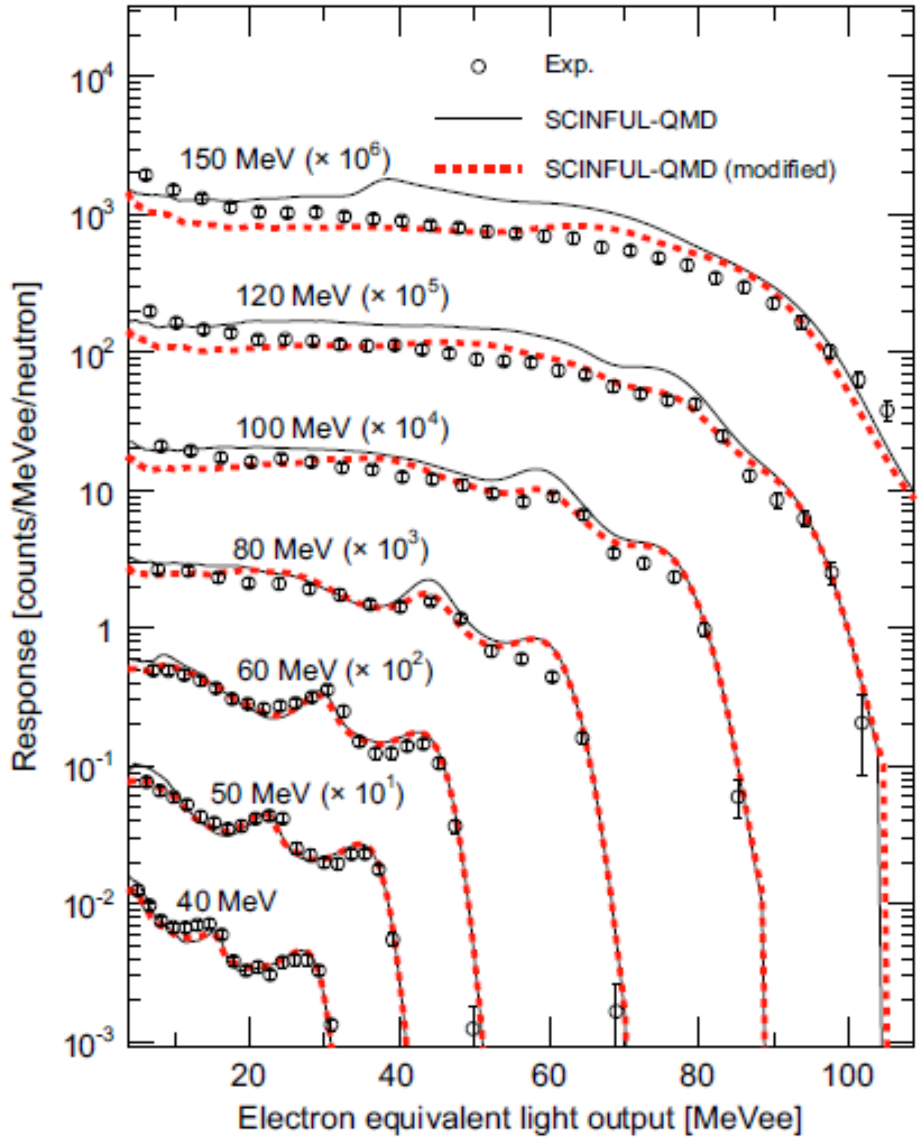
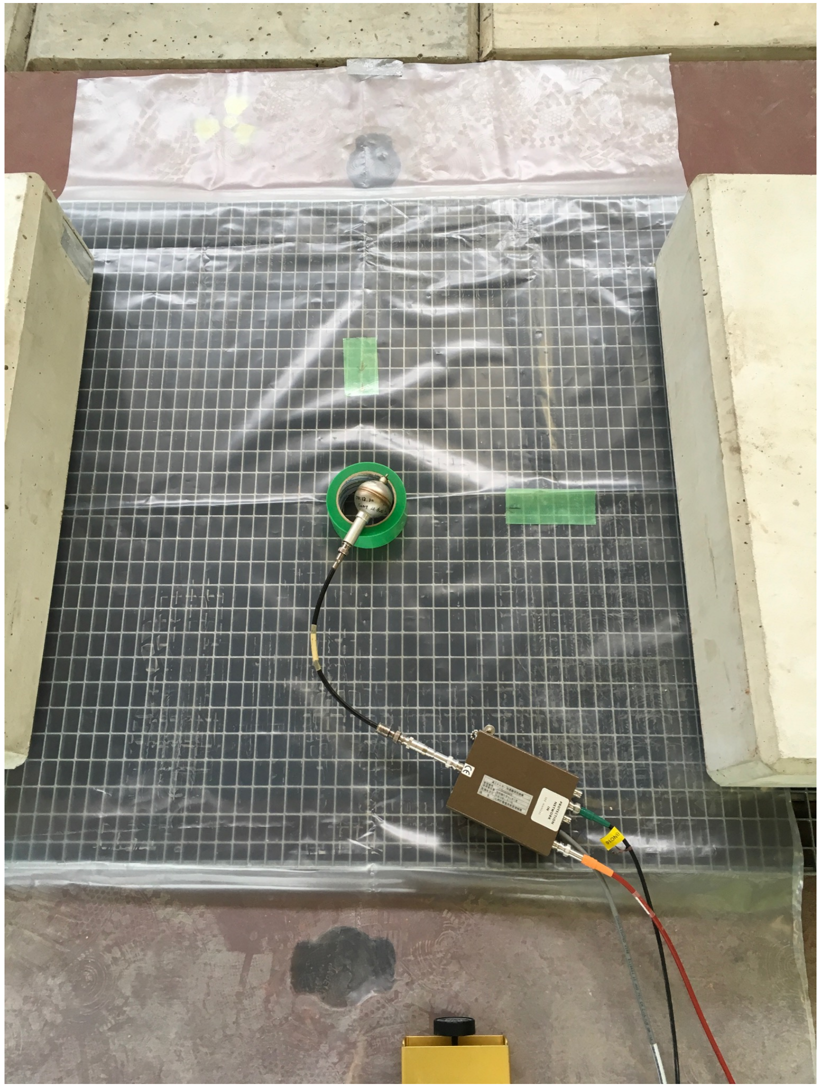
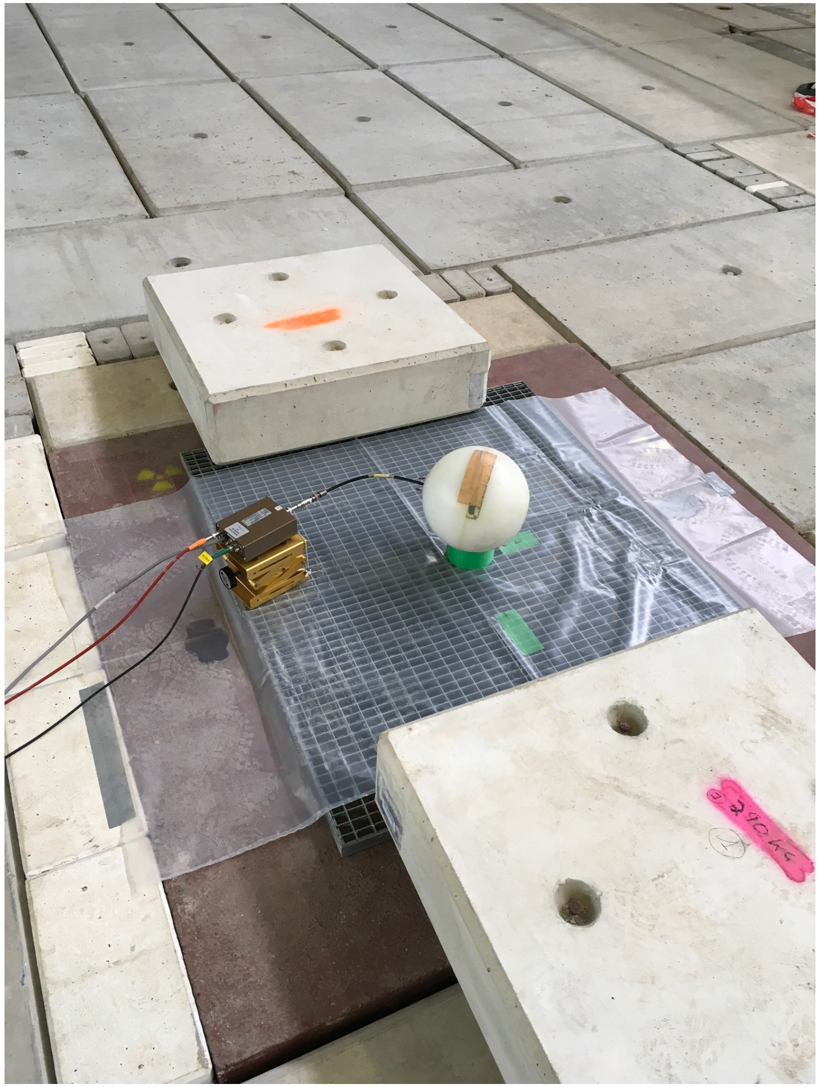


Fig. 18. Measured response functions for 40, 50, 60, 80, 100, 120, and 150 MeV neutron incidence. Experimental data are compared with the respective calculations from the original and modified codes.

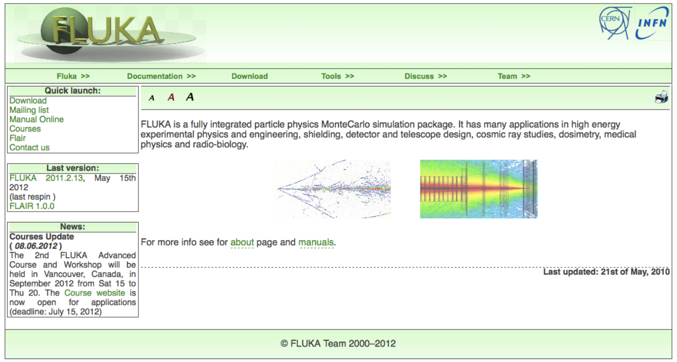
Measurement (Bonner sphere)

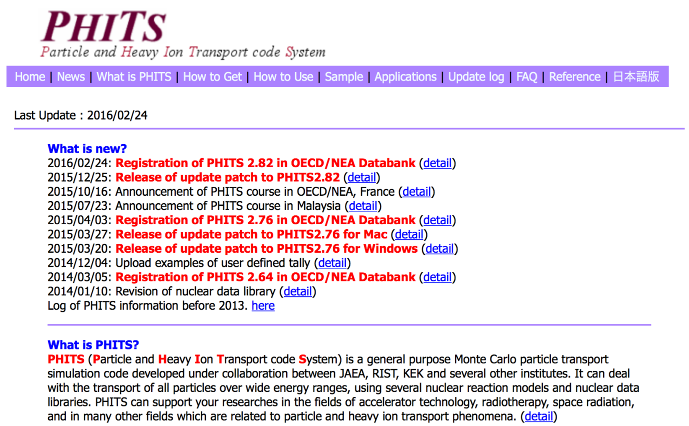




Monte Carlo Simulation

- FLUKA
  - http://www.fluka.org/fluka.php
  - LCLS, LCLS-II, EuroXFEL, LHC, Therapy, Synchrotron light source facility
- MARS
  - http://www.fnal.gov/MARS/
  - LCLS, Tevatron, Neutrino, J-PARC MR, KEK-LINAC, SuperKEKB
- PHITS
  - http://phits.jaea.go.jp, J-PARC MLF
- MCNP, Geant,,
- Combination of models
  - QMD, INC, GEM and low energy neutron transport

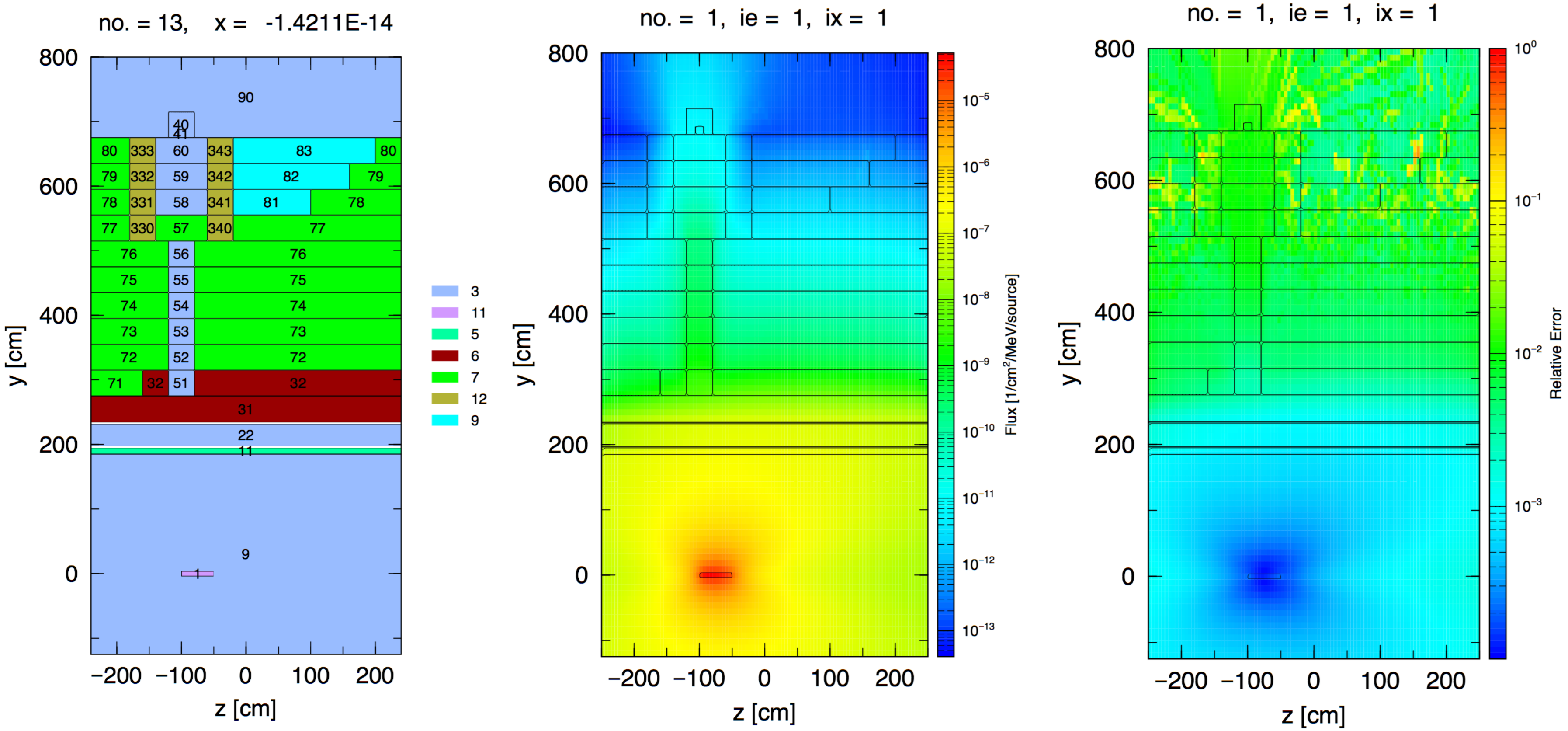




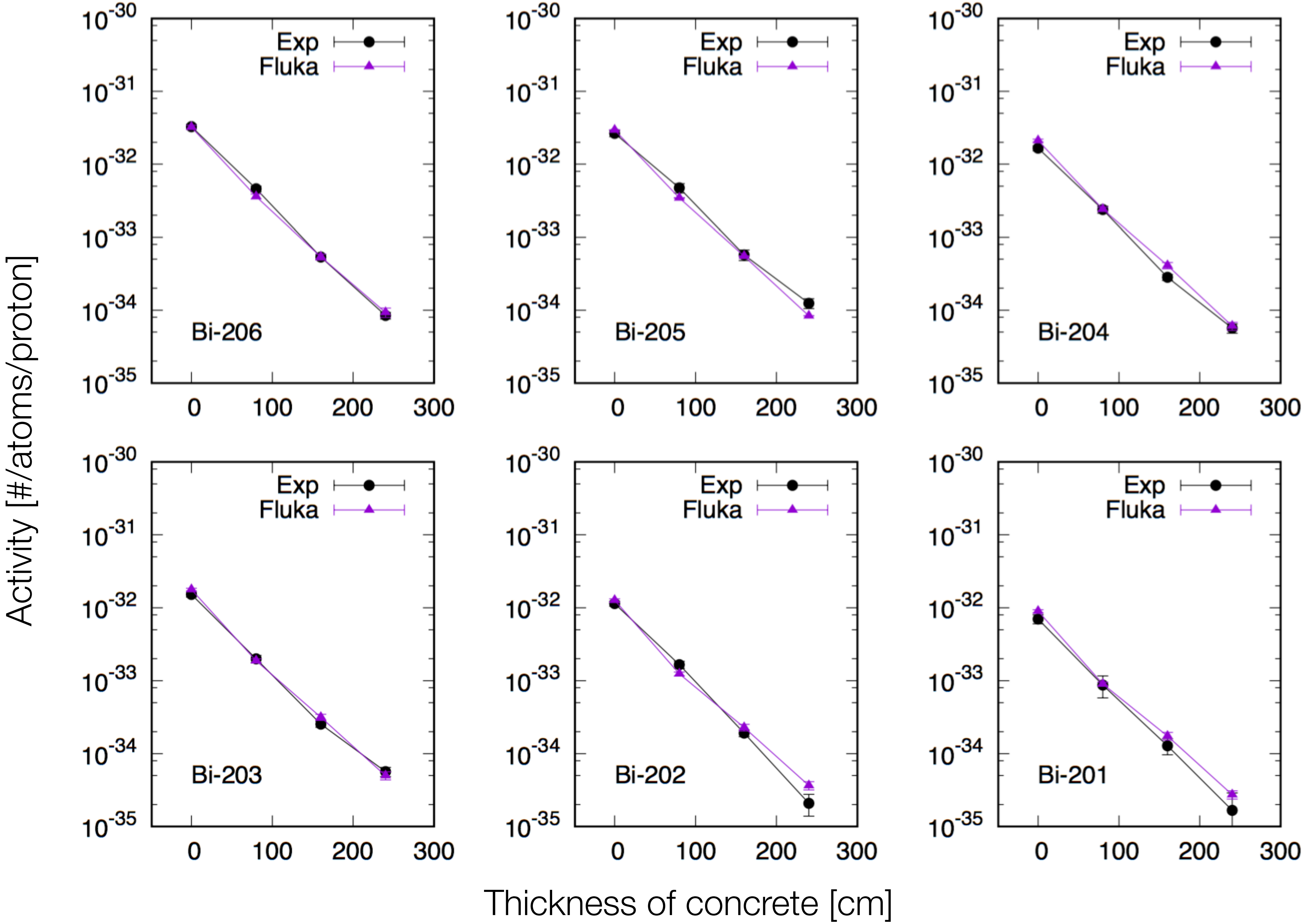
Simulation

- 440cm iron and concrete thickness gives more than 3 orders of magnitude attenuation, small solid angle for detector region

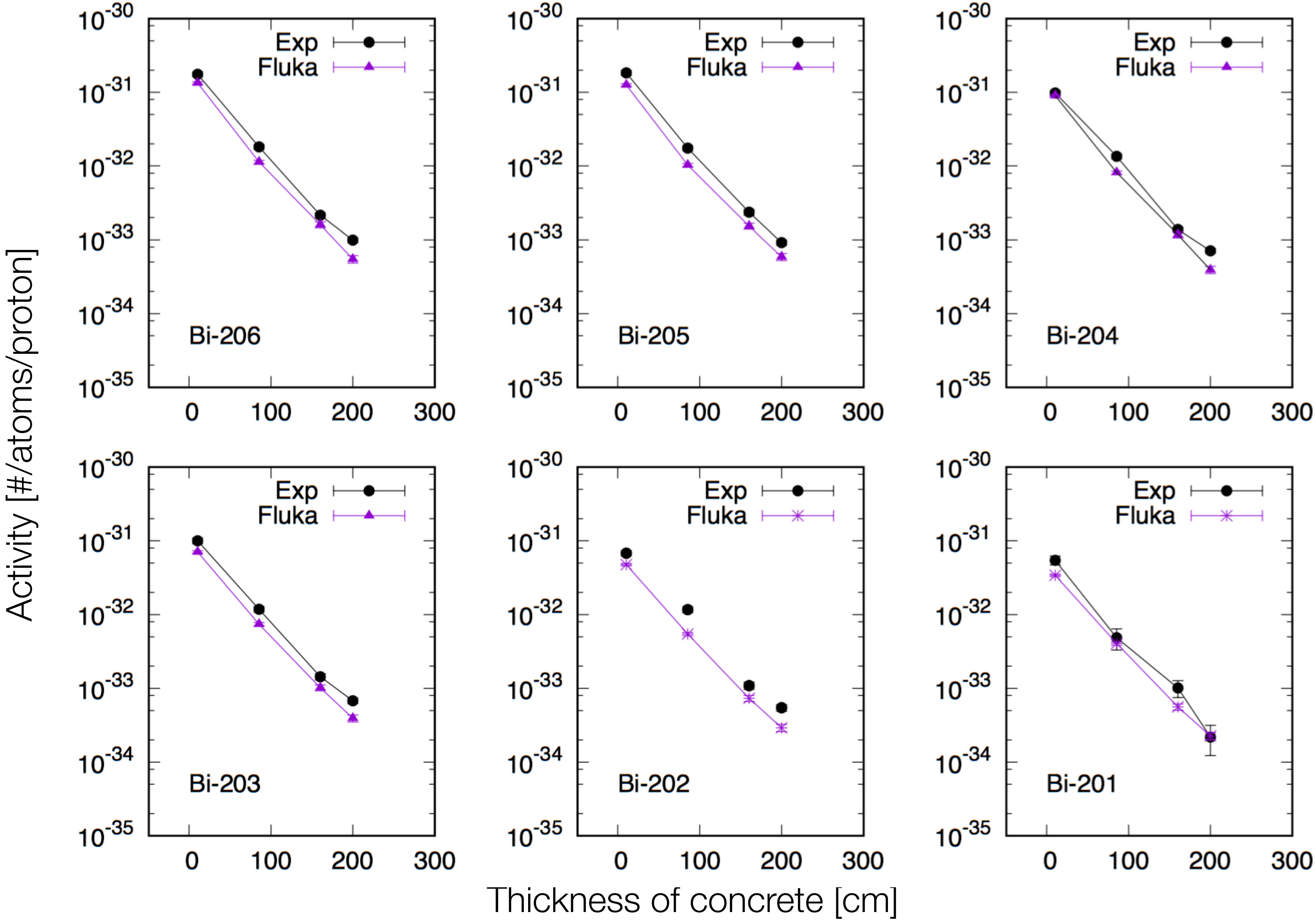
- Variance reduction technique is required



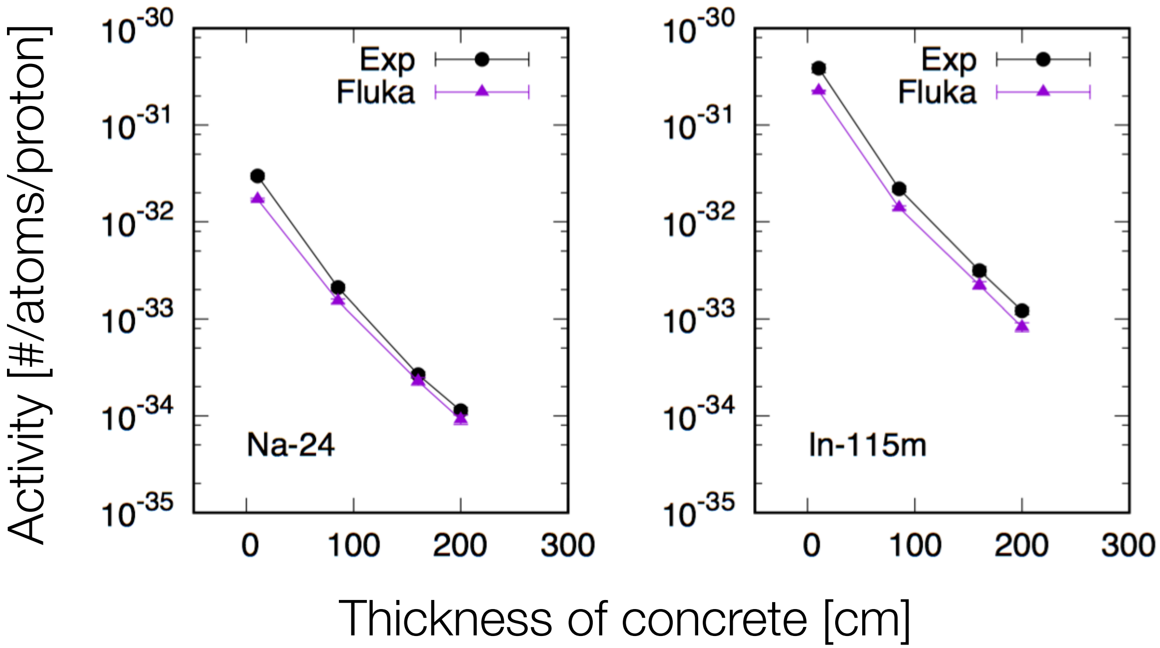
Results - Activation (2015)



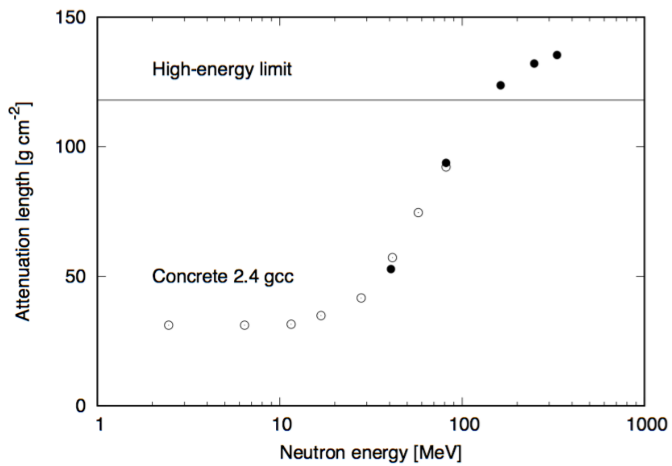
Results - Activation (2016)



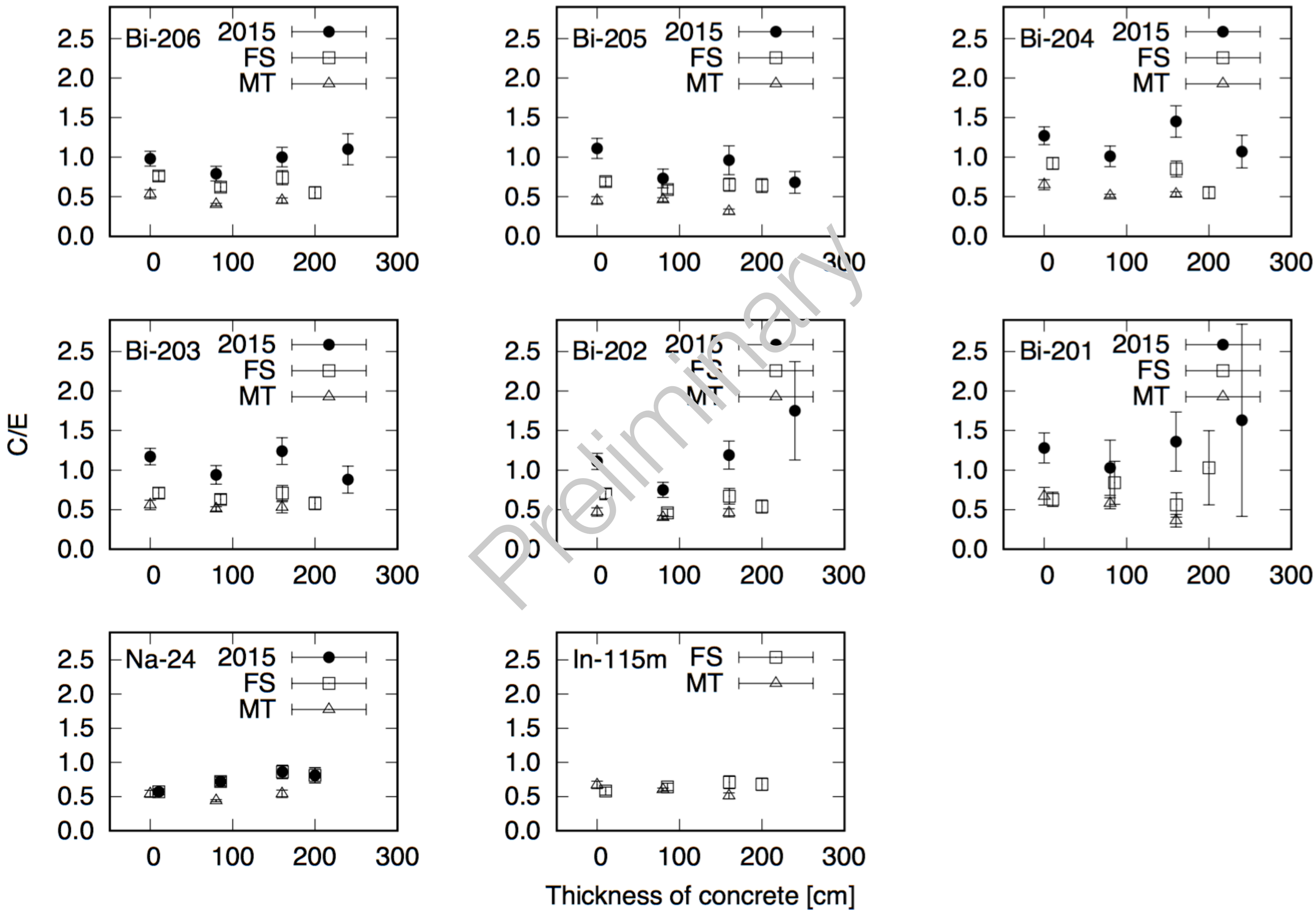
Results - Activation (2016)



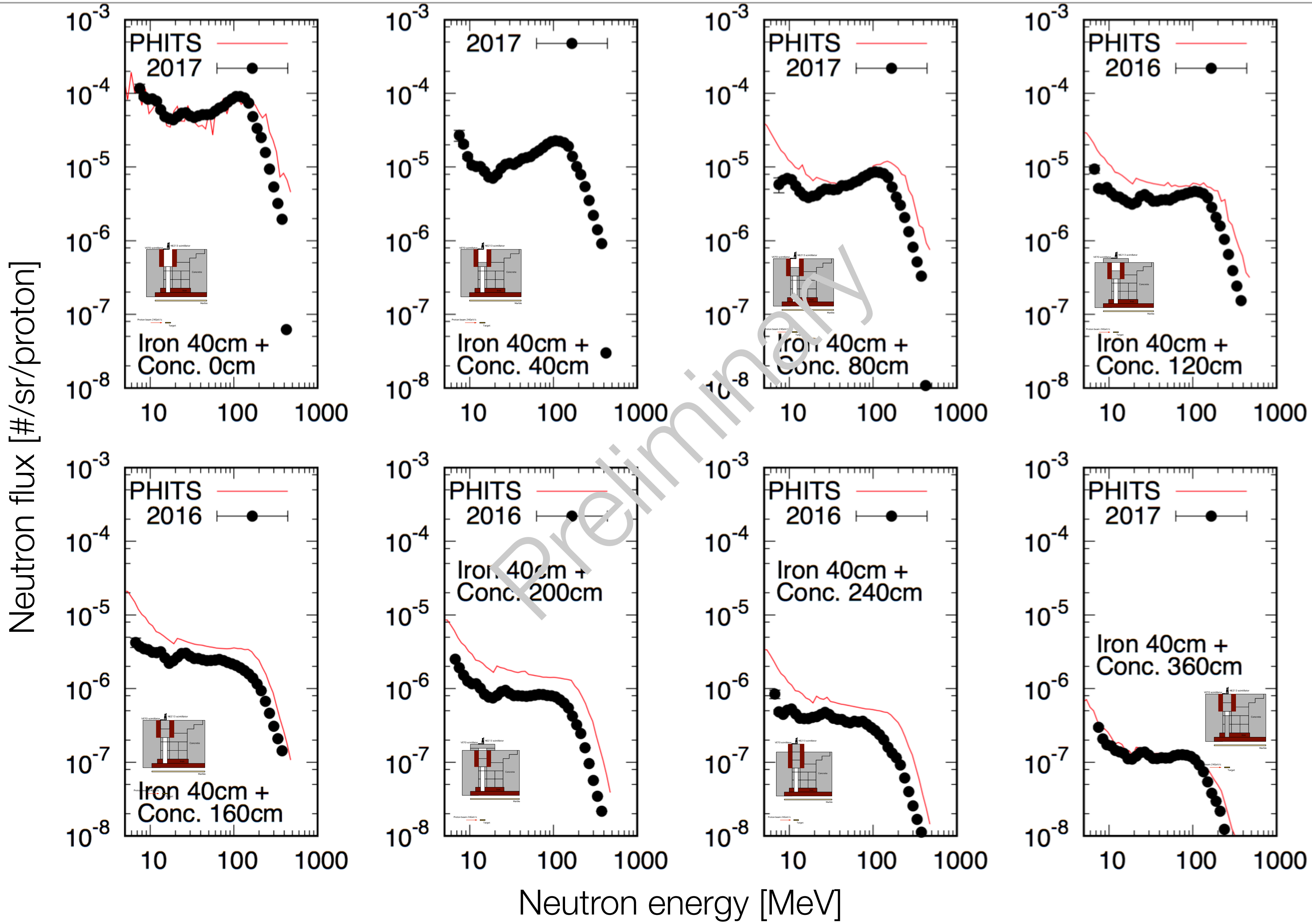
- Deduce attenuation length for all these results, compare with previous data



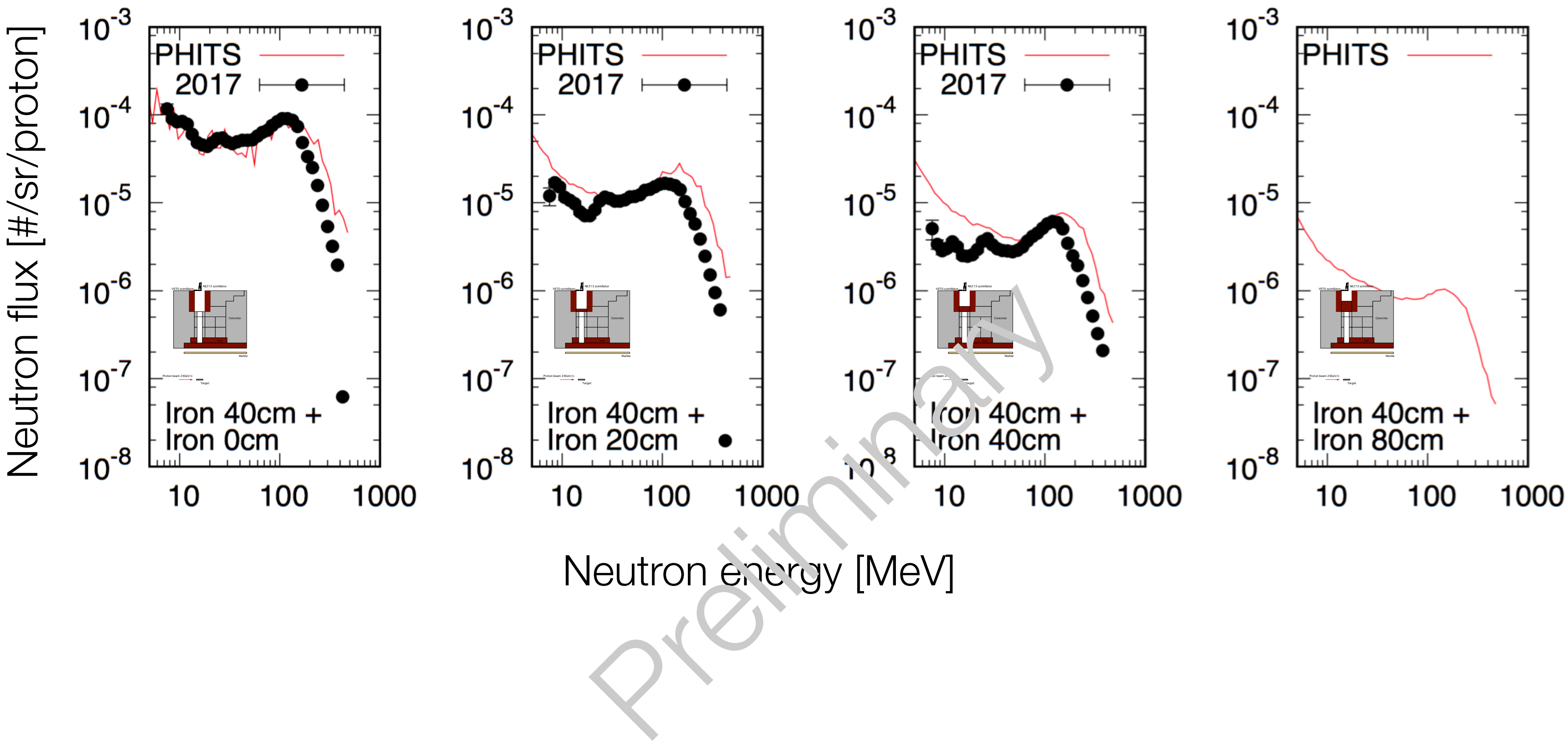
Results - C/E Activation (2015, 2016)



Results concrete attenuation - Unfolding

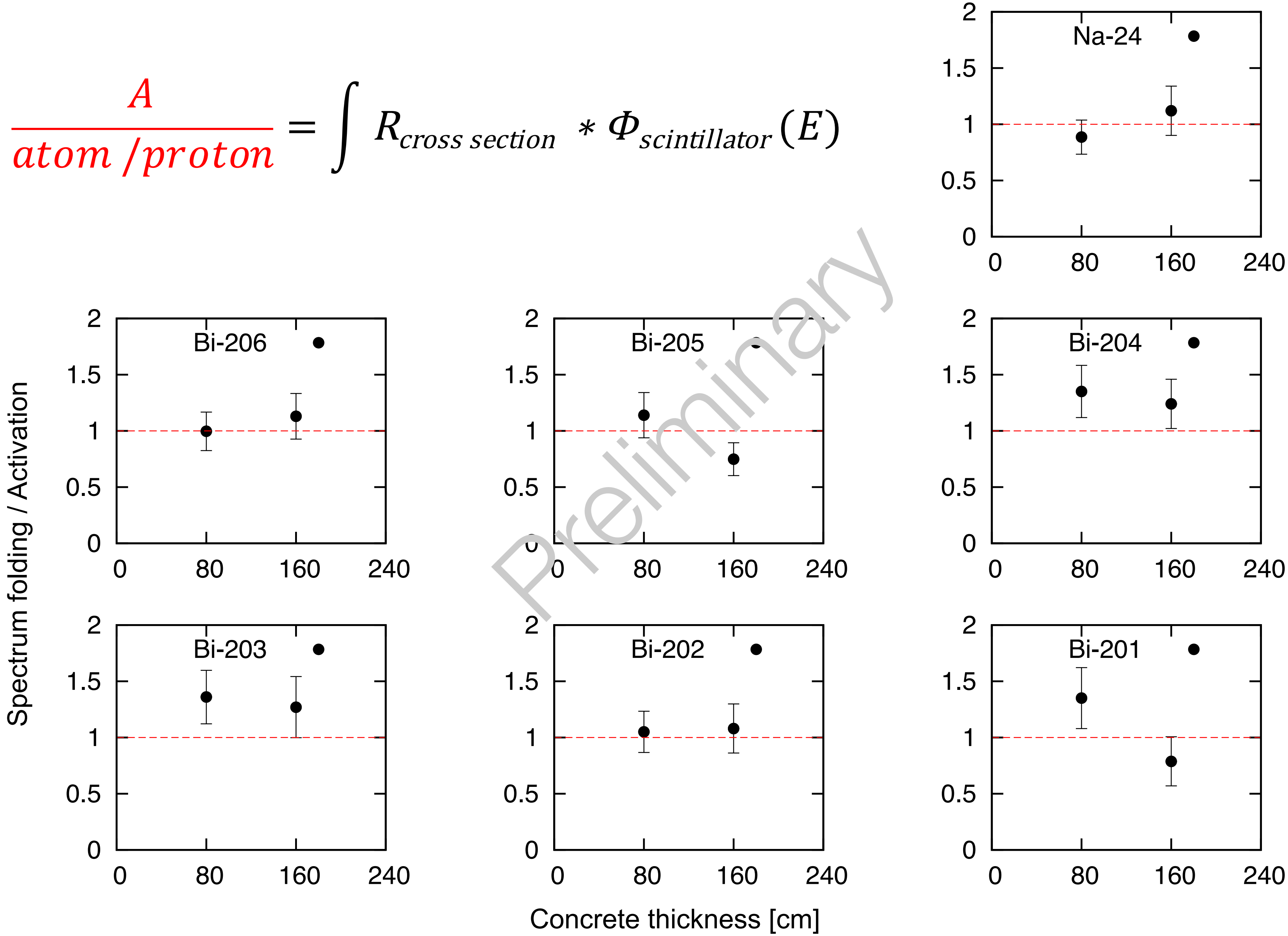


Results iron attenuation - Unfolding

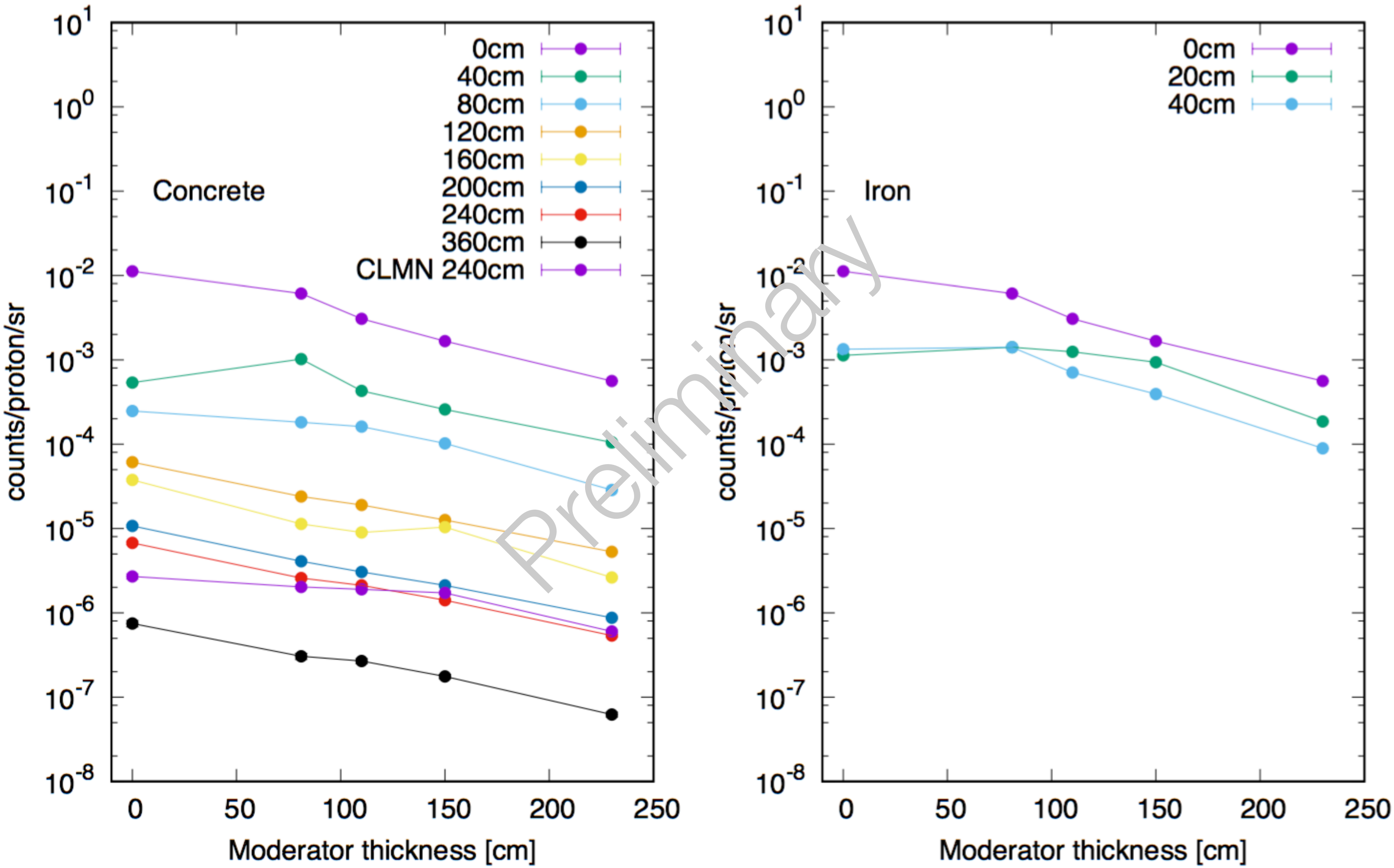


Results - Consistency

$$\frac{A}{atom\ /proton} = \int R_{cross\ section} * \Phi_{scintillator}(E)$$



Results - Bonner spheres



Summary

- General features of neutron interaction, spectrum, simulation and measurement
- Introduce an activity of neutron spectrum measurement at CERN CHARM facility
  - Activation method BI,Al,In
  - Unfolding method
- In future
  - Deduce spectrum accommodate all the data
  - Establish data set for neutron spectrum and its attenuation

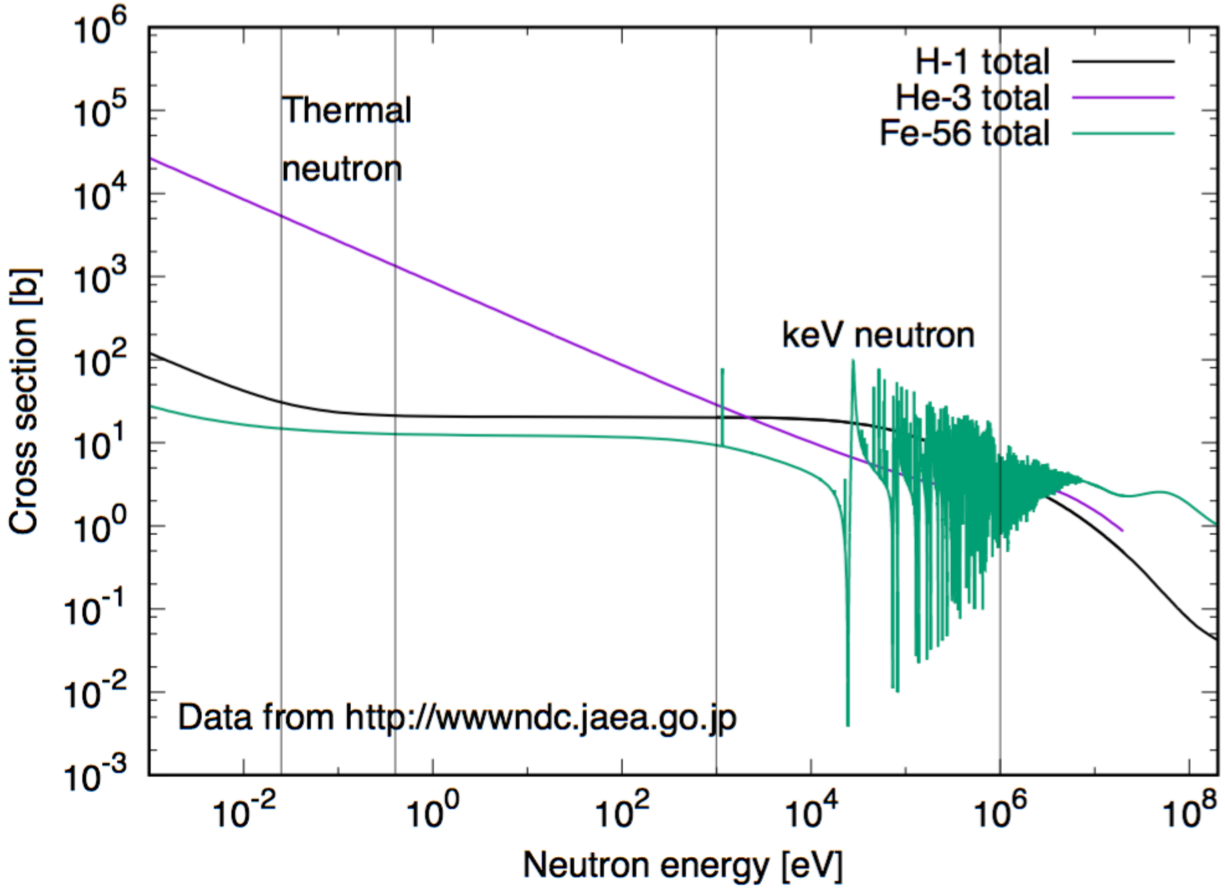
Spare

Spare

Sample	Major peak [keV]	Production rate [#/atom/p]	Err	Err [%]
Bi-206	803.1 881.0 1718.7	2.77E-33 3.13E-34	4.81E-35 1.69E-35	1.7 5.4
Bi-205	703.4	2.55E-33 4.38E-34	1.01E-34 4.02E-05	4.00 9.20
Bi-204	899.2 984.0	1.82E-33 2.02E-34	2.24E-35 8.06E-36	1.20 4.00
Bi-203	820.2 825.3 1847.4	1.68E-33 1.79E-34	5.87E-35 2.30E-35	3.50 12.80
Bi-202	422.2 657.5 960.7	1.62E-33 1.55E-34	4.90E-35 1.64E-35	3.00 10.60
Bi-201	629.1	9.23E-34 1.67E-34	9.59E-35 3.63E-35	10.40 21.70
Na-24	1368.6	3.56E-34 3.63E-35	3.66E-36 3.39E-36	1.00 9.30

General features of neutron interaction

- Neutron interaction strongly depends on their energy
- Detection and shielding strategy is relay on neutron energy
- For high energy, slowing down by heavy material with inelastic scattering, then absorb with converting charged particles

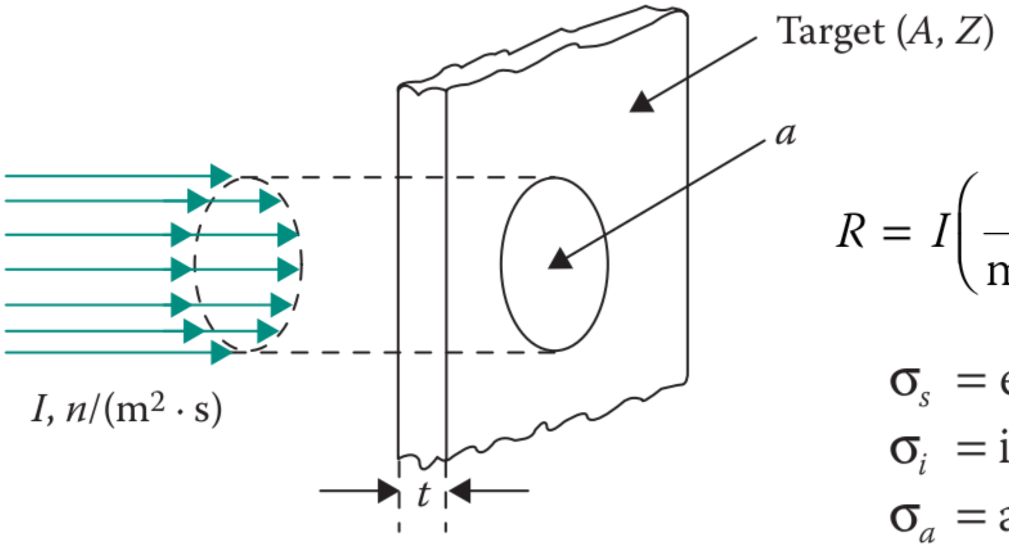


General features of neutron interaction

- R : Number of nuclear interactions for target (thickness, t)
- σ : cross section. Its unit is(b,barn)

$$1\,\text{b} = 10^{-24}\,\text{cm}^2 = 10^{-28}\,\text{m}^2$$

- Radius of nucleus is 10^{-14}m, thus 1 barn is close to geometrical cross section



$$R = I\left(\frac{n}{\text{m}^2\text{s}}\right) \times \left\{N\left(\frac{\text{nuclei}}{\text{m}^3}\right) \times a(\text{m}^2) \times t(\text{m})\right\} \times \sigma(\text{m}^2)$$

σ_s = elastic scattering cross section

σ_i = inelastic scattering cross section

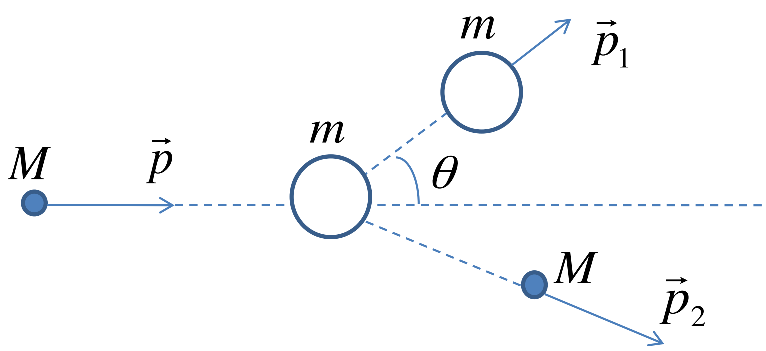
σ_a = absorption cross section

σ_γ = capture cross section

σ_f = fission cross section

General features of neutron interaction

- **Elastic scattering：**
  - Kinetic energy is conserved
  - No change for internal energy state of nucleus



$$\frac{|\vec{p}|^2}{2M} = \frac{|\vec{p}_1|^2}{2m} + \frac{|\vec{p}_2|^2}{2M}$$

$$\vec{p} = \vec{p}_1 + \vec{p}_2$$

$$|\vec{p}_1| = \frac{2m}{M+m}|\vec{p}|\cos\theta \qquad T_{\max} = \left(\frac{|\vec{p}_1|^2}{2m}\right)_{\theta=0} \cong \frac{4mM}{(M+m)^2}\cdot\frac{|\vec{p}|^2}{2M}$$

  - Elastic scattering of hydrogen nucleus：m=M
    - Most effective slowing down
    - Average energy after single elastic scattering $\quad (T_{ave})_1 = \frac{T_0}{2}$

General features of neutron interaction

- **Q value：Energy difference between rest energies before and after interaction**

$$Q = (m_{in}c^2 + M_{tgt}c^2) - (\Sigma m_{out}c^2 + M^*_{prod})$$

m_{in}：入射粒子の質量

m_{out}：放出粒子の質量

M_{tgt}：ターゲット原子核の質量

$Q > 0$: 発熱反応

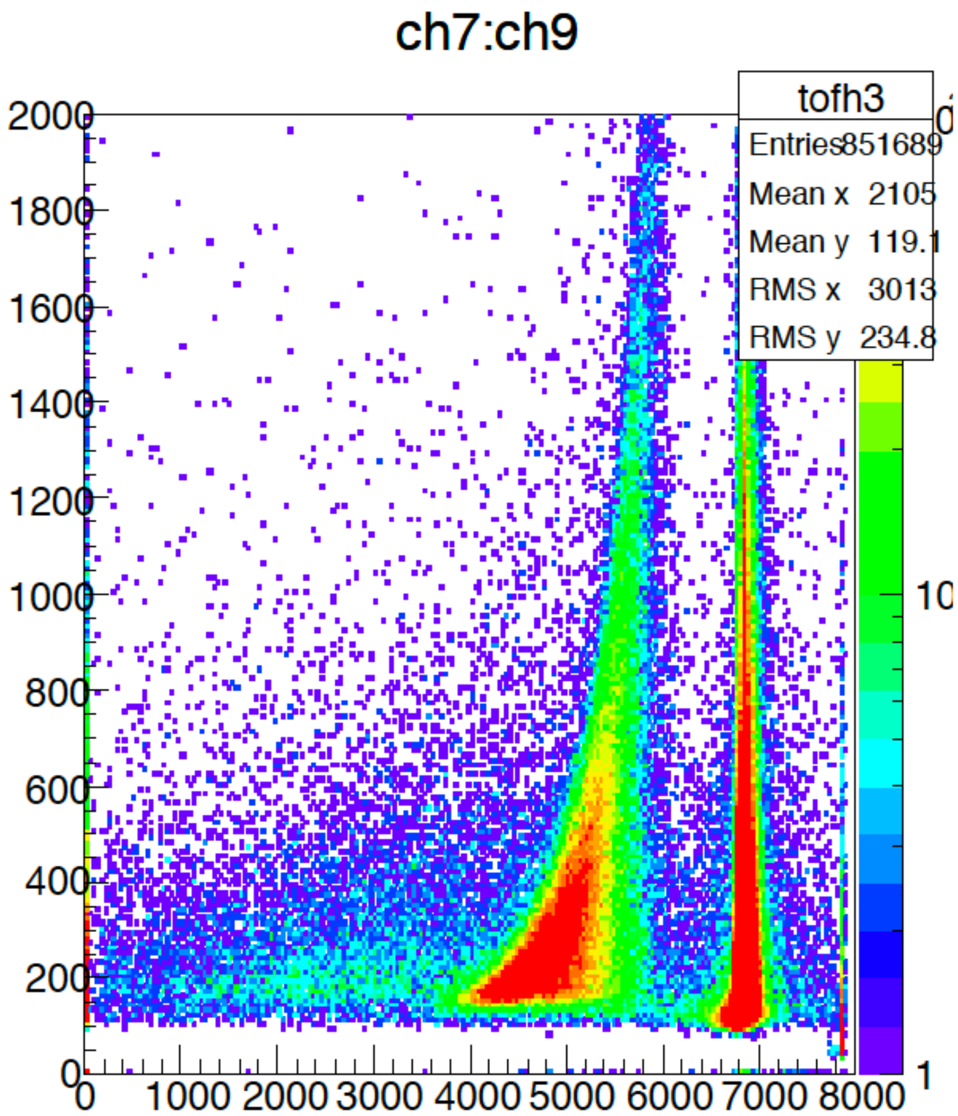
$Q < 0$: 吸熱反応

吸熱反応には反応の閾値 T_{three}がある

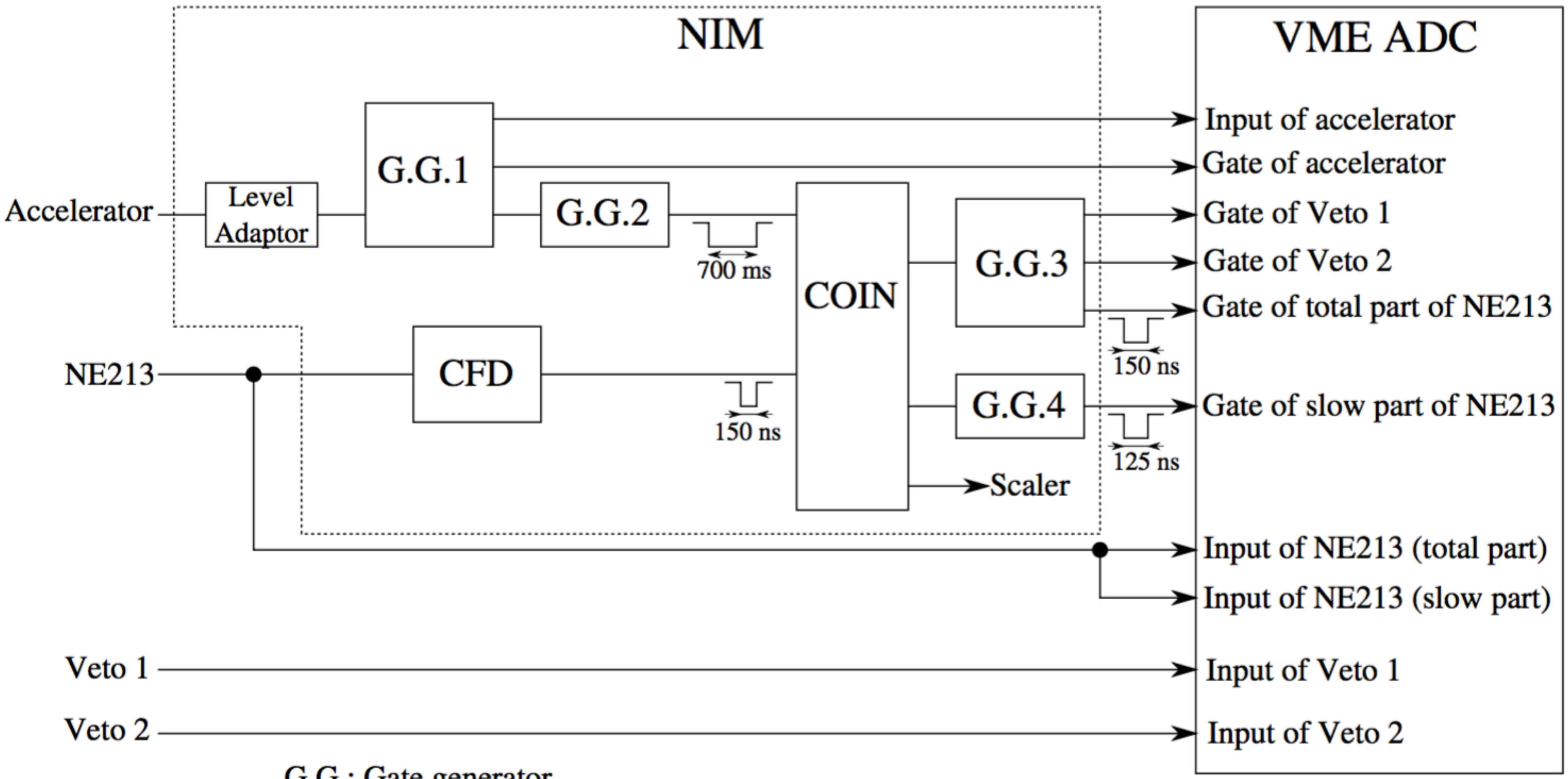
$$T_{thres} = |Q| \cdot \frac{m_{in} + M_{tgt}}{M_{tgt}}$$

Time of flight

- Time of flight
  - Neutron energy spectrum is deduced from its flight time
  - Accelerator base experiment
  - Precise energy determination up to a few 100 MeV
  - Pulsed neutron source
  - Relatively low efficiency due to long flight path
  - Direct path (W/O shielding material)
  - Not applicable for shielding experiment



NE213 electronics circuit



G.G.: Gate generator
CFD: Constant fraction discriminator
COIN: Coincidence