Implementation of neutron capture process for KASKA experiment

2006/01/26 M.Aoki

GEANT4 workshop 2005

Outline

This presentation is about implementation of the physics process which was developed to simulate neutron capture by gadolinium, for KASKA experiment.

- Why is it developed?
- What are requested?
- What kind of mechanism of the physics process?
- Is simulation result appropriate?
And, is there room for the improvement?

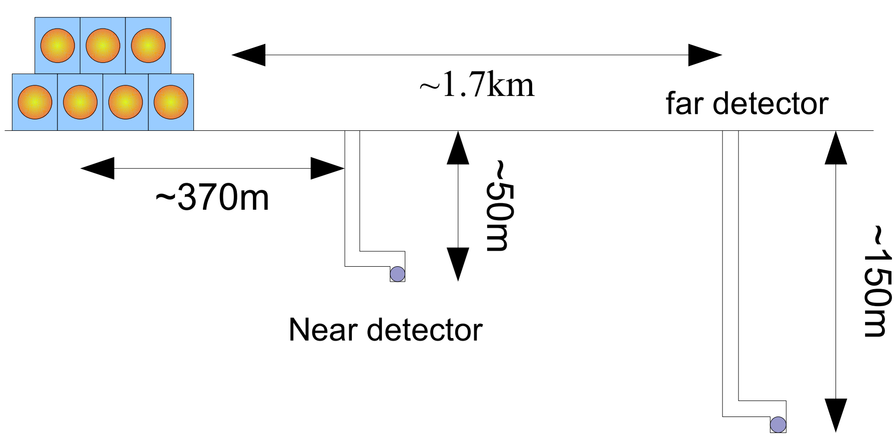
What's KASKA experiment

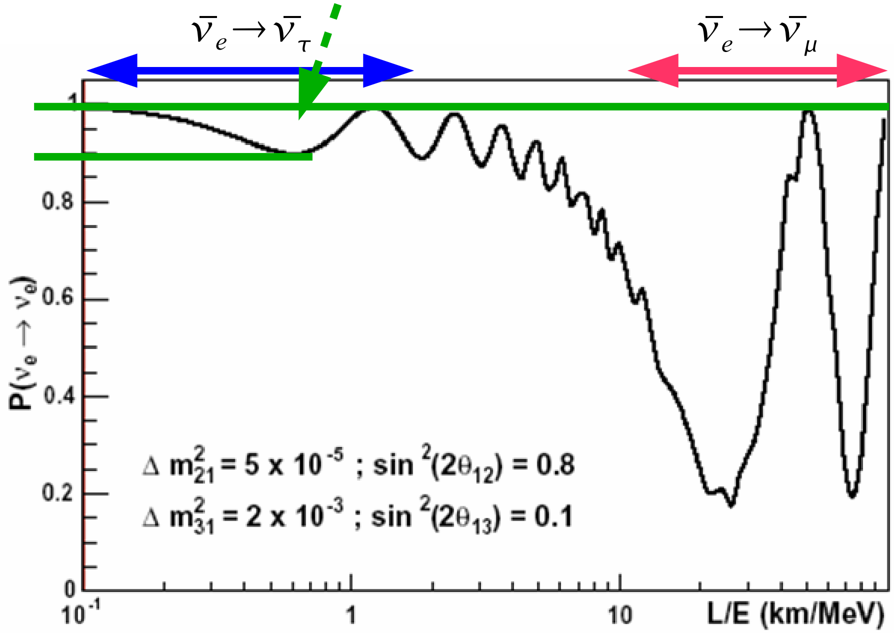
KASKA is reactor neutrino experiment.
Its goal is to measure θ_{13} (E~4.0MeV, L=1~2km).

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E} + O(10^{-3}) \text{ from } \Delta m_{12}^2 \text{ oscillation}$$

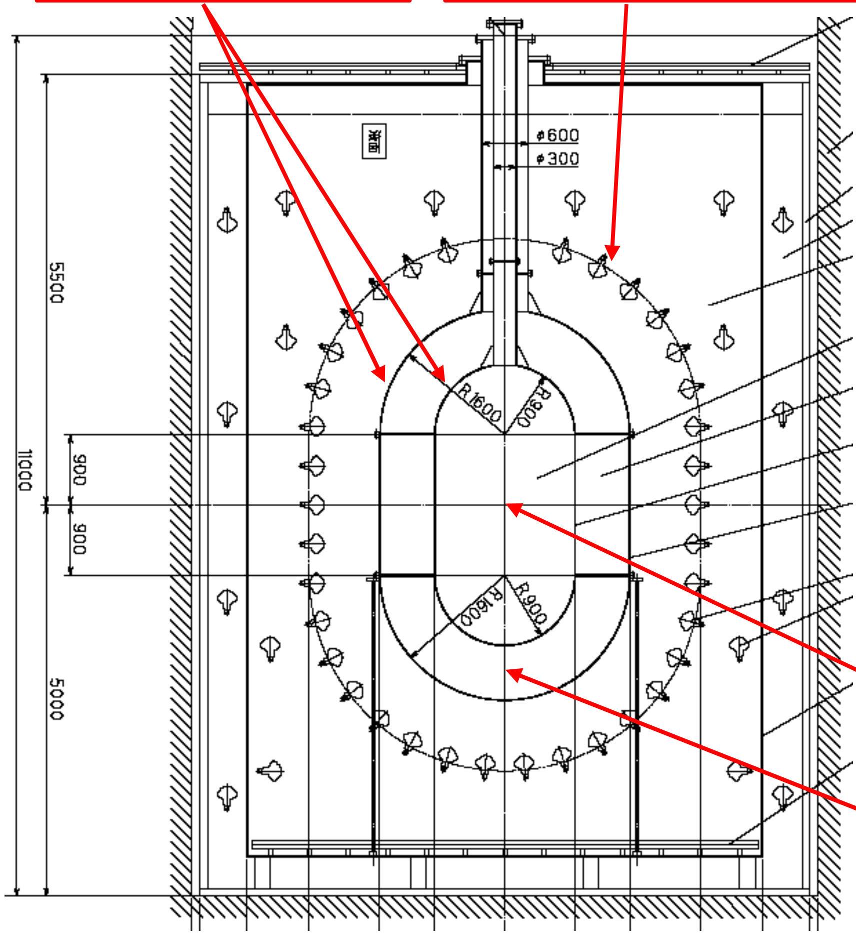
NOTE: $\Delta m^2_{13} = \Delta m^2_{12} + \Delta m^2_{23} \sim \Delta m^2_{23}$

This small deficit $\sim\sin^2 2\theta_{13}$ to be measured



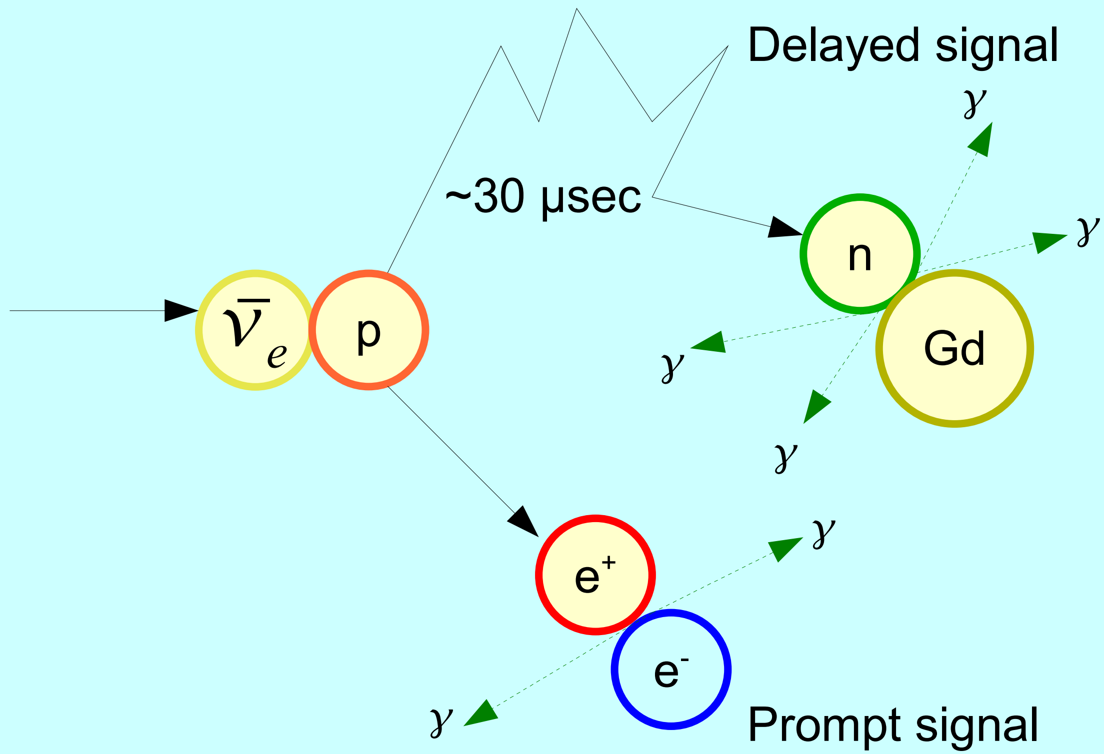


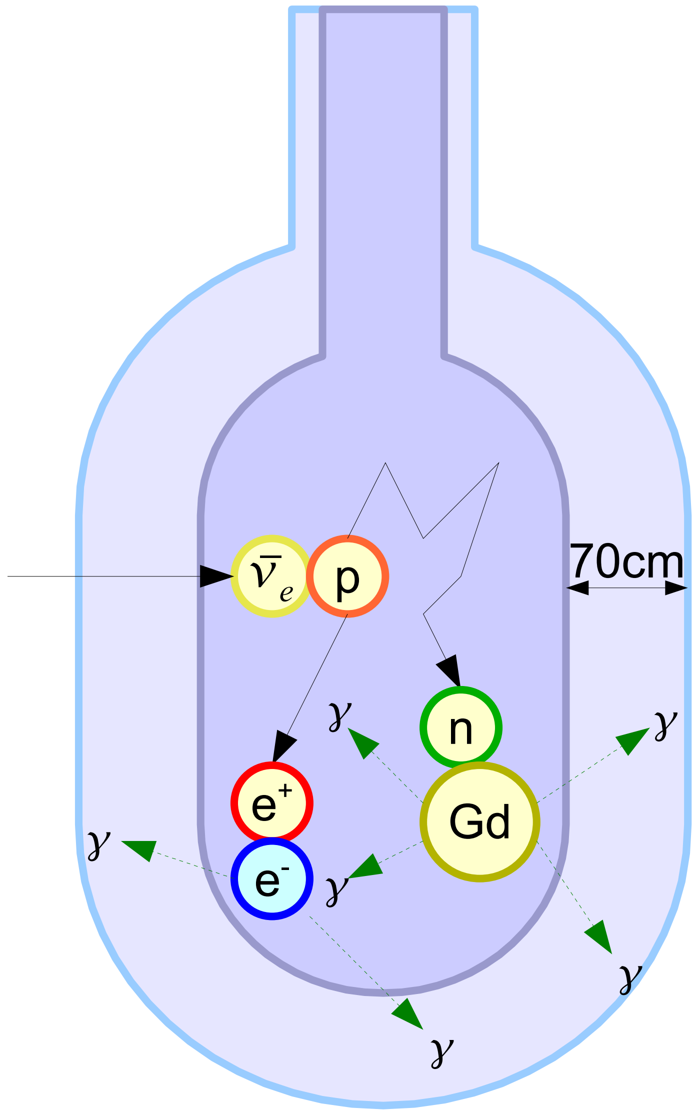
Detector



- 1^{st} layer :
  neutrino target.
  - Gd Liquid Scintillator
- 2^{nd} layer :
  gamma catcher
  - Liquid Scintillator
- 1^{st}, 2^{nd} + 3^{rd} layer PMT
  - It measures energy of neutrino event.

Inverse beta decay and neutron capture by Gd





Motive of the development of the neutron capture process

A lot of physics processes and models to manage hadronic physics are included by GEANT4 package. Also, the physics list to install these modules is equipped.

The class 'G4NeutronHPCapture' has method for low energy (thermal) neutron capture.
In this case, it is correct to use this model.

It requires various data tables concerning isotopes in material.
However, current version (4.8.0), GEANT4 package has no data for gadolinium.

Therefore, we must cover on this point, by using self-made physics process.

What are requested?

As for data tables concerning gadolinium, it is scheduled to be equipped by the GEANT4 of future version.
Thus, the self-made physics process is temporal measure consistently, and it need not has fancy capability same as standard modules of GEANT4.

The goal is

- It is necessary to capture a neutron at correct position, time, and rate (There is neutron which is captured by other element).
- The energy of gamma rays emitted after neutron capture should be appropriate.
- We want to develop easily, by using existing source code.

What kind of mechanism of the physics process?

As already stated, it is possible to simulate elastic or inelastic scattering, capture, fission of neutron by GEANT4 that includes various physics process and model for hadronic physics

These physics processes can be installed to simulator program by class 'HadronicPhysics_LHEP_PRECO_HP' easily.

On the other hand, gadolinium in liquid scintillator for KASKA experiment is very low (about 0.1%).
And as for neutron scattering,
the effect by gadolinium is low as well.

Thus...

In this case, as for scattering, we should give up simulating the effect by gadolinium!

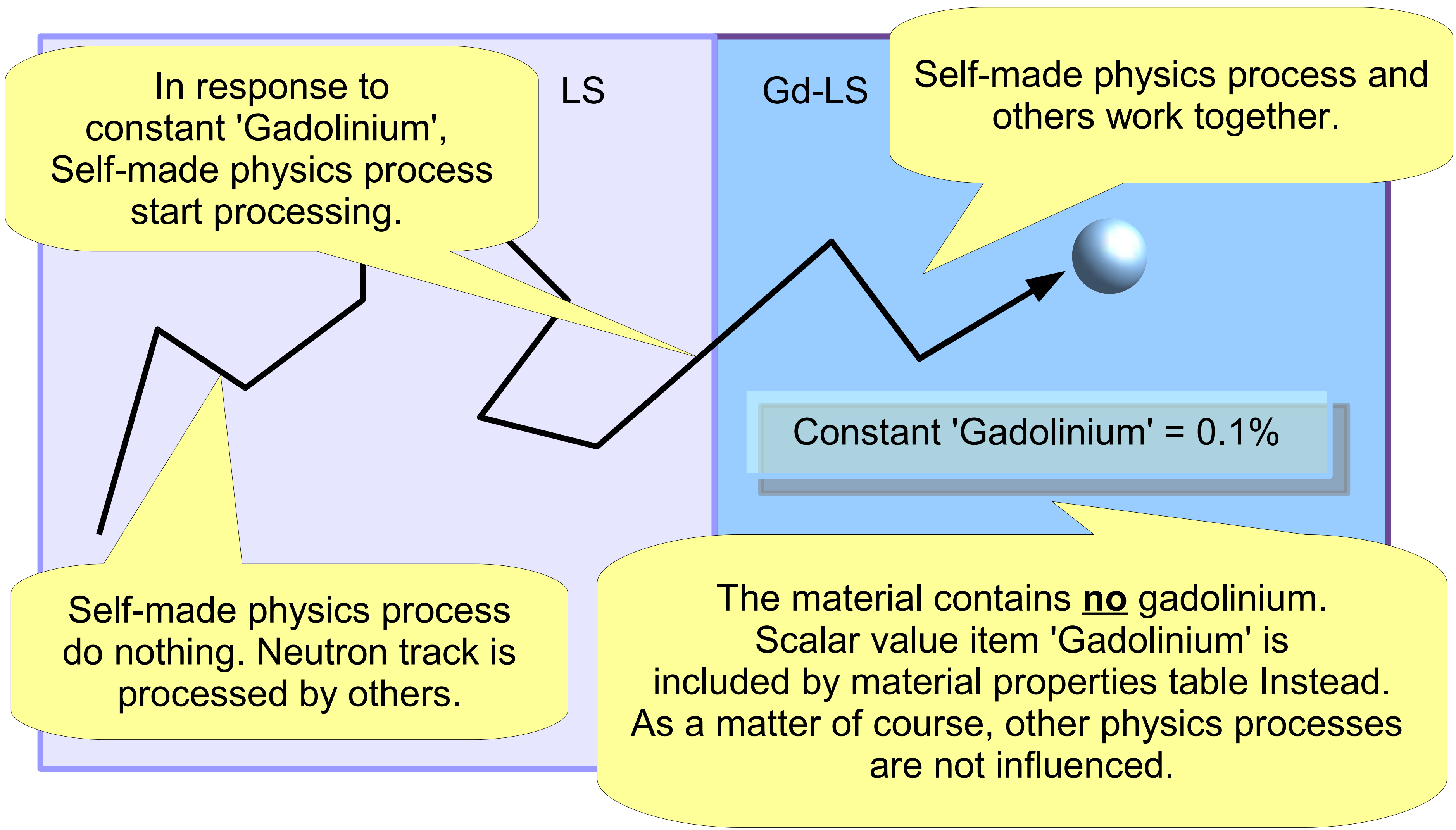
Only physics process for management of neutron capture by gadolinium should be developed, and append the physics list made by 'HadronicPhysics_LHEP_PRECO_HP'.

The physics list made by above idea is ...

- It is possible to manage neutron capture by various isotopes including gadolinium.

- On the other hand, as for neutron scattering, it is not possible to manage the effect by gadolinium.

Detail


In response to constant 'Gadolinium', Self-made physics process start processing.
LS
Gd-LS
Self-made physics process and others work together.
Constant 'Gadolinium' = 0.1%
Self-made physics process do nothing. Neutron track is processed by others.
The material contains **no** gadolinium. Scalar value item 'Gadolinium' is included by material properties table Instead. As a matter of course, other physics processes are not influenced.

Calculation of mean free path length

Neutron capture cross-section of Gd

$$\sigma_{\mathrm{Gd}}(E) = d_{\mathrm{GdLS}}\,\theta_{\mathrm{Gd}} \sum_{Z} \frac{\theta_{Z}}{m_{Z}} \sigma_{Z}(E)$$

d_{GdLS} : Density of Gd-LS θ_{Gd} : Mass fraction of Gd
θ_{Z} : Abundance of ^{Z}Gd m_{Z} : Atomic mass of ^{Z}Gd
$\sigma_{Z}(E)$: Neucton capture cross-sectino of ^{Z}Gd

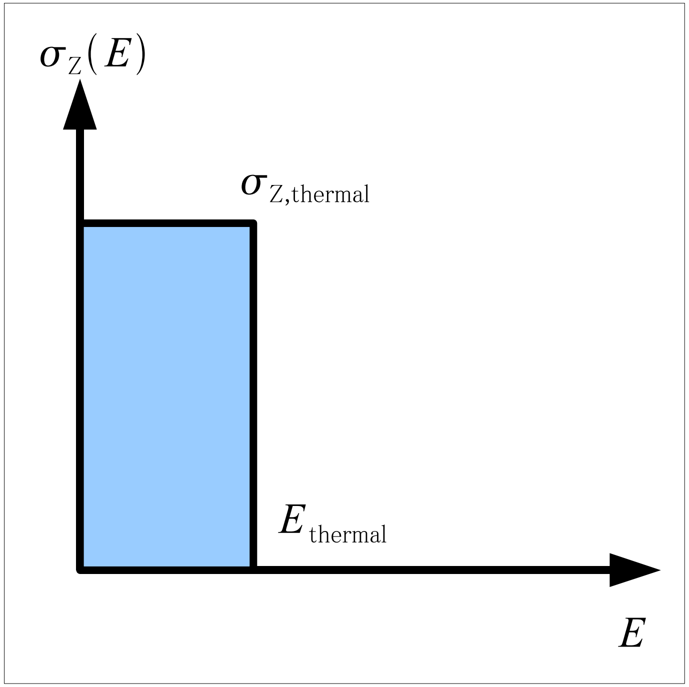
Neutron capture cross section of isotope ^{Z}Gd

$$\sigma_{Z}(E) = \begin{cases} 0 & : E > E_{\mathrm{thermal}} \\ \sigma_{Z,\ \mathrm{thermal}} & : E \leq E_{\mathrm{thermal}} \end{cases}$$

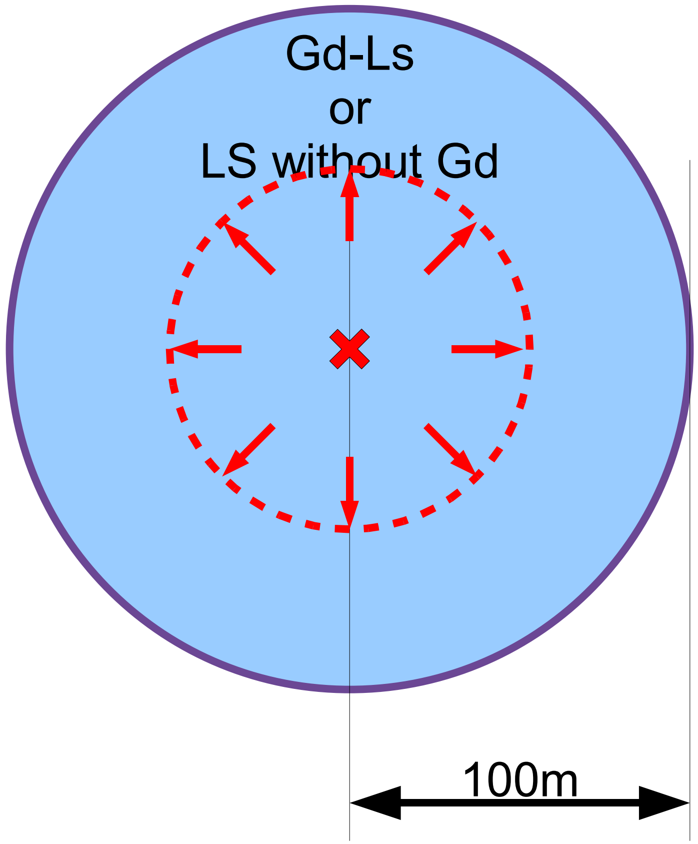
Notice : It is temporary on current version.

Mean free path length

$$\bar{L}_{\mathrm{path}} = \frac{-1.0}{\log(1.0 - \sigma_{\mathrm{Gd}})}$$



Functional Check



- Radius of the sphere that is filled with liquid scintillator is 100m.
- Composition of the liquid scintillator is equal to that of CHOOZ experiment.
  - Gadolinium loaded
    H(13.3%) C(85.5%)
    others (1.2%)
  - Gadolinium unloaded
    H(1.22%) C(84.4%)
    Gd(0.09%) others (3.3%)
- Neutrons are emitted isotropic from center of the sphere.
- Initial kinetic energy is 2.0MeV

- For neutron are captured by gadolinium.

Event rate	: 86%	84.1%	
Mean diffusion path length after thermalize	: 6.72	6	[cm]
Mean time until capture	: 30.5	30.5	[micro sec]

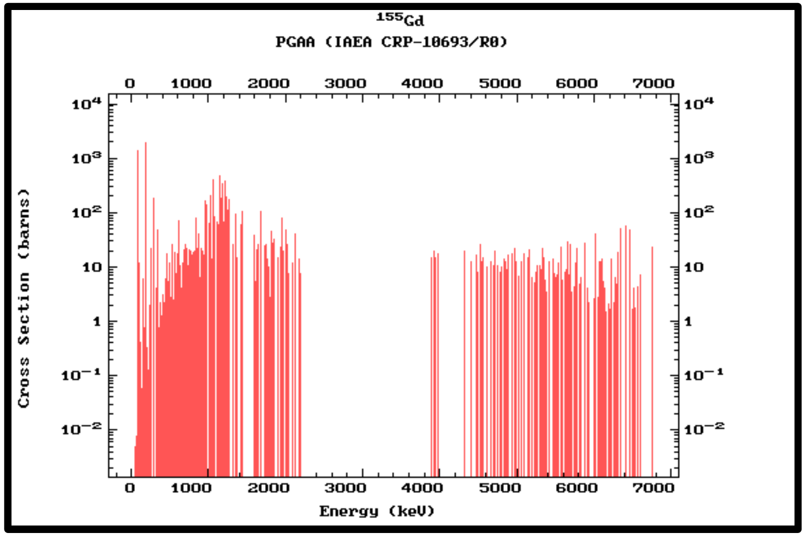
(A red color shows a value of the CHOOZ experiment.)

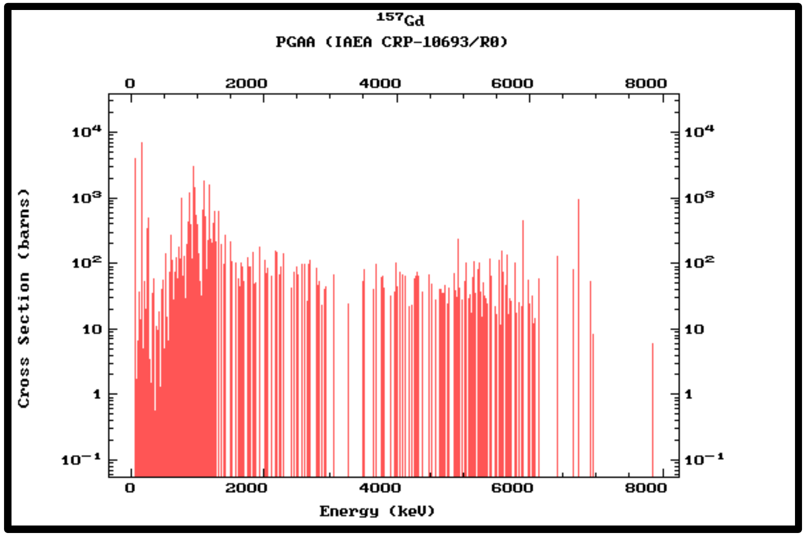
- For neutron are captured by other element.

Event rate	: 15%	
Mean diffusion path length after thermalize	: 5.80	[cm]
Mean time until capture	: 26.76	[micro sec]

Gamma ray that is emitted after neutron capture.

As for neutron capture, Isotope ^{155}Gd and ^{157}Gd is most effective (rate of neutrons that are captured by others is less than 1%).
This is energy and intensity of the gamma ray which was emitted after neutron capture.





<u>However, information of cascade is not known.</u>
Alternative method to be investigated.

Algorithm of gamma ray track generation

Outline

N is total number of gamma lays emitted from
multiple neutron capture.
And, number of emitted gamma rays which have certain
energy is proportional to the product of N and its intensity.

Thus, if we count number of generated gamma rays
that have certain energy, we can calculate deficiency number of
this. Where the value is 'priority'.

If the gamma ray which is higher priority is generated,
it is sure to obtain the result
that approximates the data
as shown previous page, after sufficient trials.

Details of algorithm

Generation queue
(was sorted according to priority)

Gamma [0]	Gamma [1]	Gamma [2]
Energy = ...	Energy = ...	Energy = ...
Intensity% = ...	Intensity% = ...	Intensity% = ...
N_{emit} = ...	N_{emit} = ...	N_{emit} = ...
Priority = ...	Priority = ...	Priority = ...

N_{total} : total number of emitted gamma ray

$$\mathrm{Intensity\%}[\mathrm{i}] = \frac{\sigma[\mathrm{i}]}{\sum_j \sigma[\mathrm{j}]}$$

$$\mathrm{Priority}[\mathrm{i}] = (\mathrm{Intensity\%}[\mathrm{i}]\, N_{\mathrm{total}}) \div N_{\mathrm{emit}}[\mathrm{i}] - 1.0$$

....

This queue is scanned from head to tail, and item what comply with following conditions is searched.
New gamma ray is generated, by above item.

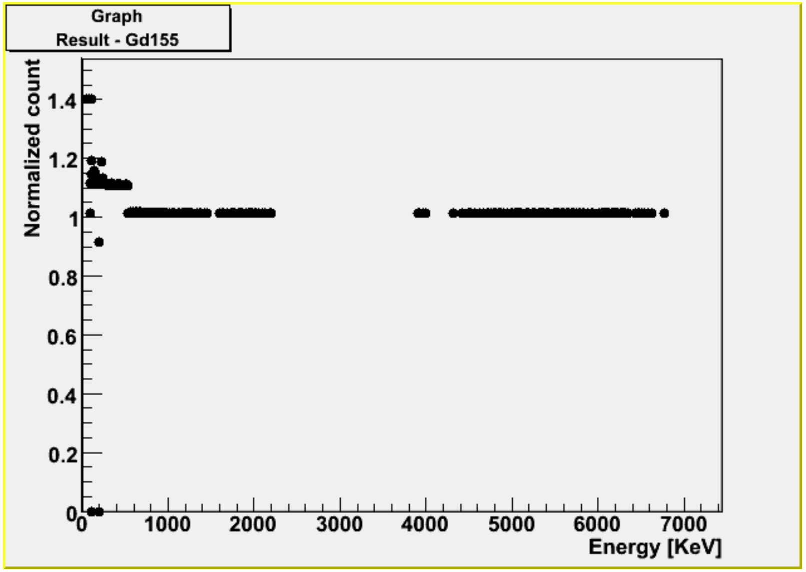
- Its priority shall not be too small.
- Total energy (is sum of energy of gamma rays had been generated and own value) must not exceed the target value (about 8MeV).

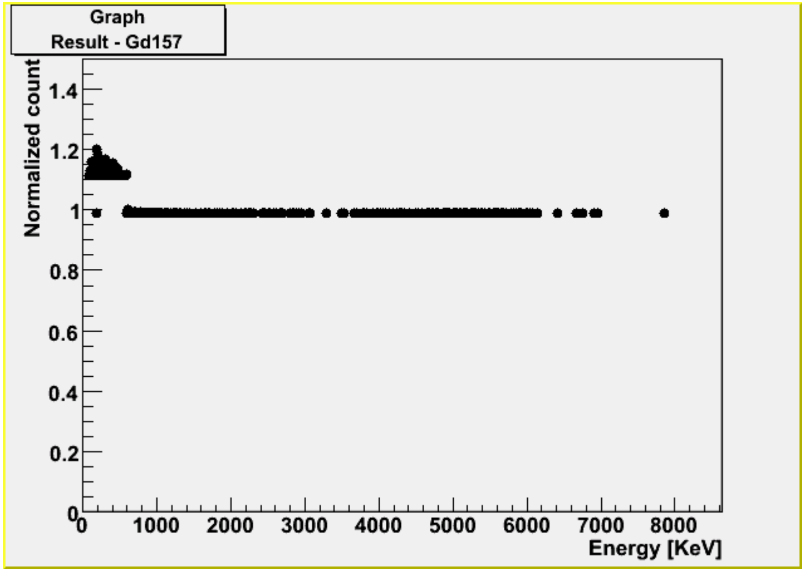
When scanning reaches tail of the queue, this processing is finished.

Total energy of gamma rays that had been generated is slightly less than target value (even if in the worst case, the difference is about 5%). Energy of each gamma ray is increased slightly, to cover this gap.

Result of generation

Followings are the result obtained by 100,000 times trial of generation engine.
These graphs show ratio of number of gamma rays with certain energy generated by this engine, and ideal value calculated by its intensity, about 155Gd and 157Gd.
When this engine works correctly, the ratio comes near to 1.0.





Summary

- I presented about implementation of physics process that was developed newly for KASKA experiment.

- It is considered that this physics process reached following goal.

  - It is necessary to capture a neutron at correct position, time, and rate.
  - The energy of gamma ray emitted after neutron capture should be appropriate.
  - Development of temporary physics process, using existing source code.