ENPH/PHYS 453-Advanced Physics Laboratory
Compton Scattering of Gamma rays

Winter 2025

January 13, 2025

1 Learning Goals

- Understand interaction of gamma rays with medium including Compton scattering
- Learn how to propagate a signal from gamma ray sensor through your apparatus

2 Introduction and Theory

In this experiment, you have a setup to study the Compton Scattering of gamma rays. Three major interactions of gamma rays play an important role in radiation measurements: photoelectric absorption, Compton scattering, and pair production. Gamma rays lose partial or total energy when they pass through the medium due to these interactions between gamma rays and electrons inside the medium.

Compton scattering is the elastic scattering of gamma rays of the electrons 1. When gamma rays pass through a medium, they transfer some energy to electrons with a certain probability. Because this is two body elastic scattering process, the energy and momentum are conserved. As gamma rays "lose" their energy as electrons gain energy, the gamma rays after the collision have smaller energy. From the conservation of the energy and momentum of the process, we can estimate the changed energy of gamma rays as shown in the equation 2.

$$\frac{1}{E_{\gamma_2}} - \frac{1}{E_{\gamma_1}} = \frac{1}{m_e c^2}(1 - cos\theta) \tag{1}$$

where E_{γ_1} is the initial energy of gamma ray, E_{γ_2} is the final energy of gamma ray after collision, m_e is the rest mass of the electron, and θ is the angle between the trajectories of the incident and scattered photon as shown in the Figure 1.

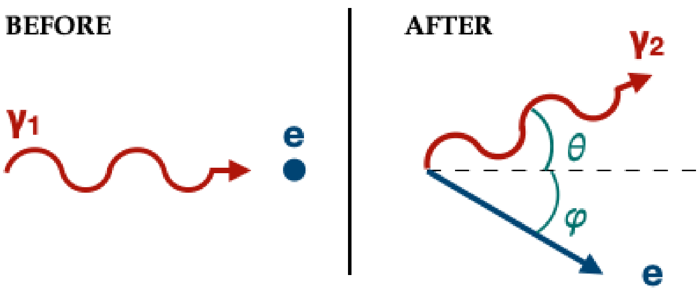

Figure 1: Before and after the Compton scattering. After colliding with an electron at rest, e, the photon transfers some of its energy to the electron (511 keV).

The probability of Compton scattering of gamma rays depends on the properties of the medium. A medium with a higher atomic number (Z) has a higher probability per atom because there are more target electrons to scatter for such a medium. The probability of Compton scattering can be described by the Klein-Nishina formula as shown below.

$$\frac{d\sigma}{d\Omega} = Zr_0^2\left(\frac{1}{1+\alpha(1-cos\theta)}\right)^2\left(\frac{1+cos^2\theta}{2}\right)\left(1+\frac{\alpha^2(1-cos\theta)^2}{(1+cos^2\theta)[1+\alpha(1-cos\theta)]}\right) \tag{2}$$

where $\alpha \equiv h\nu/m_ec^2$, m_0c^2 is the rest-mass energy of the electron, θ is the angle between the trajectories of the incident and scattered photon, and r_0 is the classical electron radius. By integrating equation 2 over all angles, you can get the total cross section.

In this setup, one can measure other properties of Compton scattering, such as the rate dependence on the angle, the probability of Compton scattering, and the rest mass of an electron. While this lab is designed to study Compton scattering, you will also observe photoelectric absorption. The energy dependency of gamma-ray interaction probability in sodium iodide can be seen in the Figure 3.

3 Apparatus

We use Thallium doped Sodium Iodide (NaI(Tl)) scintillation crystal as our target and scatter detector. The gamma rays will scatter off electrons from a target NaI(Tl) crystal. After the scattering, the gamma rays will transfer some or total energies to another NaI(Tl) crystal (part of a scatter detector) with a certain probability. Scintillating light generated in NaI(Tl) crystal will be collected by a photomultiplier (PMT), read by a series of NIM modules, and eventually by a computer. The concept of experimental arrangement for the Compton scattering is shown schematically in Figure 2.

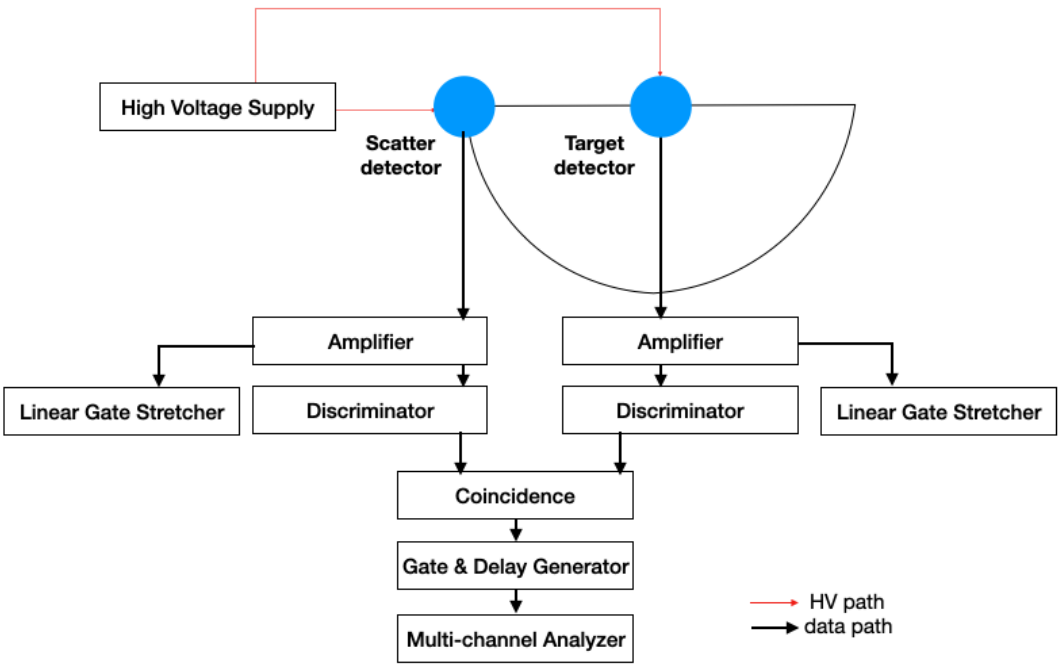

Figure 2: Apparatus diagram

4 Lab Safety and Upkeep

Since you will be dealing with radioactive sources in this experiment, it is crucial that you adhere to all health and safety protocols for handling radioactive materials.

- No food or drink in the lab
- When sources need to be removed from the lead box, sign them out and sign them back in upon returning them

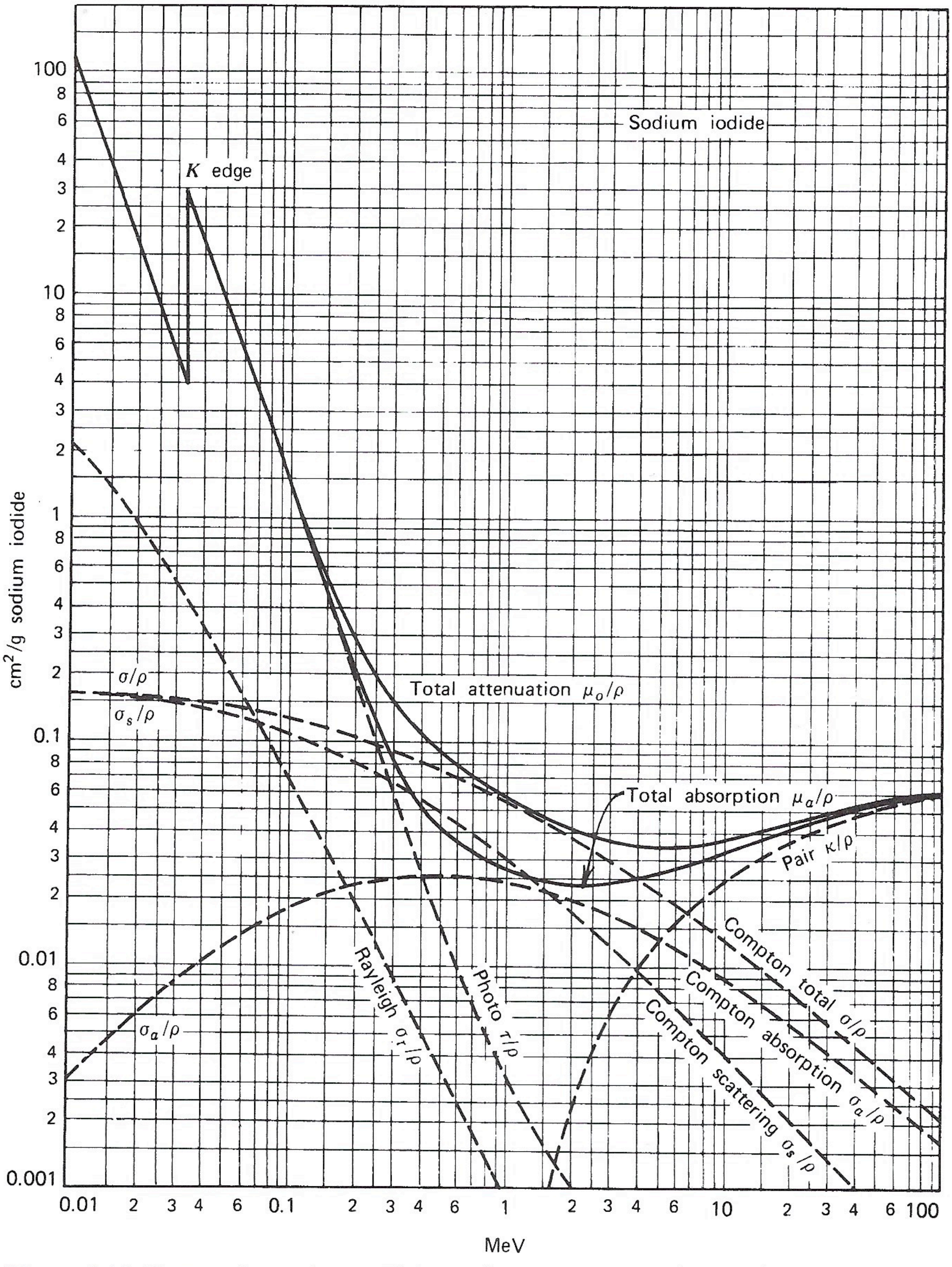

Figure 2.18 Energy dependence of the various gamma–ray interaction processes in sodium iodide. (From *The Atomic Nucleus* by R. D. Evans. Copyright 1955 by the McGraw-Hill Book Company. Used with permission.)

Figure 3: Energy dependence of gamma-ray interaction procsses in sodium iodide (1)

- Handle radioactive sources with latex gloves
- DO NOT leave radioactive sources out in the open

Note: you can leave a radioactive source in your apparatus over night to maximize statistics for your measurement. Please talk with the teaching team if you decided to do this.

You will also be using high voltage sources to power the PMTs. Unless you plan on keeping your data acquisition going overnight, be sure to turn off the PMT high voltage source when you leave the lab.

You may need to move the lead blocks frequently. Please be careful when you move the lead blocks to rearrange your setup for your safety as well as the safety of the equipment. (PMT and sodium iodine crystal are both fragile.)

Finally, each of your electronic modules (TAC, CFD, Amplifiers, etc.) are powered by a Nuclear Instrumentation Module (NIM) Bin. Generally speaking, before turning the bin itself on or off, all modules plugged into the bin must be turned OFF. You shouldn't need to remove any of the modules from the bin given to you, but in the event that you do, please inform your TA for further instruction

5 Equipment Inventory

NIM Bin Modules

- 2 ORTEC 575A, Amplifier
- 2 ORTEC 553, Timing SCA
- 2 ORTEC 442, Linear Gate Stretcher
- ORTEC 414A, Fast coincidence
- ORTEC 416, Gate and Delay Generator device

External Components

- Multi-channel Analyzer
- 2 PMTs and NaI(Tl) crystal arrays
- BNC cables
- LabView DAQ interface
- Radioactive source holder
- Many lead blocks

References

[1] Knoll (2000) *Radiation Detection and Measurement*, Addison Wesley, Massachusetts, 3rd ed.