Compton edge-based energy resolution measurements with a coincidence setup

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In this laboratory activity, students will measure the energy resolution of a scintillator detector using gamma rays. This will be possible due to the ability of photons to Compton scatter electrons in the scintillator target material and then be detected in temporal coincidence by a reference detector with known energy calibration. The setup will allow students to familiarize themselves with standard acquisition electronics in nuclear and particle physics as well as coincidence trigger logic. The reference detector will be a high-resolution solid-state device (HPGe High Purity Germanium Radiation Detector) working at cryogenic temperatures to provide a reference energy measurement based on the photoelectric effect. Students should work on the determination of the energy resolution of the scintillator by analyzing the scintillator pulse height distribution acquired in coincidence with the HPGe detector.

1 Experimental Setup

For this experiment we will need an instrumentation related to plastic scintillators (PSci) and HPGe detectors. Figure 1 shows these instrumentations and their connections.

For the PSci:

- EJ-276 Plastic Scintillator coupled to a Hamamatsu PMT R7724 (negative bias) [1, 2].
- High Voltage ORTEC 556 Power supply (works up to 2900 V) [3].
- Two RG-62 A/U cables, one to power the PMT with module 571 and another to send pulses from PMT to digitizer.

For the HPGe:

- High Purity Germanium Radiation Detector, ORTEC model GEM-301185-P [4], 2000 V, positive bias.

- 5kV ORTEC 659 Bias Supply [5].
- ORTEC 572 amplifier [6].
- Cable RG-62 A/U to power HPGe using module 659.
- Two cables RG-62 A/U. One to send signal from HPGe preamp to Amplifier 572. The other one to send signal from the Amplifier 572 to the digitizer.

Radioactive source:

- Cesium 137 (137Cs): source of monoenergetic (662 keV) photons.

Data acquisition:

- CAEN 2740/2745 digitizer (64 channel 16 bits)(50 ohms impedance) [7].
- MIDAS data taking software [8].
- red-midas reconstruction code.

2 Experimental Proceeding

Place the following modules into th ORTEC NIM bins [9]: ORTEC 572 amplifier, ORTEC 556 amplifier and ORTEC 659 bias supply.
For PMT:

1. Put the output terminal from the back of the 556 HV Power Supply into the PMT HV input.
2. Put the PMT anode cable output directly into Channel 8 of the digitizer.
3. Turn Amplifier 556 ON and then rise voltage as specified.

For HPGe: :

1. For the ORTEC 659 module, check if its bias shutdown is set. This prevents detector damage in case of high temperature, shutting down the voltage supply.
2. This HPGe model works on positive bias. So, rise its voltage up to 2000 V (not beyond this!).
3. The HPGe has two preamp outputs. One of them we will plug directly to the digitizer's channel 11.
4. The second preamp output we insert into ORTEC 572. It is already configured for pulse shape of 2 μs Coarse gain 50/14(50) and unipolar output. This is a standard pulse shape in nuclear physics instrumentation.

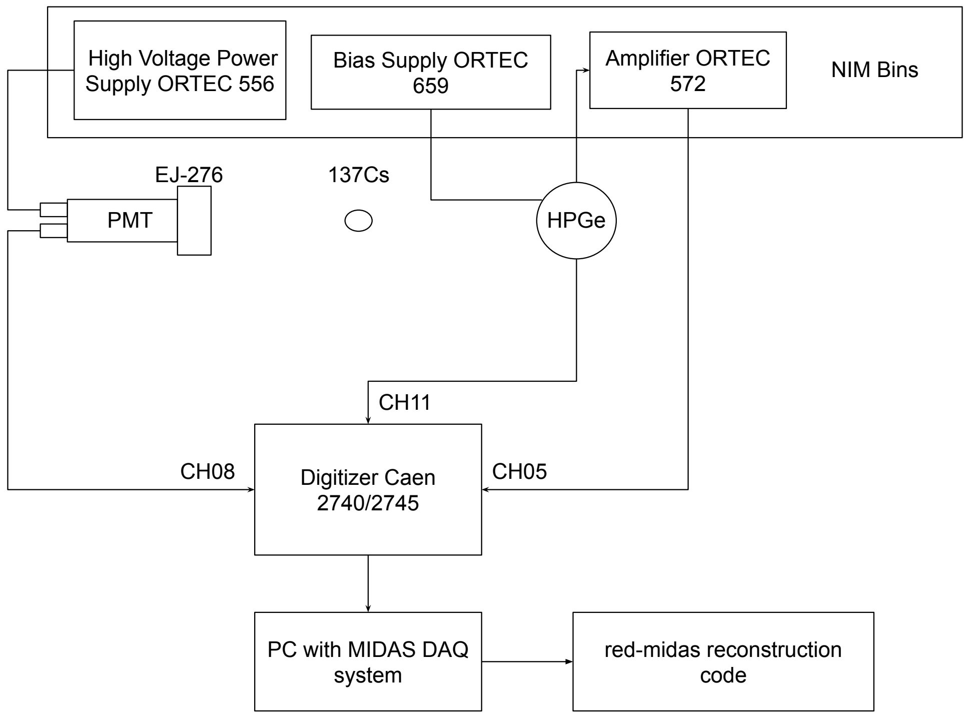


Figure 1: Instrumentation and cable connections.

5. the unipolar output is now inserted into channel 5 of the digitizer.

Experimental geometry setup:

1. Set the detectors against each other with the source between them. Try to align the active area of the detectors with the center of the 137Cs source.

Data taking:

1. if necessary check outputs using a oscilloscope.
2. Using the DAQ computer: open MIDAS data acquisition system that communicates with the digitizer.
3. Go to the ODB section and load the following configuration file: SchoolExp08.json.
4. Click on start run. Check the rate is about X events/s.
5. After accumulating some statistics, stop this run.
6. Now we are ready to reconstruct the raw data.

3 Data Analysis

The goal of this experiment is to determine the scintillator detector energy resolution by a coincidence method with a reference detector [10]. The reason for using this technique will be clear later on during data analysis. Now, we should reconstruct the data with the red-midas code. Basically this code calculates the baseline for each pulse and then determines pulse height, integration for PSD and pulse time stamps. Before taking a look into the data, let's introduce some basic concepts of photon interaction in the target detector.

In this setup, the 662 keV photons from the 137Cs source interact in the scintillator via Compton Scattering [11]. These photons then scatter with probability given by the Klein-Nishina formula [12]:

$$P(t_e; k_0) = \frac{1}{A}\left(\frac{E}{E_0} + \frac{E_0}{E} - \sin^2\theta\right) \tag{1}$$

with

$$\sin^2\theta = 2\left(\frac{m_e c^2 E_e}{E_0 E}\right) - \left(\frac{m_e c^2 E_e}{E_0 E}\right)^2 \tag{2}$$

and

$$E = E_0 - E_e \tag{3}$$

where E_0 is the incoming photon energy (662 keV for 137Cs), E is the scattered photon energy and E_e is the energy given to the electrons of the target in the Compton interaction. For our setup, we are interested in the backscattering process ($\theta = 180°$) which should happen with the highest probability and lead to scattered photons with the minimum energy

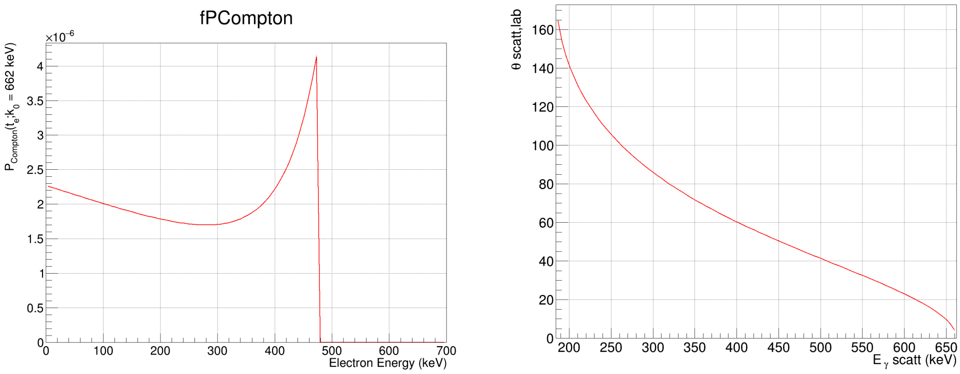
$$E_{min} = \frac{E_0}{1 + \frac{2E_0}{m_e c^2}} \tag{4}$$

so that the electron in the target material of the scintillator recoils with maximum energy E^e_{max} known as the Compton edge. The energy given to electrons convert into prompt photons in the target which then are collected by the PMT.

Figure 2 (a) shows the (Compton) probability for 662 kV photons as a function of the target electron recoil energy. In (b), the photon scattering angle as a function of its energy after the scattering is shown.

In our coincidence setup we will open a window in time to detect the photons that interact in the scintillator and backscatter to the HPGe where they are finally absorbed via photoelectric effect. Therefore, we expect photon energy at 180° (minimum) $E_{min} =$ 184.35 keV and $E_0 - E_{min} = E^e_{max} = 477$ keV (the Compton edge) for $k = 662$ keV incoming 137Cs photons. Due to the scintilator finite energy resolution, this energy might be shifted to lower or higher values. For the detectors used here, the energy resolution of the HPGe can be neglected when compared with that of the PSci.

In this activity, we want to determine the PSci detector resolution using events detected in coincidence with the HPGe. In principle, it would be possible to determine this



(a) (b)

Figure 2: (a) Compton Scattering Probability. (b) Scattered output angle in function of its associated photon energy in the Compton interaction.

resolution using only the PSci, but in that case, we would detect scatterings in a very broad interval of angles, requiring a more elaborate convolution procedure to extract the energy resolution. By using the HPGe and a geometry that selects only a narrow interval of scattering angles around 180°, we are in fact selecting photons with well defined energy. The deposited energy in the PSci will be determined by subtracting from the photon incoming energy, the energy measured in the HPGe. In that situation, the width of the PSci deposited energy will be dominated by this detector resolution which we will approximate by a Gaussian.

Notice that the HPGe is already calibrated and that our scintillator might not be, which it is the case assumed in this activity.

Reconstructing data:

- cd to red-midas directory. The reconstruction command is:

  `bash rec.sh 294 PSciGeDet (change 294 to your run number).`

- check pulse traces with the following command:

  `./RedLevel1 -s 1 -r 294 -p.`

- open ROOT [13] and plot data with the commands:

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(root) .L analysis/ExpSchool08.cpp
(root) HPGePSciCoinc(294).
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- Check the Gaussian fit values e calculate the scintillator resolution $R(\%) = 100\sigma/mean$. What is the photon energy to which this resolution applies? Can you think of a formula to model the energy dependence of the PSci resolution?

- You might also check the HPGe specifications to compare its expected resolution with that of the PSci.

Congratulations, now you know how to use the coincidence method to determine a detector energy resolution (scintillator) using a reference detector (HPGe).

References

[1] https://eljentechnology.com/products/plastic-scintillators/ej-276

[2] https://www.hamamatsu.com/us/en/product/optical-sensors/pmt/pmt_tube-alone/head-on-type/R7724.html

[3] High Voltage Power Supply Ortec 556.

[4] High Purity Germanium (HPGe) Radiation Detector ORTEC model GEM-301185-P

[5] ORTEC 659 5 kV Radiation Detector Bias Supply

[6] ORTEC Model 572A Spectroscopy Amplifier

[7] Caen DT2745 digitizer.(https://www.caen.it/products/dt2745/)

[8] MIDAS (acronym for Maximum Integrated Data Acquisition System) is a modern data acquisition system developed at Paul Scherrer Institute - PSI and TRIUMF Canada's particle accelerator center. Installation webpage: MidasWiki Quickstart Linux (https://daq00.triumf.ca/MidasWiki).

[9] ORTEC NIM bin 4001A and 4001C

[10] B.D. Rooney; J.D. Valentine, Benchmarking the Compton coincidence technique for measuring electron response nonproportionality in inorganic scintillators IEEE Transactions on Nuclear Science (Volume: 43, Issue: 3, June 1996).

[11] http://www.sophphx.caltech.edu/Physics_7/General_Appendix_D.pdf

[12] Quantum Electrodynamics, Walter Greiner and Joachim Reinhadt, Springer.

[13] https://root.cern/