

Pulse-shape discrimination for gamma-neutron separation

Second School on Dark Matter and Neutrino Detection

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Plastic or liquid scintillators are very powerful fast neutron detectors and have been extensively employed in nuclear and particle physics applications. For example, in experiments such as those designed to measure the response of liquefied noble gases (like Liquid Argon LAr) to low-energy nuclear recoils induced by neutrons, they are used as the main neutron detectors. Even in the presence of ubiquitous gamma radiation, scintillators show excellent photon-neutron separation power through the Pulse Shape Discrimination (PSD) technique. In this laboratory activity, students will study the time response of a scintillator detector to a gamma source and learn to construct such pulse-shape parameters using an experimental setup that includes nanosecond time-resolution electronics. Finally, neutron and gamma population data will be analyzed to demonstrate separation power.

1 Experimental Setup

Figure 1 shows the instrumentation and their connection as used in this experiment. They are:

- EJ-276 PSD Plastic Scintillator [1].
- PMT Hamamatsu R7724 negative HV. Max operation 2000 V [2].
- High Voltage Power supply ORTEC 556 (up to 2900V \pm 3 V) [3].
- Cables RG-62 A/U to power PMT and to send pulses from PMT anode output into digitizer.
- Digitizer Caen 2740/2745 (64 channel 16 bits)(50 ohms impedance) [4].
- MIDAS software for data taking [5].
- red-midas code for data reconstruction.
- Radioactive source: Americium 241Am, mono energetic photons of 59.54 keV.

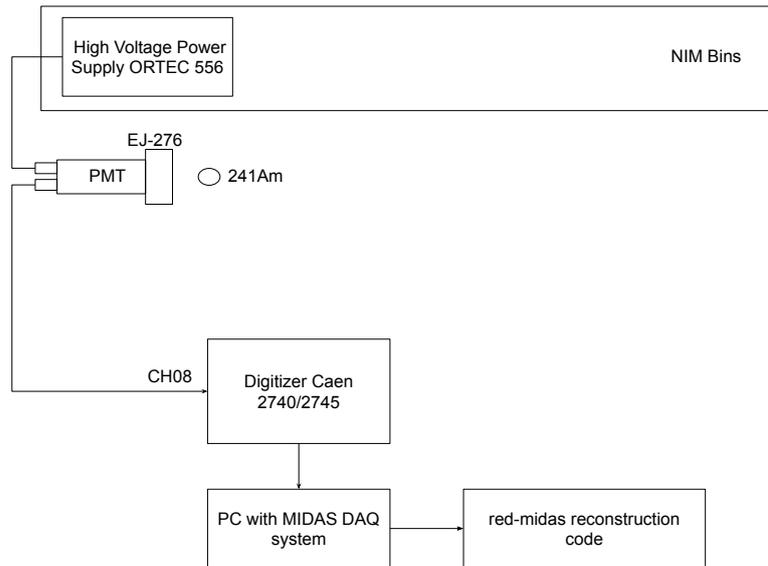


Figure 1: Instrumentation and cable connections.

2 Experimental Proceeding

1. Place the ORTEC 556 into the NIM Bins [6] and feed its power supply (110 or 220V). Check if the appropriate polarity has been selected at the back of th module.
2. Connect the output terminal cable from the back of the HV Power Supply into PMT HV power input.
3. Connect the other cable from the PMT output anode to the oscilloscope channel. Check the pulses displayed on the screen. Observe the pulse characteristics: rise time, peak height, fall time.
4. Take the PMT anode cable from oscilloscope and put it directly into channel 8 of the digitizer.
5. Using the DAQ computer: open MIDAS data acquisition system that communicates with the digitizer.
6. Go to section ODB and load the following configuration file: SchoolExp07.json.
7. Click on start run. Check rating of X events/s.
8. After accumulating some statistics, stop this run.
9. Now we are ready to reconstruct raw data. But before that, let's define the Pulse Shape Discrimination.

3 Pulse Shape Analysis

Pulse Shape Discrimination (PSD)[7] is a tool used to distinguish different particles that interact within a given detector. Consider gammas and neutrons interacting with a scintillator. On average, the pulses of gammas decay faster than those of neutrons, so a shape analysis determine a PSD characteristic for each particle population. In Figure 2 we represent an average pulse for gamma and neutron particles. The difference in shape is prominent when time integration of the pulse is performed.

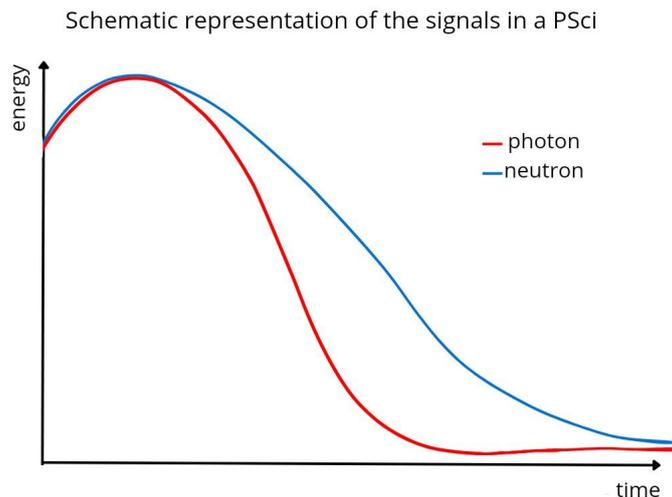


Figure 2: Average time profile of scintillation pulses generated by gammas and neutrons. Gammas decay faster than neutrons.

In this lab activity, we will define the PSD variable as:

$$\text{PSD} \equiv 1 - \frac{Q_s}{Q_l} \quad (1)$$

where Q_s and Q_l are either ADC counts for uncalibrated detectors or deposited energy for calibrated ones and obtained using short (Δt_s) and long (Δt_l) time integration windows of the scintillator charge $\text{Signal}(t)$

$$Q_s \equiv \int_{t_0}^{t_0 + \Delta t_s} \text{Signal}(t) dt, \quad Q_l \equiv \int_{t_0}^{t_0 + \Delta t_l} \text{Signal}(t) dt \quad (2)$$

with $\Delta t_l > \Delta t_s$. The initial integration time t_0 . If detector is calibrated (this is the case for our experiment), we can plot the PSD as a function of the particle energy, which here is given by Q_l , since Δt_l is chosen in such a way as to contain the whole scintillation signal induced by the incoming particle (photon or neutron).

We can also work with the so called *fprompt* parameter, given by:

$$f_{prompt} \equiv 1 - \text{PSD} = \frac{Q_s}{Q_l}. \quad (3)$$

3.1 Data Reconstruction

Now after data taking, we should reconstruct data with the red-midas code. This piece software access raw data where the pulses were recorded in the disc and calculates baseline for each pulse and determines pulse height and signal integration for the PSD.

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

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

- check pulse traces with the following command:

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

- open ROOT and plot PSD with the following commands:

```
.L analysis/ExpSchool01.cpp and then PlotPDS(294).
```

- time window integration configurations are stored in `cfg/detector.cfg`. Inside this file, find the detector label `PSci0`, go to column 7 and change the time window width in number of digitizer's sample (1 sample equals to 8 ns). The longer window is located at column 5 and it is set to 100 samples.
- Reconstruct the same event again but with the following command:

```
./RedLevel1 -s 1 -r 294 -o results.red/run\_294\_1.root
```

Congratulations, now you know how to calculate PSD for photons.

3.2 Neutron and Gamma Separation Analysis

Since we do not have a neutron source in our experiment 7, we provide a root file with data taken from radioactive source Californium 252 (^{252}Cf). This is a source of gammas and neutrons with energy ranging from tens of keV to a few GeV. In the following we describe the experimental setup used for acquiring these data and then instructions to run scripts that will access them and perform PSD analysis.

3.2.1 The ReD Experiment

The Recoil Directionality Experiment (ReD) is a subgroup of the eDarkSide collaboration and it has a three-fold goal: check if a dual phase Liquid Argon (LAr) Time Projection Chamber (TPC) has sensitivity to the direction of Ar recoil; characterize the response of the LAr TPC to low-energy recoils (a few keV); and act as a test bench of the technical solutions for DarkSide-20k TPC.

Figure 3 shows a scheme of ReD experimental setup. The radioactive Californium ^{252}Cf undergoes spontaneous fission in 3% of its decays emitting gammas and neutrons in the process. For each fission an average of 18 photons and 4 neutrons are produced as well as fission fragments.

Neutrons generate low-energy nuclear recoils inside the TPC and by the geometrical configuration, these neutrons are detected by the Plastic Scintillator (PSci) as shown in Figure 3. **We use the PSD technique to select neutrons in the PSci that were scattered in LAr TPC. So this is the main role of the PSD analysis in ReD experiment.**

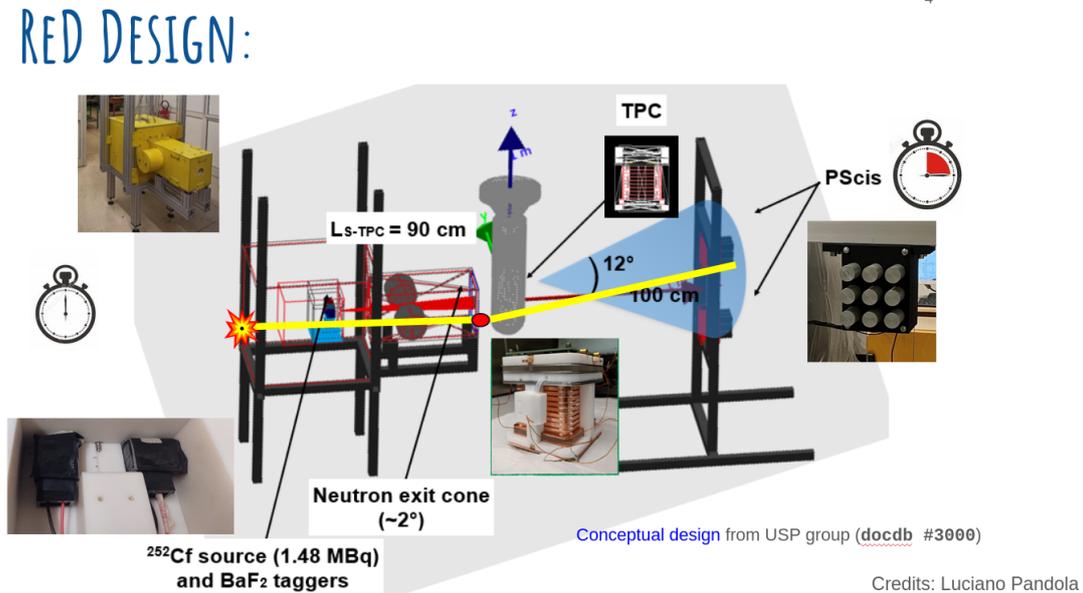


Figure 3: ReD experiment configuration to take data from ^{252}Cf which is a source of gamma and neutrons. In this analysis we are interested in the PSD from the neutron spectrometer in the form of a PSci.

In the following we give a description on how ReD works: Two Barium Fluoride detectors (BaF_2) are located near the ^{252}Cf source so they detect the photons from the fissions acting as time taggers. After this, the neutrons are collimated by a lead apparatus in a 2° cone and then reach the TPC, located 90 cm away from the source. The neutrons then interact with the Liquid Argon (LAr) nucleus inside the TPC, generating

a low energy nuclear recoil that gives rise to two signals inside the TPC, the S1 due to scintillation and the S2 due to electroluminescence. The neutrons than reach the PSci array, located at a distance of 100 cm from the TPC, displaced from the beam center oby an average of 12° . We have two PSci array, each one with 9 PSci, one above and the another below the beam axis. This geometry constrain neutrons that are scattered in LAr to come out at low angles, leaving an energy of a few keV in the TPC. The time difference between the BaF₂ tagger and the PSci is used to eliminate background interactions.

So, to acquire the data we used the coincidence between the BaF₂ and the PSci to select events. When a signal is detected by a PSci, the signal of all the 18 PSci is also registered. In this setup, BaF₂ is used as a tagger and we have all PSci used as slaves. The electronic setup allows us to have a time resolution of 2 ns, so each sample bin is equivalent to 2 ns in our data (that is, ReD electronics has a time resolution a factor better than the one used in the first part of this acitivity).

3.2.2 Data structure

There is one root file for each run and inside these files one can find a tree named *treetraces* with the basic information of the traces saved in it. The four variables inside the tree are:

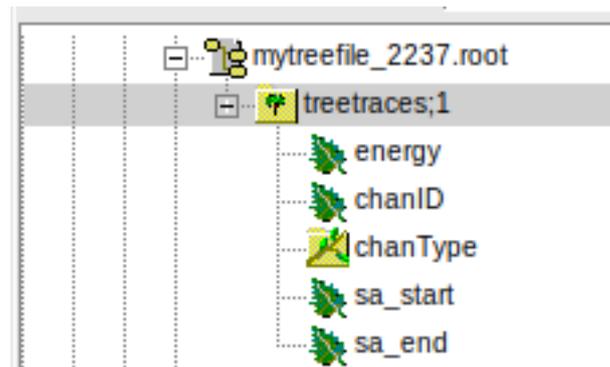


Figure 4: Structure of the tree with the traces information.

- energy: a `std::vector<float>` with the energy of the trace per sample (2 ns) in each bin;
- chanID: an `int` containing the channel number of the PSci which acquired the trace;
- chanType: a `std::string` containing the type of detector used (for this data set, we only used PSci's);
- sa_start: an `int` containing the start time of the trace;
- sa_stop: an `int` containing the stop time of the trace;

3.2.3 How to use the code

First of all you need to put all the code files and the folder of root files in the same folder. In the material you received there are three files (`trace_viewer`, `fprompt_analyzer`, `selection.runs`) and one folder (`threes_school`) that contains all the root files mentioned above. The `selection.runs` is just a file containing a list of the run numbers used in this activity, used for simplicity.

The *trace_viewer* is a pulse visualizer, in which you can choose the run number and event number to visualize the trace detected in the triggered PSci in that event. The trace is shown in keV vs sample (2 ns). To use this code you need to open root inside the folder containing the code and load the file into root. Then, call the function `TraceViewer`, with a run and an event number. See Figure 5. If you choose an event number above the number of events in that run, the code will return an error showing the total number of events in that run, so that you can choose a valid event number.

```
root [0] .L trace-viewer.C
root [1] TraceViewer(2237,20)█
```

Figure 5: Loading script for trace viewer.

The *fprompt-analyzer* is the main code, used to analyze each event and calculate the *fprompt* for each trace, using the time windows of your choice. The code returns a 2D histogram of *fprompt* vs. energy, where you can see all the particles plotted, and a 1D histogram of *fprompt*, where you can see the projection in *fprompt* of the previous 2D histogram. To use this code you need to open root inside the directory containing the code, and load the code into root. After that you can call the function `FpromptCalc`, which receive two variables, W_{short} and W_{long} to calculate the *fprompt* of the particles. See Figure 6. It's important to note that the choice of time windows can change considerably how good the particle populations are distinguishable from each other, so you can test different choices of windows to see how it changes. A good reasonable choice to start with a $W_{short} = 20sa$ and $W_{long} = 200sa$. It's important to choose a W_{long} considerably bigger than W_{short} , otherwise you won't see any population separation at all.

```
root [0] .L fprompt-analyzer.C
root [1] FpromptCalc(20,200)█
```

Figure 6: Commands to be entered in root to use the *fprompt-analyzer* code.

Congratulations, now you know how separate gammas from neutrons using PSD. Also there is a way to tune the best signal integration gates to better distinguish each particle population. This is done through the so called Merit Factor.

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] Caen DT2745 digitizer. (<https://www.caen.it/products/dt2745/>)
- [5] 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>).
- [6] ORTEC NIM bin 4001A and 4001C
- [7] G.F. Knoll, Radiation Detection and Measurement, 4th edition, John Wiley & Sons, Hoboken (2010).
- [8] <https://root.cern/>