Adaptive triggering for scintillation signals

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-The optimum choice of detector depends on the requirements of the experiment.

-HPGe – the highest resolution.

-Scintillator based detectors:

+Good timing properties and effeciencies at reasonable cost

- not great resolution.

The detection of ionizing radiation by the scintillation light (produced in certain materials) is one of the oldest techniques used .

The scintillation process is however one of the most useful methods nowdays available for the detection and spectroscopy of a wide assortiment of radiation.

The ideal scintillation material should posses the following properties:

- It should convert the kinetic energy of charged particles into detectable light with a high scintillation efficiency.
- The conversion should be linear.
- The medium should be transparent to the wavelength of its own emission.
- The decay time of the induced luminescence should be short – Fast signal pulses.
- The material should be of good optical quality/subject to manifacture in various sizes.
- Its index of refraction should be near that of glass (in case of a coupling to a PM tube).

No material simultaneously meets all the criteria

The most widely applied scintillator include the inorganic alkali halide crystals (of which sodium iodide is the favorite) and organic-based liquids and plastics.

Inorganic halide crystals + The best light output and linearity

- Relatively slow in their response time

Organic scintillators + Generally faster

- Yield less light

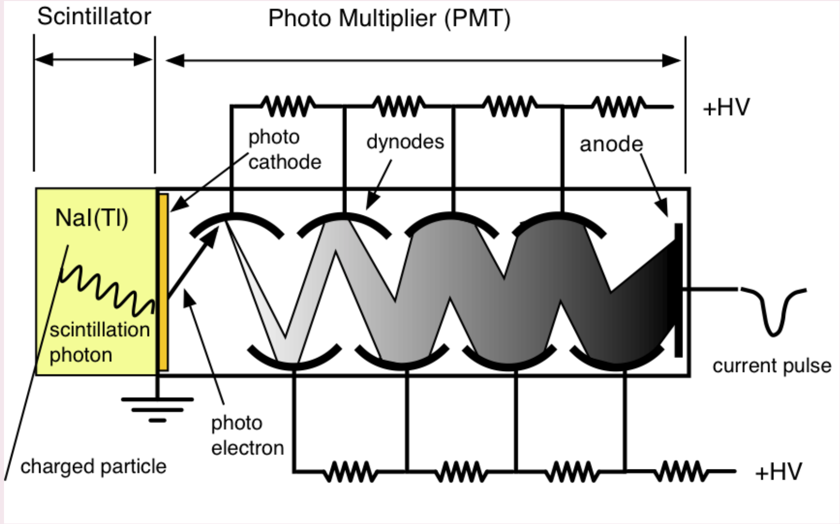
(Plastic scintillators) (+ Can be easily shaped)

The high Z-value of the constituents and high density of inorganic crystals - Gamma ray spectroscopy

Organics - Beta spectroscopy/Fast neutron detection.

Typical pulse from a scintillator – a few hundred (thousand) photons – Too small to be measured.

The PM tube convert a weak pulse from the scintillator into a corresponding electrical signal – 10^{7}-10^{10} electrons (Without adding a large amount of noise to the signal).



Signal evolution:

1. Energy is absorbed in scintillator.
2. Population of states that emit photons.
3. Decay of radiative states: Governed by Poisson distribution:

$$P(x) = \frac{(pn)^x e^{-pn}}{x!} = \frac{\mu^x e^{-\mu}}{x!}$$

$$\mu = \sum_{x=0}^{n} x P(x) = pn$$

$$\sigma^2 = \sum_{x=0}^{n} (x-\mu)^2 P(x) = pn$$

4. Photons absorbed in photocatode by expelling photoelectrons.
5. Finally the photoelectrons are multiplied through the gain structure.

$$I_{anode}(t) = G \cdot Q \cdot N_o \cdot e^{-t/\tau}$$

Precision of signal magnitude is limited by fluctuations

1. Fluctuations due to the stohastic nature of the pulse creation.
2. Baseline fluctuations due to the electronics – „Electronic noise“

Main contribution to the fluctuations in scintillator signals - Statistical fluctuations

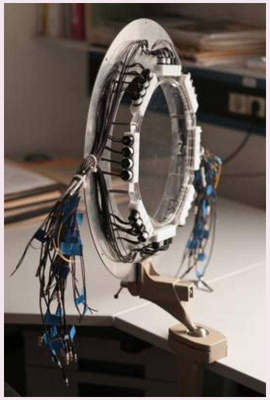
The output pulses are not all the same shape but rather „noised“ with statistical fluctuations on the pulse tails -Afterpulsing.

Caution - Some non statistical processes can also give rise to the afterpulsing

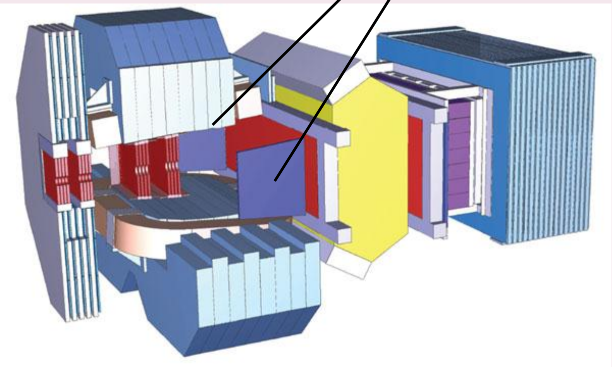
- The emission of light from the latter stages of the multiplier structure which comes back to the photocatode.
- Imperfect vacuum in the tube – Traces of residual gas can be ionized.

Scintillators @

TOF measurements with relativistic heavy – ion beams

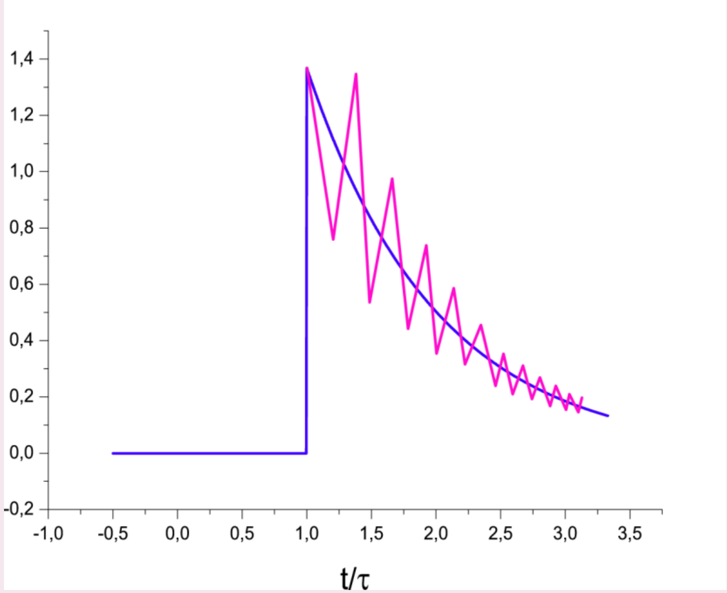


Plastic scintillator Time-Of-Flight system. (PANDA)

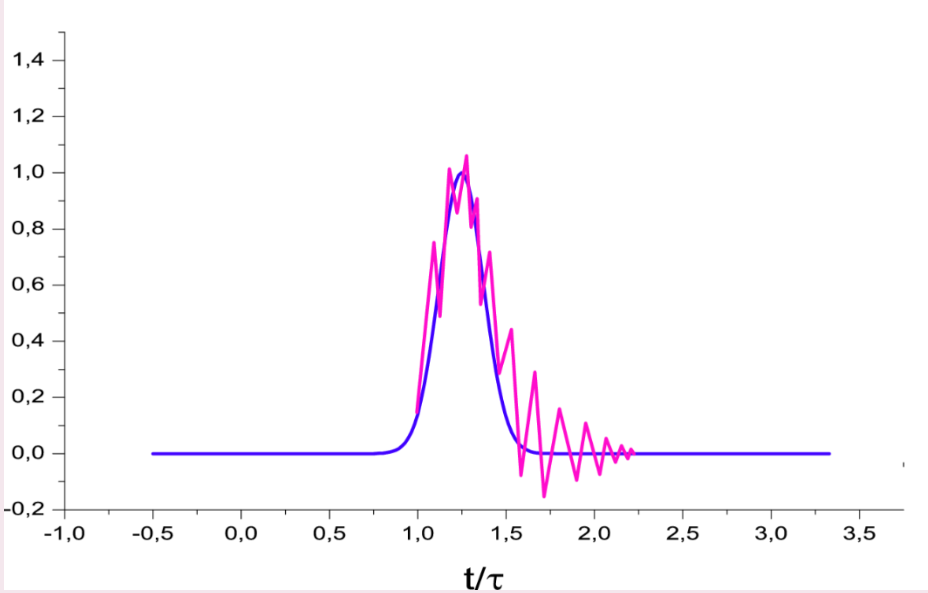


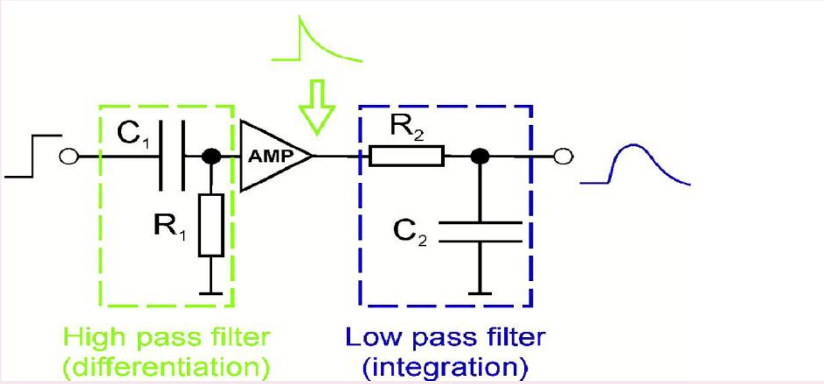
Afterpulsing+Analog electronics

Area=Energy



Amplitude=Energy





Moving window deconvolution: (MWD)

The single exponential decay with a starting time t=0 is written as:

$$f(t) = Ae^{-t/\tau}, t \geq 0$$
$$0, t < 0$$

Knowing the value $f(t_n)$ at time t_n the initial amplitude can be found as:

$$A = f(t_n) + A - f(t_n) = f(t_n) + A\left(1 - e^{-\frac{t_n}{\tau}}\right) = f(t_n) + \frac{\int_0^{t_n} f(t)dt}{\tau}.$$

In digital domain:

$$A[n] = x[n] + \frac{\sum_{k=0}^{n-1} x[k]}{\tau} = \mathrm{x[n]} - \left(1 - \frac{1}{\tau}\right)\mathrm{x[n-1]} + \mathrm{A[n-1]}.$$

Differentiate the deconvulated signal – obtain the MWD equation with a window M:

$$MWD_M[n] = A[n] - A[n-M] = x[n] - x[n-M] + \frac{1}{\tau}\sum_{k=n-M}^{n-1} x[k].$$

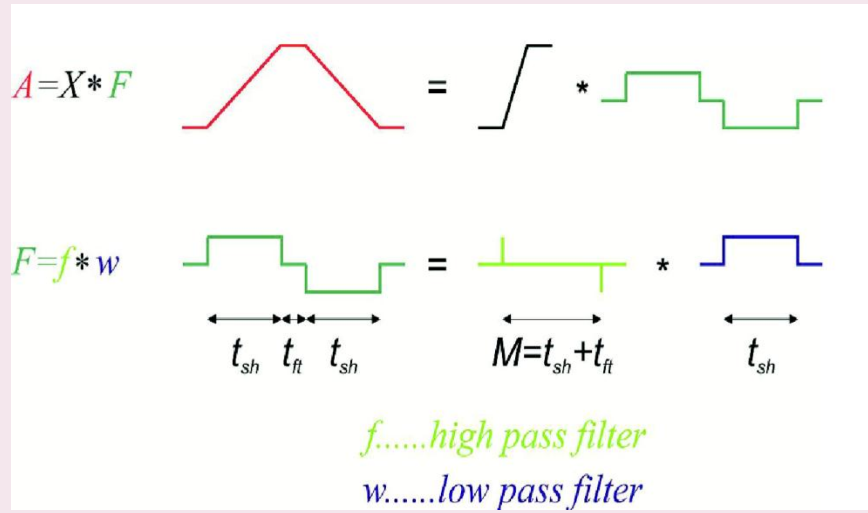
The MWD algorithm converts an exponentially decaying signal into a step signal of length M.

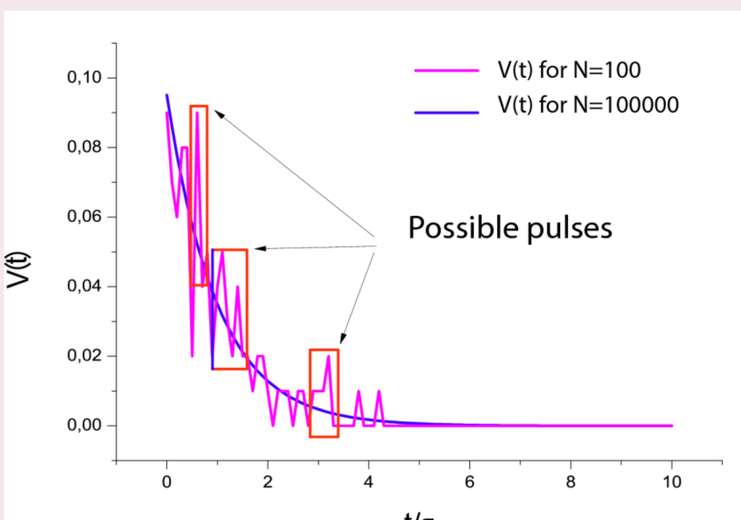
Signal to noise ratio?

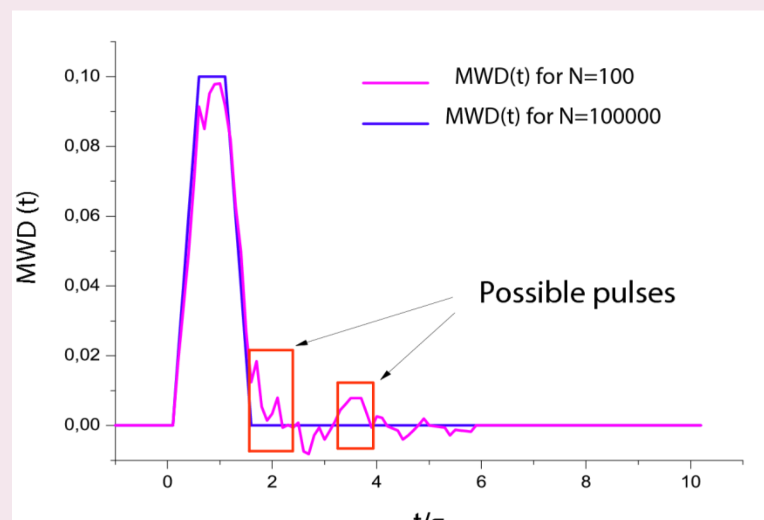
To impove the signal to noise ratio, a low pass filter is applied after the MWD module.

$$f_n = \begin{cases} 1 & n = 1 \\ \frac{1}{\tau} & 1 < n < M \\ \frac{1}{\tau} - 1 & n = M \end{cases} \qquad M = t_{sh} + t_{ft}$$

$$w_n = \begin{cases} 1/N_{sh} & 1 \le n \le N_{sh} \\ 0 & \text{otherwise} \end{cases} \qquad N_{sh} = t_{sh}$$

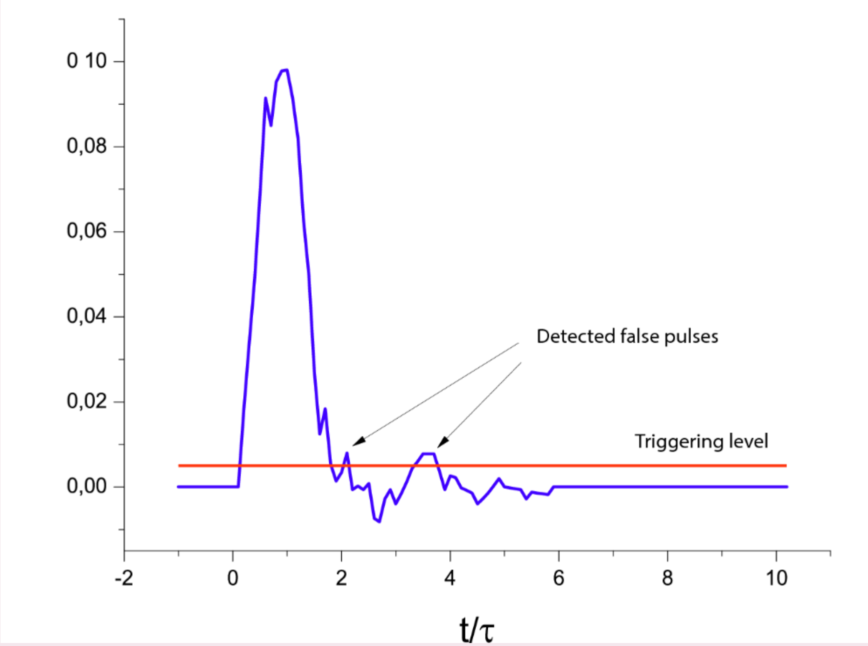




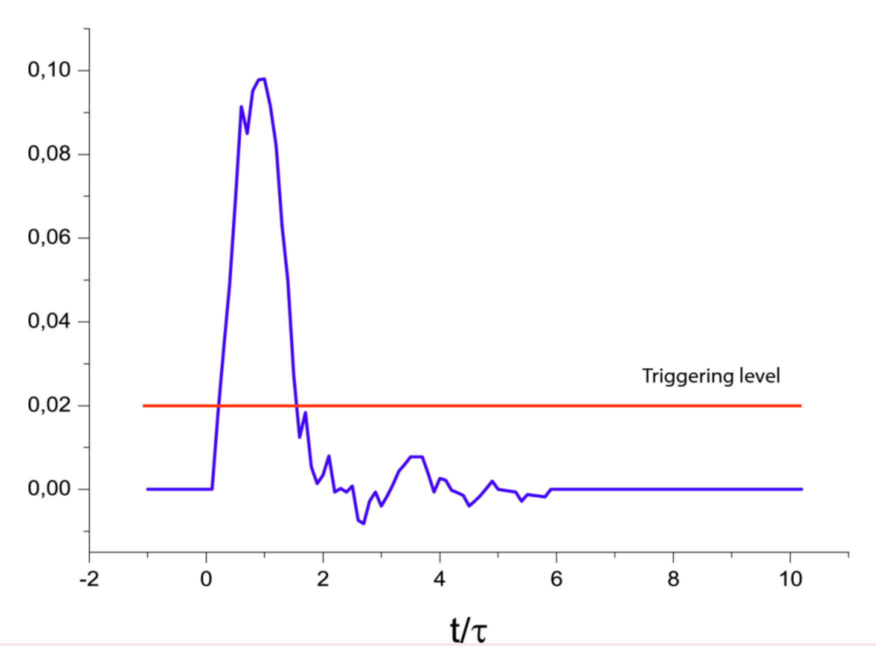


State of art –Increase trigger level/Deadtime

Low triggering level:

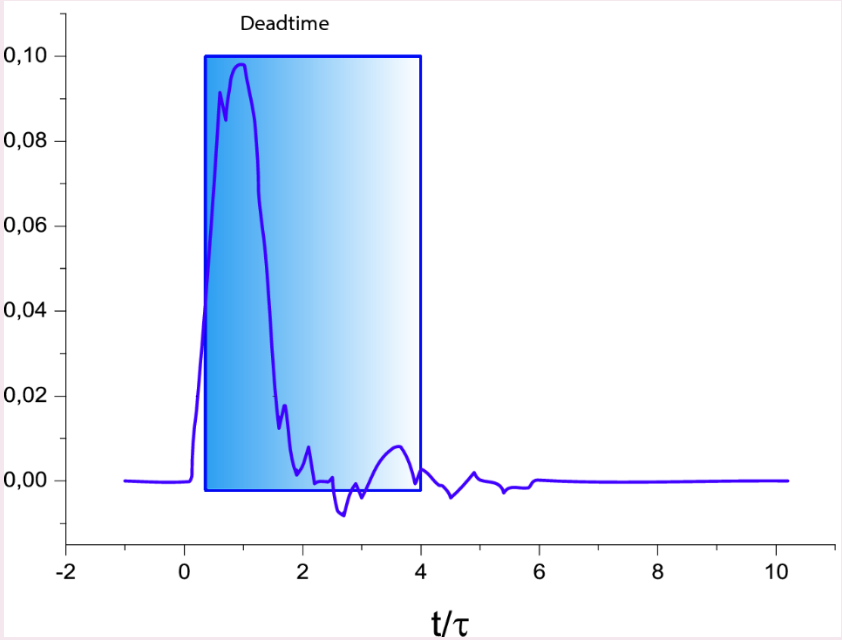


Increase triggering level:



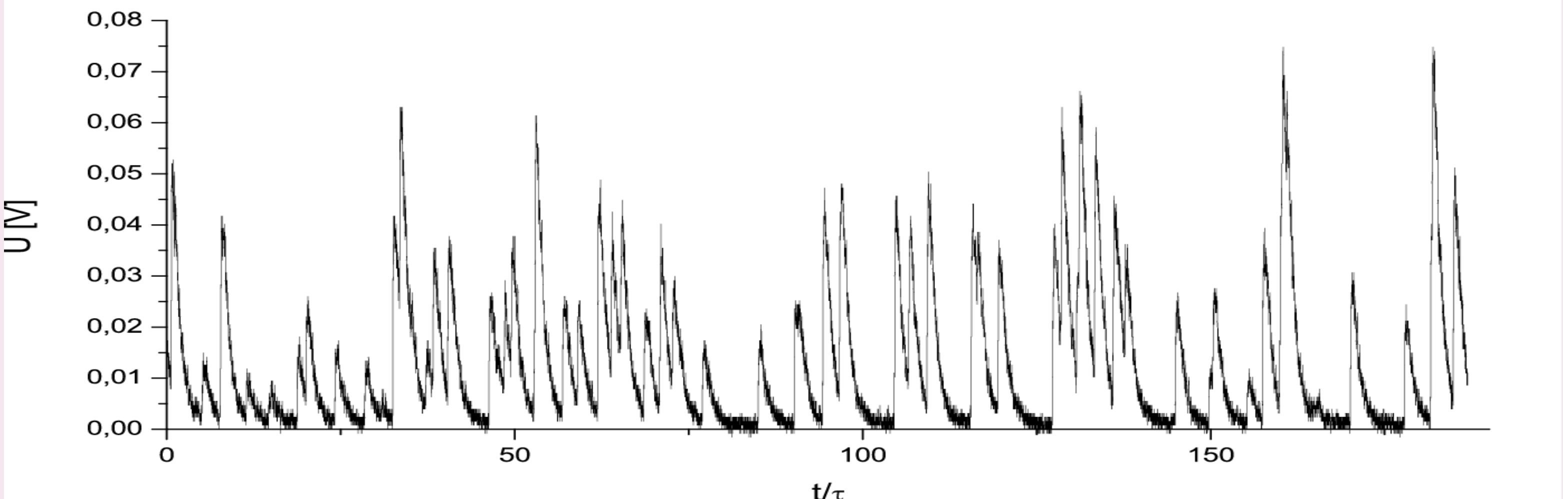
Lowers the dynamic range of the detector.

Deadtime

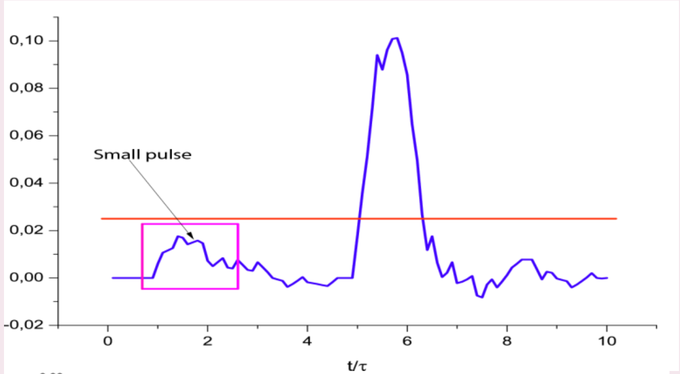


Introduce a deadtime after each pulse.

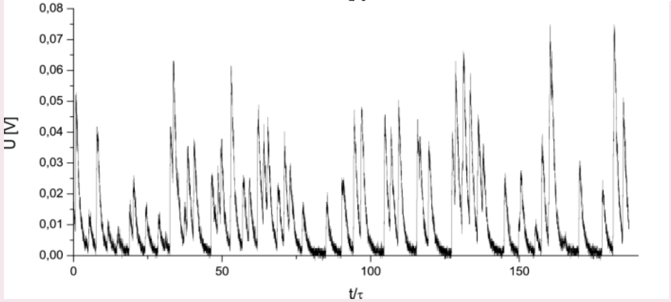
What about a high count rates ?



Increasing trigger level-Lowers the dynamic range.

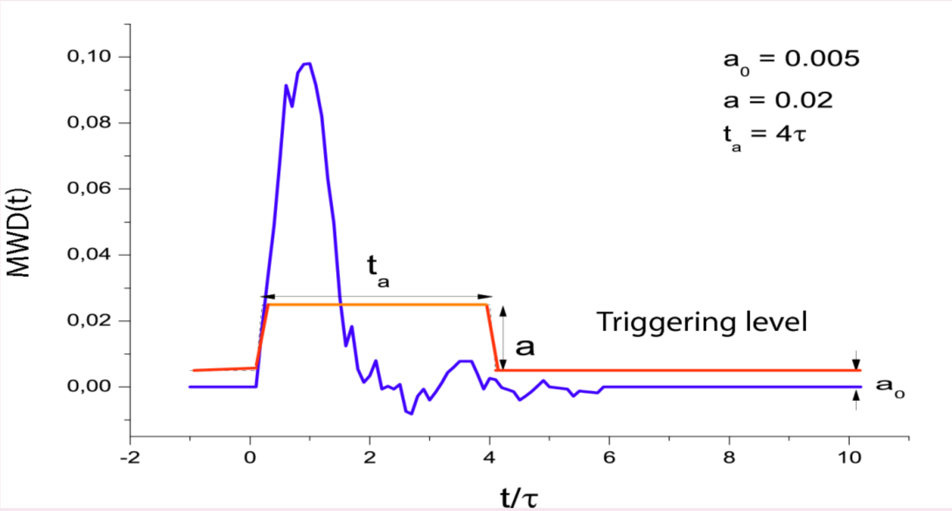


Introducing the deadtime - Makes the detector inefficient at higher count rates.

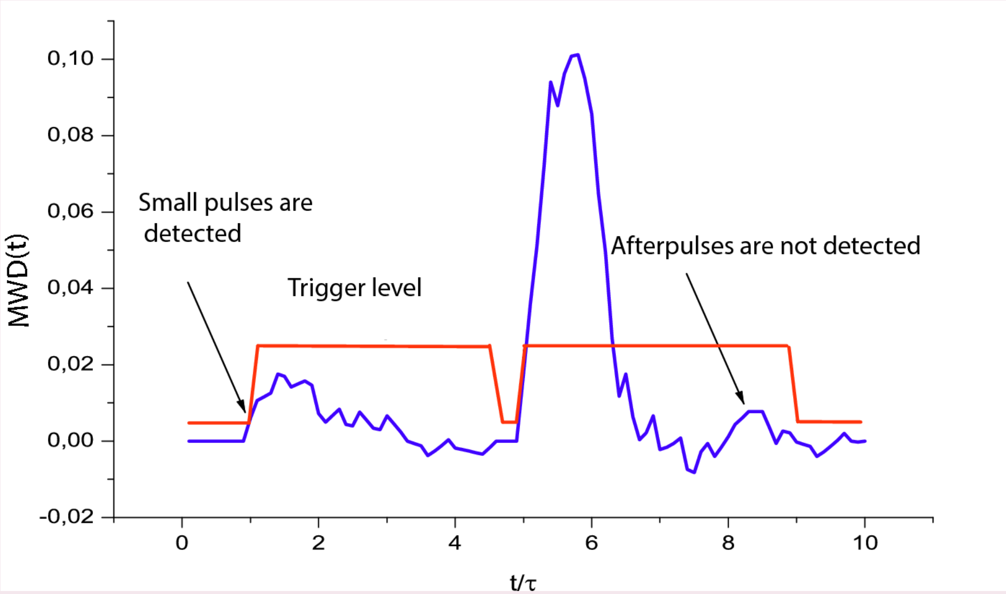


Solution – Raise the trigger by a finite value and for a finite amount of time after each pulse.

Adaptive triggering for scintillation signals



$$\mathrm{THR}(t) \begin{cases} a_o, t \le t_o \\ a_0 + a,\ t_0 < t < t_0 + t_a \\ a_0, t_0 + t_a \le t \end{cases}$$



Simulation

1. Simple energy spectrum given by the equation:

$$\frac{1}{N_0}\frac{dN(E)}{dE} = \frac{1}{2}\Big(c\delta(E - E_1) + (1 - c)\delta(E - E_2)\Big), \qquad c = \frac{N_1}{N_o}$$

2. Every event is described with the time of event and energy (Energy is randomly sampled from the energy spectrum, time is sampled from uniform time distribution).

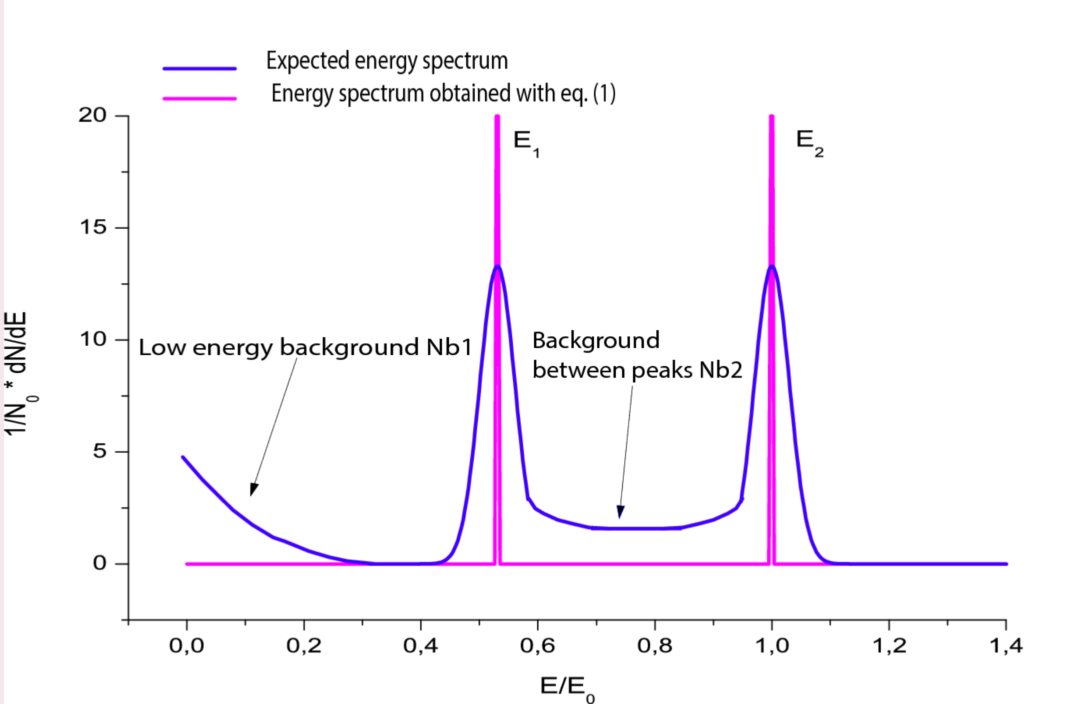
3. Every event excites n states proportional to its energy (Decay times are sampled from exponential distribution).

4. Every photon gets time stamp.

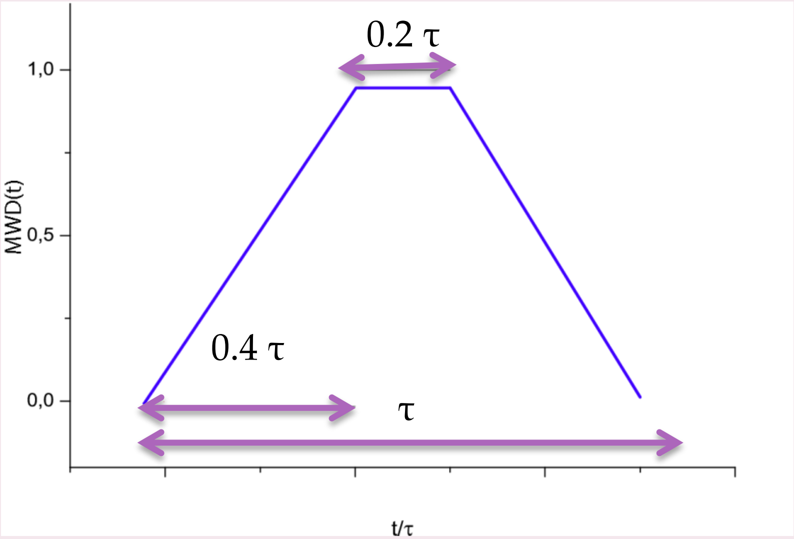
5. Put the time stamps into histogram with a bandwidth ω.

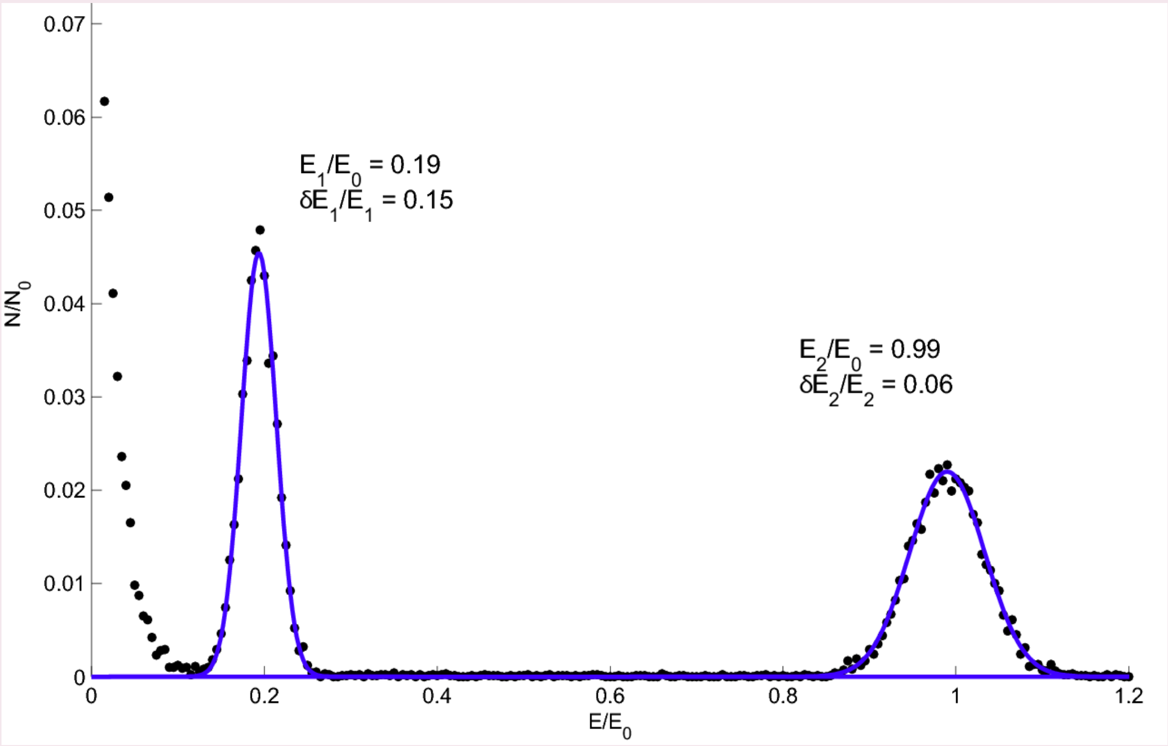
6. Histogram values - Amplitude of a current pulse from a photomultiplier.

Simulation parameters	Parameter values
Energy spectrum	$\frac{1}{N_0}\frac{dN(E)}{dE} = \frac{1}{2}\left(c\delta(E - E_1) + (1 - c)\delta(E - E_2)\right)$ (1)
Beam frequency	10^5 Hz
Decay time	250 ns
Proportionality constant (Reference energy corresponds to 1000 detected photoelectrons)	1000
Bandwidth	200 MHz



MWD parameters:



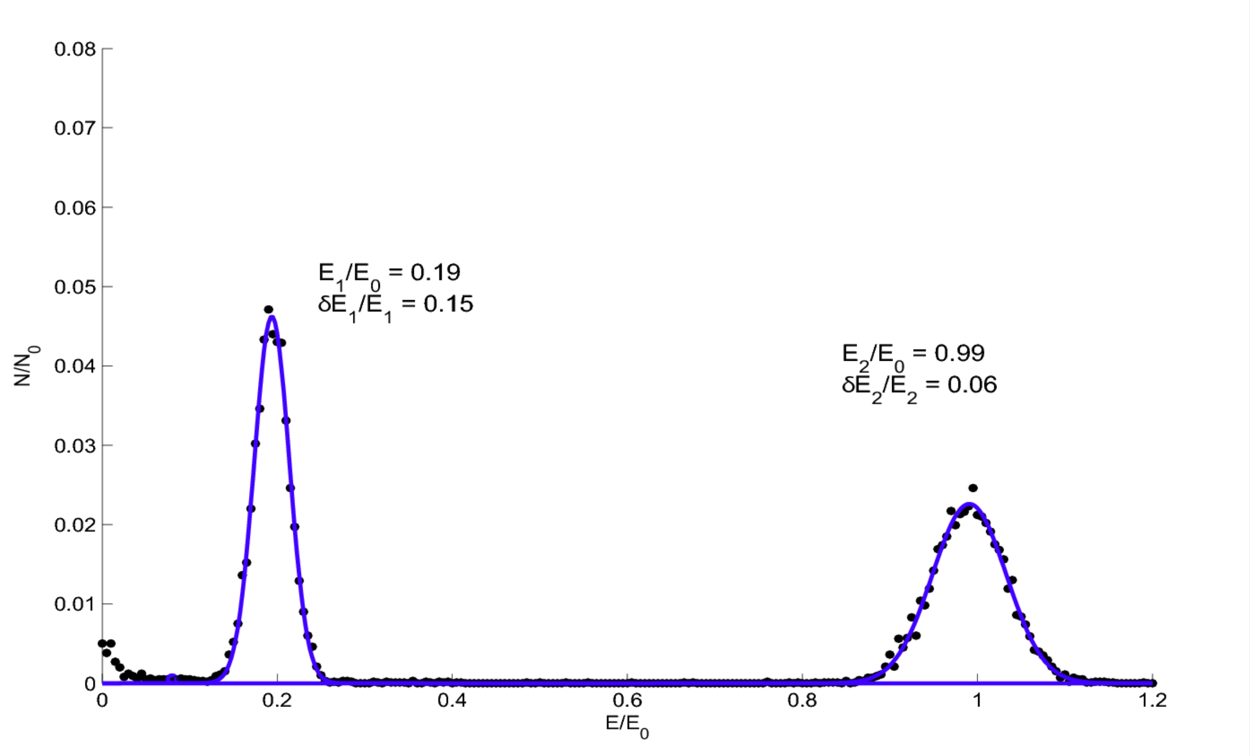


E_1/E_0=0.2 E_2/E_0=1, c=0.5

Adaptive triggering OFF

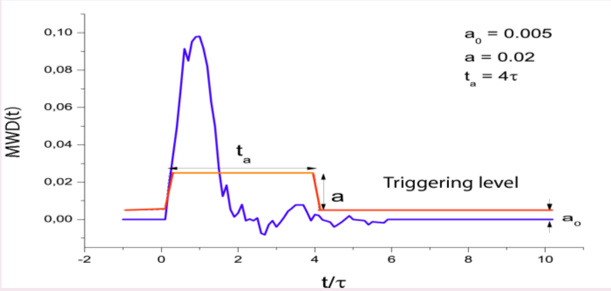
THR=0.025 E_0

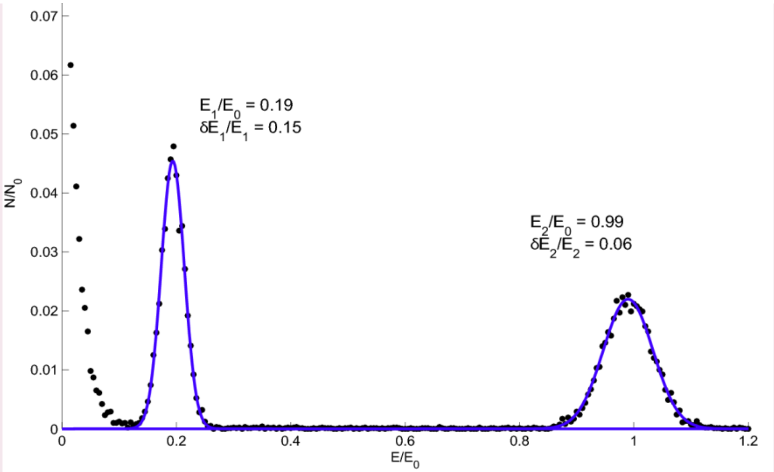
E_1/E_0=0.2 E_2/E_0=1, c=0.5



Adaptive triggering ON

$a=0.1\ E_0$
$t_a=4\tau$

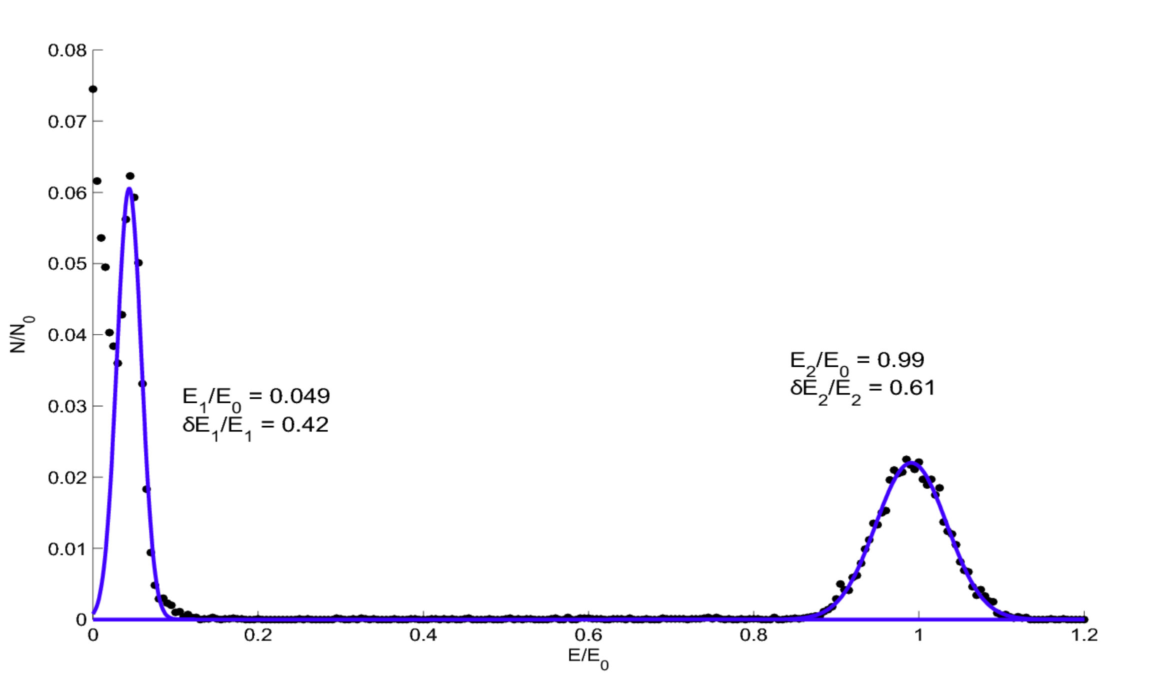




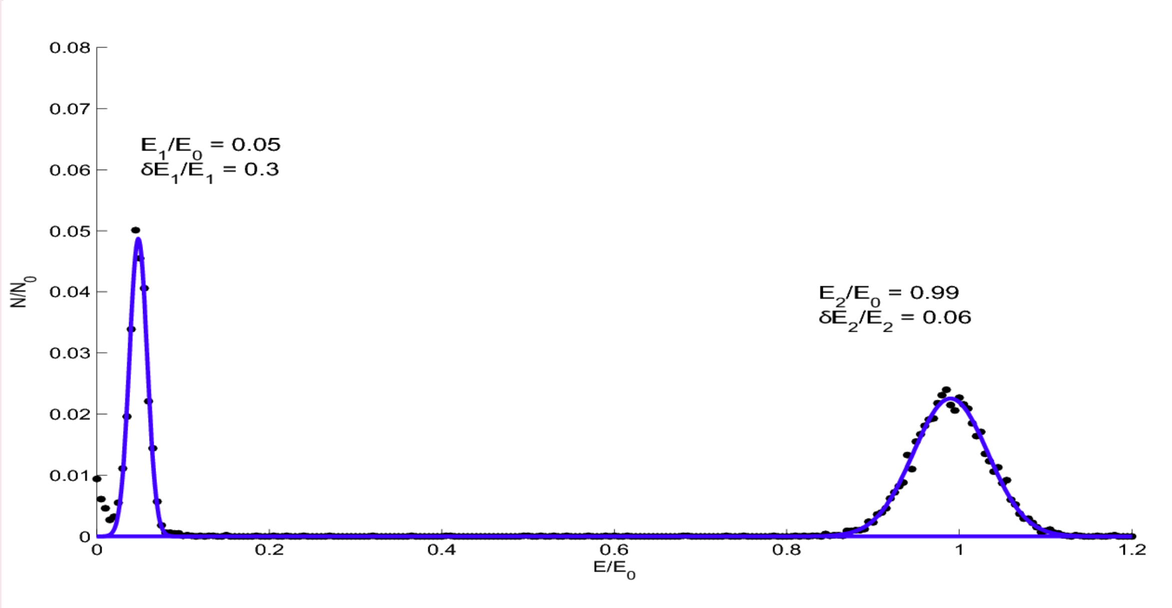
Low energy background – Due to the afterpulses

Background between peaks – Real pulses that follow the afterpulses.

E_1/E_0=0.05 E_2/E_0=1, c=0.5

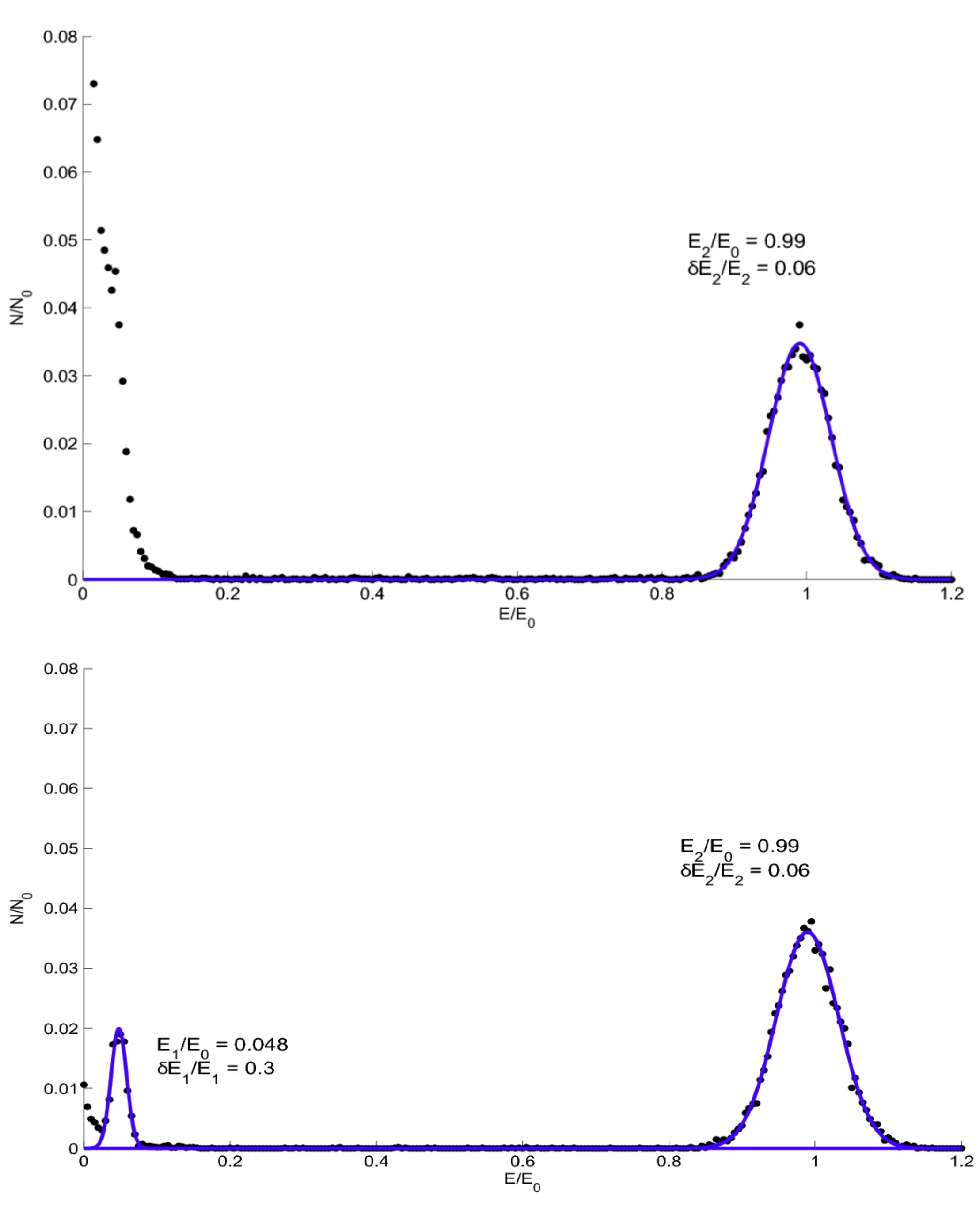


Adaptive triggering OFF
THR=0.025 E_0



Adaptive triggering ON
a=0.1 E_0
t_a=4τ

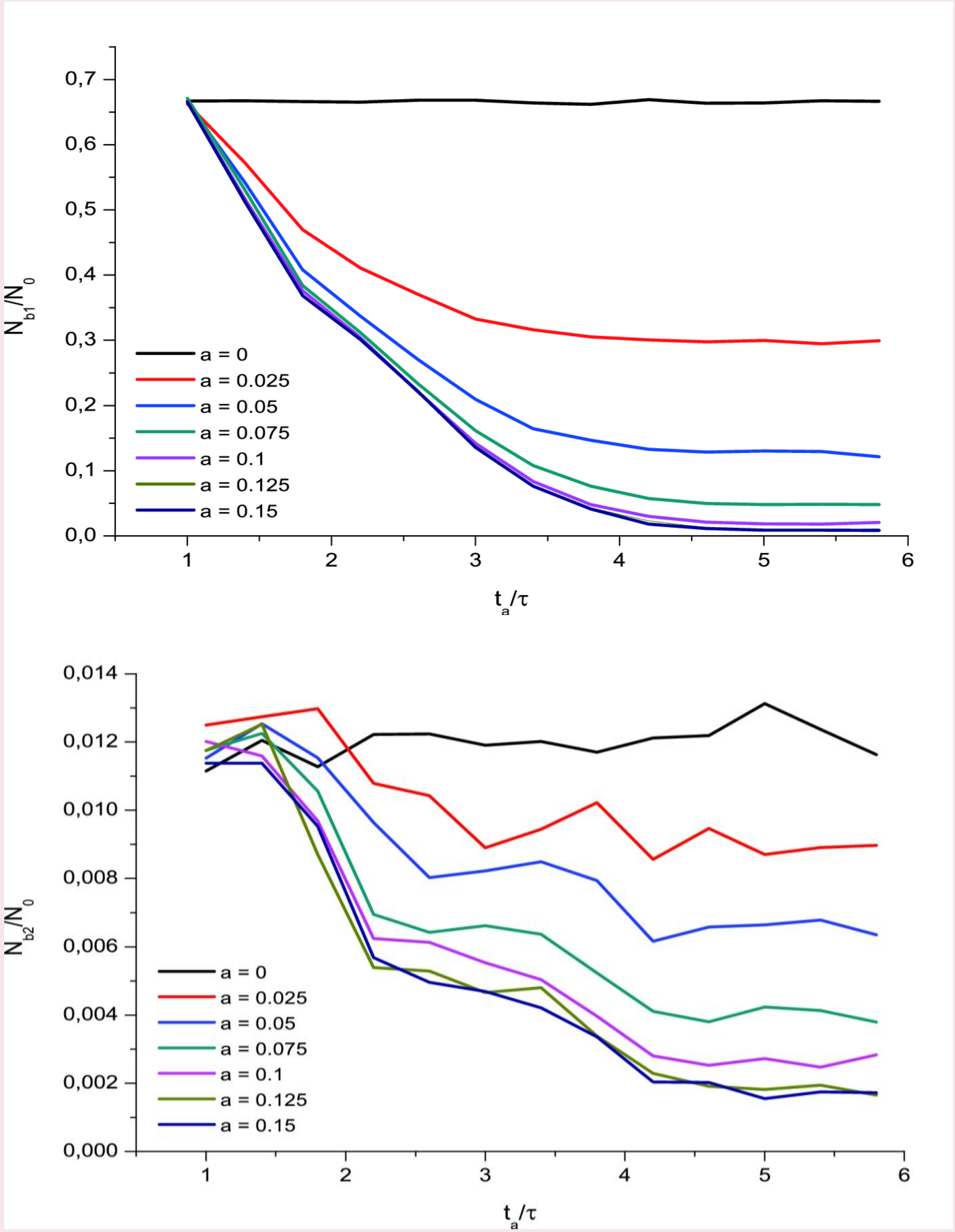
E_1/E_0=0.05, E_2/E_0=1, c=0.2



Adaptive triggering OFF
THR=0.025 E_0

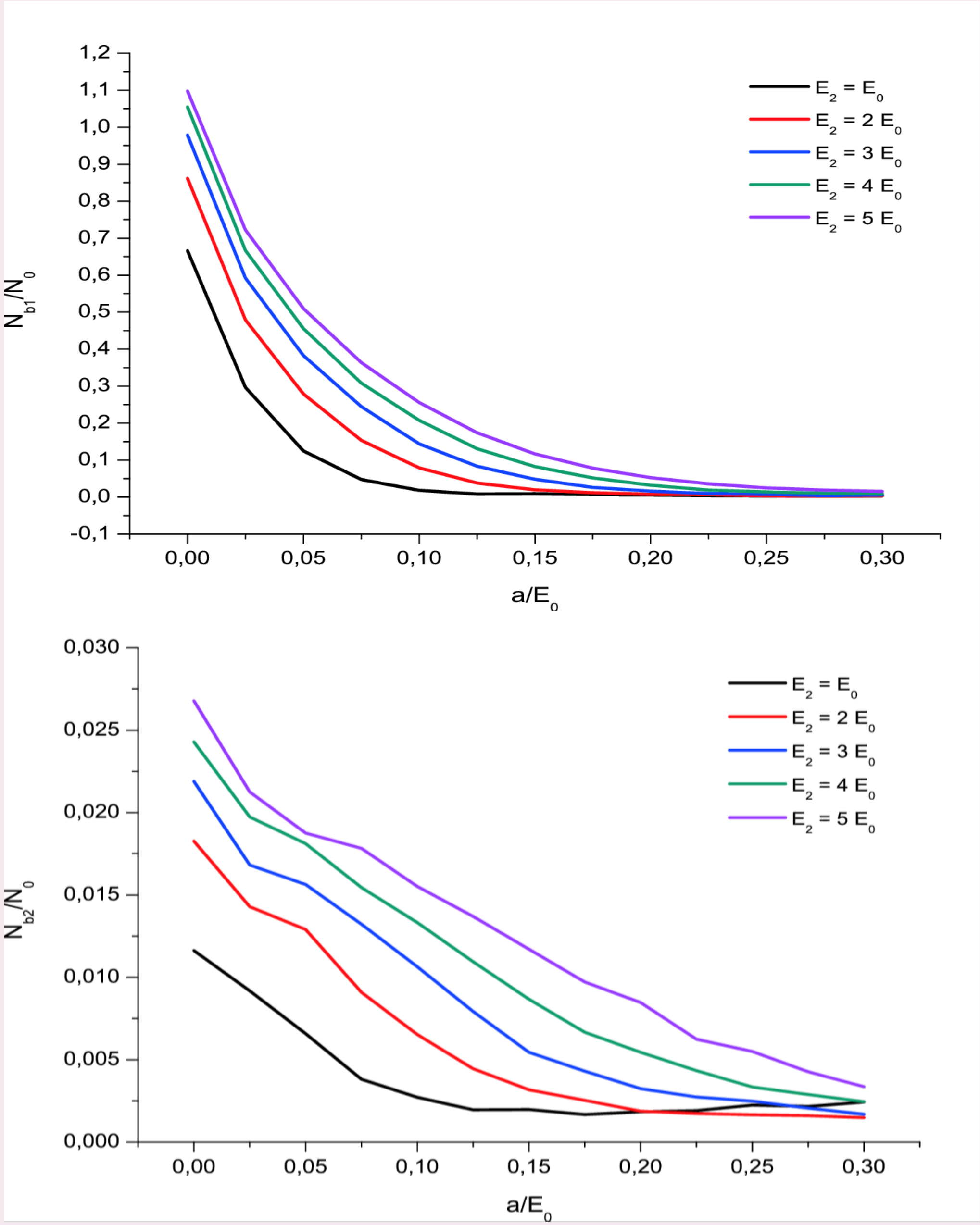
Adaptive triggering ON
a=0.1 E_0
t_a=4τ

E_1/E_0=0.2, c=0.2



THR=0.025 E_0

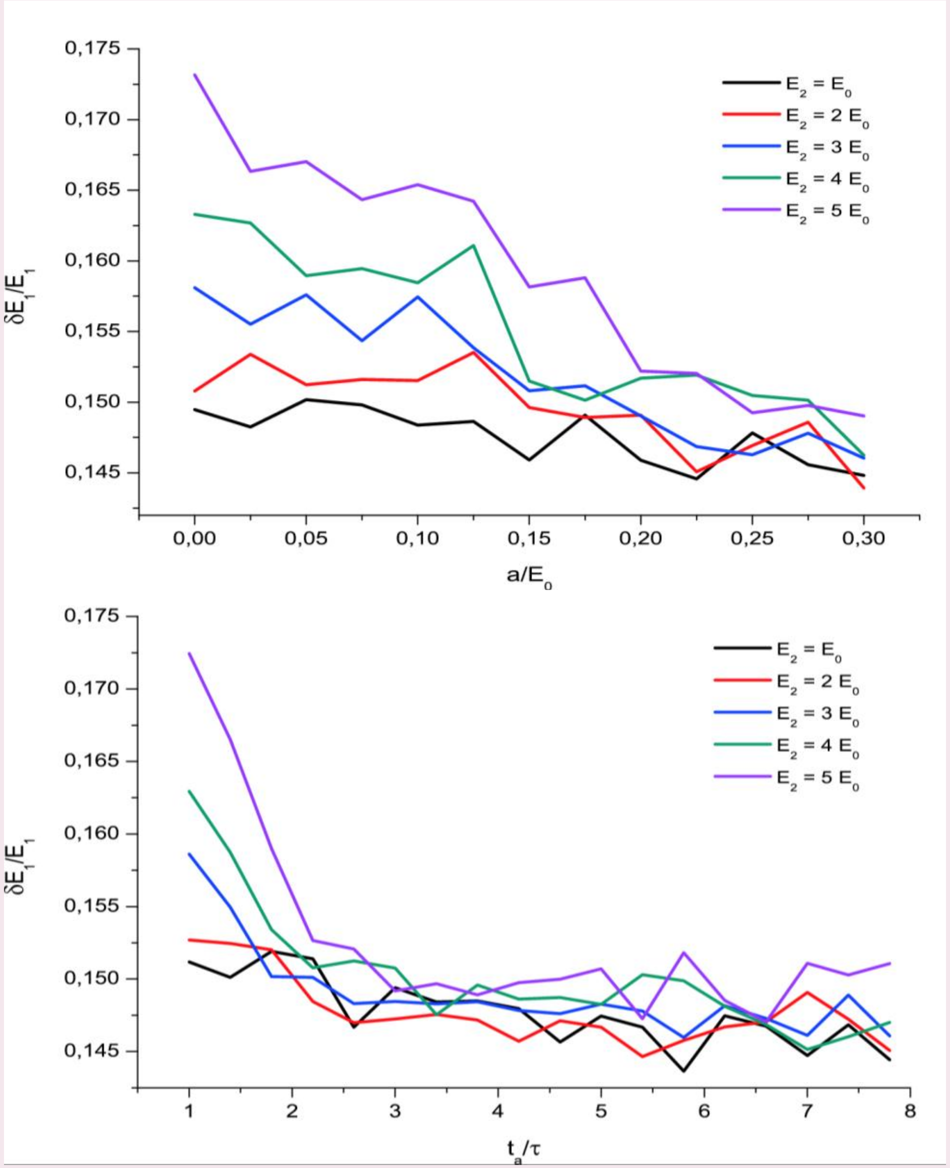
E_1/E_0=0.2, c=0.2



t=τ

THR=0.025 E_0

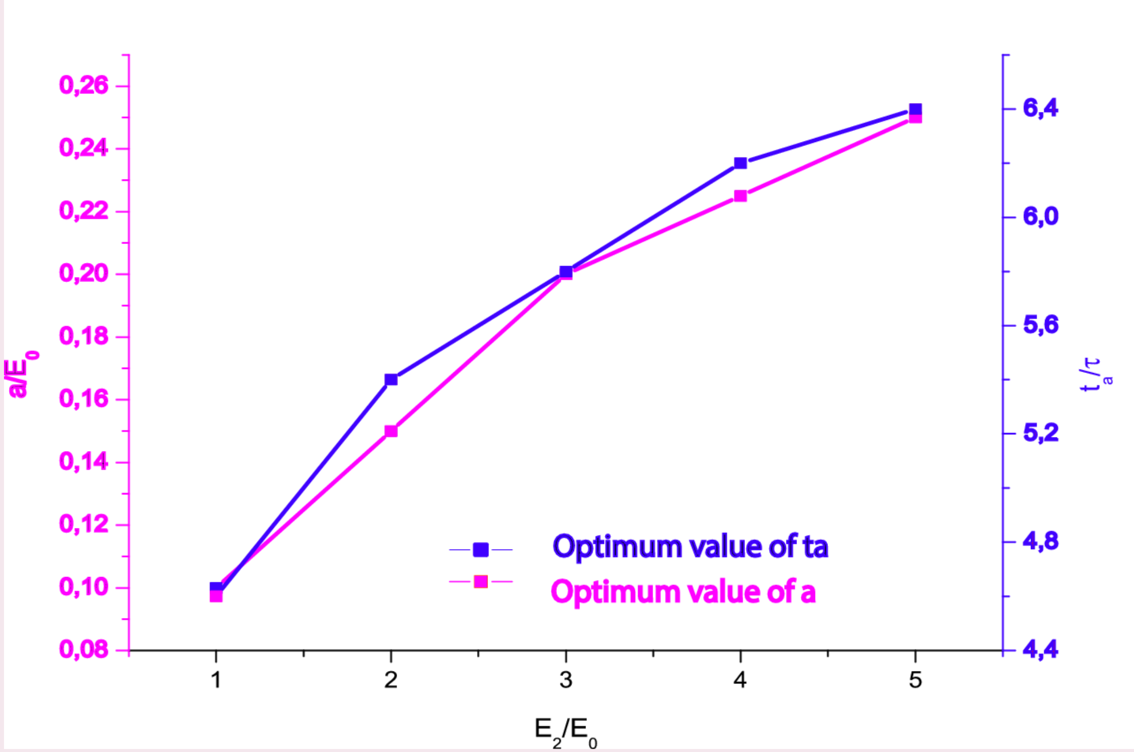
$E_1/E_0=0.2$, $c=0.2$



0,175
0,170
0,165
0,160
0,155
0,150
0,145
δE1/E1
0,00
0,05
0,10
0,15
0,20
0,25
0,30
a/E0
E2 = E0
E2 = 2 E0
E2 = 3 E0
E2 = 4 E0
E2 = 5 E0
1
2
3
4
5
6
7
8
ta/τ

The optimal triggering parameters

E_1/E_0=0.2, c=0.2



$$\frac{t_{opt}}{\tau}=3.76+0.95\frac{E}{E_0}-0.086\left(\frac{E}{E_0}\right)^2$$

$$\frac{a_{opt}}{E_0}=0.035+0.07\frac{E}{E_0}-0.005\left(\frac{E}{E_0}\right)^2$$

Test of the optimal triggering parameters – simulated signal

Simulated sintetic signal using an energy spectrum given by eq.:

$$\frac{1}{N_0} h_{ideal}(\mathrm{E}) = \frac{1}{N_0}\frac{dN(E)}{d(E)} = \begin{cases} \frac{1}{E_1} & ; \ \mathrm{E} < E_1 \\ 0 & ; \ \mathrm{E} > E_1 \end{cases}$$

The quality of parameters was deduced using:

$$\sigma_{spect} = \left(\frac{1}{n-1}\sum_{i=1}^{n}\left(h(E_i) - h_{ideal}(E_i)\right)^2\right)^{1/2}$$

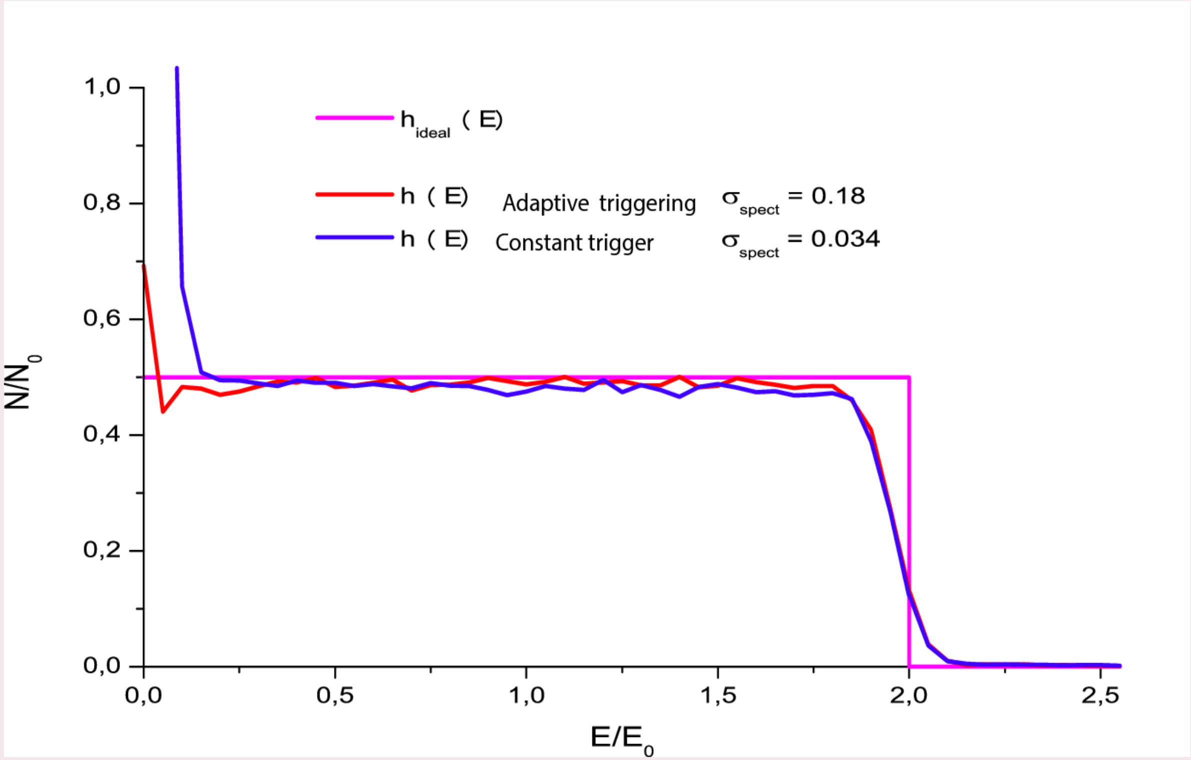
Adaptive triggering OFF: σ_{spect}.

Adaptive triggering ON: With every simulated pulse we have chosen new t and a, $\sigma_{spect}/30$.

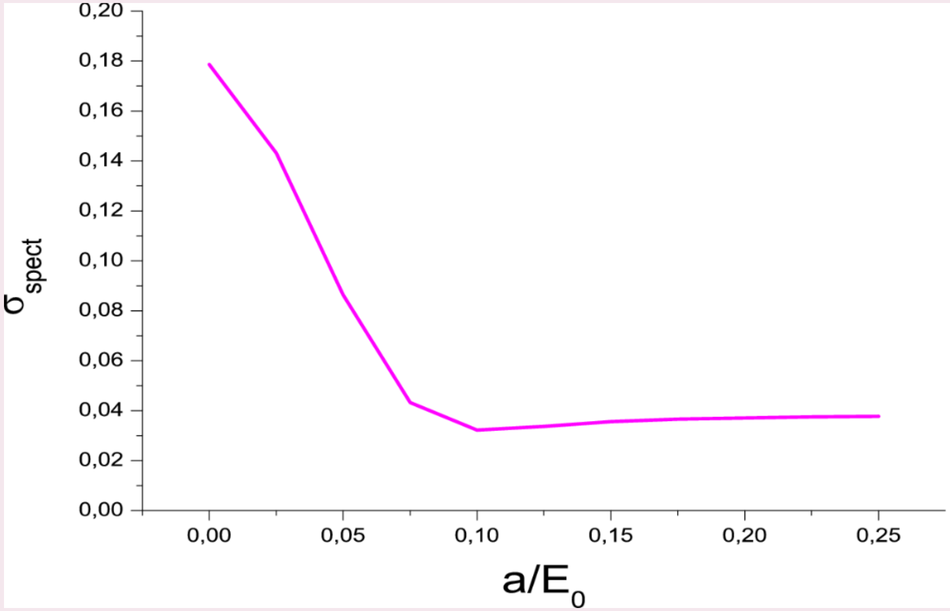
$$\begin{pmatrix} \frac{t_{opt}}{\tau} = 3.76 + 0.95\frac{E}{E_0} - 0.086\left(\frac{E}{E_0}\right)^2 \\ \frac{a_{opt}}{E_0} = 0.035 + 0.07\frac{E}{E_0} - 0.005\left(\frac{E}{E_0}\right)^2 \end{pmatrix}$$

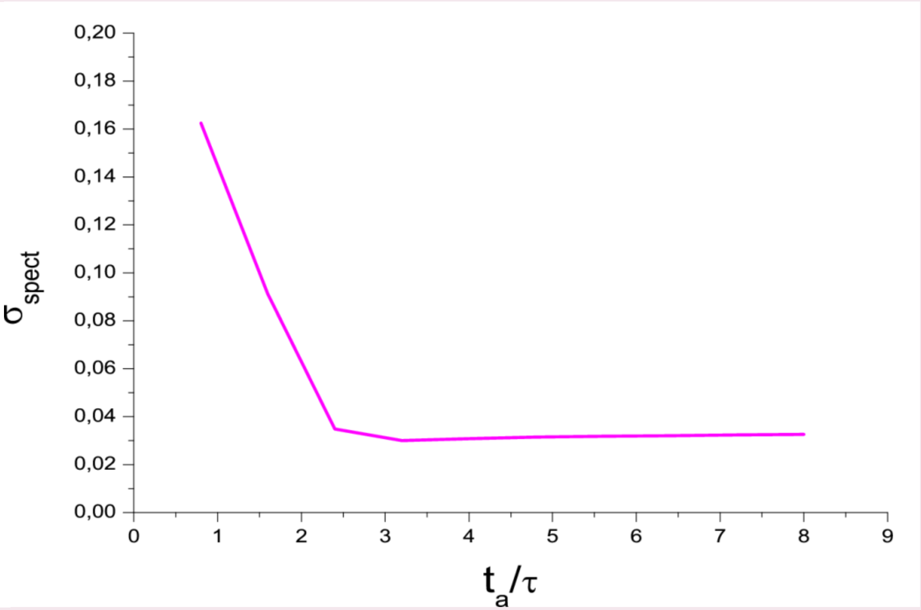
Simulated signal – With and without adaptive triggering

$$\frac{1}{N_0} h_{ideal}(\mathrm{E}) = \frac{1}{N_0}\frac{dN(E)}{d(E)} = \begin{cases} \frac{1}{E} & ; \ \mathrm{E} < 2E_0 \\ 0 & ; \ \mathrm{E} > 2E_0 \end{cases}$$



$t_a=4\tau$ THR=0.125 E_0





Instead of simultaneosly adapting a and t_a, choose the values of a and t_a for the highest energy in the spectrum!

EXPERIMENT

^{137}Cs as a radiation source (A=88.4 GBq).

NaI(Tl) scintillator Photonis XP2040/PC PMT

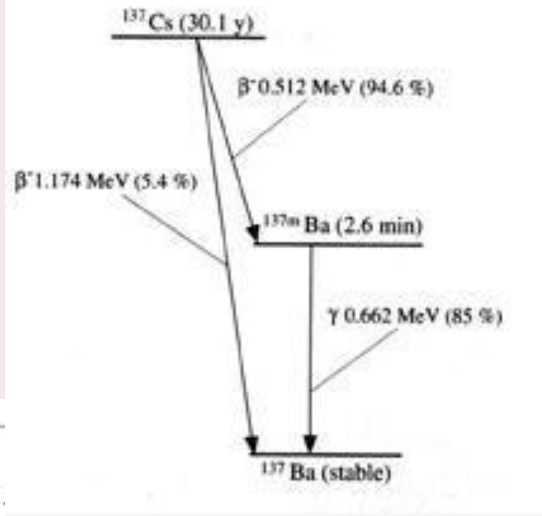
Raw anode output signal was sampled with digital PicoScope oscilloscope.

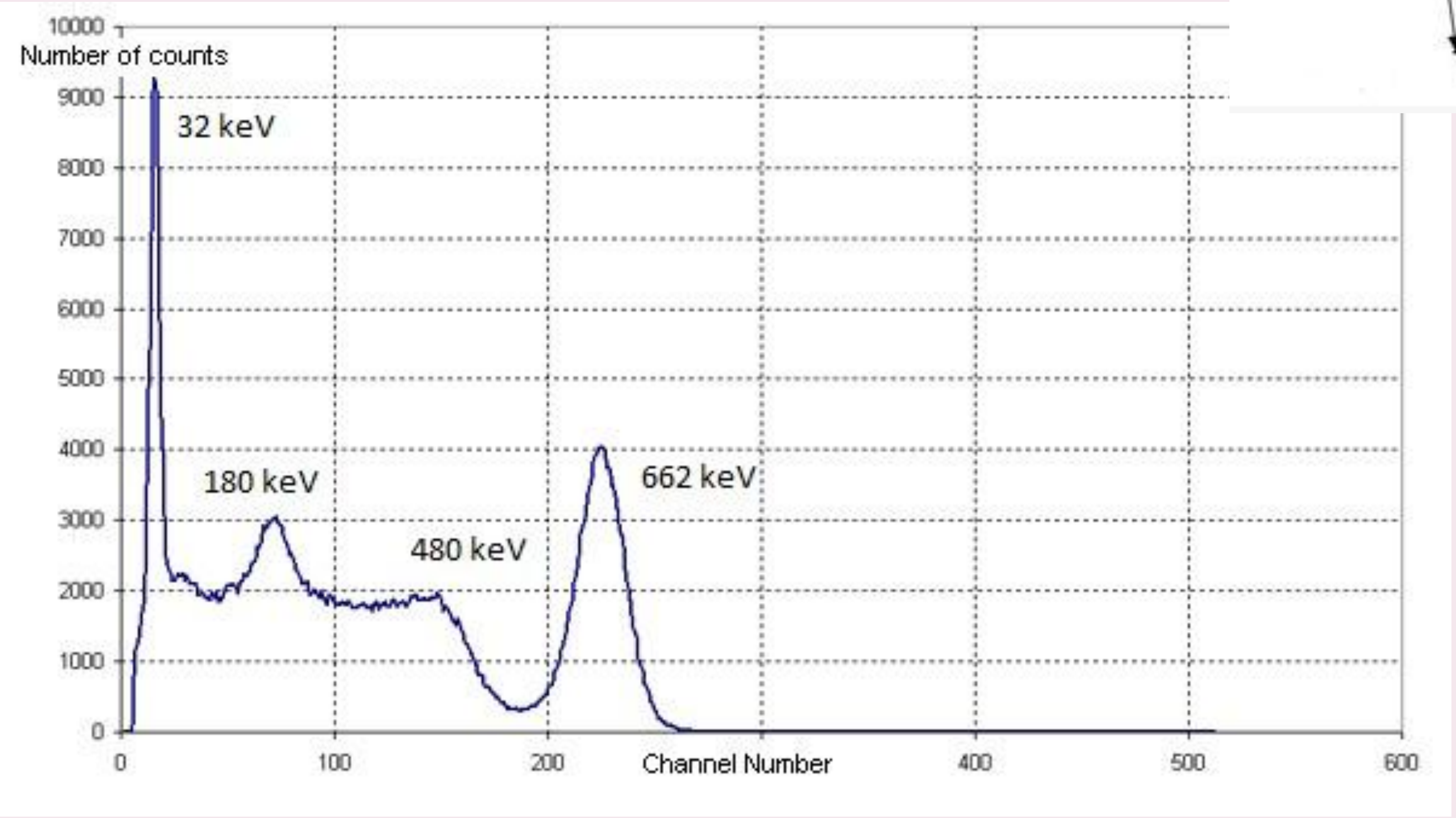
Scintillation material	NaI(Tl) (2″*2″)
Voltage between catode and anode of PMT	716 V
Sampling period	200 ps
Resolution	8 bits

Two setups:

Distance between the source and detector	**Pulse frequency [Hz]**
d_1=3.95 m	$7.3 \cdot 10^5$
d_2=8.67 m	$1.6 \cdot 10^5$

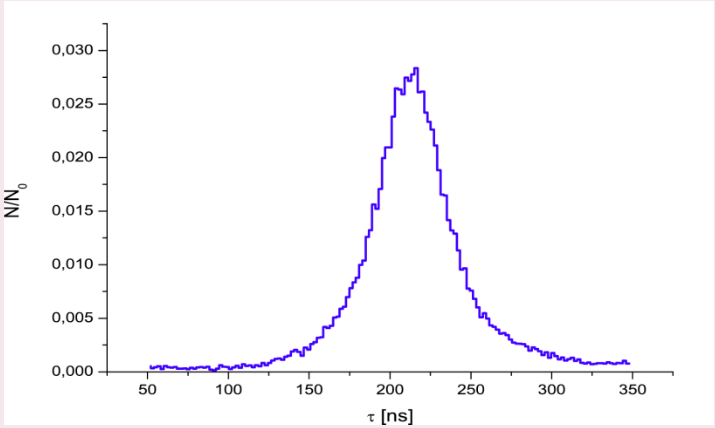
^{137}Cs Spectrum





Step 1. Deduce a reference spectrum (At lower pulse frequency)

1. Deduce τ – Fit the exponential tail of every raw pulse, τ=214 ns

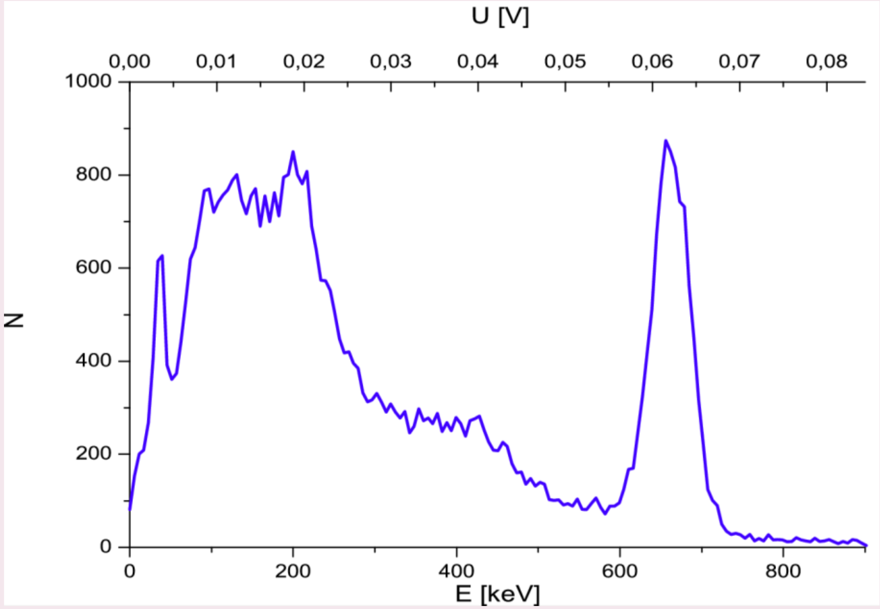


2. Deduce timing and energy

MWD parameters	Timestamp*	Energy**
Shaping time	100 ns	300 ns
Flattop	0 ns	300 ns
MWD pulse length	200 ns	900 ns

- * Only pulses that are more than 3τ separated are taken into account.
- ** THR=0.002 V, a=0.005 V, t_a=300 ns.

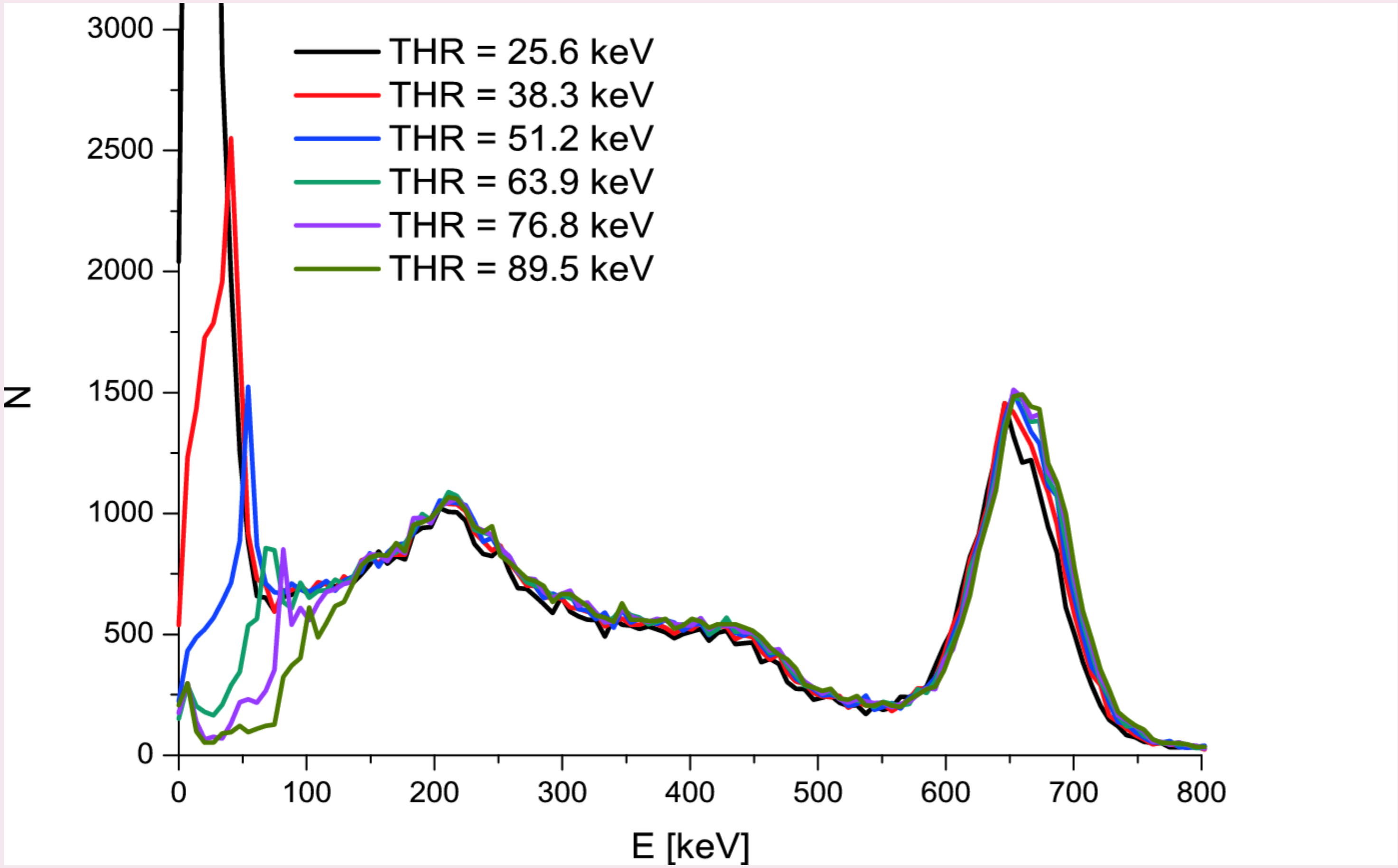
Reference spectrum :



Spectrum at higher beam frequency:

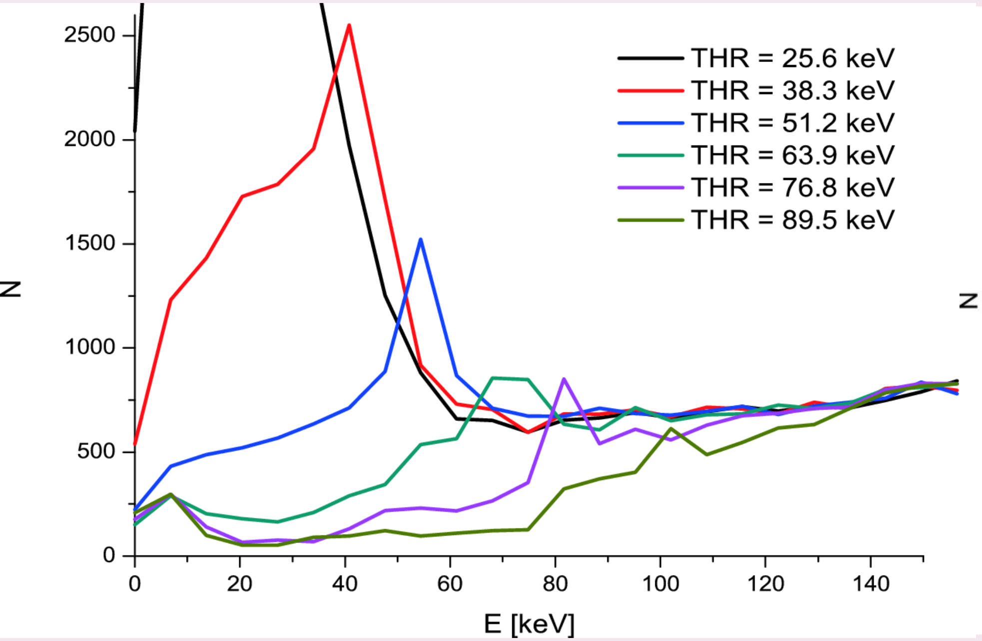
MWD parameters	Values
Shaping time	50 ns
Flattop time	50 ns
MWD pulse length	150 ns

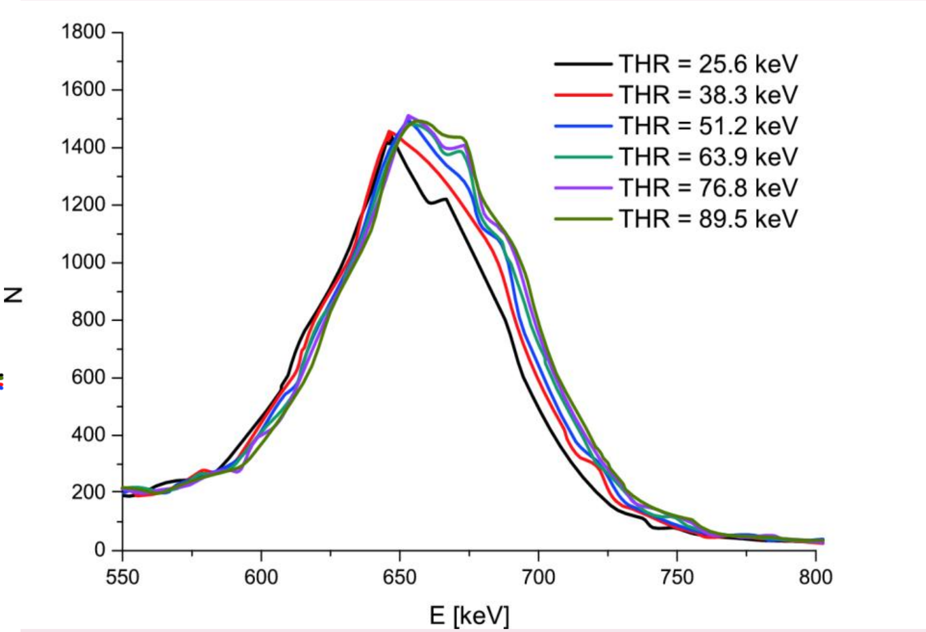
Results – Adaptive triggering OFF



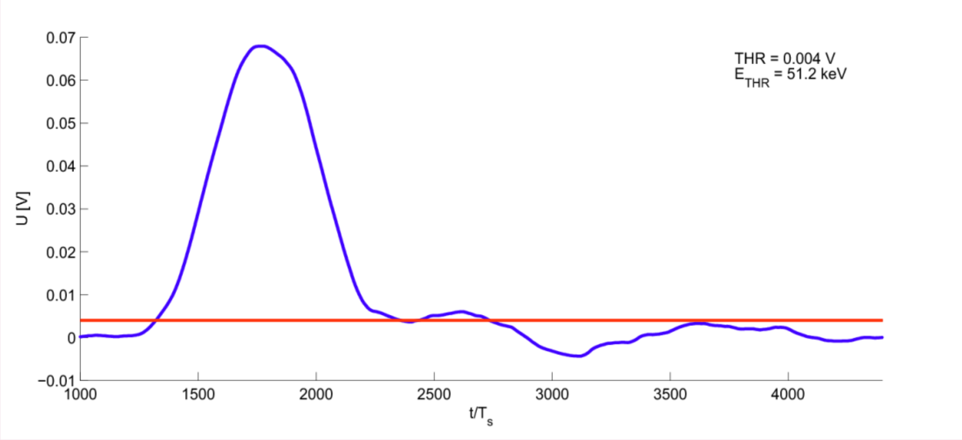
-E=32 keV is not visible.

Adaptive triggering OFF –Enhanced spectrum



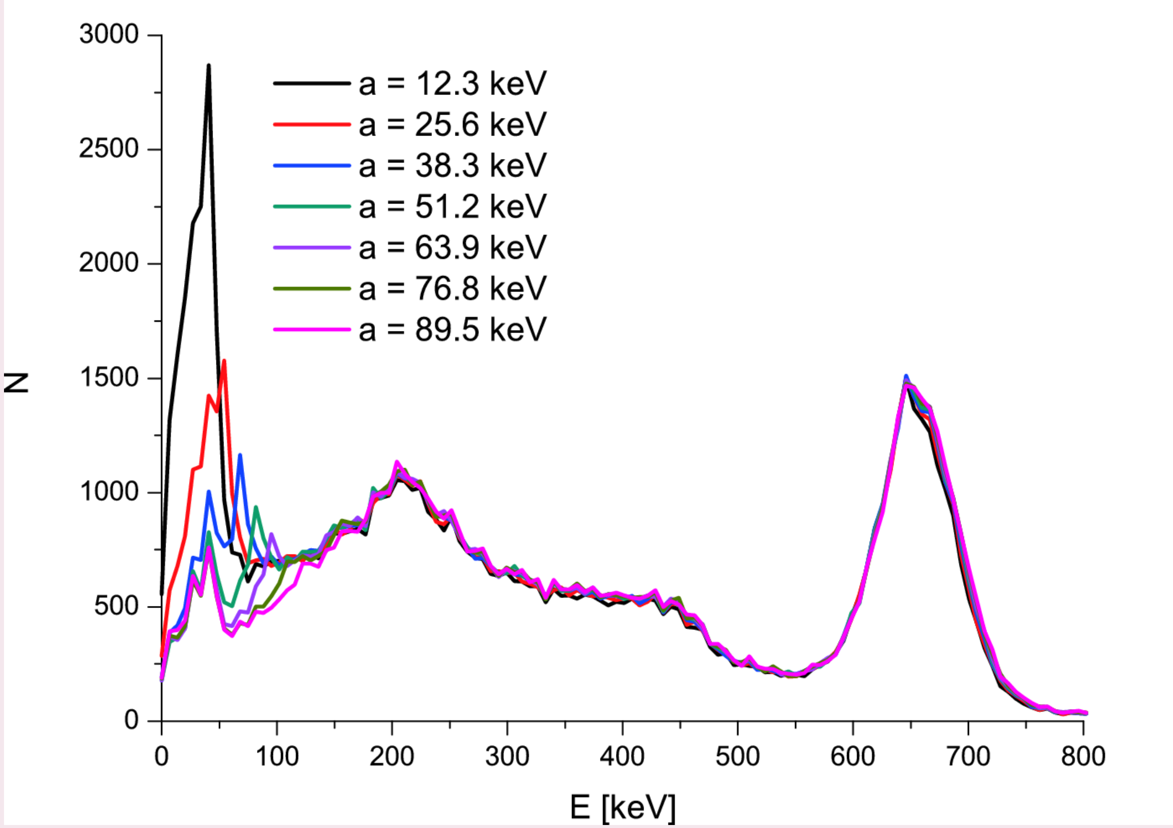


False peak with energy approximately equal to the THR energy occurs.



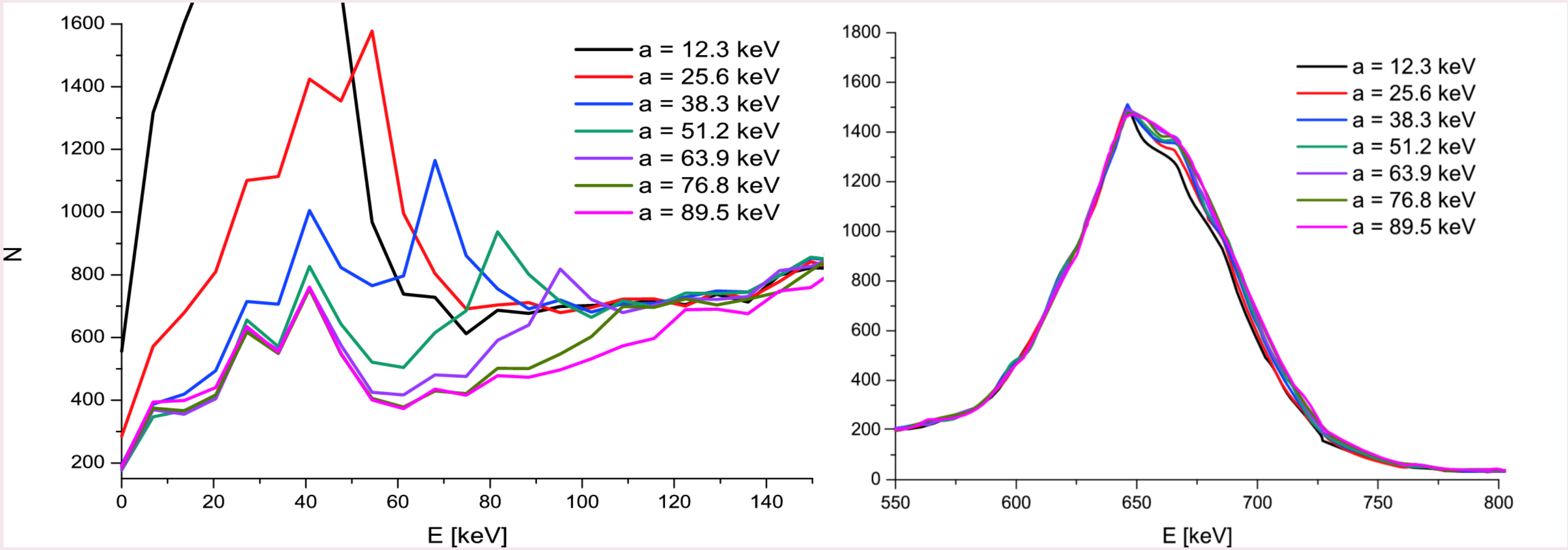
Results – Adaptive triggering ON

t_a=920 ns, THR=26 keV



- Low a - Low energy peak is piled up with the afterpulses.
- High a- Low energy peak is clearly visible.

Adaptive triggering ON – Enhanced spectrum



- False peak with energy approximately equal to the THR+a energy.

The optimal triggering parameters – E_{max}=662 keV, a_{opt}=76 keV, t_{opt}=920 ns

(Seems ok!)

Applications

- High throughput in-beam experiments
- QA systems in medical radiotherapies
- Active interrogation analysis / homeland security
- Industrial construction imaging

Conclusions:

- The adaptive triggering is a relatively simple method that significantly extends the useful energy range on the low energy side of the spectrum

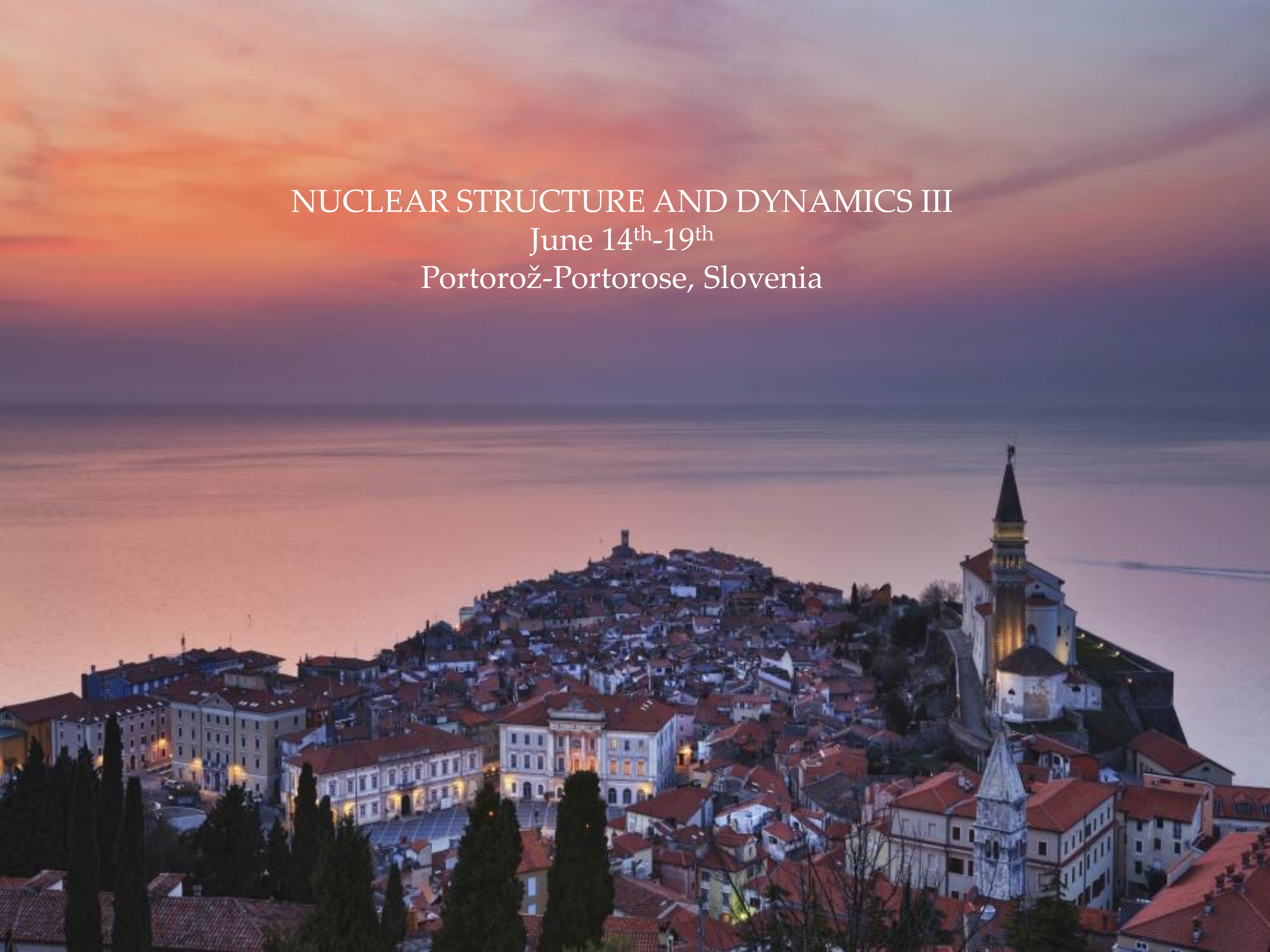
(when post-pulse inhibition is not applicable due to high count rates)

-This method is crucial if the desired information is presented there.

Future work:

1. More complicated synthetised signals
2. Dependence of this method on:

- MWD parameters
- Initial pulse frequency


NUCLEAR STRUCTURE AND DYNAMICS III
June 14th-19th
Portorož-Portorose, Slovenia