Bench test of LaBr3(Ce) Detector array for fast-timing gamma-ray measurements and GCD method

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Lifetime measurement for Nuclear Structure study

- Nuclear Deformation

$$R(\theta,\phi) = R_0[1 + \sum_\lambda \sum_\mu \alpha_{\lambda\mu} Y_{\lambda\mu}(\theta,\phi)]$$

λ=2 : quadrupole deformation

in principal axis and O(λ>3)=0,

$$R(\theta,\phi) \approx R_0[1 + \alpha_{0,0} Y_{0,0} + \alpha_{2,2}(Y_{2,2} + Y_{2,-2})]$$
$$= R_0[1 + \beta_2 \cos\gamma\, Y_{0,0} - \frac{1}{\sqrt{2}}\beta_2 \sin\gamma\,(Y_{2,2} + Y_{2,-2})]$$

- Transition matrix (Wigner Eckart Theorem)

$$< I_2 M_2|\hat{O}_{\lambda\mu}|I_1 M_1 >= \frac{1}{\sqrt{2I_2+1}} < I_1 M_1 \lambda\mu | I_2 M_2 >< I_2||\hat{O}_\lambda||I_1 >$$

→ Reduced transition probability $B(O_\lambda; I_i \to I_f) = \frac{1}{2I_i}\left|< I_f||\hat{O}_\lambda||I_i >\right|^2$

and transition rate $\frac{1}{\tau} = T(O_\lambda) = \frac{8\pi(\lambda+1)}{\lambda[(2\lambda+1)!!]^2}\frac{k^{2\lambda+1}}{\bar{h}}B(O_\lambda)$

Lifetime measurement for Nuclear Structure study

For E2 transition,

$$B(E2; I \rightarrow I-2) = \{5/16\pi\}\, Q_0^2 \mid < I,\ K,\ 2,\ 0 \,| I-2,\ K\ > |^2$$

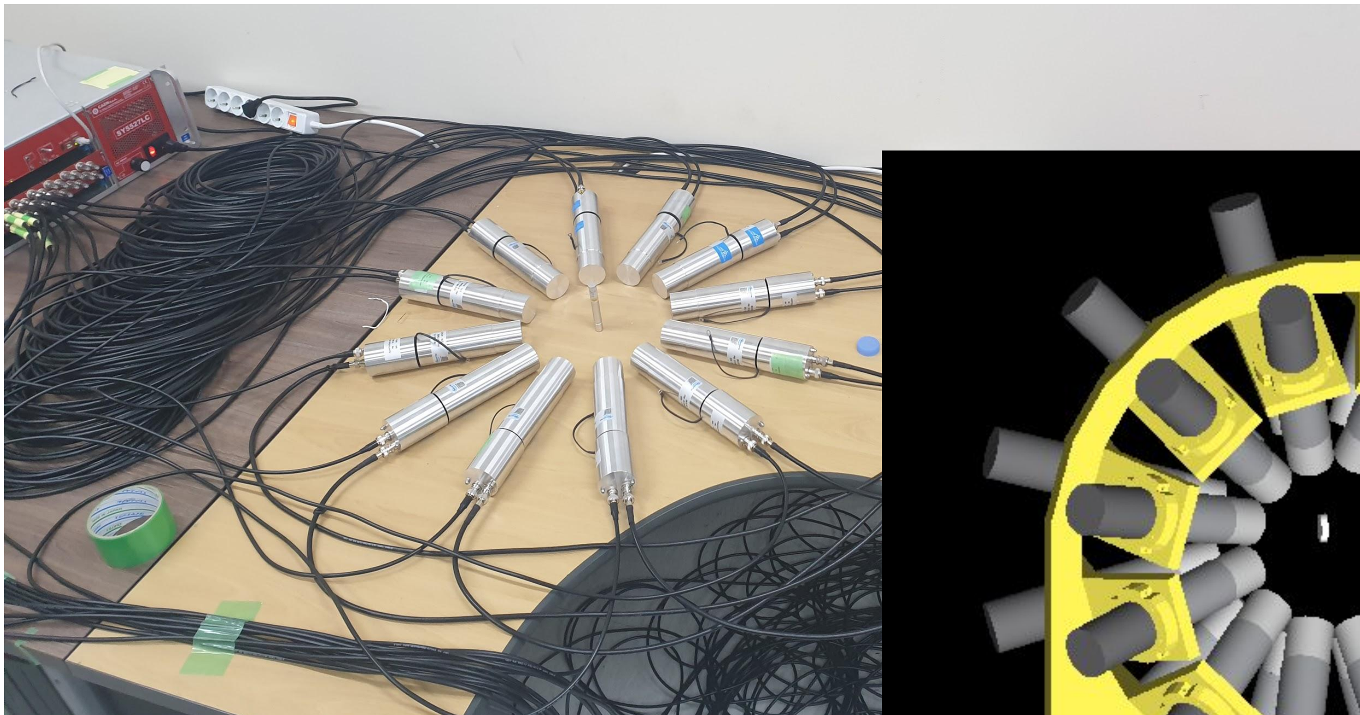
$$\tau[\text{ps}] = \frac{0.0816}{E_\gamma^5[\text{MeV}] \times B[e^2 b^2]}$$

Provided lifetime of first 2+ state, electric quadrupole moment(Q_0), quadrupole deformation(beta_2) are directly calculated!

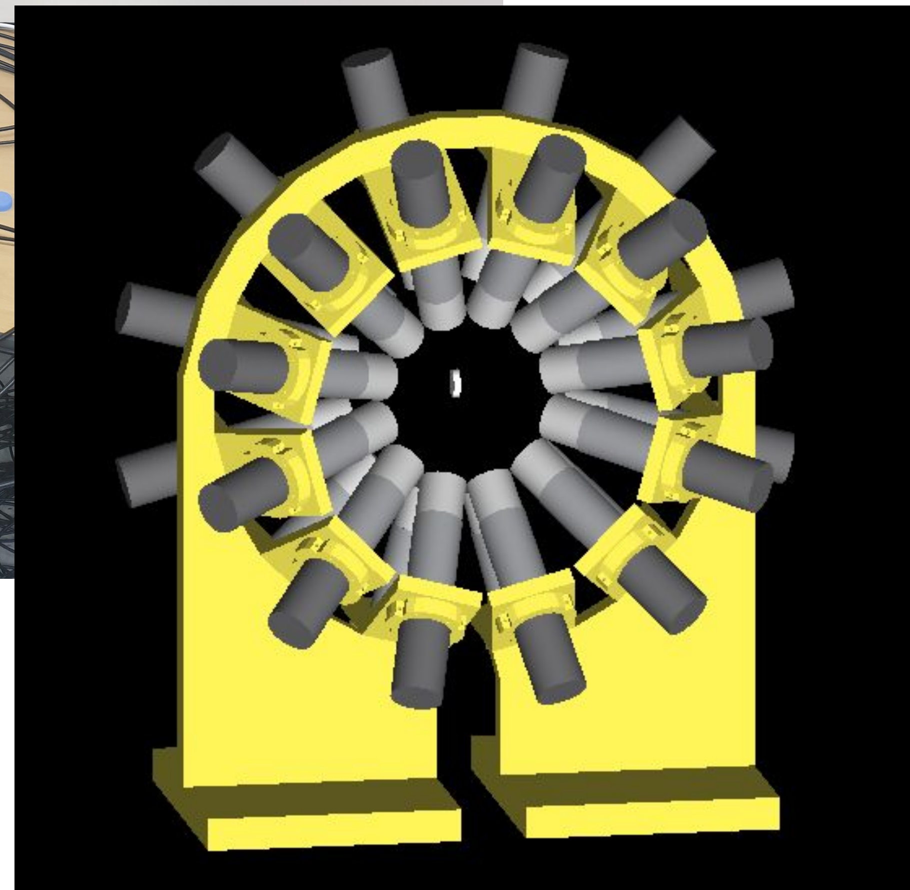
LaBr3(Ce) gamma-ray detector array

Bench test configuration

LaBr3(Ce) gamma-ray detector array



Bench test configuration



24 detectors with supporting structure, in CAD

LaBr3(Ce) Scintillator

- Technical specification

	LaBr3(Ce)	NaI(Tl)
Light yield*	63 photons/keVγ	55 photons/keVγ
wavelength of maximum emission	380nm	415nm
Energy resolution @662keV	2.6% FWHM	6.5% FWHM
Density	5.08g/cm^3	3.67g/cm^3
Radiation length	1.8cm	2.6cm
Decay time*	16ns	250ns

PMT FADC

- R13408 PMT, Hamamatsu

Tube size	Dia.38 mm
wavelength	300~650nm, peak 420nm
Dynode stages	8
Anode-cathode supply voltage	1500V
Gain typ.	5.3 x 10^5
Dark current (after 30min.)	Typ. 3nA, Max. 30nA
Rise time typ.	1.2ns
Transit time typ.	13ns (spread 0.19ns)
Pulse linearity	2%dev 20mA, 5%dev 50mA

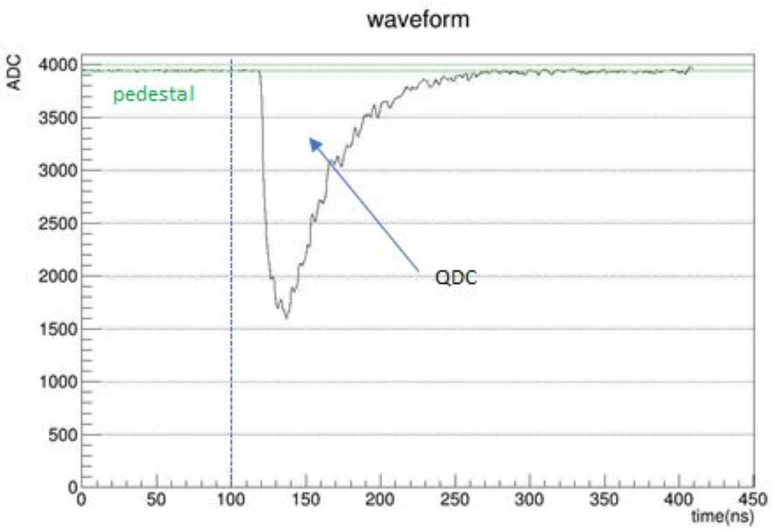
- V1742 FADC, CAEN

Channels	32+2
Sampling rate	5, 2.5, 1, 0.75 GSa/s selectable
Sampling length	1024, 520, 256, 136 selectable
Dead-time due to conversion	110μs, 181μs
Input dynamic range	1Vpp
Resolution	4096ch (12bit)

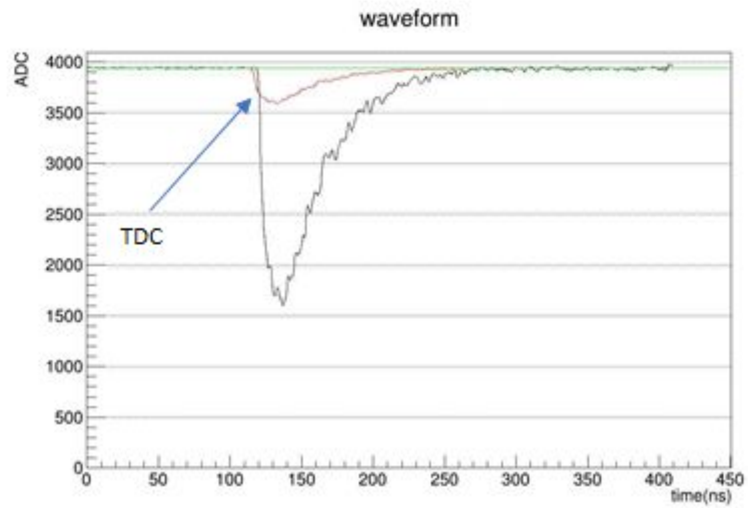
Pulse analysis

- QDC

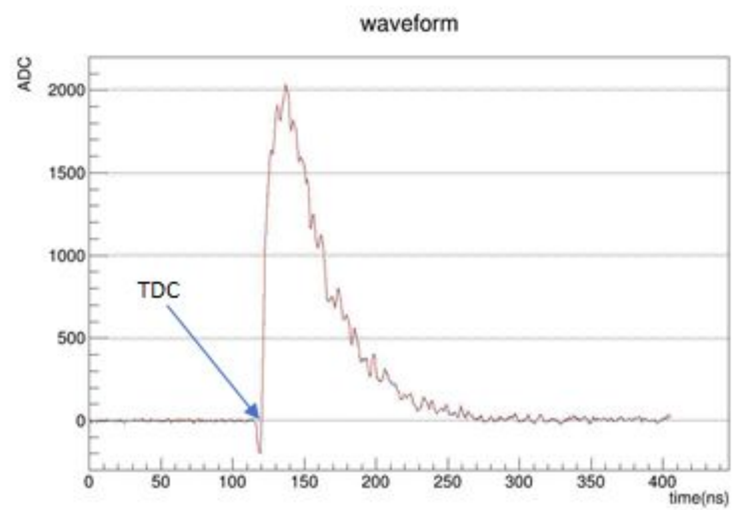
$$QDC = \sum_i (pedestal - ADC[i])$$



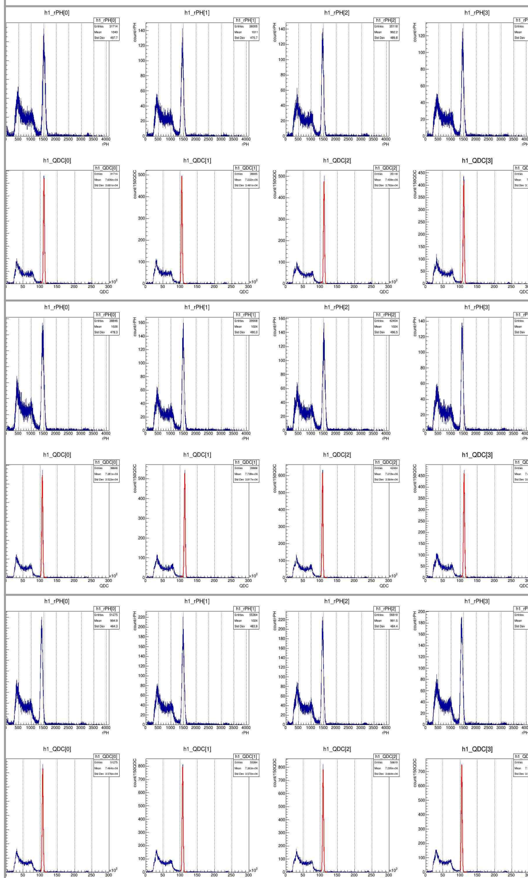
- TDC : CFD method



linear approximation ->



Energy resolution with Cs-137 (individual)



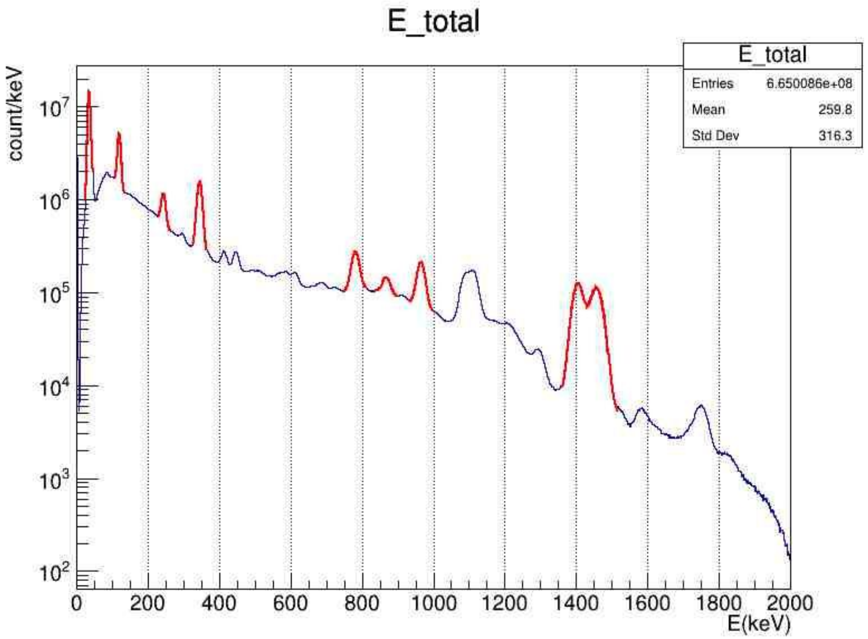
			HV(V)	E res(%)
Set0	Ch0	#0	1130	3.45
	Ch1	#1	1010	3.32
	Ch2	#2	1050	3.27
	Ch3	#3	1040	3.26
Set1	Ch0	#4	1090	3.43
	Ch1	#5	1170	3.33
	Ch2	#6	1060	3.19
	Ch3	#7	1100	3.27
Set2	Ch0	#8	1130	3.25
	Ch1	#9	1030	3.18
	Ch2	#10	1030	3.16
	Ch3	#11	1090	3.32

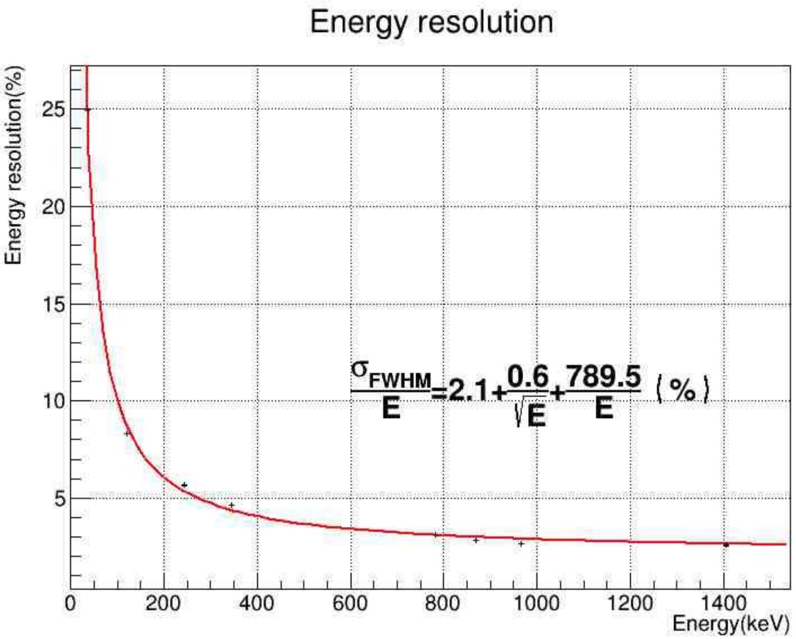
HV lowered to 1000~1200V, rPH=1500ADC for 662keV

Energy resolution(FWHM)
(fit sig/mean*2.35)
: 3.2%~3.5% @662keV

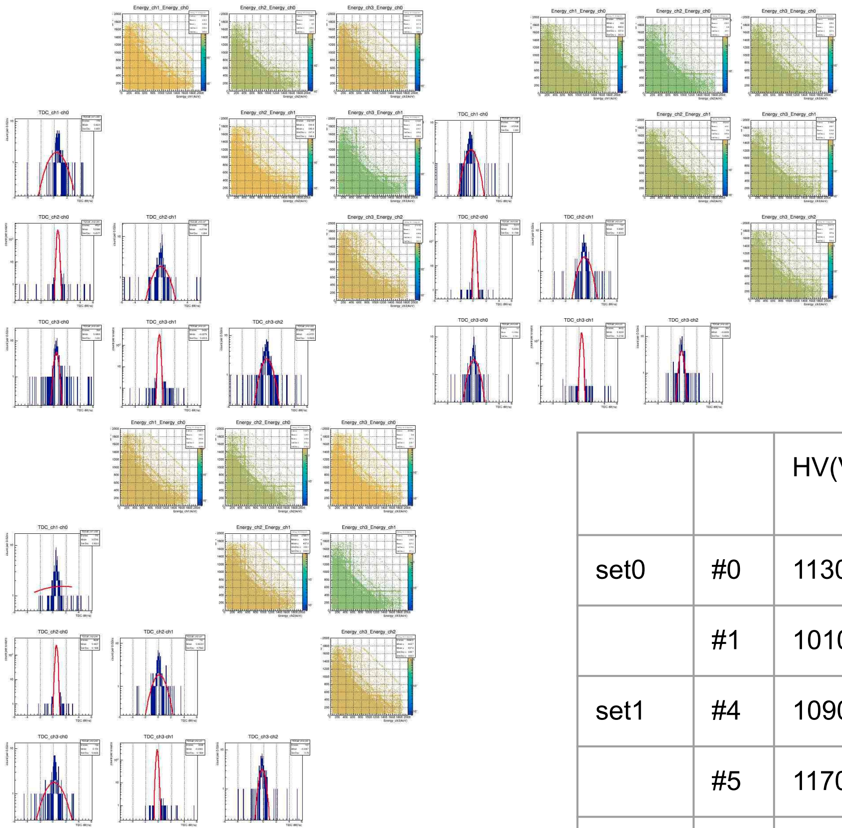
cf)prototype: 3.9% @662keV

Energy resolution with Eu-152 (12ea array)





Time resolution with Na-22



- Na-22 : positron annihilation
- 511keV gamma in opposite direction
- T resolution~240ps @511keV

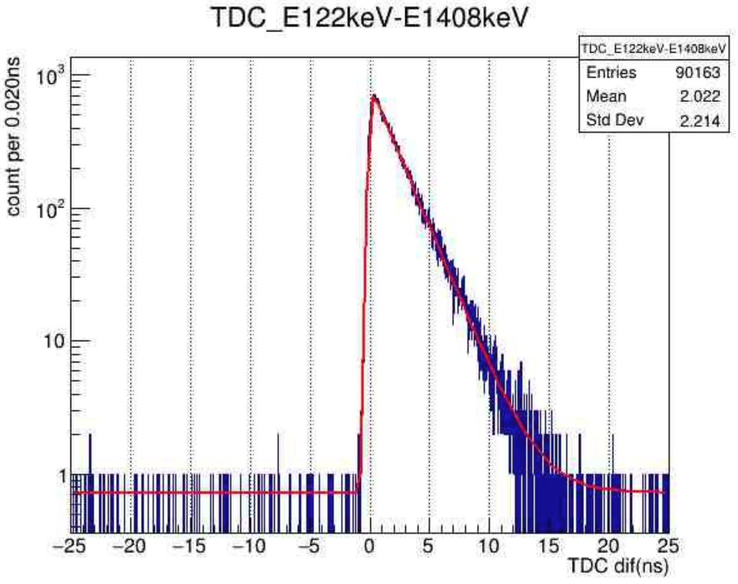
		HV(V)	E res(%)		HV(V)	E res(%)	sig(ps) FWHM	sig/1.414(ps) FWHM
set0	#0	1130	3.91	#2	1050	3.67	342.0(40)	241.9(28)
	#1	1010	3.71	#3	1040	3.94	337.6(34)	238.7(24)
set1	#4	1090	3.85	#6	1060	3.65	329.9(34)	233.3(24)
	#5	1170	3.83	#7	1100	3.91	347.2(39)	245.6(27)
set2	#8	1130	3.82	#10	1030	3.73	350.5(37)	247.9(26)
	#9	1030	3.72	#11	1090	3.79	321.8(36)	227.6(25)

Lifetime decision - conv

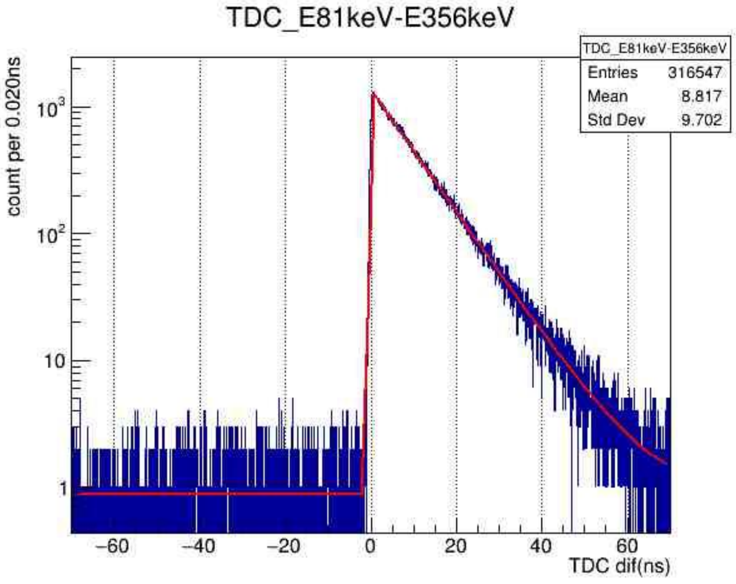
Time difference distribution of gamma cascade
has visible tail for $\tau > \sigma$
->fitting is possible with conv. function

$$(f * g)(t) = \int_{-\infty}^{+\infty} f(\tau) g(t-\tau)\, d\tau$$

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2},\ g(t>0) = Ae^{-\lambda t}$$



Eu-152 122keV | 1408keV cascade
ref τ=2024(16)ps, measured τ=2018(8)ps



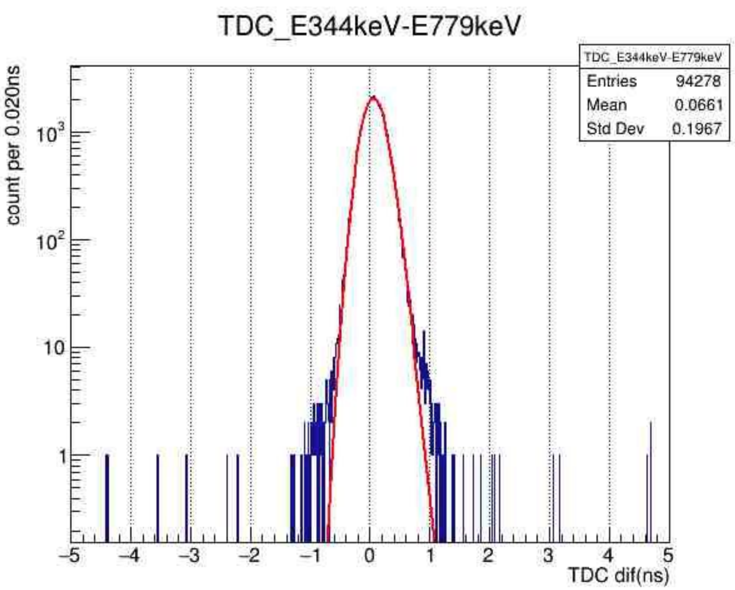
Ba-133 81keV | 356keV cascade
ref τ=9064(20)ps, measured τ=9023(18)ps

Lifetime decision - conv

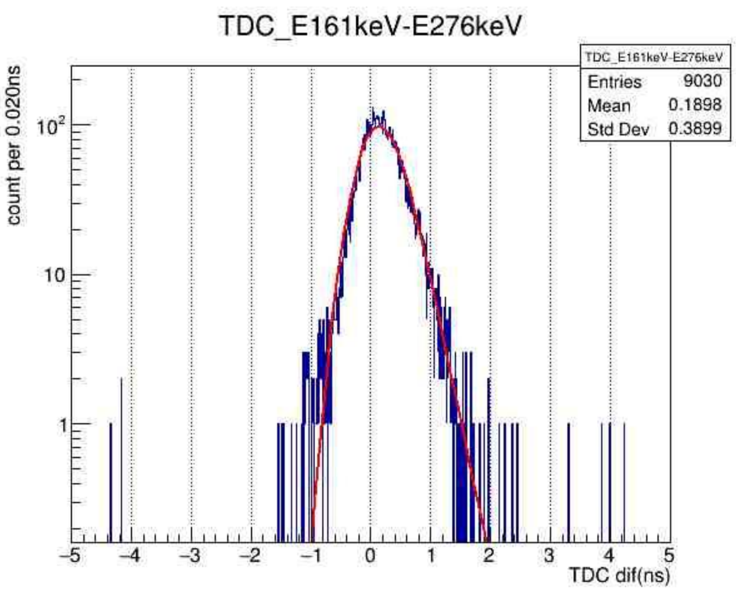
Time difference distribution of gamma cascade
: tail is <u>not distinguishable</u> for $\tau<\sigma$
->fitting is <u>impossible</u> with conv. function

$$(f*g)(t)=\int_{-\infty}^{+\infty} f(\tau)g(t-\tau)\,d\tau$$

$$f(t)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2},\ g(t>0)=Ae^{-\lambda t}$$



Eu-152 344keV | 779keV cascade
ref τ=46.7(25)ps, measured τ=NAN



Ba-133 161keV | 276keV cascade
ref τ=248(6)ps, measured τ=231(7)ps?

Lifetime decision - GCD

"Mean" lifetime

$$\frac{\int_0^\infty tP(t)\,dt}{\int_0^\infty P(t)\,dt} = \frac{1}{\lambda} = \tau$$

In reality,

$$\frac{\int_0^\infty tP(t)\,dt}{\int_0^\infty P(t)\,dt} = \frac{\sum^{count} t_{measure}}{count} = \tau + D$$

By averaging combinations of start-stop channel, energy independent offsets vanish.

$$TDC_i(E) = T(E) + D_i(E) + P_i$$

$$\Delta_{ij}TDC(E_d, E_f) = [T(E_d) + D_i(E_d) + P_i] - [T(E_f) + D_j(E_f) + P_j]$$

$$= \{T(E_d) - T(E_f)\} + \{D_i(E_d) - D_j(E_f)\} + \{P_i - P_j\}$$

$$C_{ij}(E_d, E_f) = \{mean\ of\ \Delta_{ij}TDC(E_d, E_f)\}$$

$$= \tau(E_d, E_f) + \{D_i(E_d) - D_j(E_f)\} + \{P_i - P_j\}$$

$$\bar{C}(E_d, E_f) = \{avg\ for\ all\ combination\ of\ i, j\}$$

$$= \tau(E_d, E_f) + \frac{(N_{ch}-1)\{\sum_i^N D_i(E_d) - \sum_j^N D_j(E_f)\}}{N_{ch}(N_{ch}-1)} + \frac{(N_{ch}-1)\{\sum_i^N P_i - \sum_j^N P_j\}}{N_{ch}(N_{ch}-1)}$$

$$= \tau(E_d, E_f) + \frac{\sum_i^N \{D_i(E_d) - D_i(E_f)\}}{N_{ch}}$$

$$Assuming\ energy\ dependent\ delay\ D(E) = 0,$$

$$\tau(E_d, E_f) = \bar{C}(E_d, E_f)$$

*linear approx in CFD

Background analysis

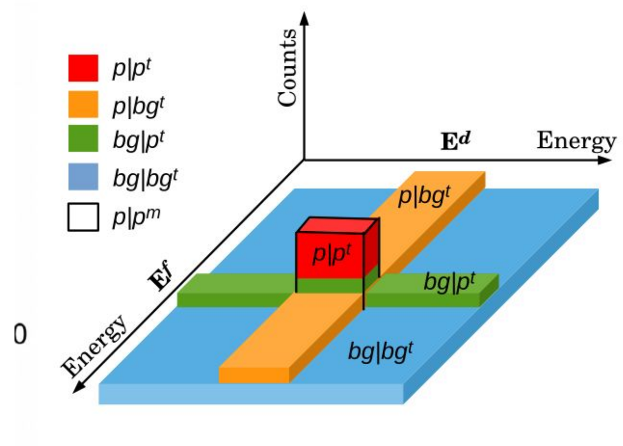
$$\sum^{count} t_{measure} = \bar{C}_{exp} \times (total\ count)$$

$$= \bar{C}_{FEP} \times (p = FEP\ count) + \bar{C}_{bg} \times (b = bg\ count)$$

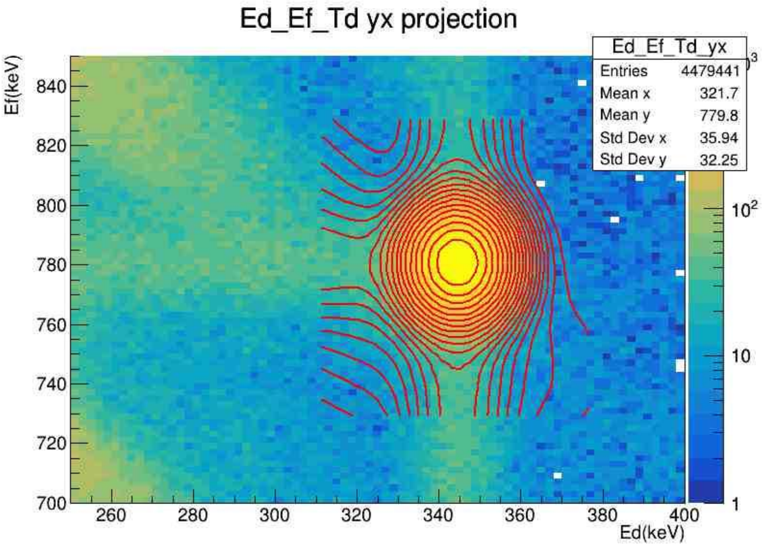
$$\tau = \bar{C}_{FEP} = \bar{C}_{exp} \cdot \frac{p+b}{p} - \bar{C}_{bg} \cdot \frac{b}{p}$$

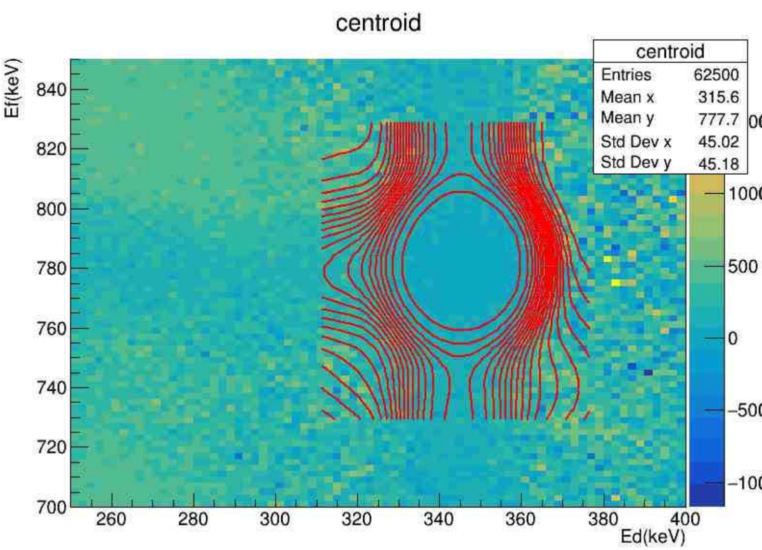
$$= \bar{C}_{exp} + \frac{\bar{C}_{exp} - \bar{C}_{bg}}{p/b}$$

(b)



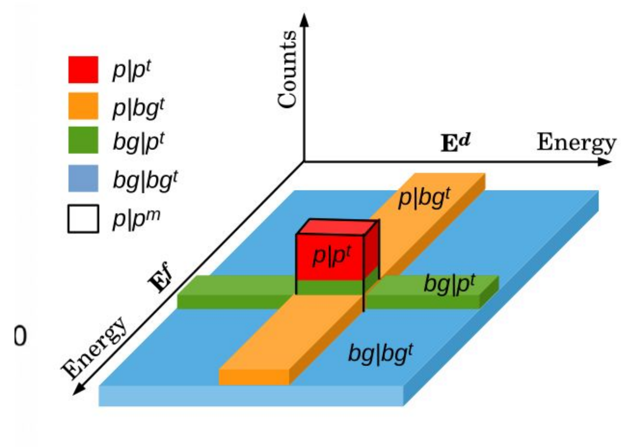
Lifetime decision - GCD





p/b ratio at each bin of 2D-histogram
->centroid of background interpolated

(b)



Gd 2+ state (344keV, 46.7(25)ps)
Lifetime measured 46.8(9)ps !

** Tests using Ba-133 ongoing.

Summary

- Lifetime is one of the significant observable for studying nuclear structure
- LaBr3(Ce) detectors array is under development for fast-timing gamma-ray measurement
  - Energy resolution: 3.3% FWHM @662keV
  - Time resolution: 240ps FWHM @511keV
- Lifetime($\tau > \sigma$) can be decided by convolution function fitting, provided time offset calibration.
- Lifetime($\tau < \sigma$) can be decided by GCD method, provided large number of statistics, BG interpolation.

Future

- Another 12 modules ordered: will be delivered Oct(?)
- Check reliability of GCD method with Ba-133