闪烁探测器
Scintillation Detector

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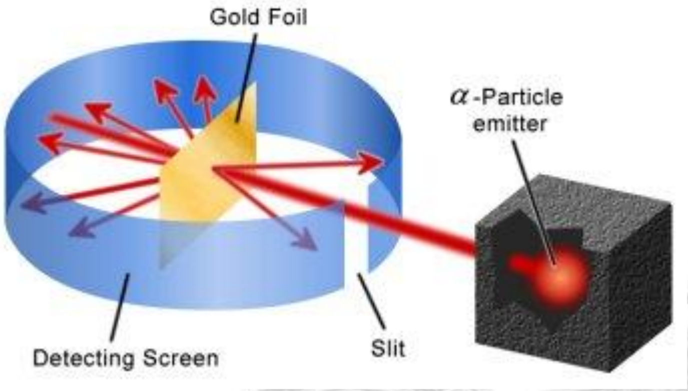
Outline

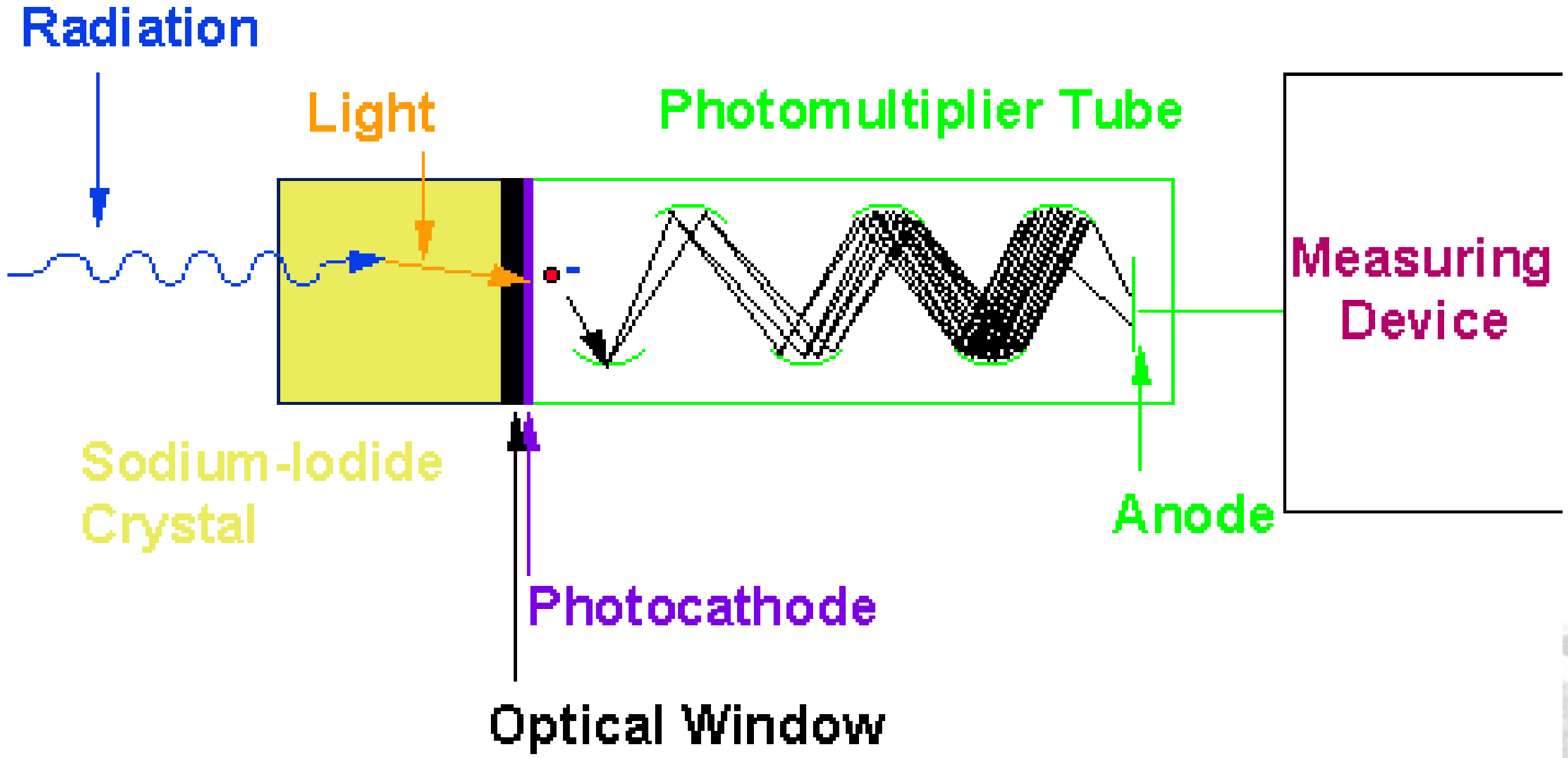
- Configuration and Principle
- Scintillator
- Photomultiplier
  - PMT
  - MCP
  - PD / APD
  - SiPM
- Scintillation Detector and Spectrometer

CONFIGURATION AND PRINCIPLE OF SCINTILLATION DETECTOR

Fluorescence Caused by Radiation



Configuration of a Scintillation Detector



Operating Principle

Radiation injects,
Molecules are excited or ionized,
Molecules de-excite,
Scintillation photons are emitted.

↓

Scintillation photons are collected by cathode of PMT,
Electrons are emitted

↓

Electrons fly into dynode and more electrons are emitted and fly into next dynode, which is electrons multiplication

→

electric signal is output from anode.

Scintillator:
radiation to photon

PMT:
photon to electric signal

SCINTILLATOR

Various Scintillator

- Inorganic scintillator
  - crystal(doped): NaI(Tl), CsI(Tl), ZnS(Ag), $LaBr_3:Ce^{3+}$, $LaCl_3:Ce^{3+}$,...
  - glass: $LiO_2 \cdot 2SiO_2(Ce)$,...
  - pure crystal: BGO, LSO, LYSO, BaF_2, ...
- Organic scintillator
  - organic crystal scintillator
  - organic liquid scintillator
  - organic plastic scintillator
- Gas scintillator
  - Ar, Xe

Characteristics of Scintillator

- Emission spectrum
- Luminous efficiency & light yield
- Decay time

Emission Spectrum

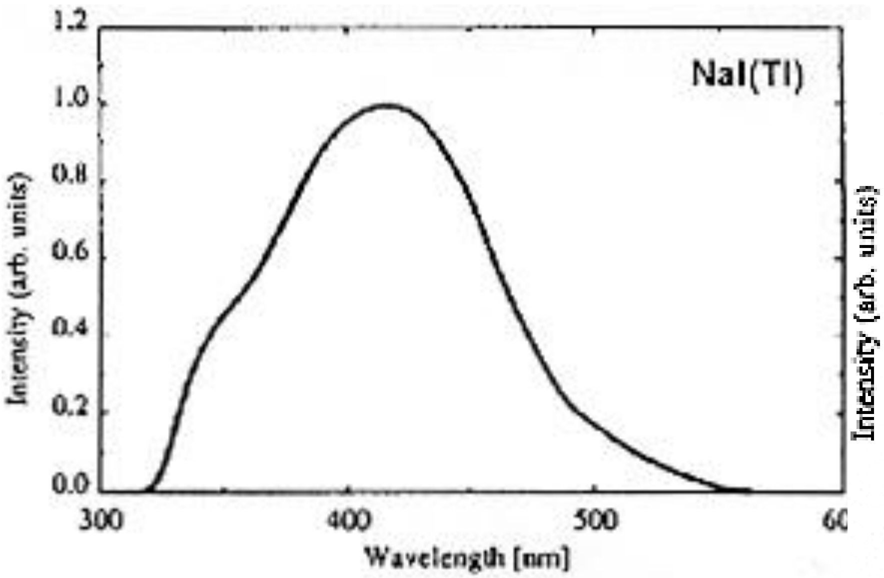


Figure 1. Scintillation emission spectrum of a canned NaI(Tl) crystal.

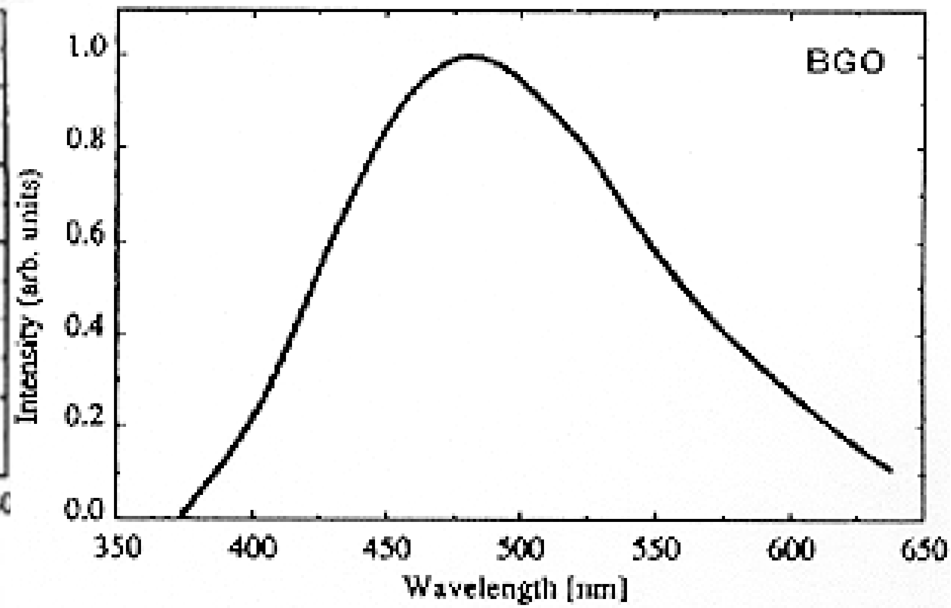


Fig. 1. Scintillation emission spectrum of BGO.

Emission spectrum of scintillator is continuous.
Emission spectrum of scintillator should match absorption spectrum of PMT when develop a detector.

Luminous efficiency

$$C_{np} = \frac{E_{ph}}{E} \times 100\%$$

total energy of output light

luminous efficiency

energy lost in scintillator of incident particles

For example: in NaI(Tl),

for β particles, C_{np}=13%,

for α particles, C_{np}=2.6%

Light Yield

$$Y_{ph} = \frac{n_{ph}}{E}$$

total number of scintillation photons

energy lost in scintillator of incident particles

$$Y_{ph} = \frac{n_{ph}}{E} = \frac{E_{ph}}{h\bar{\nu}} \cdot \frac{1}{E} = \frac{C_{np}}{h\bar{\nu}}$$

For example: in NaI(Tl), for β particles of 1MeV, hv≈3eV,

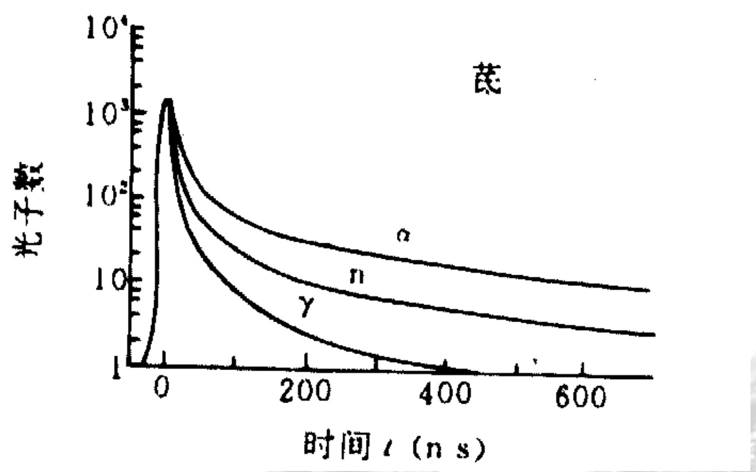
$$Y_{ph} = \frac{0.13}{3eV} = 4.3 \times 10^{4}\ \mathrm{MeV}^{-1}$$

Decay time

- excitation process takes 10^{-11}~10^{-9} second
- de-excitation and light output obey exponential decrease.

$$n(t) = n(0)e^{-t/\tau}$$

Decay time



$$n_{ph} = \int_0^\infty n(0)e^{-t/\tau}dt = n(0)\cdot\tau \Rightarrow n(t) = \frac{n_{ph}}{\tau}e^{-t/\tau}$$

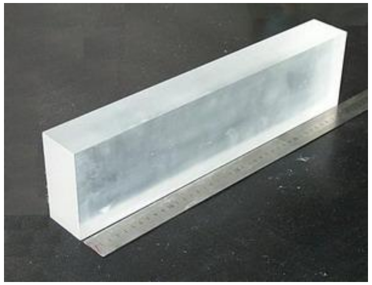
Fast and Slow decay

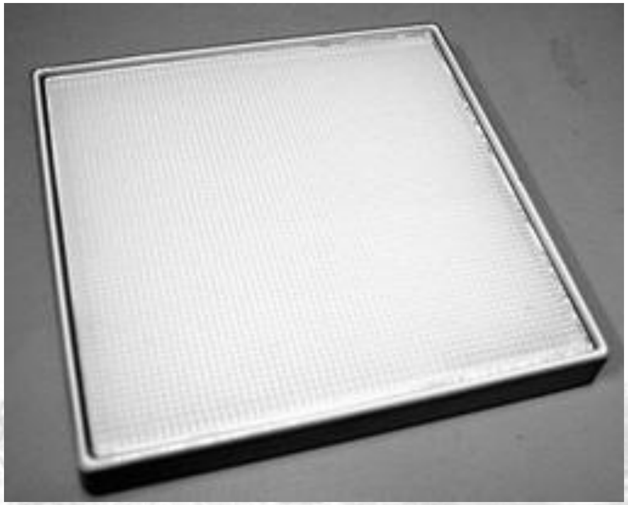
$$n(t) = n_f(t) + n_s(t) = \frac{n_f}{\tau_f} e^{-t/\tau_f} + \frac{n_s}{\tau_s} e^{-t/\tau_s}$$

The ratio of n_f and n_s has connection with incident particles, which could be used to discriminate particle category.

NaI(Tl) Crystal

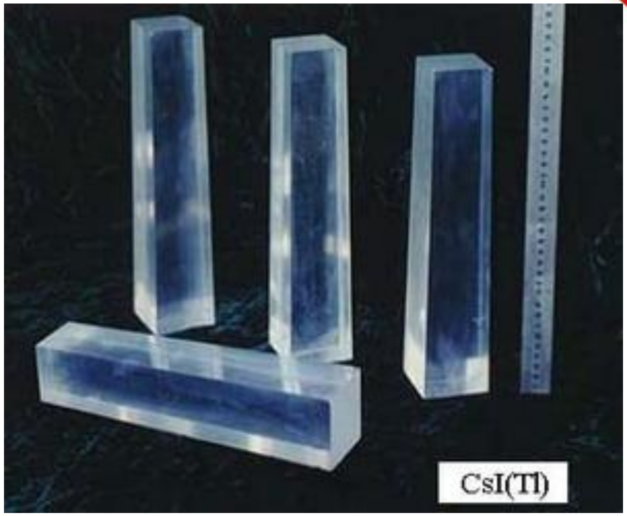
- High light yield
- High Z and ρ(3.67g/cm³)
- Hygroscopic

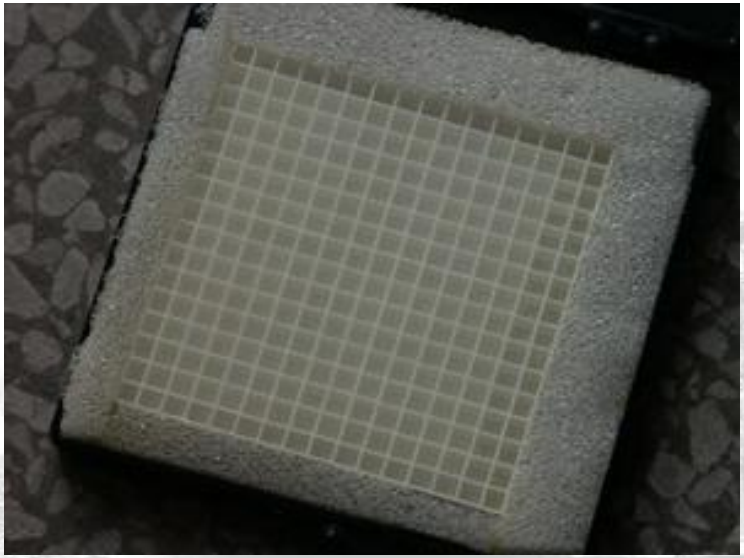




CsI(Tl)

- Expansive
- High Z and ρ(4.51g/cm³)
- Low light yield
- Tractable





Other Scintillation

- ZnS(Ag): translucent, for α counts measurement
- BGO:High Z and ρ
- BaF_2: fast decay time(0.6ns)
- Liquid scintillator: fast decay time(2.4ns)
- Plastic scintillator: fast decay time(1~3ns)

Scintillator Table

Table 1 : Summary of Scintillator Characteristics

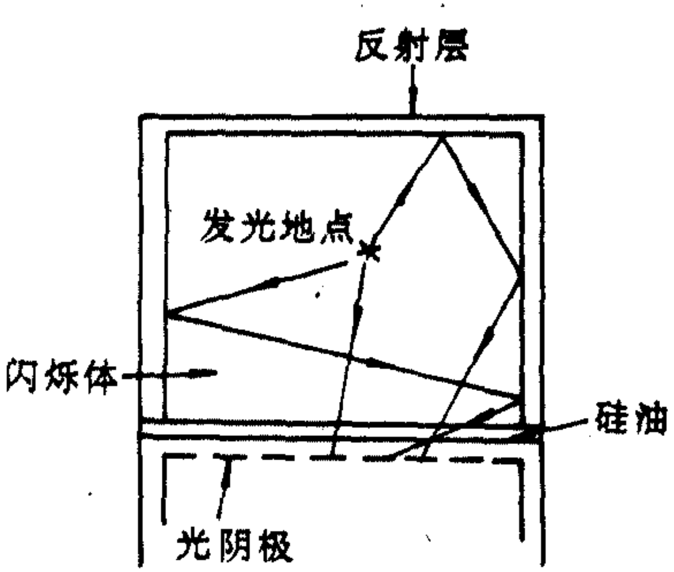
	NaI(Tl)	BGO	CsI(Tl)	Pure CsI	BaF_2	GSO: Ce	Plastic	LSO	PWO	YAP
Density(g/cm³)	3.67	7.13	4.51	4.51	4.88	6.71	1.03	7.35	8.28	5.55
Refractive Index	1.85	2.15	1.80	1.80	1.58	1.85	1.58	1.82	2.16	1.97
Hygroscopic	Yes	No	Slightly	Slightly	Slightly	No	No	No	No	No
Luminescence	410	480	530	310	325	430	400	420	470	380
(nm)					220	310				
Decay Time	230	300	1000	10	630	30	2.0	40	15	30
(nsec)					0.9					
Relative Light Output	100	15	45 to 50	<10	20	20	25	70	0.7	40

A Good Scintillator

- Suitable for detected particles
- match PMT well
- high stopping power
- high light yield
- fast decay time
- wide linear region of energy reponse

Collection of light

- Reflecting layer
- light coupling agent
- light guide



PHOTOMULTIPLIER

Photomultiplier

- Photomultiplier Tube(PMT)
- Micro channel plate
- (Avalanche) Photodiode (PD/APD)
- Silicon Photomultiplier(SiPM)

PMT

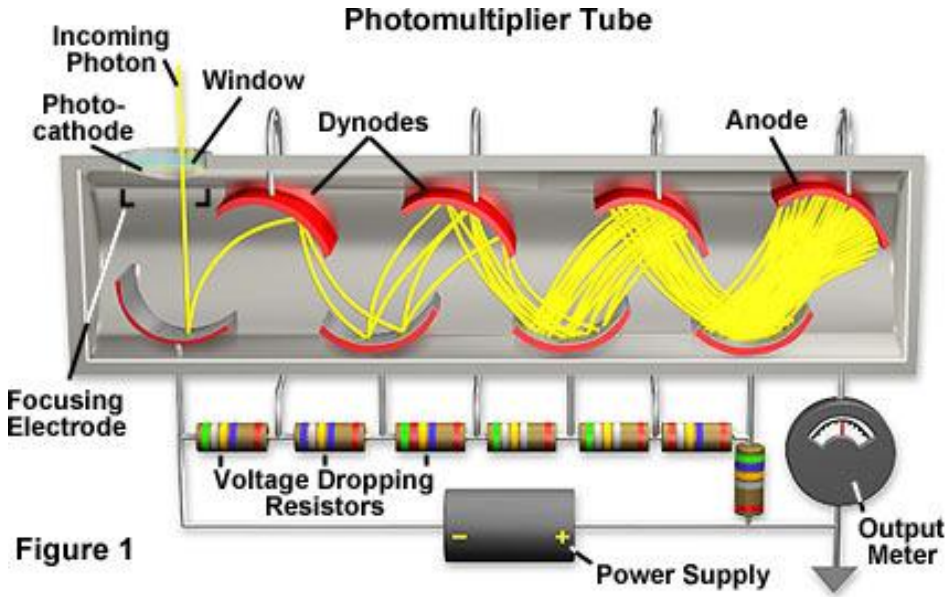
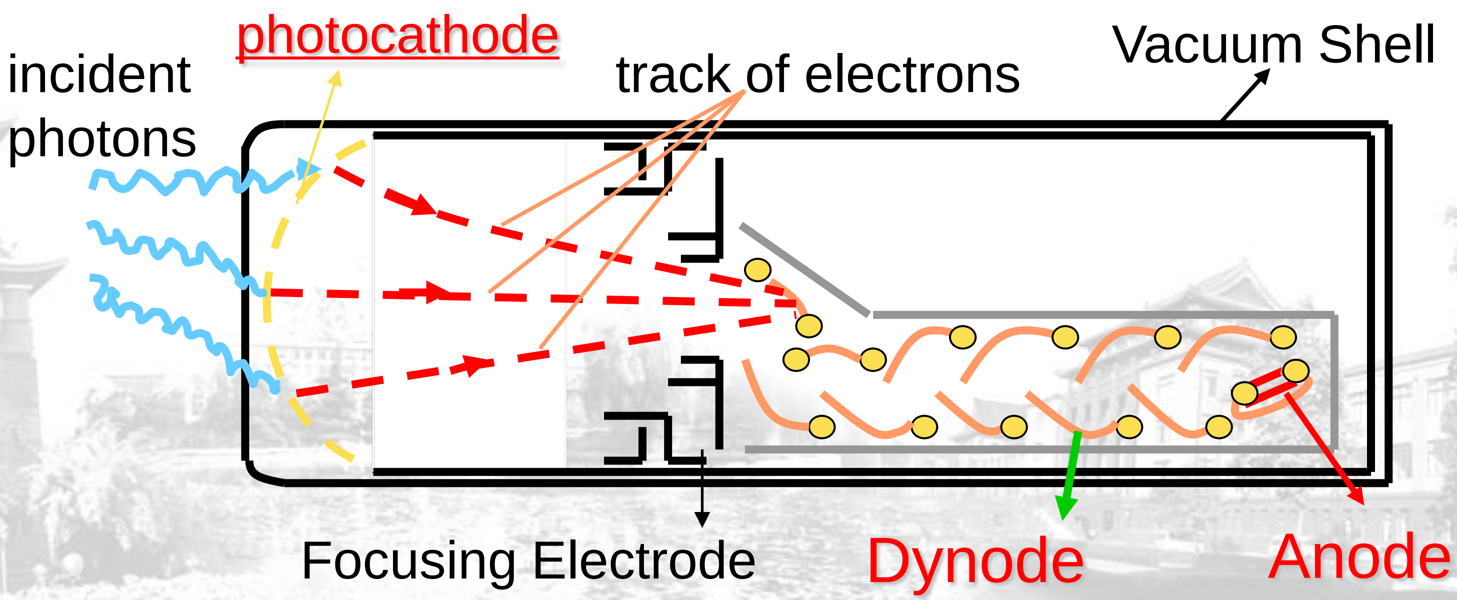
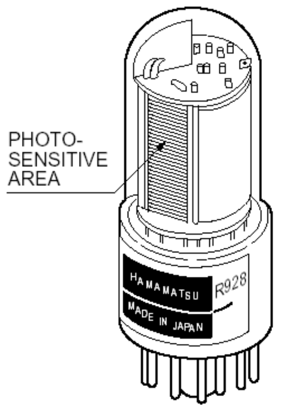

Photomultiplier Tube
Incoming Photon
Window
Photo-cathode
Dynodes
Anode
Focusing Electrode
Voltage Dropping Resistors
Output Meter
Power Supply

Figure 1

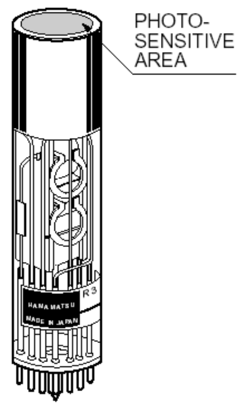

incident photons
photocathode
track of electrons
Vacuum Shell
Focusing Electrode
Dynode
Anode

Various type of PMT

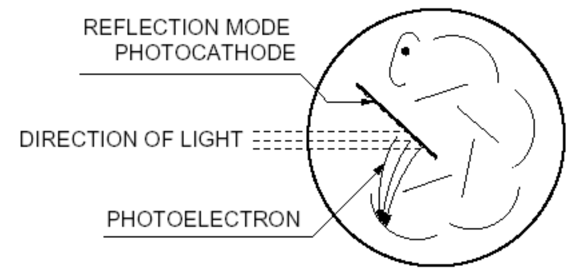
a) Side-On Type



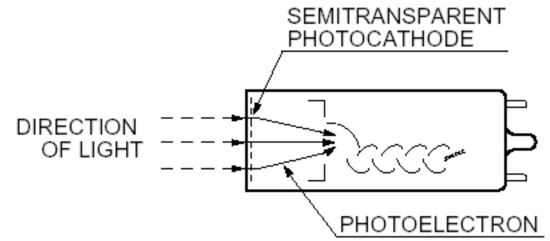
b) Head-On Type



a) Reflection Mode



b) Transmission Mode



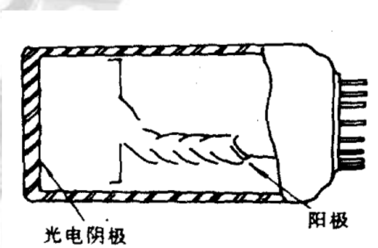
Focusing type VS non-focusing type

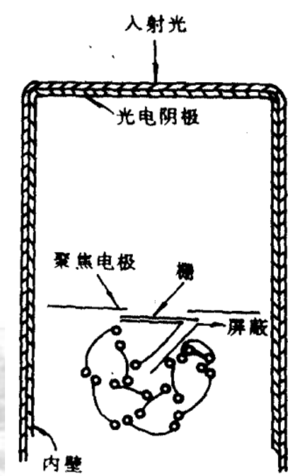
Focusing PMT

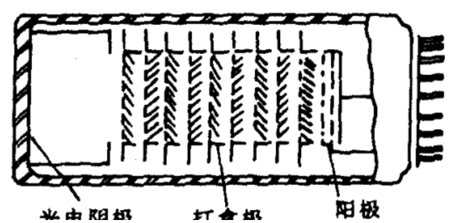
- Fast response time
- Time measurement
- Line or ring structure

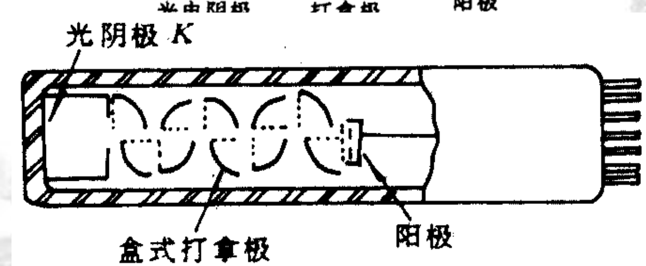
Non-focusing PMT

- Large gain
- Eenergy measurement
- Shutter or box-grate structure

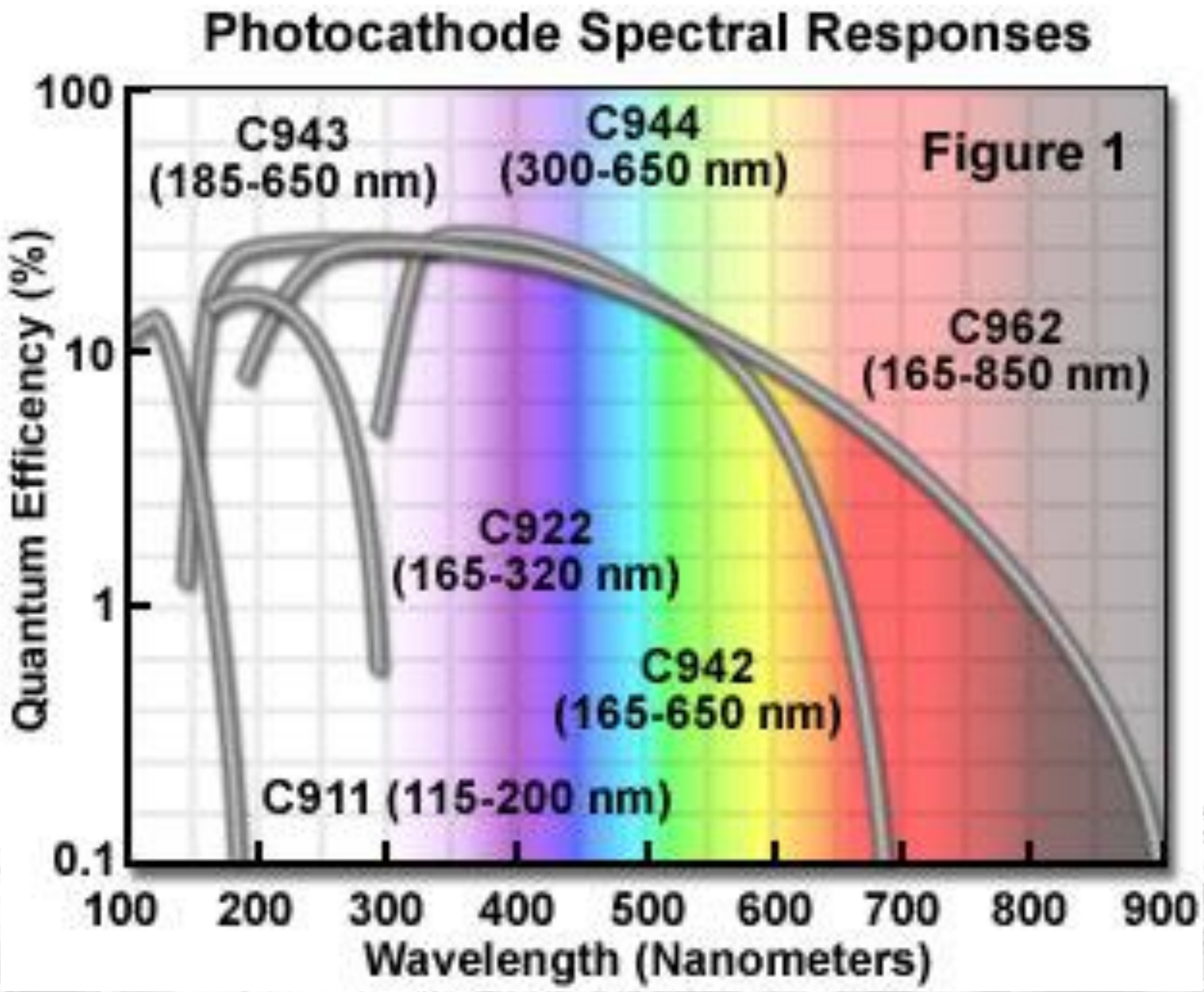








Response Spectrum



Luminous Sensitivity

- Cathode luminous sensitivity

current of cathode

$$S_k = {i_k}/{F} \quad [\mu A / Lm]$$

light flux

- Anode luminous sensitivity

current of aode

$$S_A = {i_A}/{F} \quad [\mu A / Lm]$$

light flux

Gain

$$M = \frac{\text{Number of electrons collected by anode}}{\text{Number of electrons gathered by the first dynode}}$$

$$M = \frac{S_A}{S_K} = \frac{i_A}{i_K} = (g\delta)^n = 10^6 \sim 10^8$$

electron transport efficiency between dynodes

Dark Current and Noise

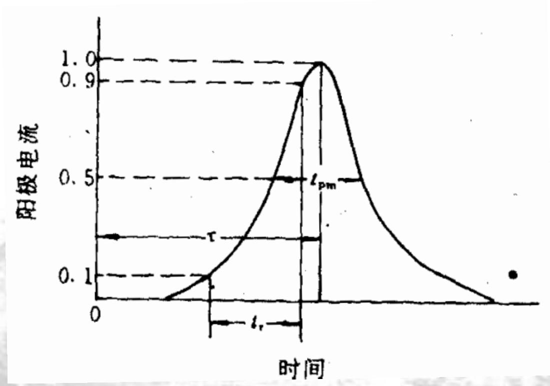
- Thermal emission
- Ionization or excitation of residual gas
- Point discharge or current leakage

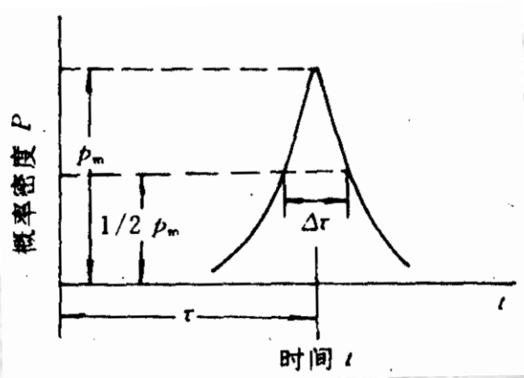
Parameter of Noise and Dark Current

- Noise energy equivalent
  - $E_{en}=V_{en}*E_{\gamma}/V_{\gamma}$ V_{en}: discrimination voltage at 50 cps
- Dark current of anode
  - its average value of noise pulses, usually $10^{-6} \sim 10^{-10}$ A

Rise Time and Transit Time

- Rise time
  - The time it takes that PMT output current increase from 10% to 90% of maximum.
- Transit time
  - The average time it takes that one electron from cathode to anode.





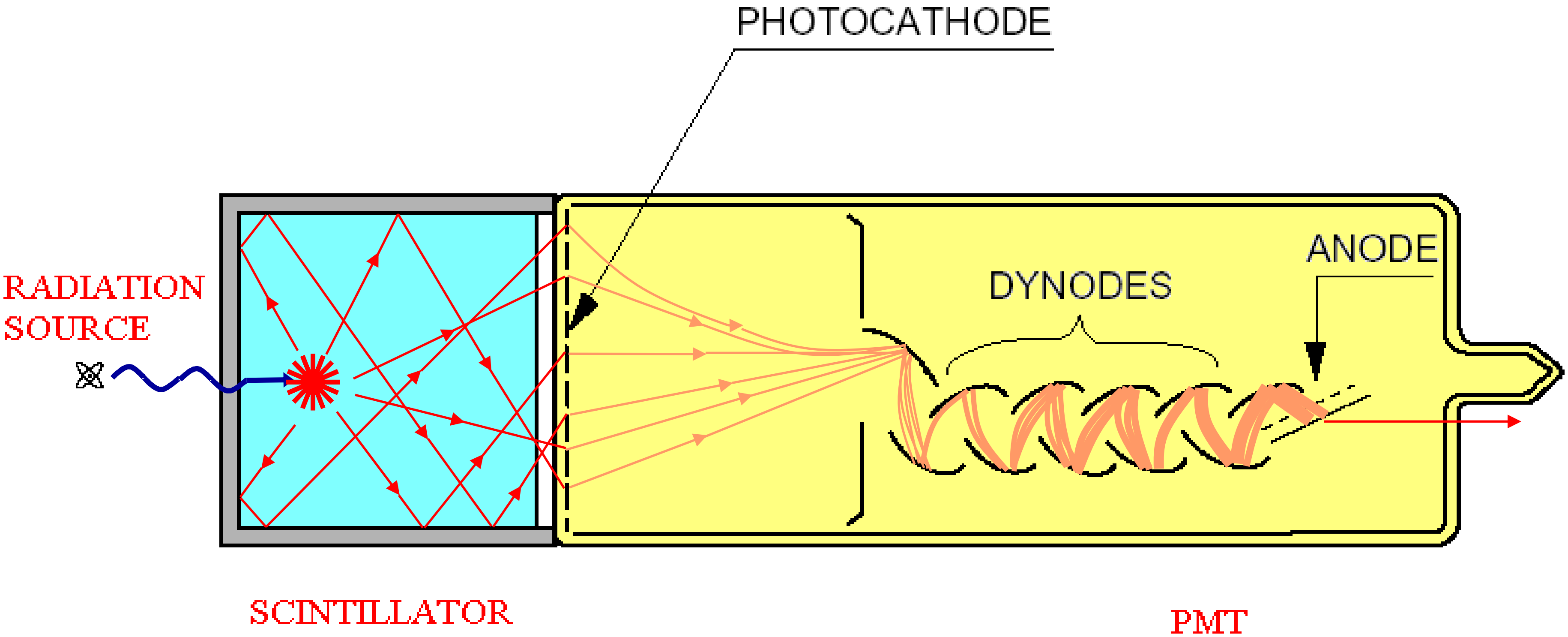
Stability

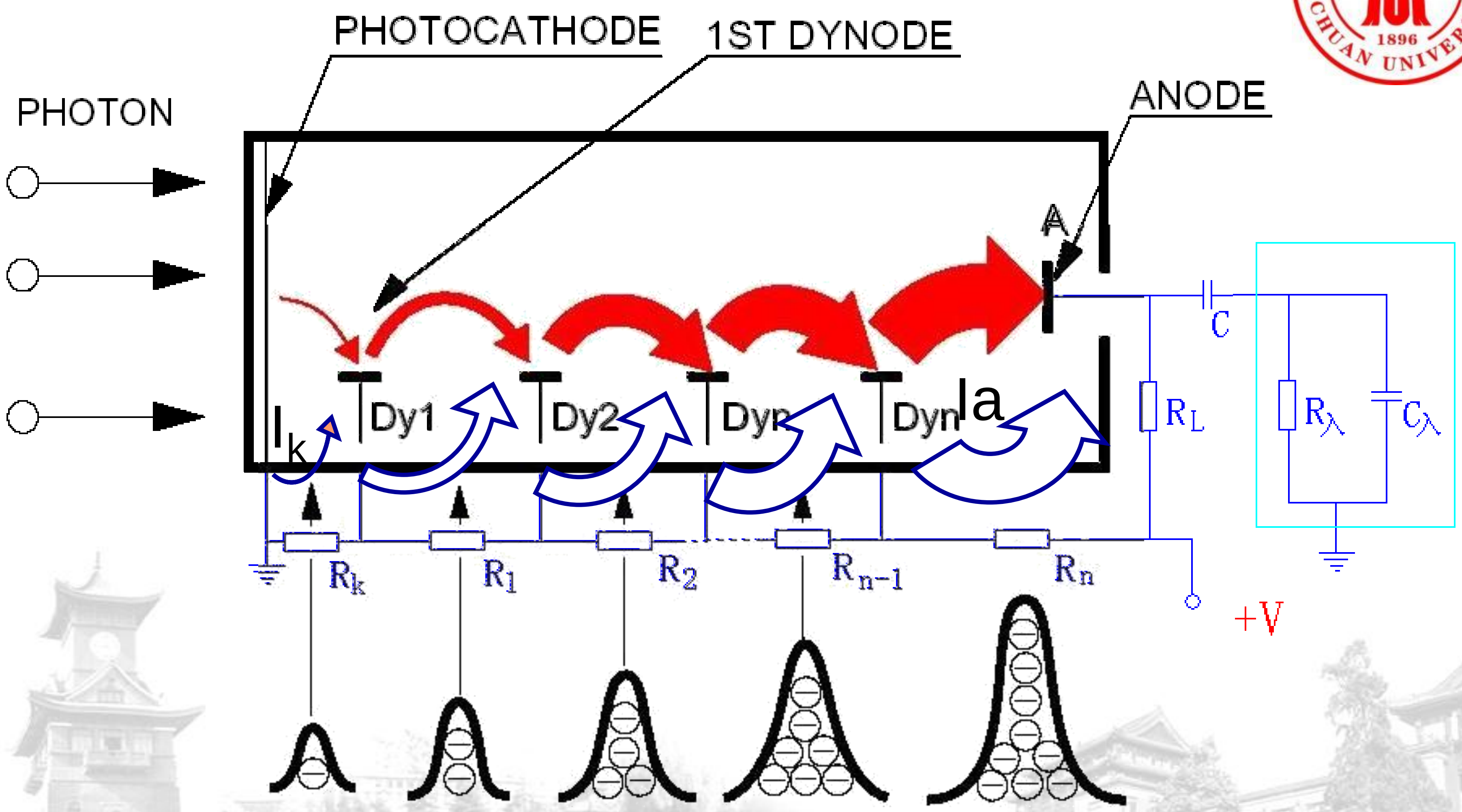
- short-time stability
  - start to measure 30 minutes after power on.
- long-time stability
  - has connection with temperature, material and technology.

Usage of PMT

- keep out of light
- supply correct H.V.
- suitable divider resistance
- add parallel capacitance between last dynodes and anodes.

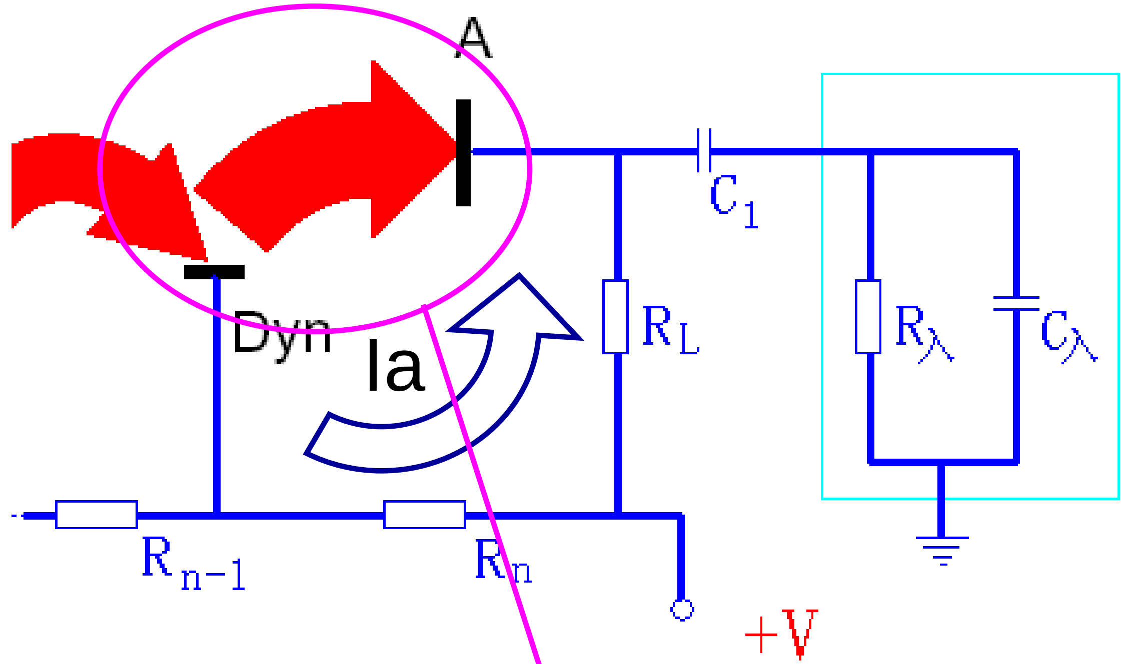
Signal Output of PMT

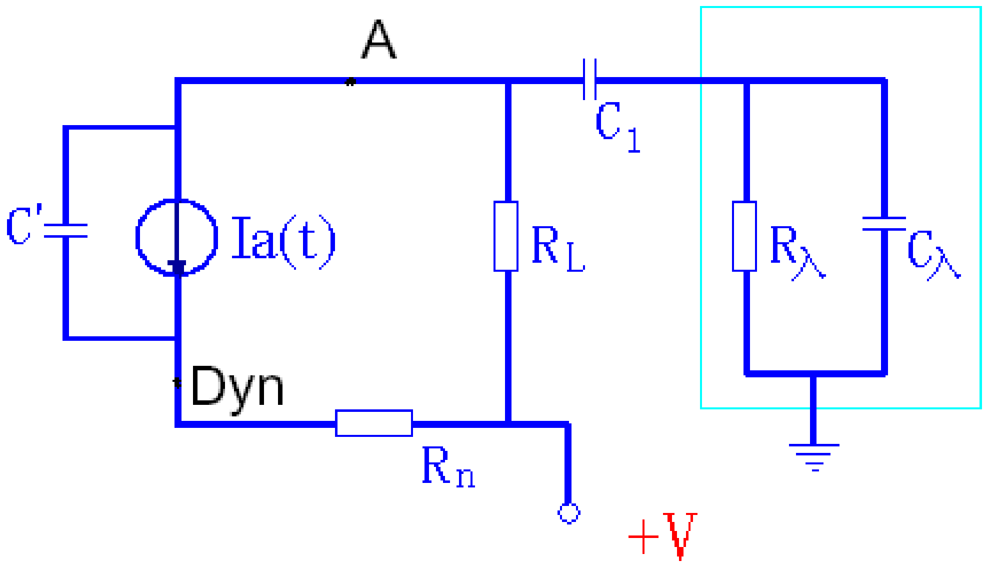


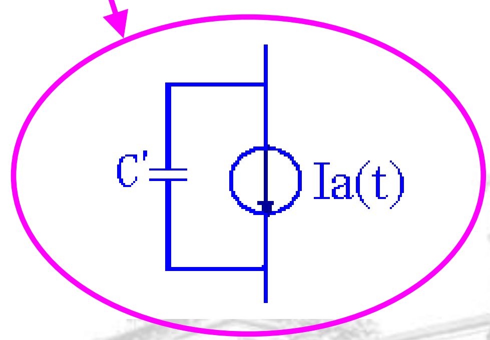


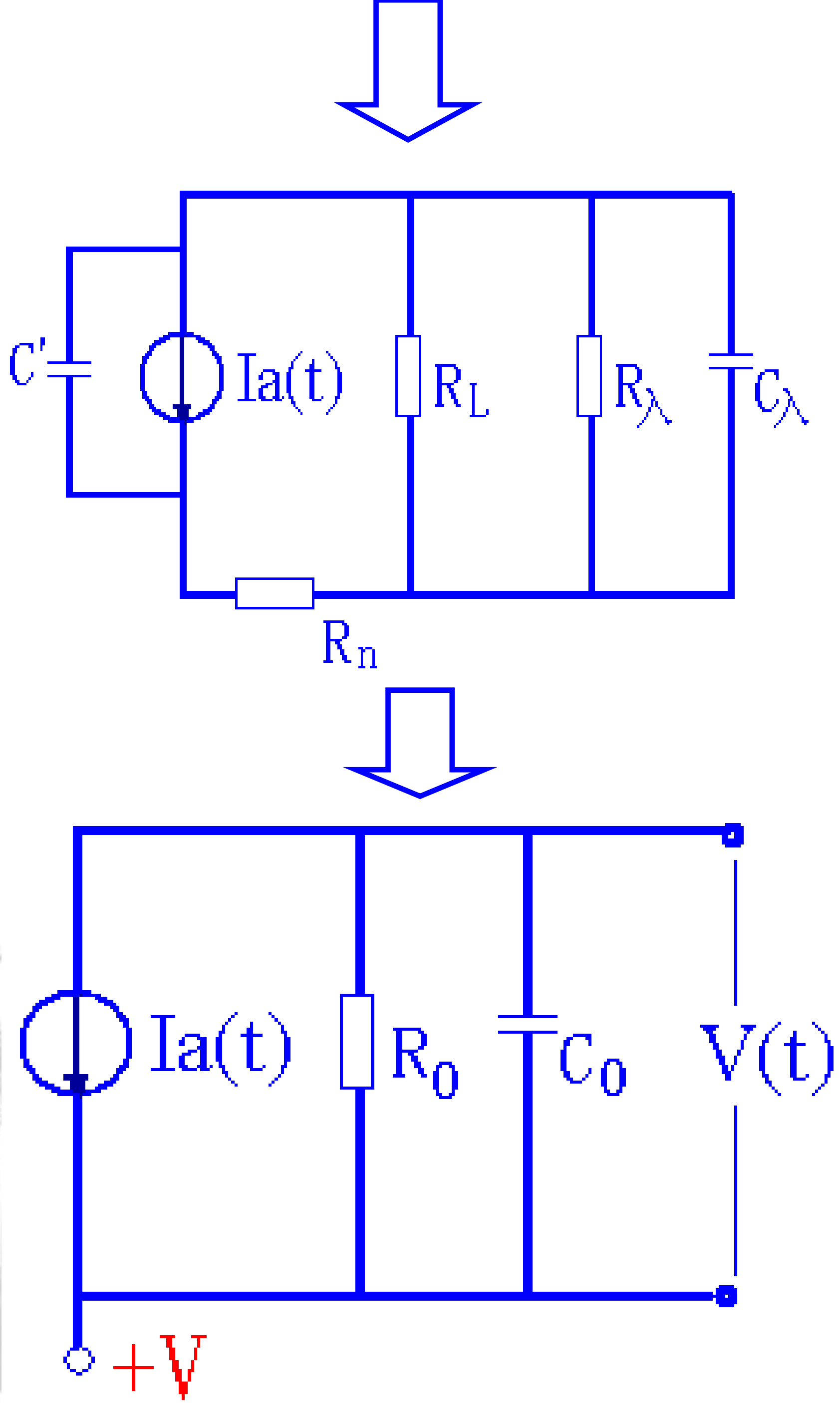
PHOTOCATHODE
1ST DYNODE
ANODE
PHOTON
A
Dy1
Dy2
Dyn
Ia
Ik
C
RL
Rλ
Cλ
Rk
R1
R2
Rn-1
Rn
+V

Equivalent output circuit









$$R_0 = R_L // R_{入}$$

$$C_0 = C' + C_{入}$$

$$+ \text{Distributed Capacitance}$$

Charge Output

$$Q = E \cdot Y_{ph} \cdot T \cdot M \cdot e$$

- e: unit charge
- M: multiplication factor of PMT
- T: efficiency from photons to electrons collected by the first dynode.
- Y_{ph}: light yield
- E: energy loss of incident particles in scintillator

$$Q \propto E$$

Current Output

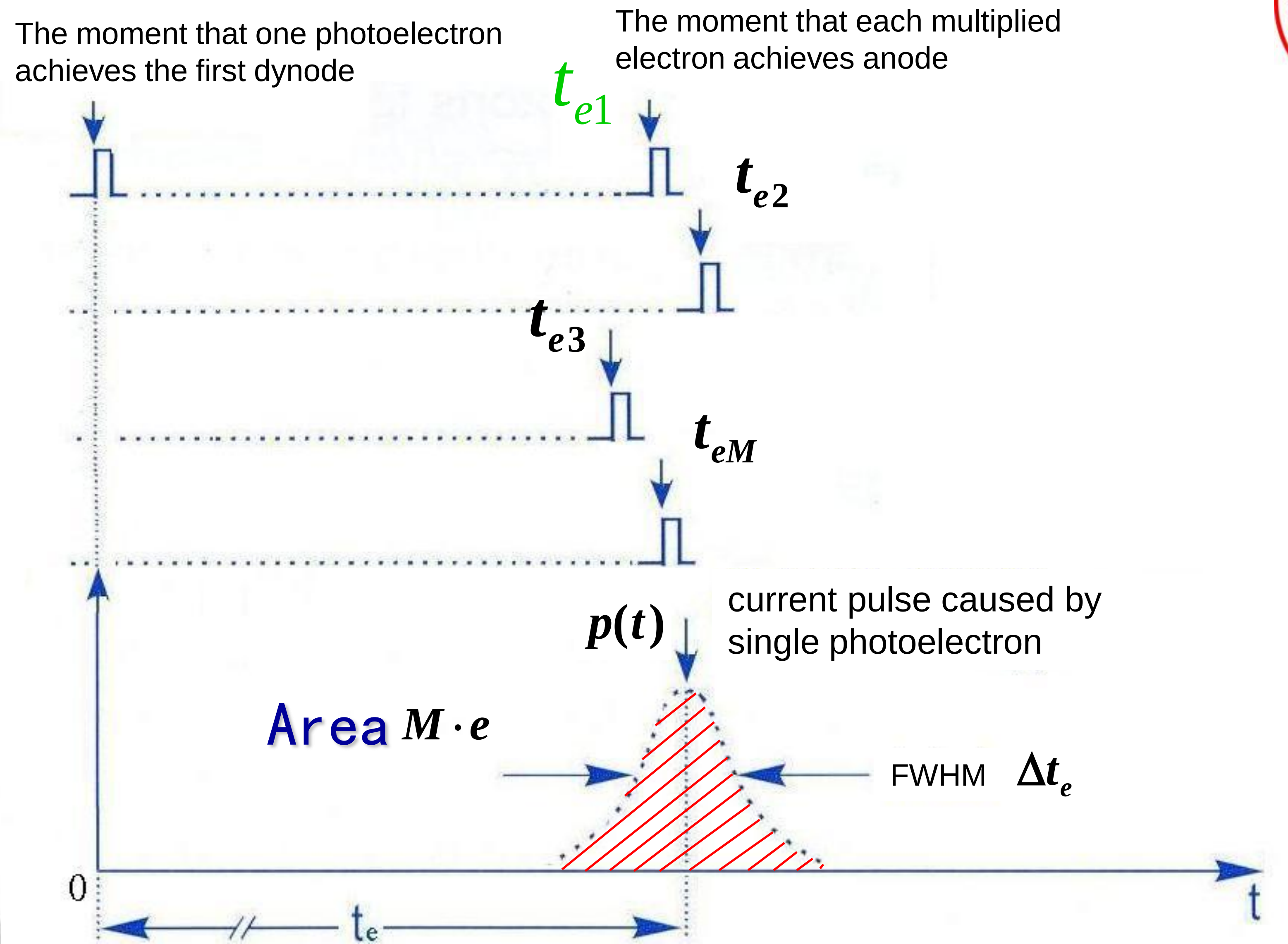
- photon number emitted by scintillator in unit time:

$$n(t) = \frac{n_{ph}}{\tau} e^{-t/\tau}$$

decay time of scintillator

- electron number collected by the first dynode in unit time

$$n_e(t) = \frac{n_{ph}}{\tau} \cdot T \cdot e^{-t/\tau}$$


The moment that one photoelectron achieves the first dynode
The moment that each multiplied electron achieves anode
t_{e1}
t_{e2}
t_{e3}
t_{eM}
$p(t)$
current pulse caused by single photoelectron
Area $M \cdot e$
FWHM Δt_e
0
t_e
t

Current Pulse of One Scintillation

$$I(t) = \int_0^t n_e(t-t')p(t')dt'$$

$$n_e(t) = \frac{n_{ph}}{\tau} \cdot T \cdot e^{-t/\tau}$$

⇩

$$I(t) = \frac{n_{ph} \cdot T}{\tau} \cdot \int_0^t e^{-(t-t')/\tau} \cdot p(t')dt'$$

⇩

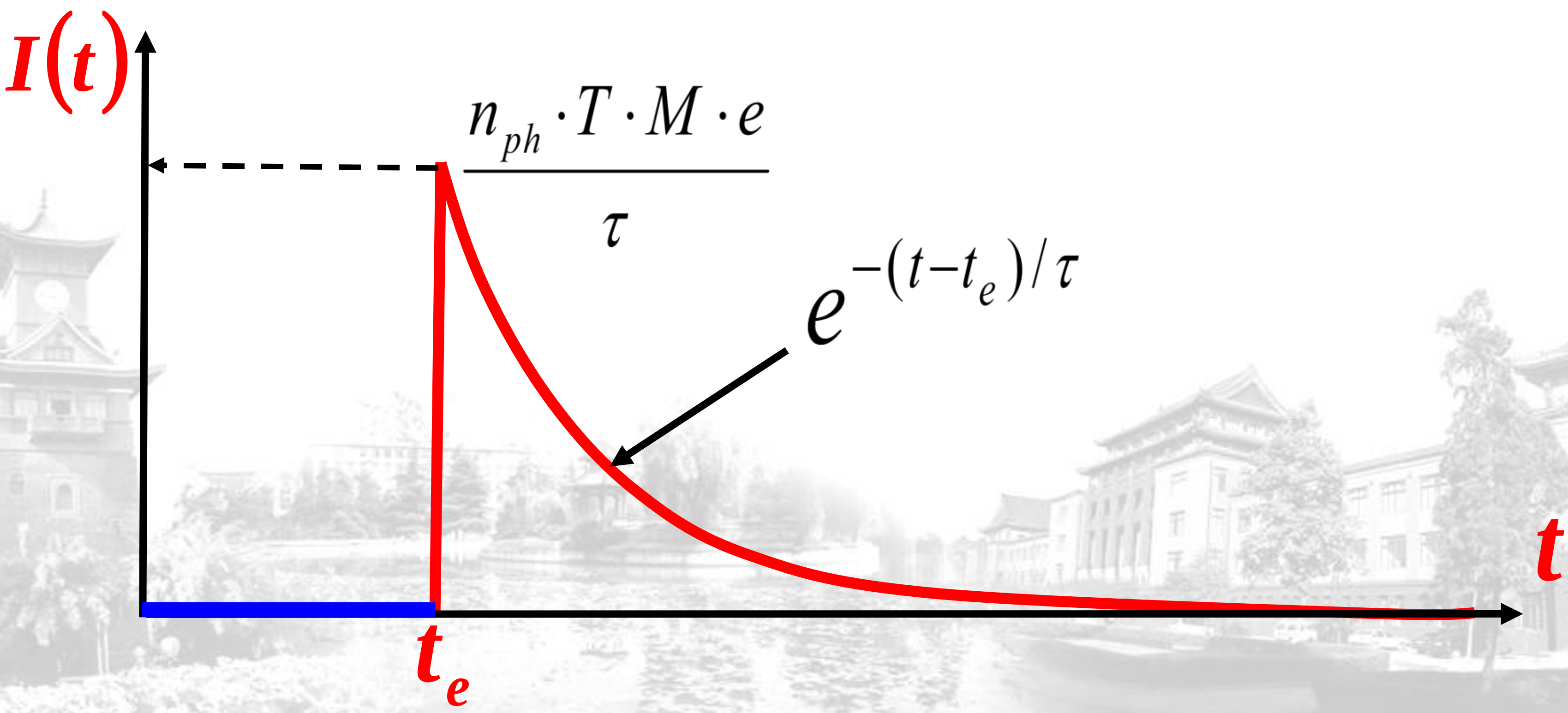
$$\tau \frac{dI(t)}{dt} + I(t) = n_{ph} \cdot T \cdot p(t)$$

if $p(t) = M \cdot e \cdot \delta(t - t_e)$

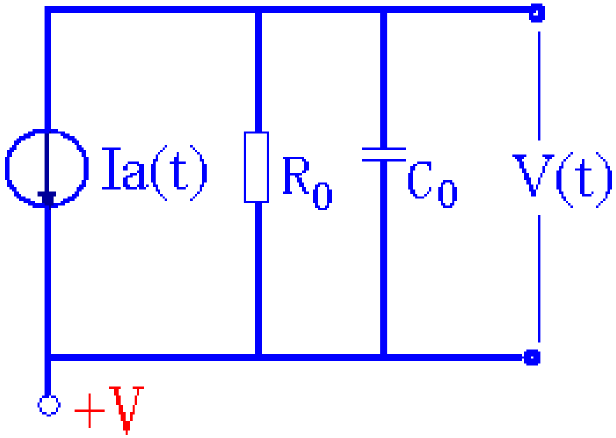
then

$$I(t) = \frac{n_{ph} \cdot T}{\tau} \cdot \int_0^t e^{-(t-t')/\tau} \cdot M \cdot e \cdot \delta(t' - t_e)dt'$$

$$I(t)=\begin{cases}0 & t<t_e\\ \dfrac{n_{ph}\cdot T\cdot M\cdot e}{\tau}e^{-(t-t_e)/\tau} & t\geq t_e\end{cases}$$



Voltage Pulse



$$I(t) = \frac{V(t)}{R_0} + C_0 \frac{dV(t)}{dt}$$

$$V(t) = \frac{e^{-t/R_0C_0}}{C_0} \int_0^t I(t') e^{t'/R_0C_0} dt'$$

$$I(t) = \frac{n_{ph} \cdot T \cdot M \cdot e}{\tau} e^{-t/\tau}$$

$$Q = n_{ph} \cdot T \cdot M \cdot e$$

$$V(t) = \frac{Q}{C_0} \cdot \frac{R_0C_0}{(R_0C_0 - \tau)} \left[e^{-t/R_0C_0} - e^{-t/\tau} \right]$$

$$V(t) \propto Q \propto E$$

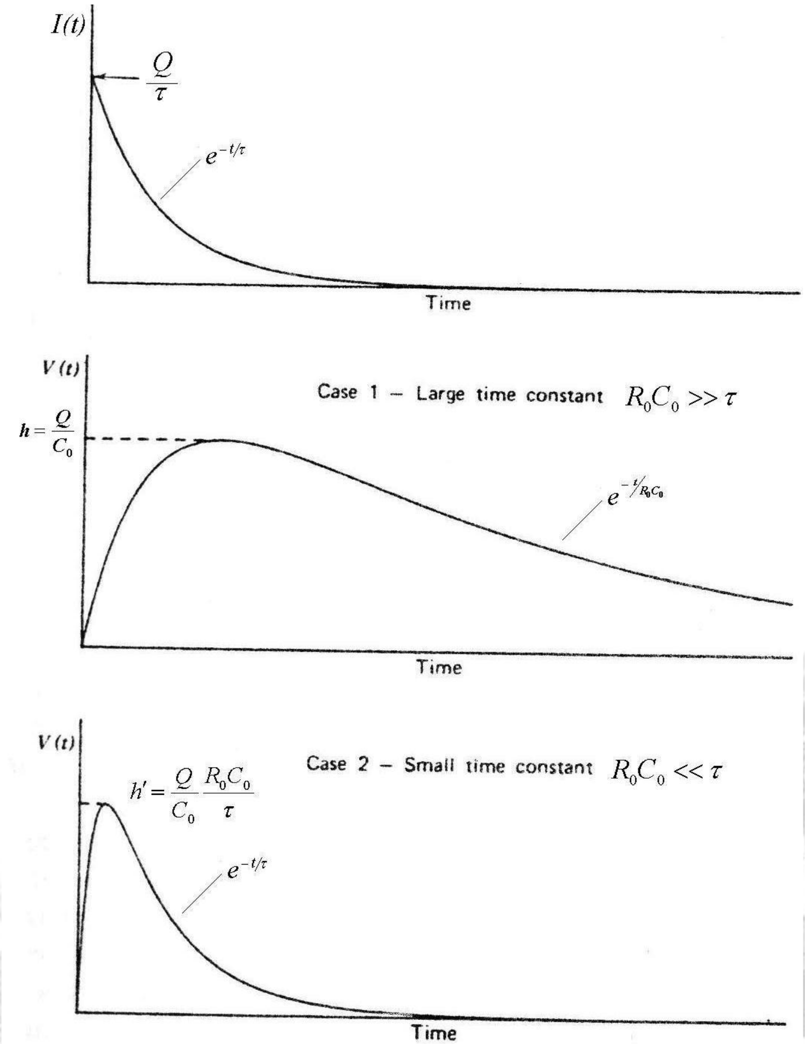
$$V(t)=\frac{Q}{C_0}\cdot\frac{R_0C_0}{(R_0C_0-\tau)}\left[e^{-t/R_0C_0}-e^{-t/\tau}\right]$$

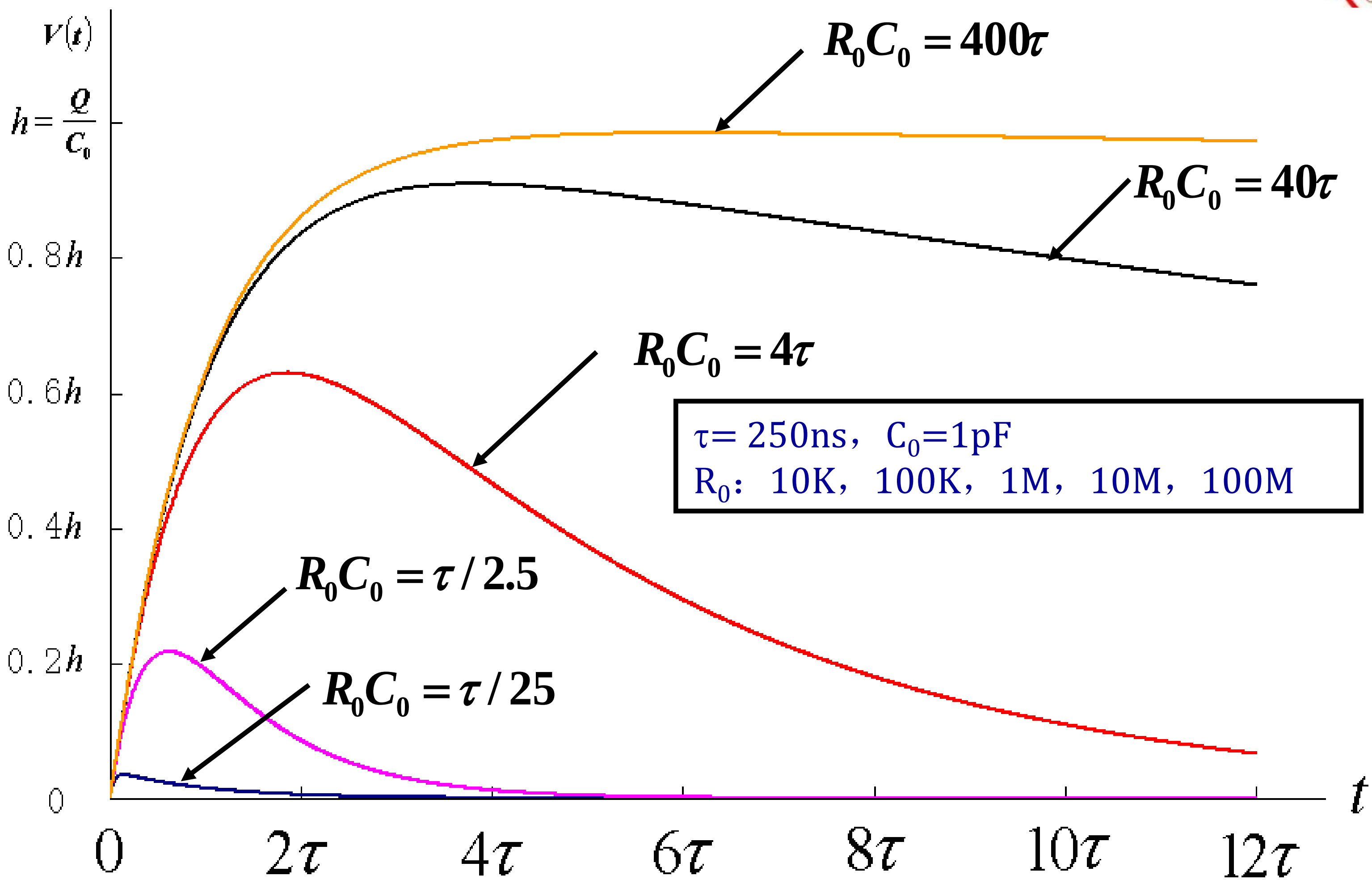
$$R_0C_0 >> \tau$$

$$V(t)=\frac{Q}{C_0}\left(e^{-t/R_0C_0}-e^{-t/\tau}\right)$$

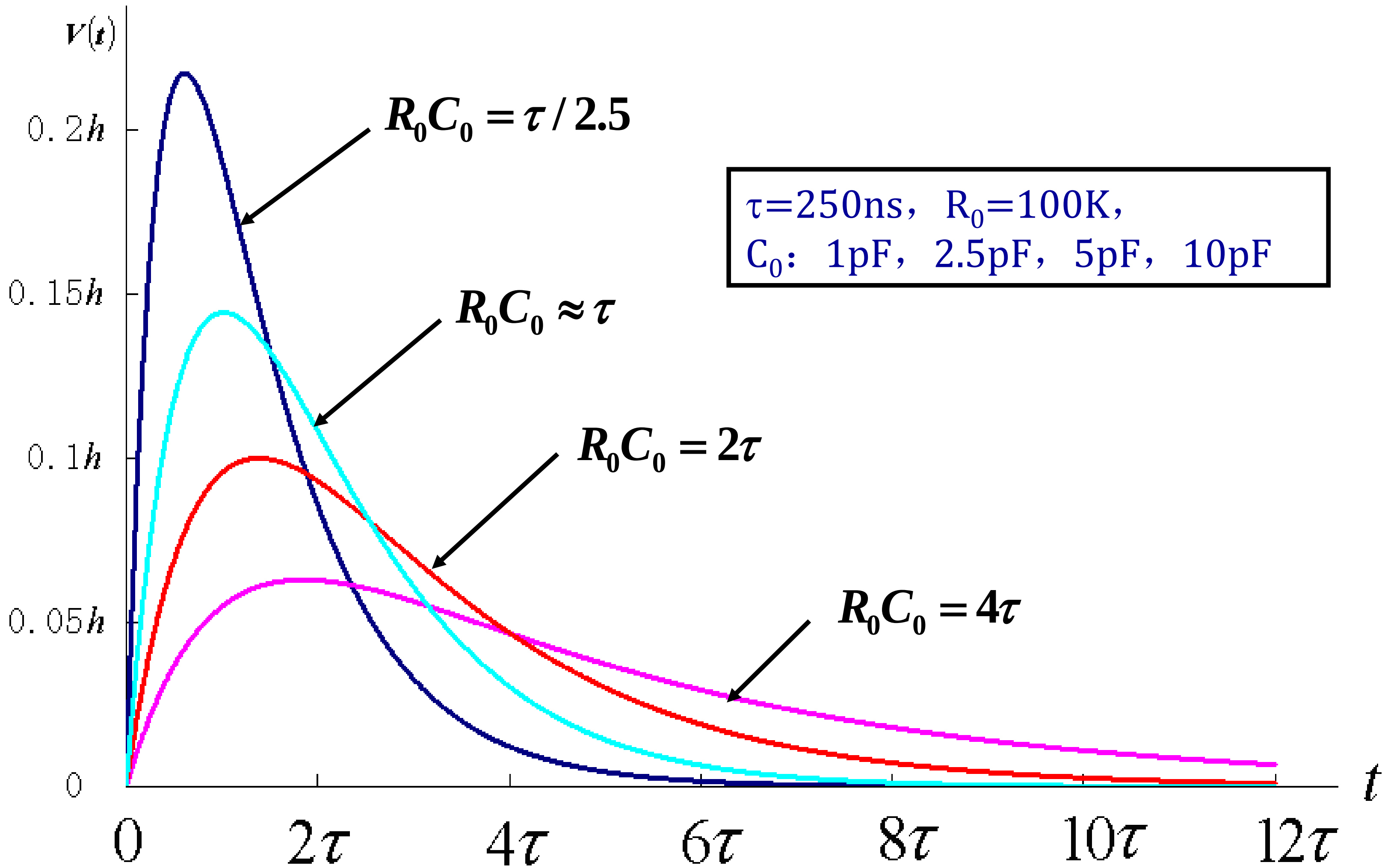
$$R_0C_0 << \tau$$

$$V(t)=\frac{Q}{C_0}\frac{R_0C_0}{\tau}\left(e^{-t/\tau}-e^{-t/R_0C_0}\right)$$





V(t)
h = Q/C0
0.8h
0.6h
0.4h
0.2h
0
R0C0 = 400τ
R0C0 = 40τ
R0C0 = 4τ
R0C0 = τ/2.5
R0C0 = τ/25
τ= 250ns，C0=1pF
R0：10K，100K，1M，10M，100M
0
2τ
4τ
6τ
8τ
10τ
12τ
t



V(t)
0.2h
0.15h
0.1h
0.05h
0
$R_0C_0 = \tau / 2.5$
$R_0C_0 \approx \tau$
$R_0C_0 = 2\tau$
$R_0C_0 = 4\tau$
τ=250ns，R0=100K，
C0：1pF，2.5pF，5pF，10pF
t
0
2τ
4τ
6τ
8τ
10τ
12τ

Output Fluctuate of PMT

$$n_A = n_e \cdot M = n_{ph} \cdot T \cdot M$$

$$\nu_{n_{ph}}^2 = \frac{1}{\bar{n}_{ph}}$$

Poisson distribution

$$n_e = n_{ph} \cdot T \qquad \nu_{n_e}^2 = \frac{1}{\bar{n}_e} = \frac{1}{\bar{n}_{ph} \cdot T}$$

$$n_A = n_e \cdot M$$

$$\bar{n}_A = \bar{n}_e \cdot \bar{M}$$

$$\nu_{n_A}^2 = \frac{1}{\bar{n}_e} + \frac{1}{\bar{n}_e} \cdot \nu_M^2 = \frac{1}{\bar{n}_e} \cdot \left(1 + \nu_M^2\right)$$

$$\overline{M} = \bar{\delta}_1 \cdot \bar{\delta}^{\,n-1}$$

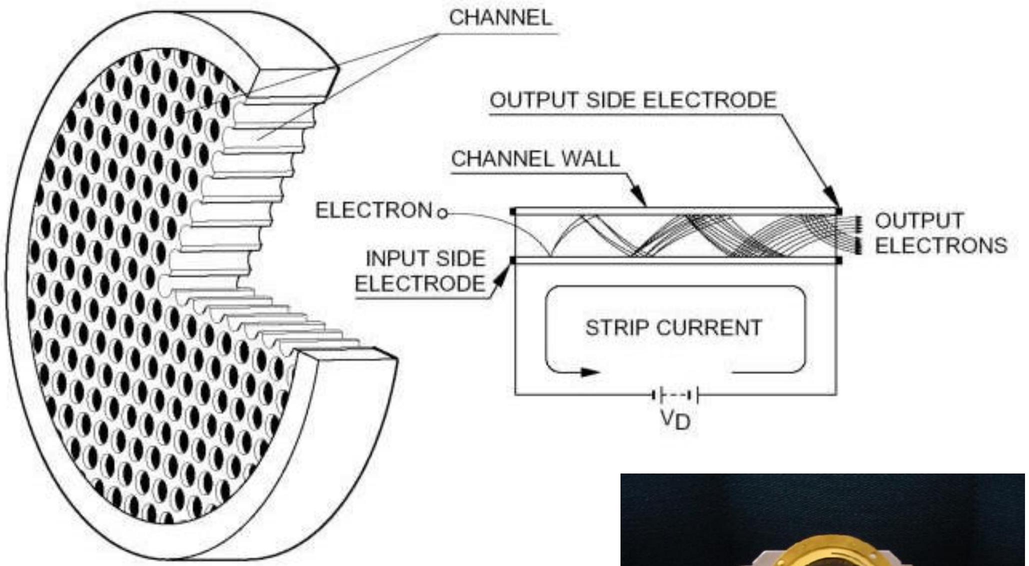
$$v_M^2 = \frac{1}{\bar{\delta}_1} + \frac{1}{\bar{\delta}_1} \cdot \frac{1}{\bar{\delta}} + \frac{1}{\bar{\delta}_1} \cdot \frac{1}{\left(\bar{\delta}\right)^2} + \ldots\ldots + \frac{1}{\bar{\delta}_1} \cdot \frac{1}{\left(\bar{\delta}\right)^{n-1}} \approx \frac{\bar{\delta}}{\bar{\delta}_1} \cdot \frac{1}{\bar{\delta} - 1}$$

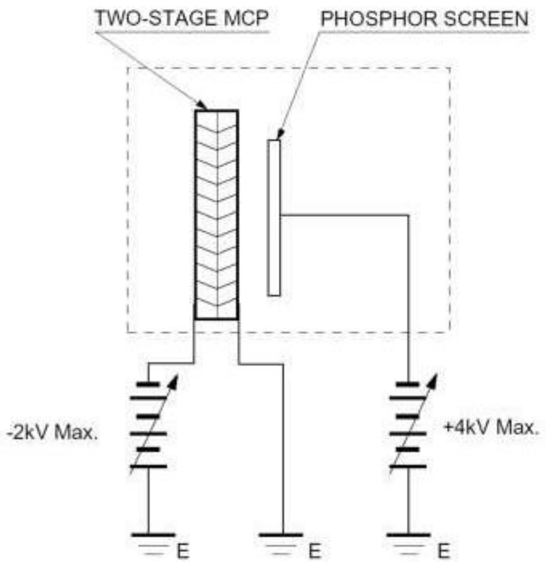
$$v_{n_A}^2 = \frac{1}{\bar{n}_e} \cdot \left(1 + v_M^2\right) = \frac{1}{\bar{n}_{ph} \cdot T}\left[1 + \frac{\bar{\delta}}{\bar{\delta}_1}\left(\frac{1}{\bar{\delta} - 1}\right)\right] = \frac{1}{\bar{n}_{ph} \cdot T}\left[1 + \frac{\delta}{\delta_1}\left(\frac{1}{\delta - 1}\right)\right]$$

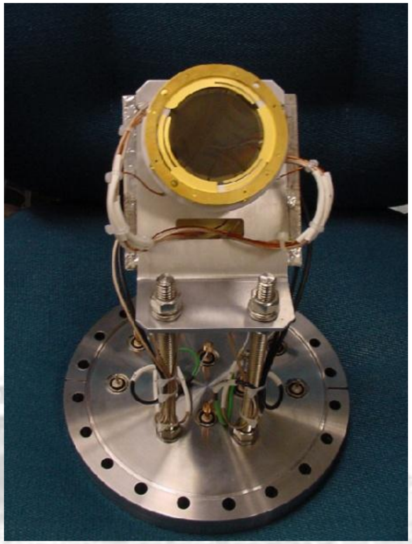
$$\eta = \frac{\Delta E}{E} = \frac{\Delta h}{h} = 2.36 v_h = 2.36 v_{n_A} = 2.36\sqrt{\frac{1}{\bar{n}_{ph} \cdot T}\left[1 + \frac{\delta}{\delta_1} \cdot \left(\frac{1}{\delta - 1}\right)\right]}$$

$$v_{n_A}^2 = \frac{1}{\bar{n}_{ph} \cdot \bar{T}}\left[1 + \frac{\delta}{\delta_1}\left(\frac{1}{\delta - 1}\right)\right] + v_T^2 + (1 + v_T^2)\left[\left(\frac{\sigma_{n_{ph}}}{\bar{n}_{ph}}\right)^2 - \frac{1}{\bar{n}_{ph}}\right]$$

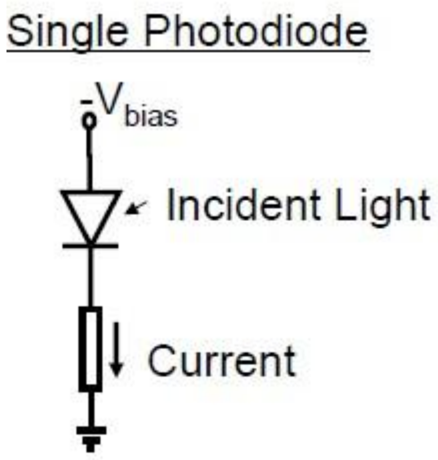
Micro Channel Plate

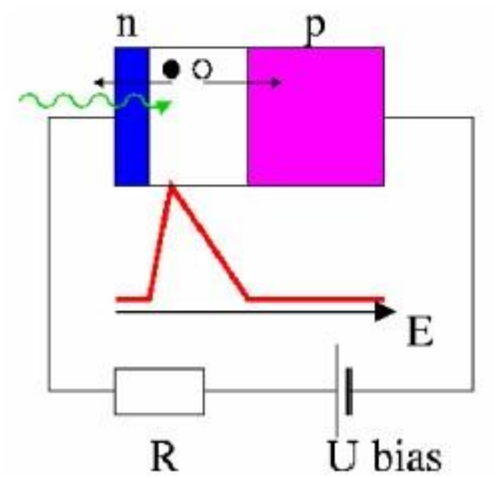


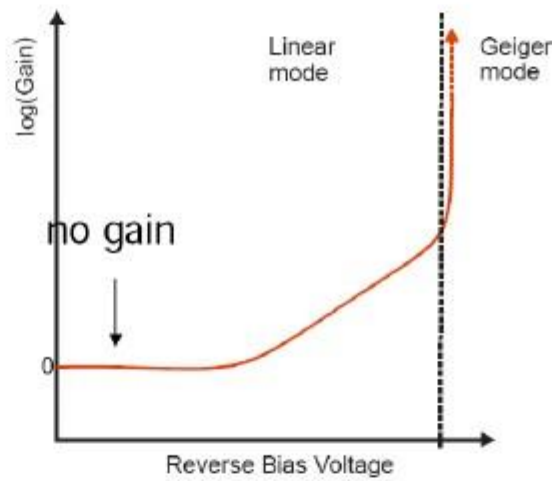




Avalanche Photodiode（APD）



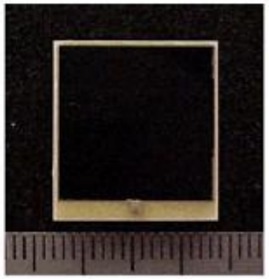




APD is a kind of diode the PN junction of which is light sensitive.

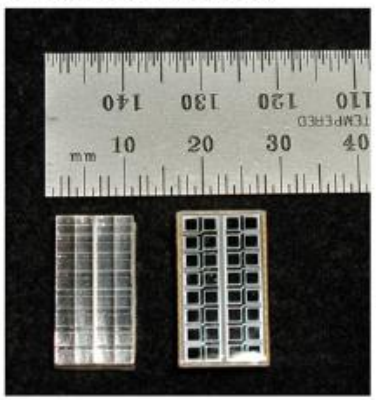
Various APD device

API 16 mm diameter
APD (SD630-70-75-500)

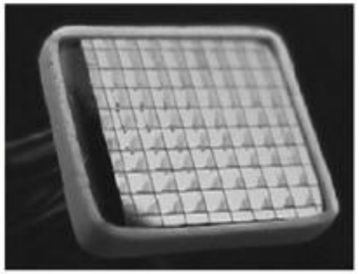


RMD 14 x 14 mm^2 APD

Hamamatsu S8664-1010



Hamamatsu S8550
4x8 array with 1.6 mm pixels

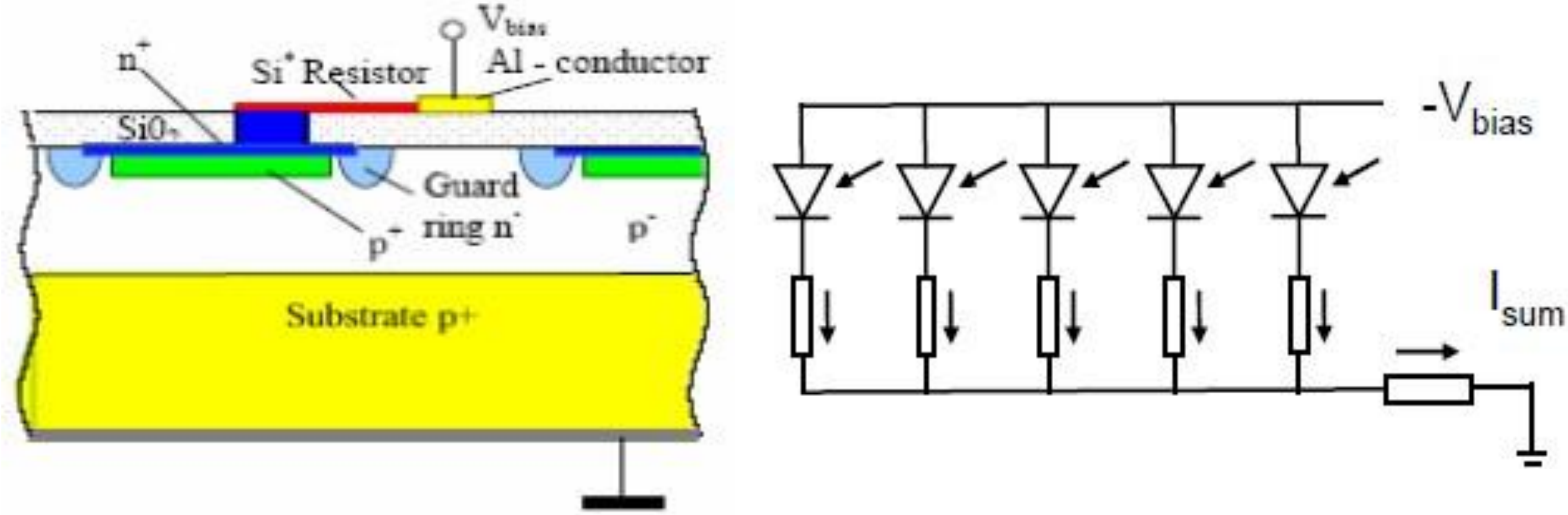


RMD 8x8 array

RMD position sensitive APD
14x14 mm

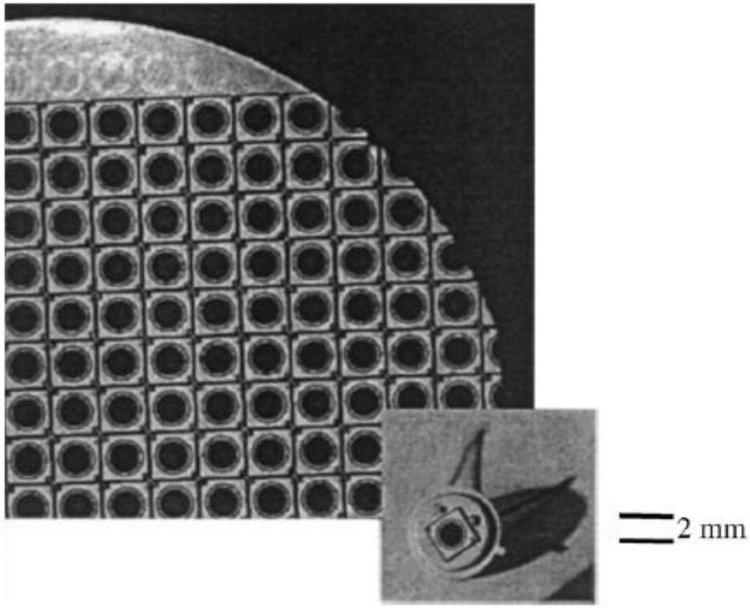
- gain 10^2~10^3， sensitive for temperature
- small volume
- suitable for MRI/PET imaging system（NOT infected by magnetic field）

Silicon Photomultiplier——SiPM



- Proposed by Russian in 1990's，a lot of APD operating in Geiger mode are collected in parallel with a common anode.

Advantage of SiPM

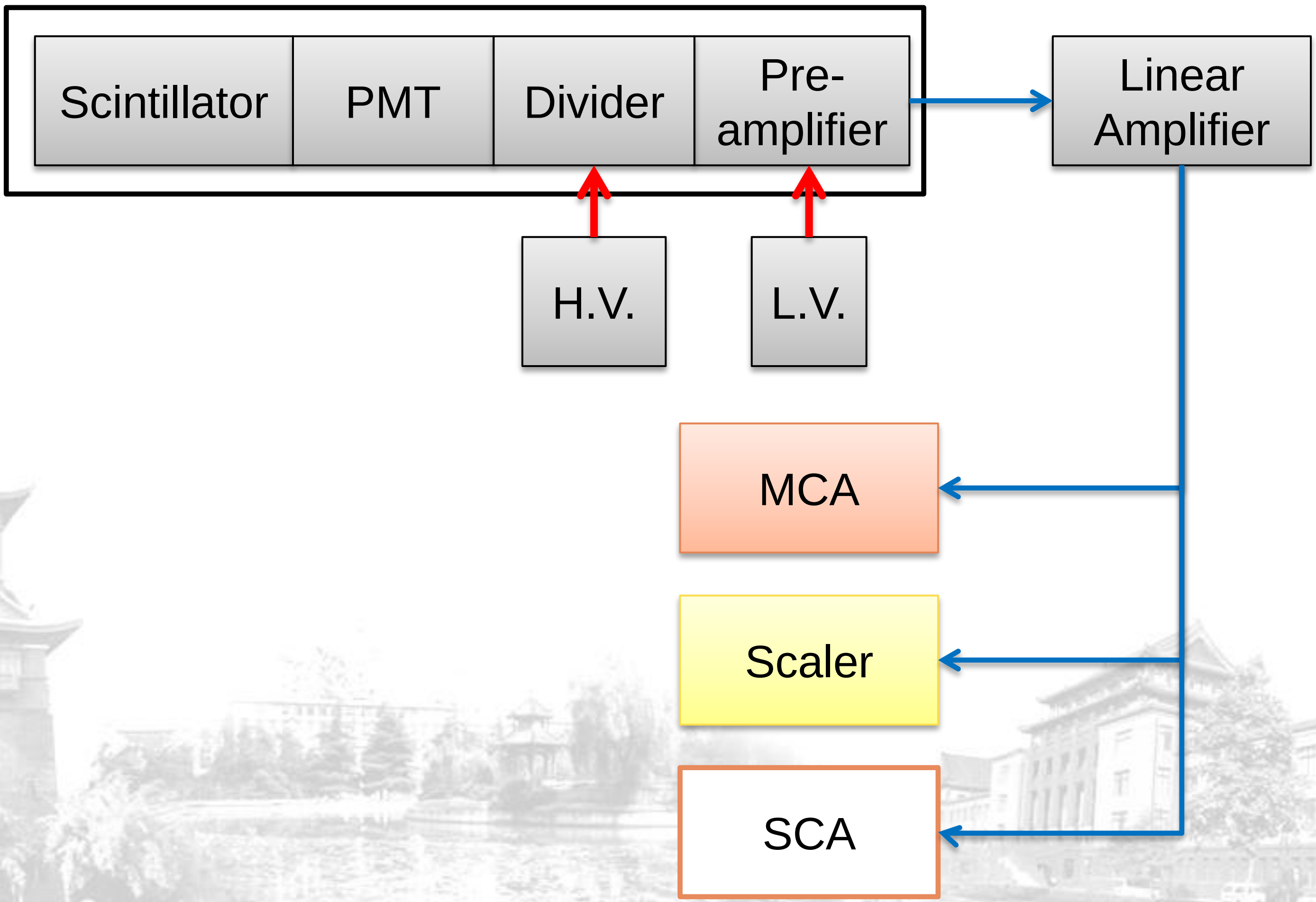


For each PAD unit occupies only hundreds of μm^2，it could contian thousands of APD unit in 1mm^2 aera！

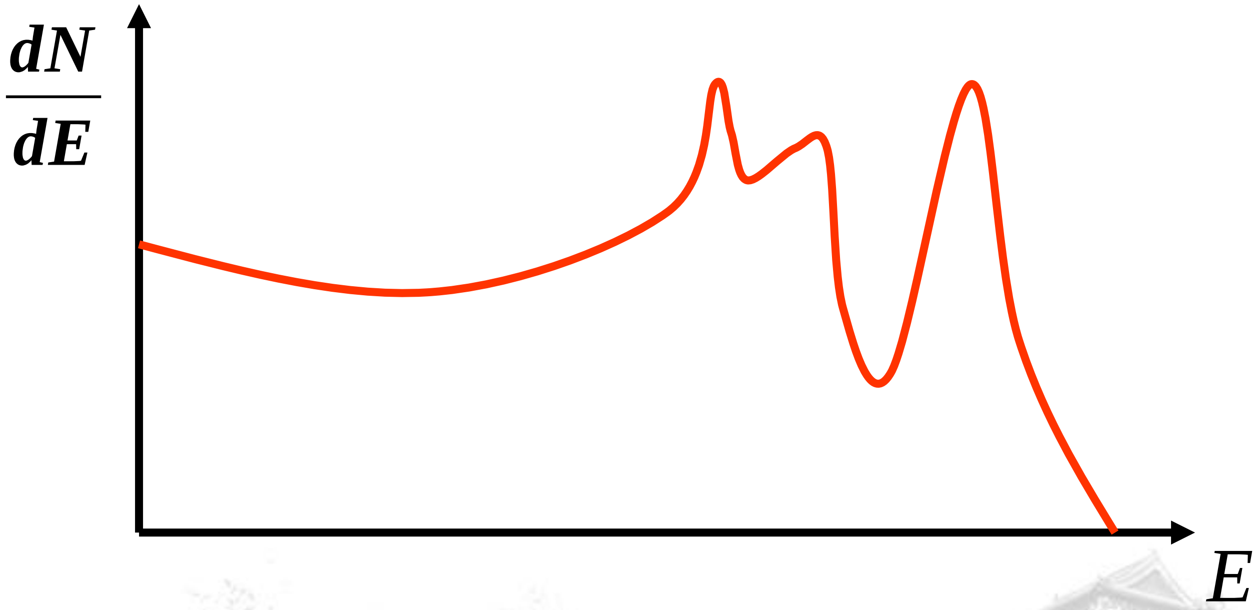
- High gain（10^5~10^6， as large as PMT）
- Low operating voltage （<100V）
- Low power consumption
- tiny volume
- high efficiency
- not sensitive for magnetic field
- easy to form large array

SCINTILLATION SPECTRAMETER OF SINGLE CRYSTAL

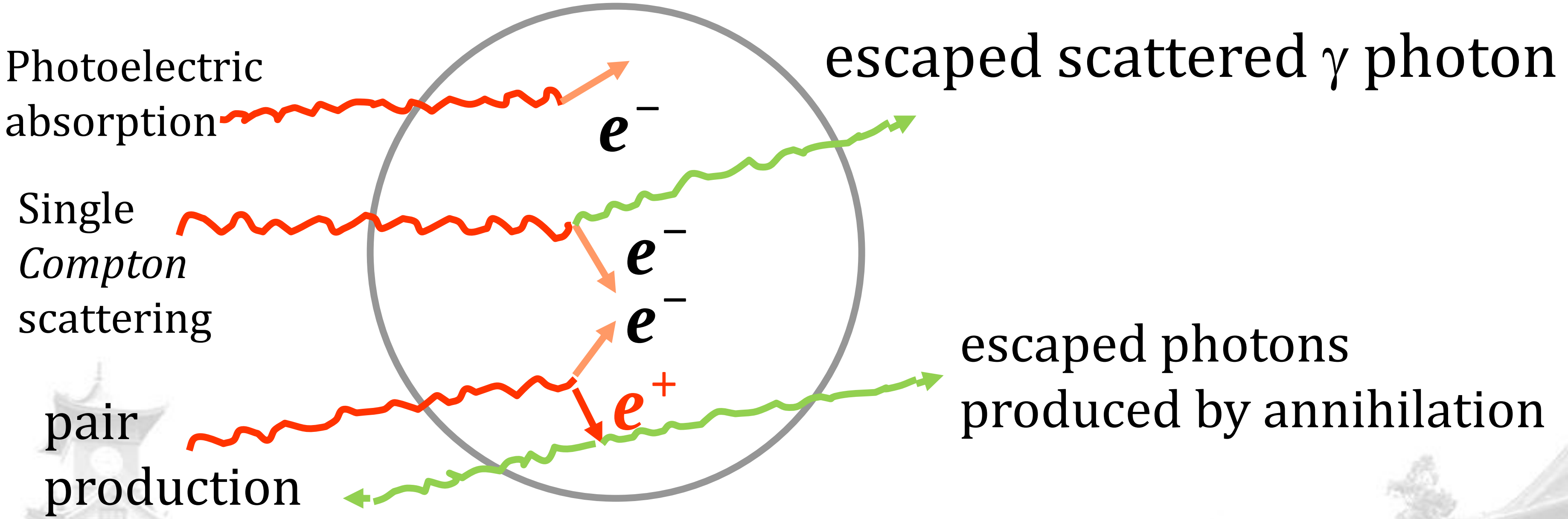
Configuration of Scintillation Spectrometer



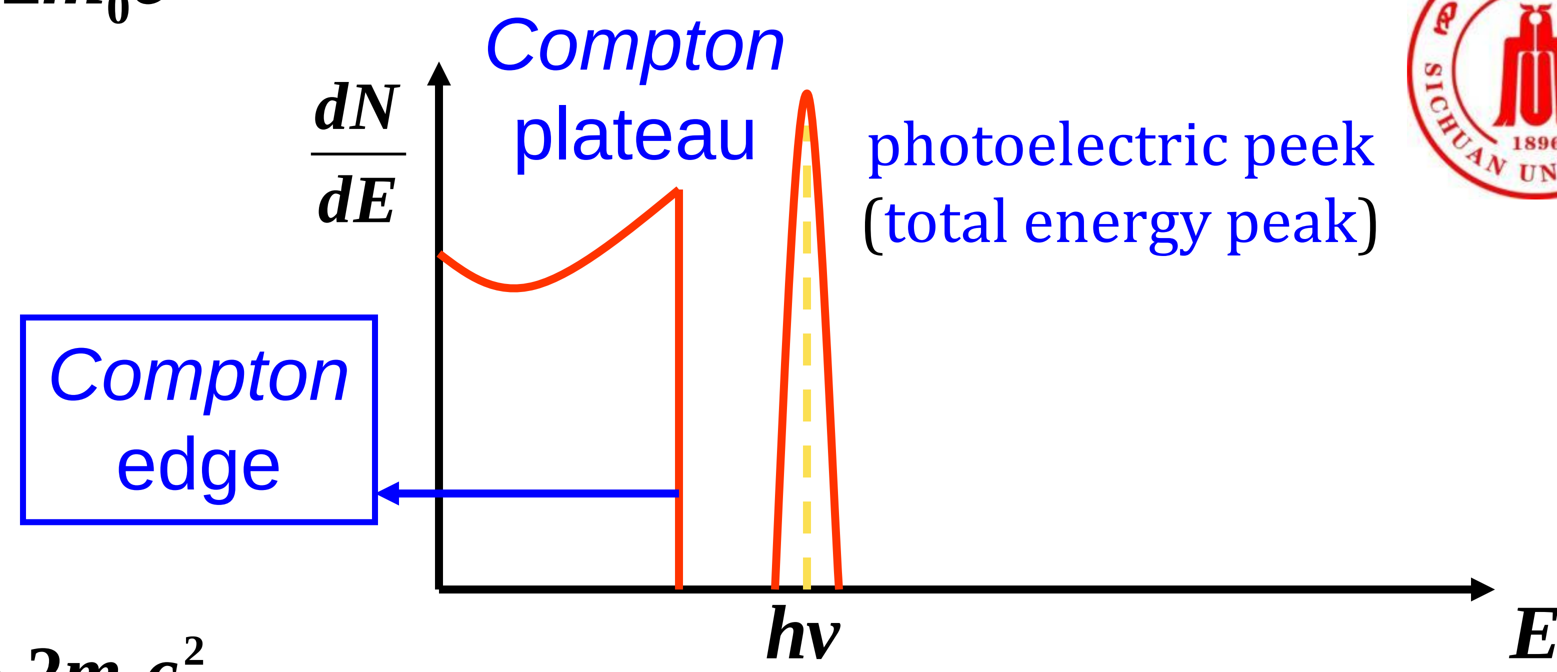
Pulse Amplitude Spectrum
Energy Spectrum



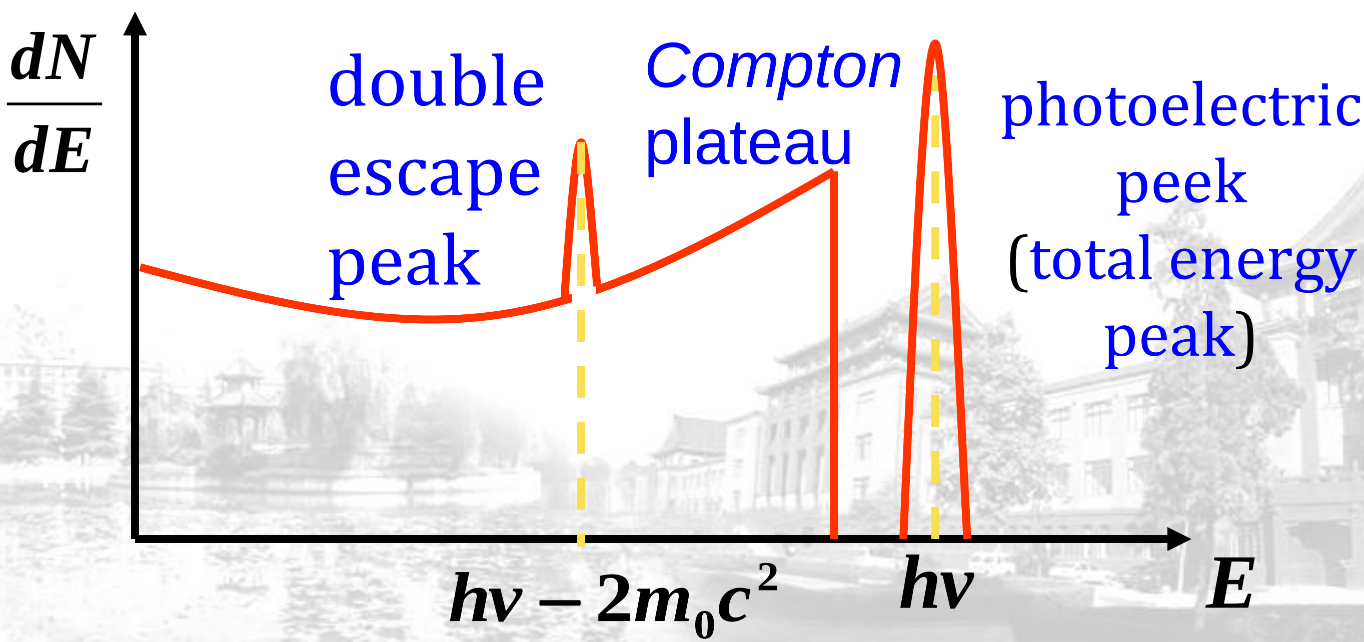
Small Size Crystal (<1cm)



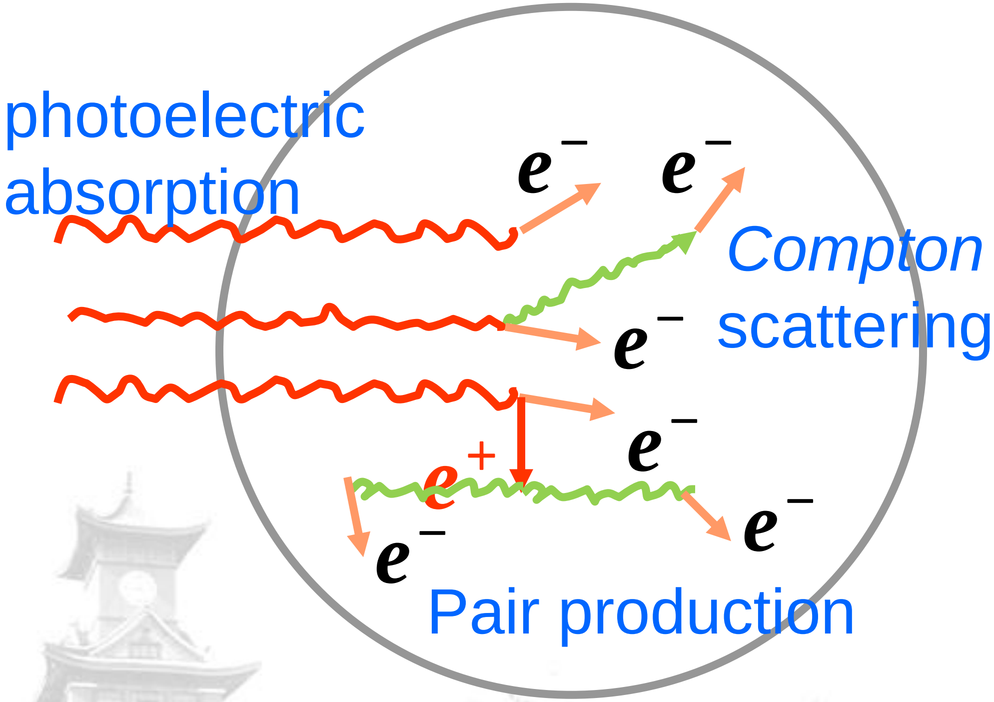
$h\nu < 2m_0c^2$

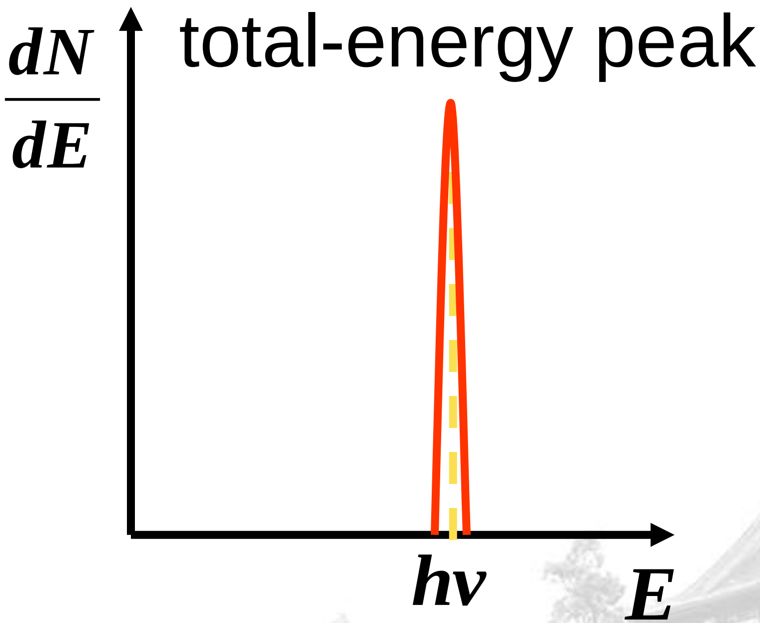


$h\nu >> 2m_0c^2$

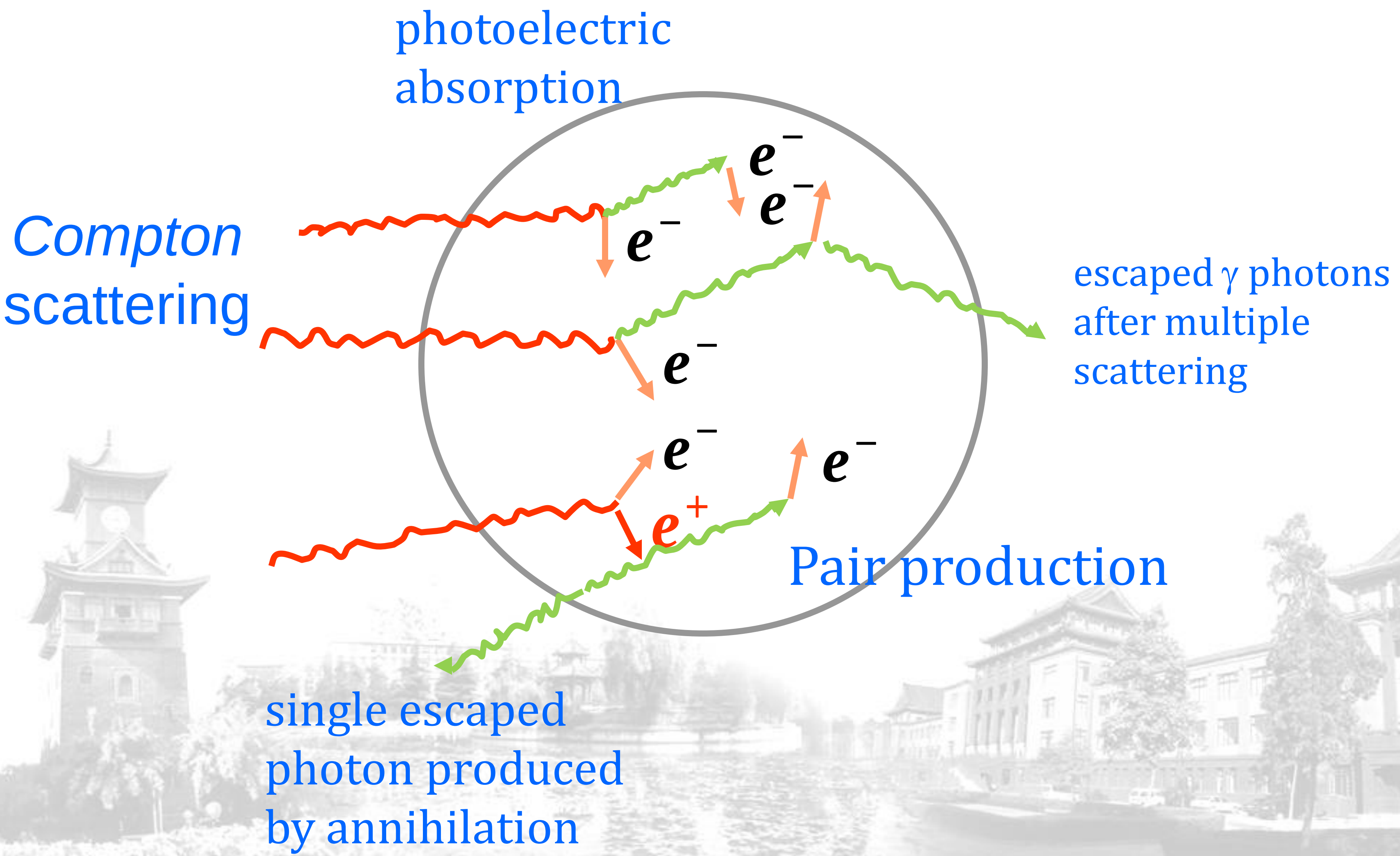


Infinite Size Crystal

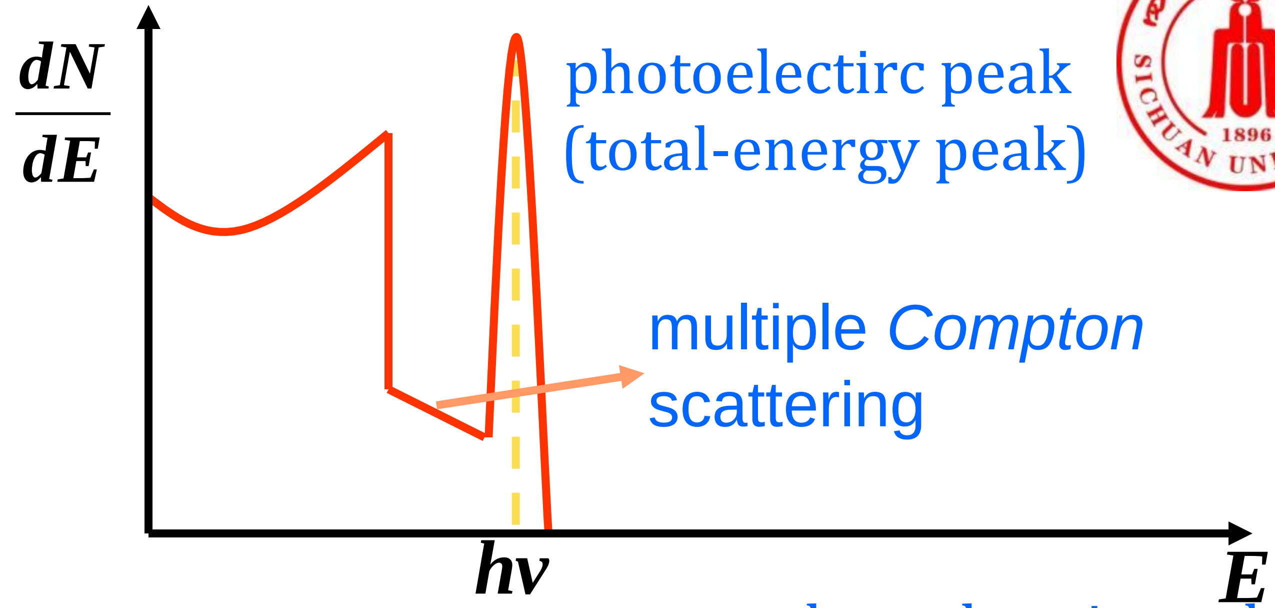




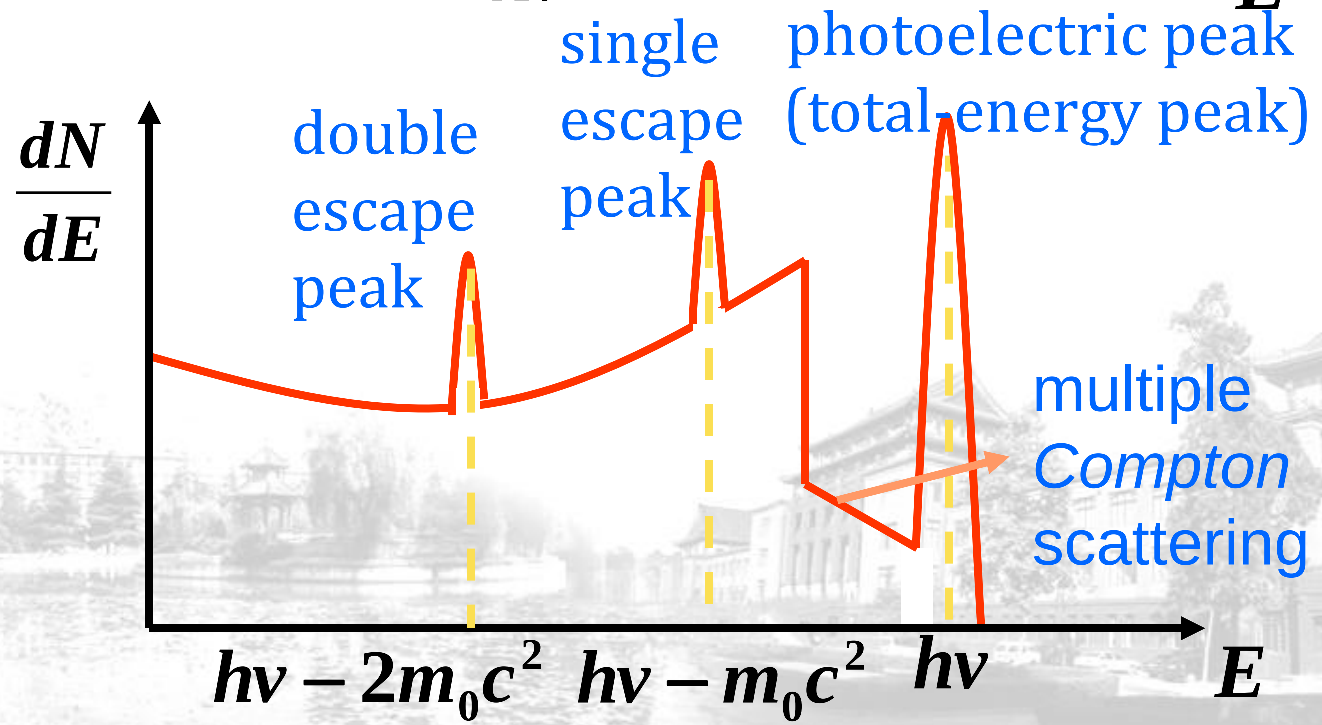
Middle Size Crystal

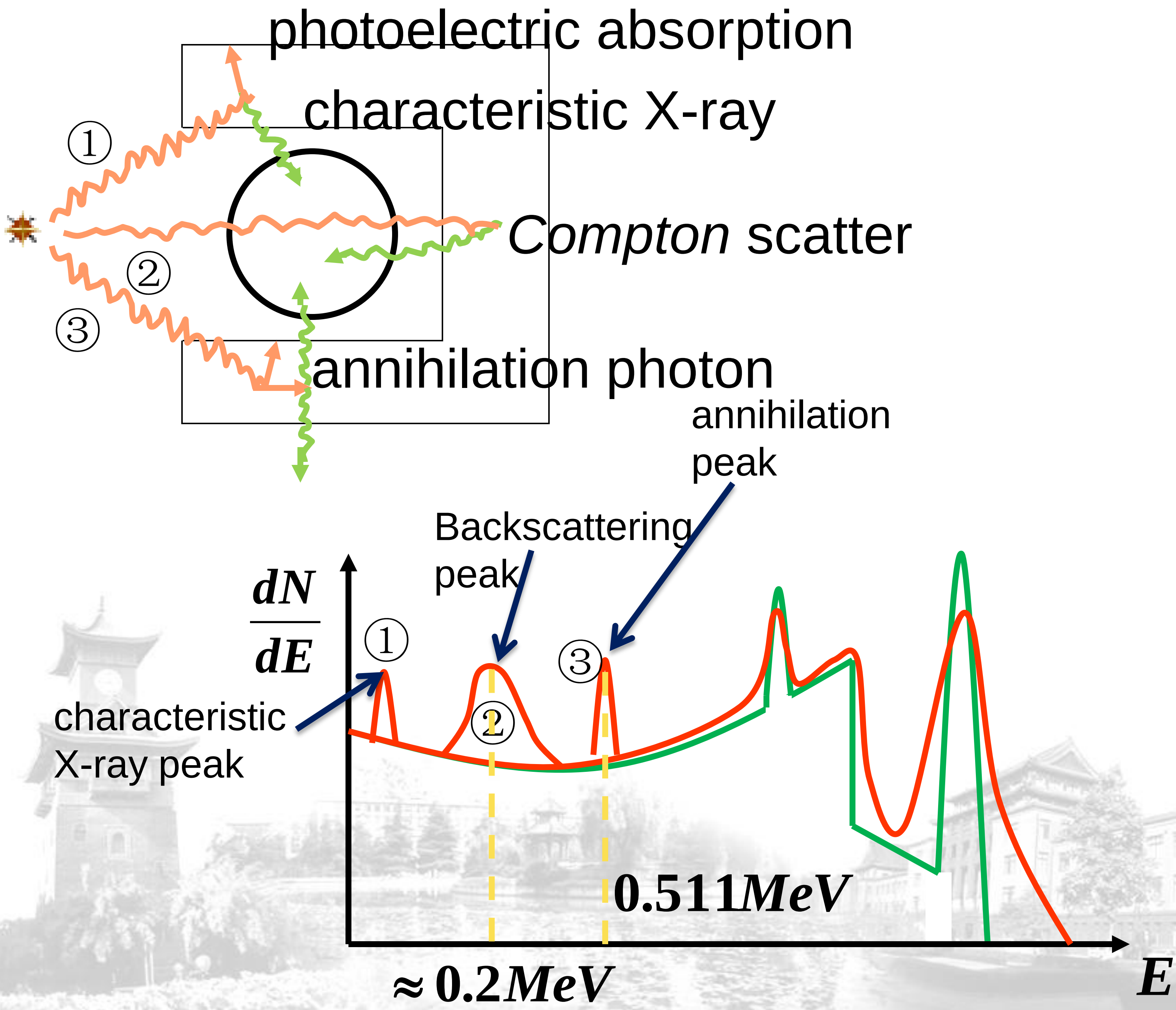


$h\nu < 2m_0c^2$

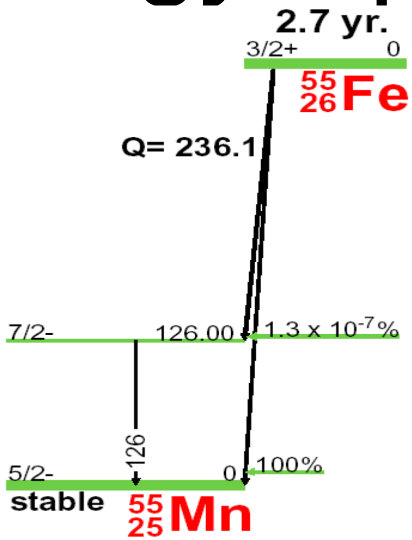


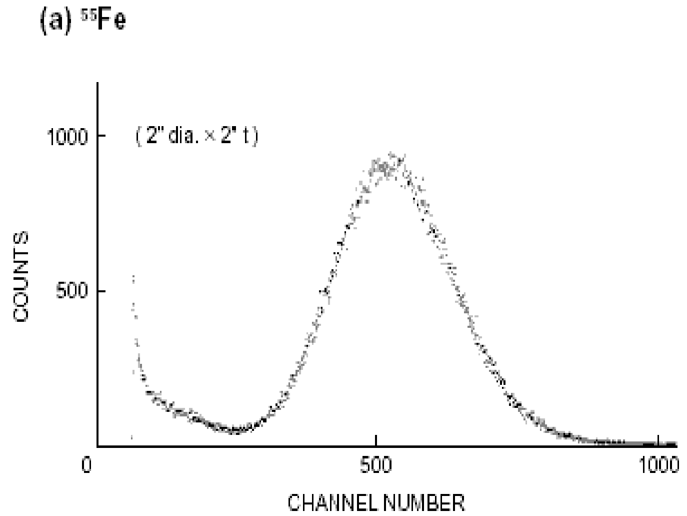
$h\nu >> 2m_0c^2$

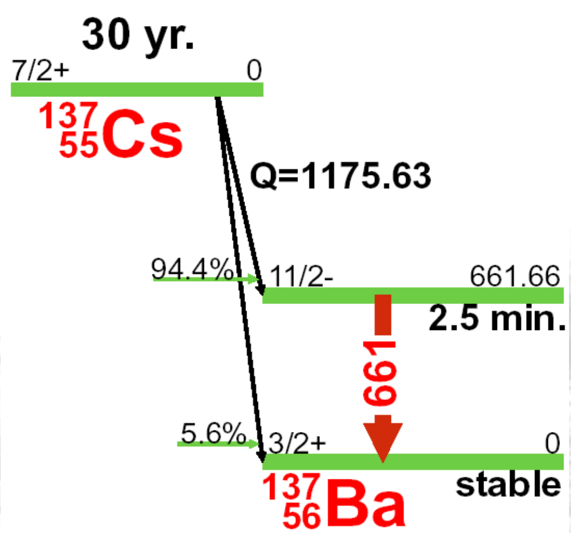


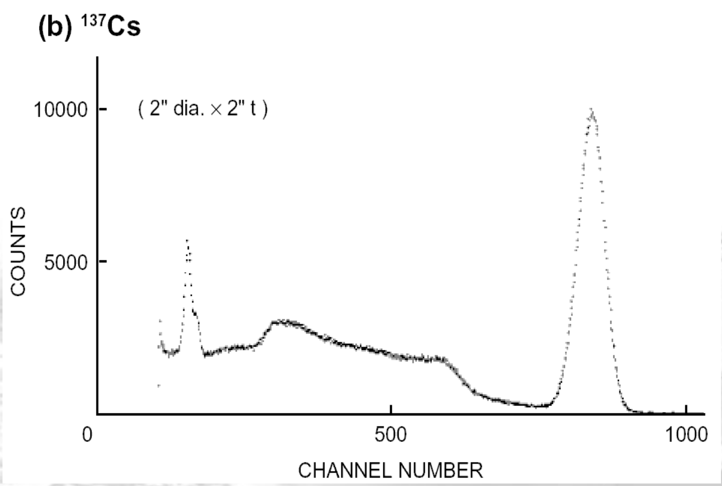

photoelectric absorption
characteristic X-ray
①
②
③
Compton scatter
annihilation photon
annihilation peak
Backscattering peak
$\frac{dN}{dE}$
①
③
②
characteristic X-ray peak
0.511MeV
≈0.2MeV
E

Example of Measured Energy Spectrum



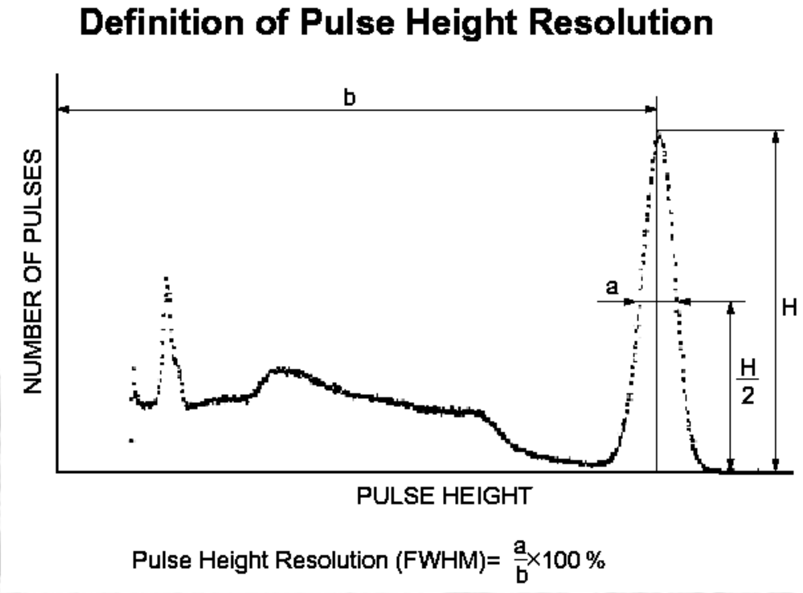






Performance of Scintillation Spectrometer

- Response Function
  - pulse amplitude spectrum of a certain monoenergetic γ ray
- Energy resolution



$$\eta = \frac{a}{b} \times 100\%$$

$$\eta = \frac{\Delta E}{E} = \frac{\Delta h}{h} = 2.36 v_h = 2.36 v_{n_A}$$

$$\eta = 2.36 \sqrt{\frac{1}{\overline{n}_e}\left[1 + \frac{\delta}{\delta_1} \cdot \left(\frac{1}{\delta - 1}\right)\right]}$$

photoelectrons'number collected by *D1 in one scintillation*

multiplication factor of D1

Let $\omega_s = \frac{E}{\overline{n}_e}$

$$\eta = 2.36 \sqrt{\frac{\omega_s}{E}\left[1 + \frac{\delta}{\delta_1}\left(\frac{1}{\delta - 1}\right)\right]}$$

Average energy needed to produce one photoelectron collected by D1。

Discussion

- $n_e = n_{ph} \cdot T$, $n_{ph}\uparrow \eta\downarrow$
- $\delta_1\uparrow$, $\eta\downarrow$
- The stability of H.V.
- Channel width

$$M = aV_0^{b \cdot n}$$

$$b \cdot n \approx 7$$

$$\frac{\Delta M}{M} = 7\frac{\Delta V_0}{V_0}$$

$$\eta' = \eta\left[1 + 0.28\left(\frac{\Delta}{\Delta h}\right)^2\right]$$

channel width

FWHM

Performance of Scintillation Spectrometer

- Energy linearity

$$E = G \times Ch + E_0$$

  - light yield varies with energy of electron.
- Detection efficiency
  - size(thickness) and Z,ρ of crystal
- Resolving time
  - RC constant of output circuit and decay time of crystal
- Time lag and Time resolution
  - electron transit time and its dispersing
- Stability
  - determined by PMT's stability

Homework

- 1,2,3,4,5,6,8,9,10