IAEA
International Atomic Energy Agency

Joint ICTP-IAEA School on LoRa Enabled Radiation and Environmental Monitoring Sensors

ICTP

Characterization of Radiation Sensors

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What can we measure ?

- A hit
  - The amount of energy in the hit
  - When the hit occurred
  - Perhaps
    - Where the hit occurred
    - If many hits occurred

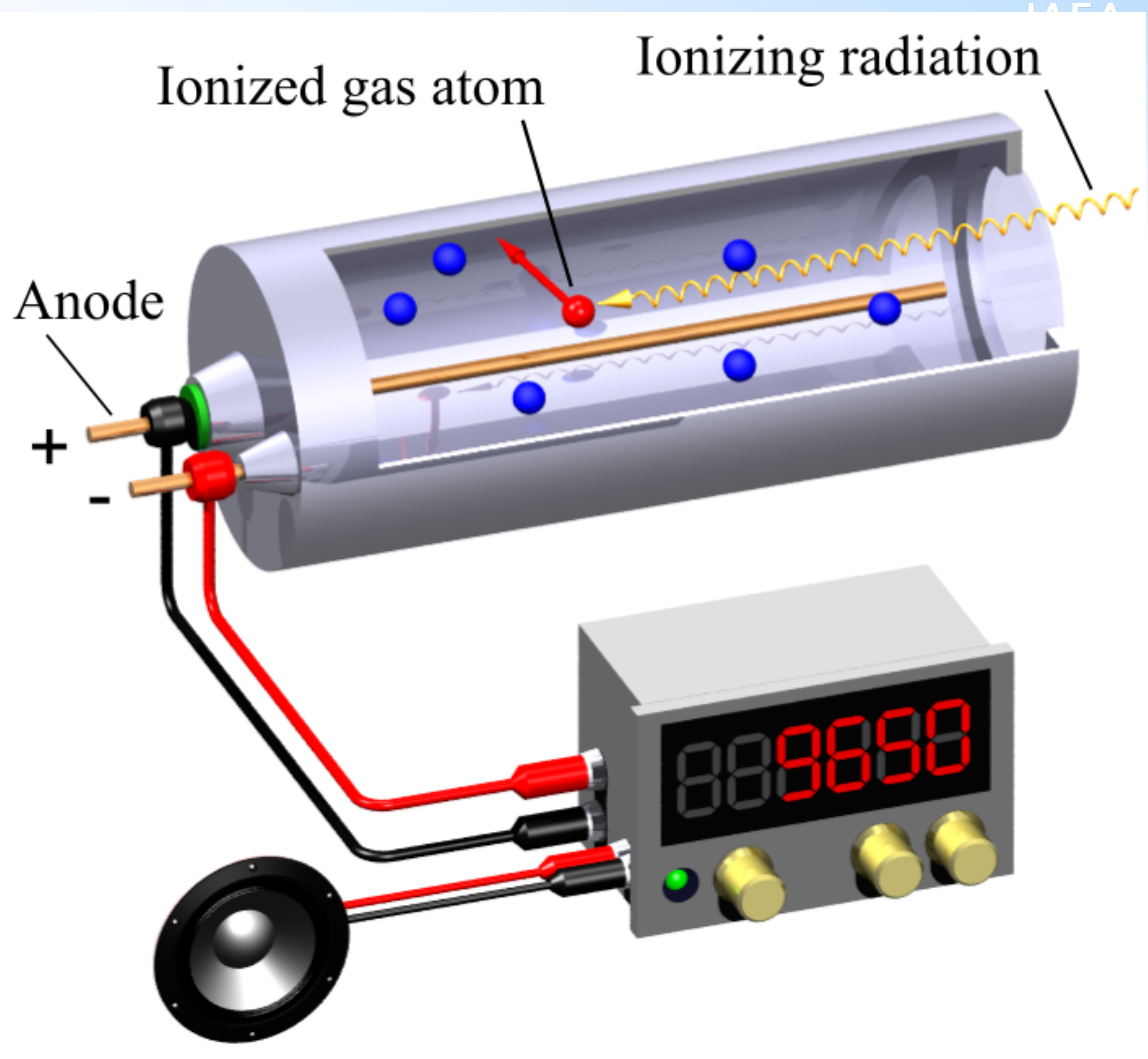
Put simply - ENERGY & TIME *… that's all folks!*

Counting system

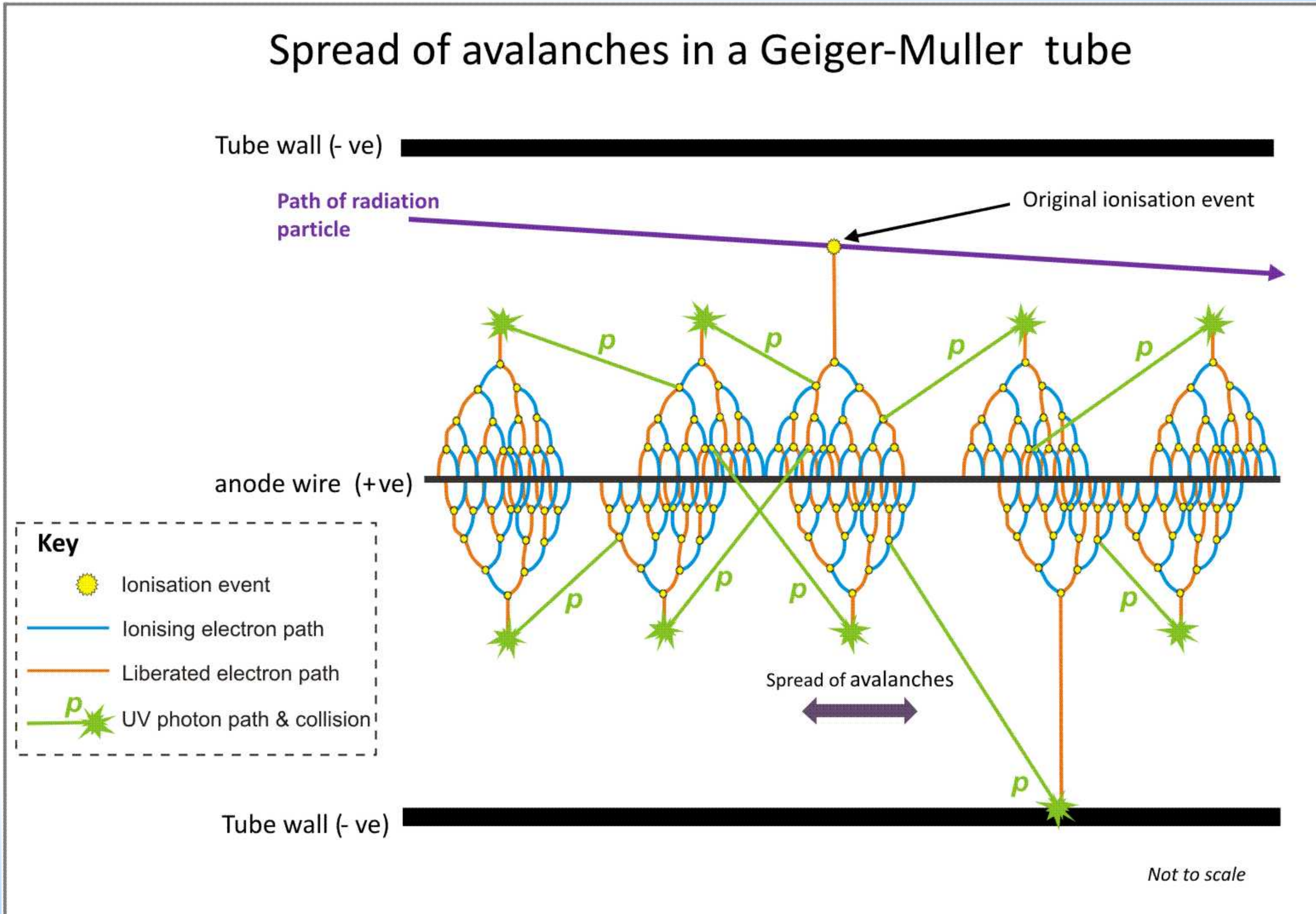
example Geiger Muller Tube

Geiger Muller

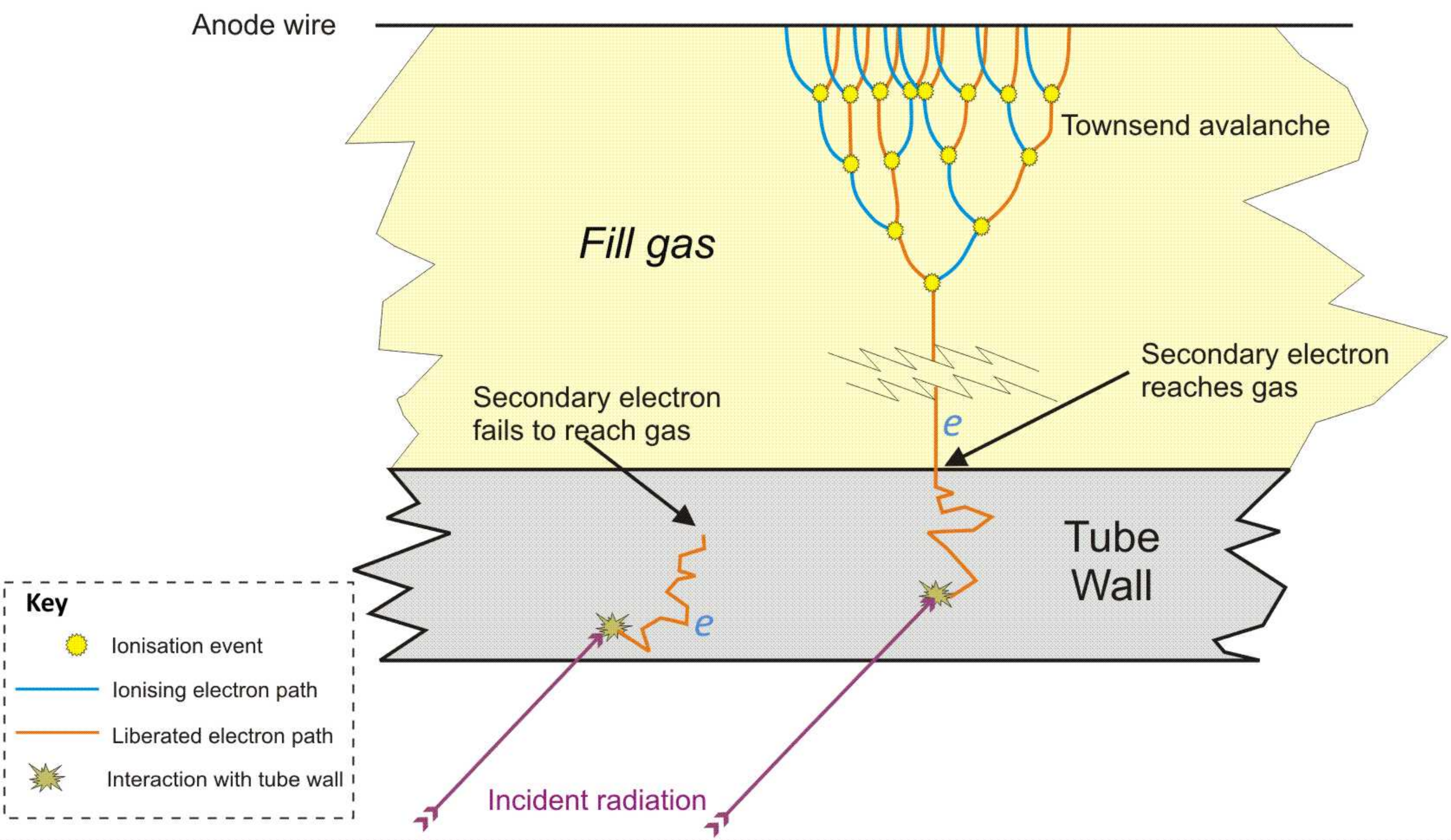
Geiger Muller



Geiger Muller



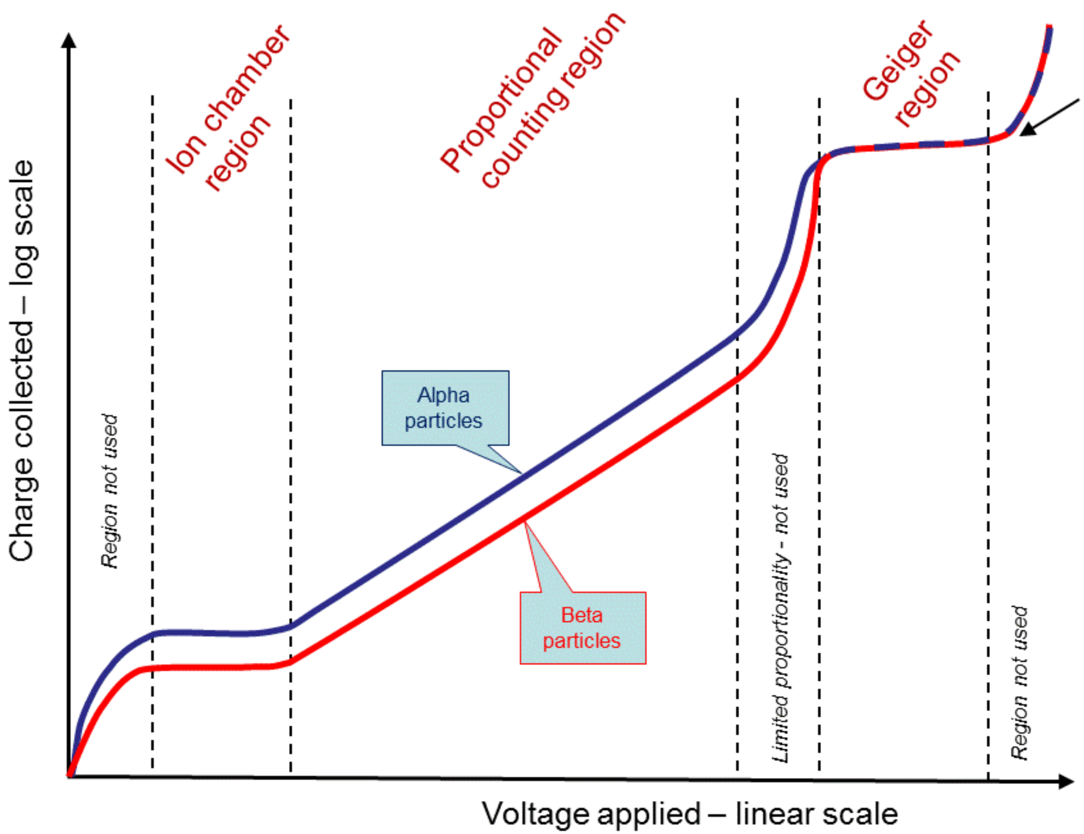
Interaction of gamma radiation with G-M tube wall



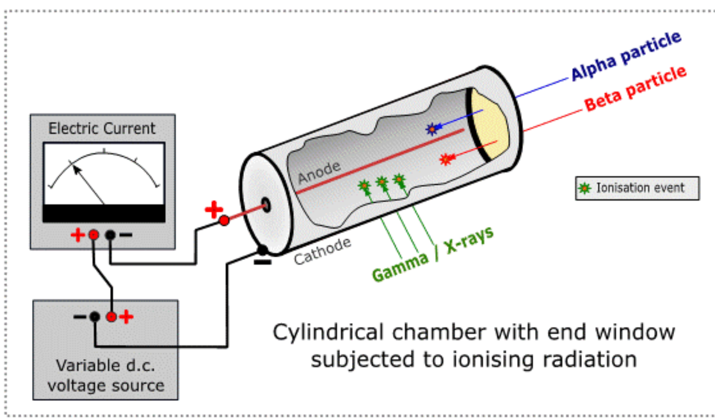
Practical Gaseous Ionisation Detection Regions

This diagram shows the relationship of the gaseous detection regions, using an experimental concept of applying a varying voltage to a cylindrical chamber which is subjected to ionising radiation. Alpha and beta particles are plotted to demonstrate the effect of different ionising energies, but the same principle extends to all forms of ionising radiation.
The ion chamber and proportional regions can operate at atmospheric pressure, and their output varies with radiation energy. However, in practice the Geiger region is operated at a reduced pressure (about 1/10th of an atmosphere) to allow operation at much lower voltages; otherwise impractically high voltages would be required. The Geiger region output does not differentiate between radiation energies.

Variation of ion pair charge with applied voltage



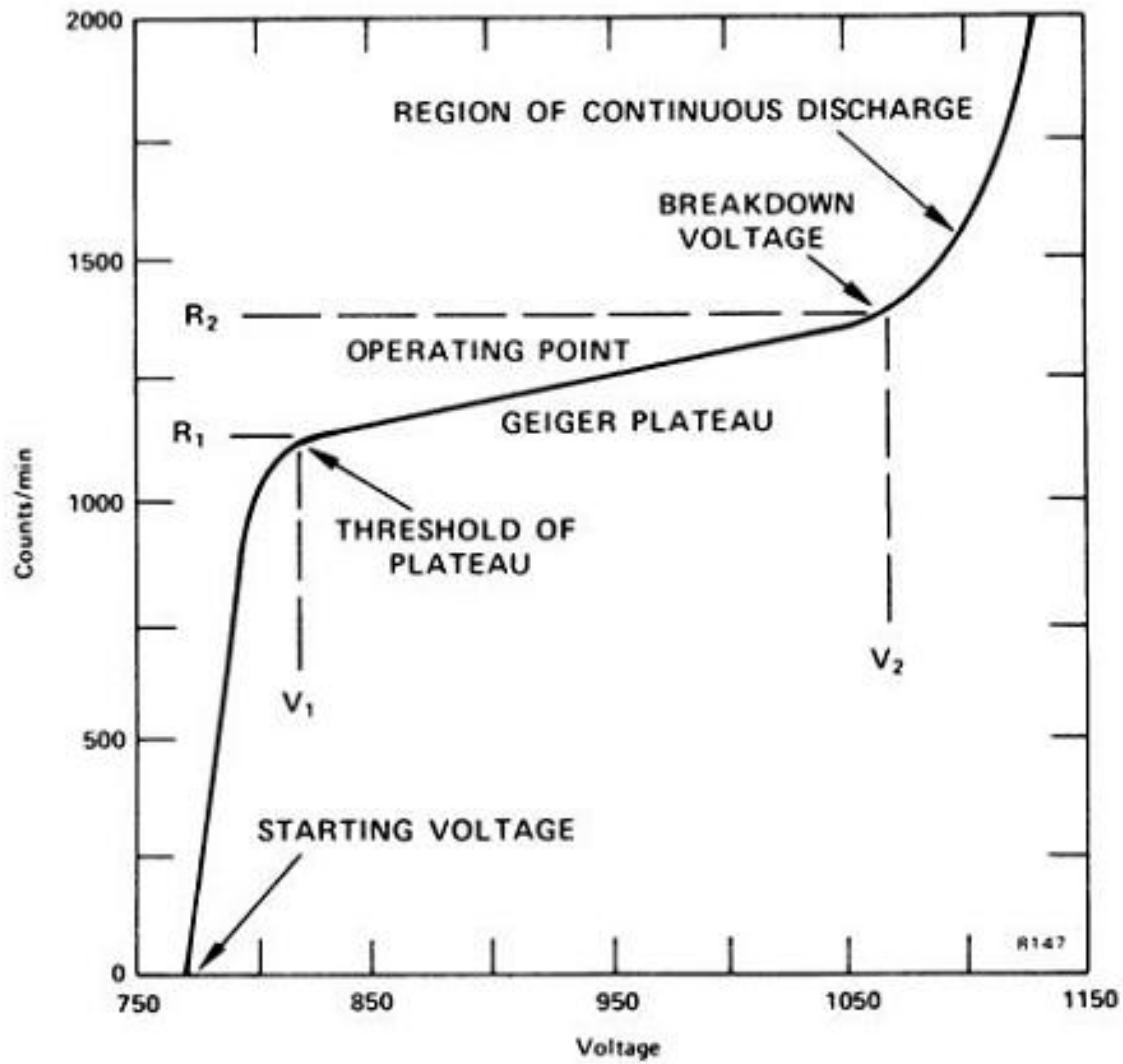
Experimental set-up of a cylindrical chamber



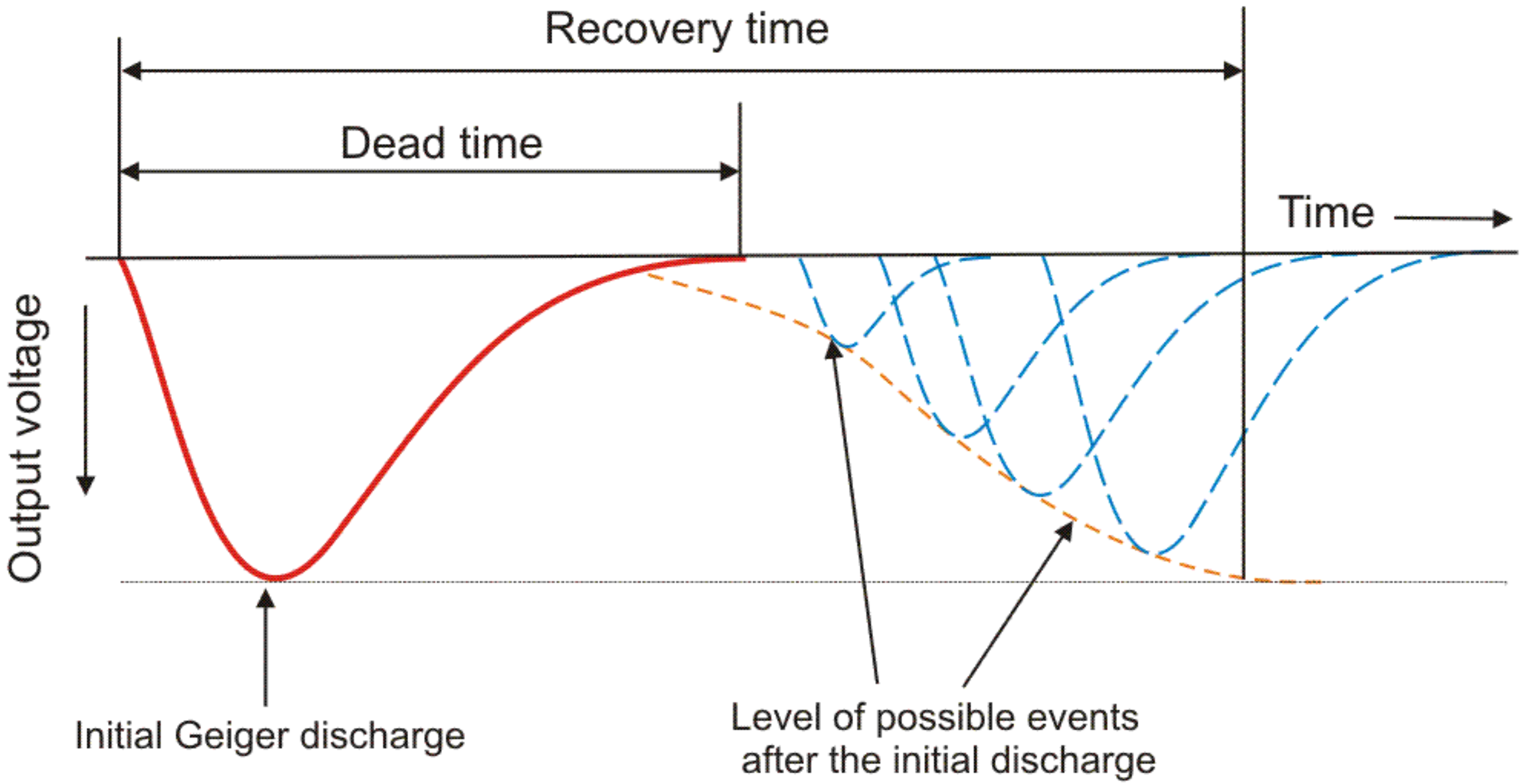
Low-penetrating radiation enters via an end window, but high-penetrating radiation can also enter via the cylinder side wall.

DS

Geiger Muller



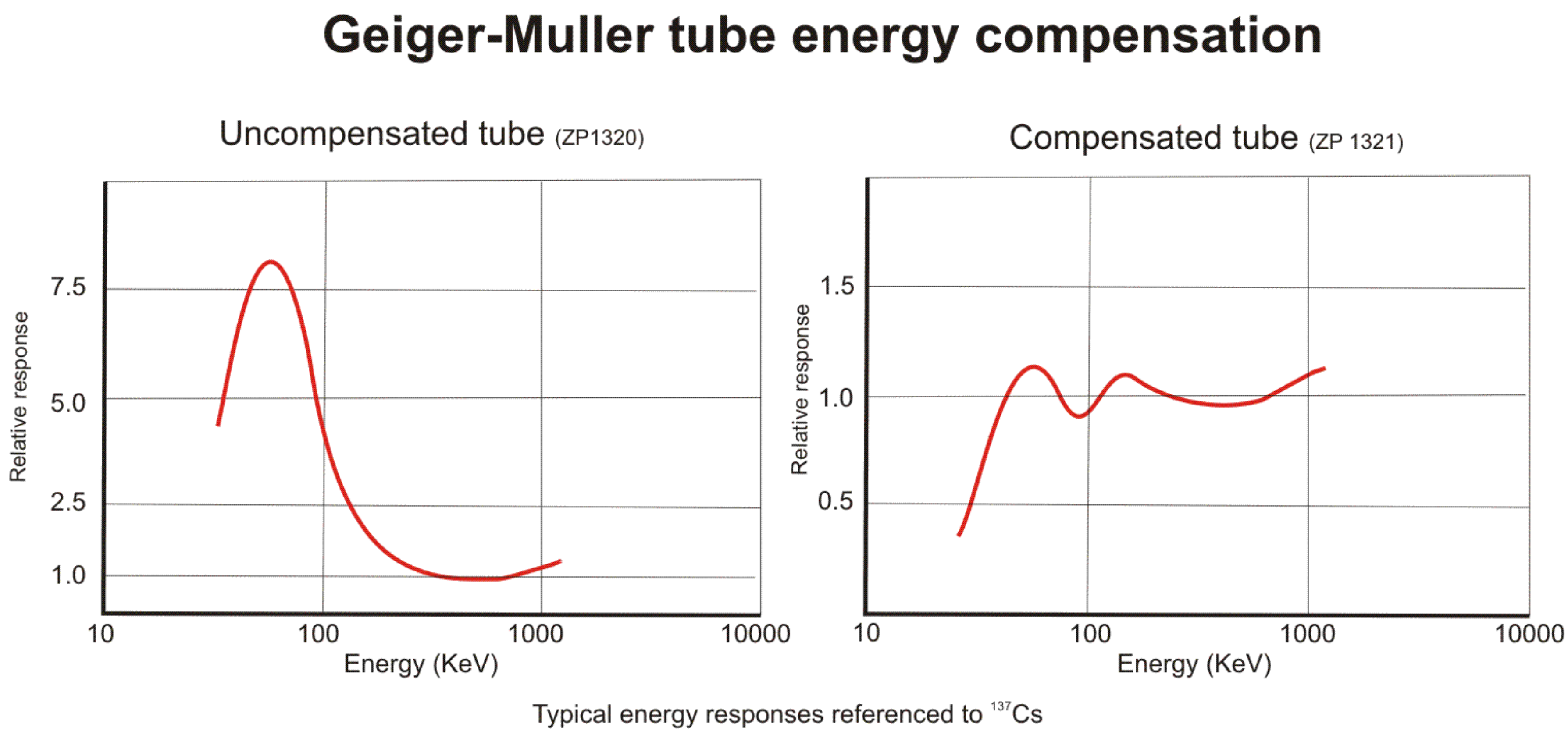
Dead time of a Geiger-Muller tube



Geiger Muller

Geiger Muller

Geiger Muller



Spectrometer - “Energy Measurement”

Scintillator

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THE UNIVERSITY of LIVERPOOL

Basic interaction processes in crystals:

(X-ray / γ radiation)

- Photoelectric effect

 => Total absorption of γ-ray

- Compton effect

=> photon energy partly absorbed

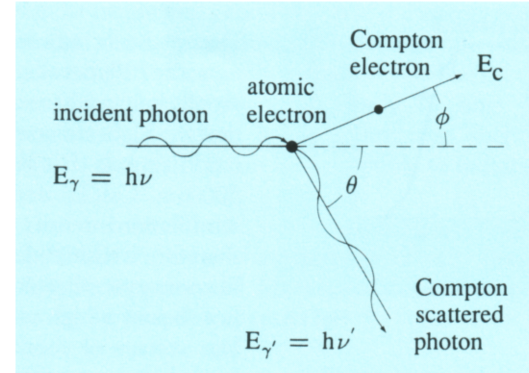
- pair production ($E \geq 1.02$ MeV)

$$E_{\gamma'} = \frac{E_\gamma}{1 + \alpha(1 - \cos\theta)}$$

with

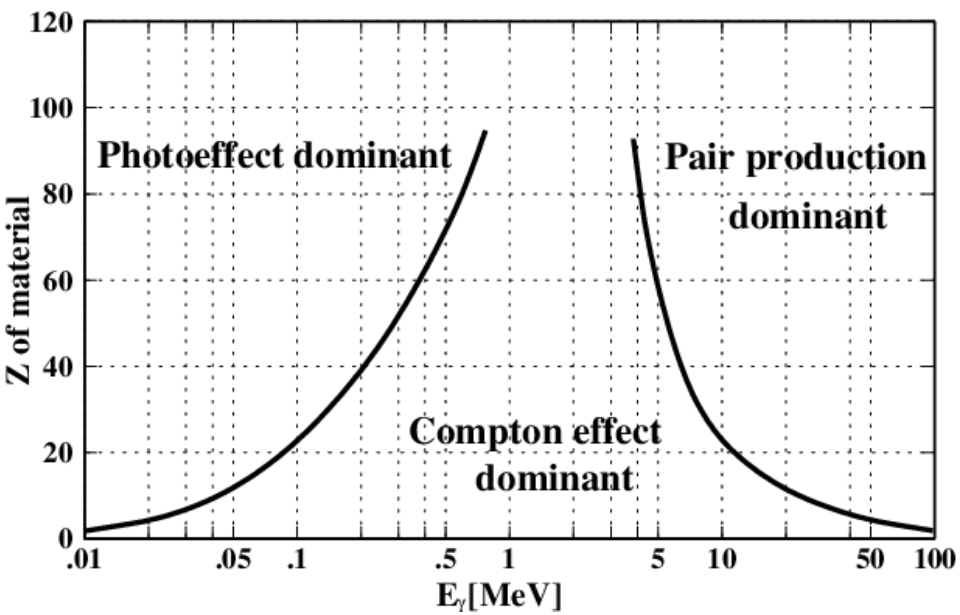
$\alpha = E_\gamma / 0.511$

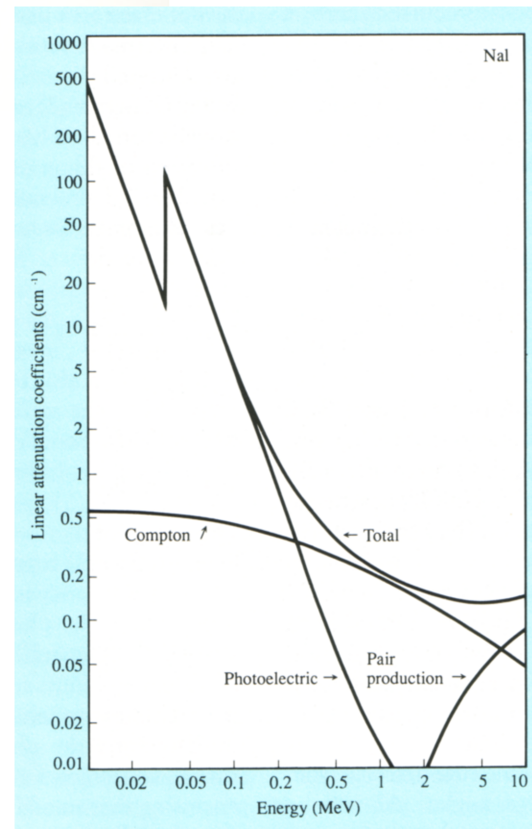
and E_γ and $E_{\gamma'}$ in MeV.



$$E_c(\max) = \frac{E_\gamma}{1 + 0.511/2E_\gamma} \text{ MeV.}$$

Relative importance effects dependent on Z of material (crystal)





<u>Various processes</u> in scintillation detectors

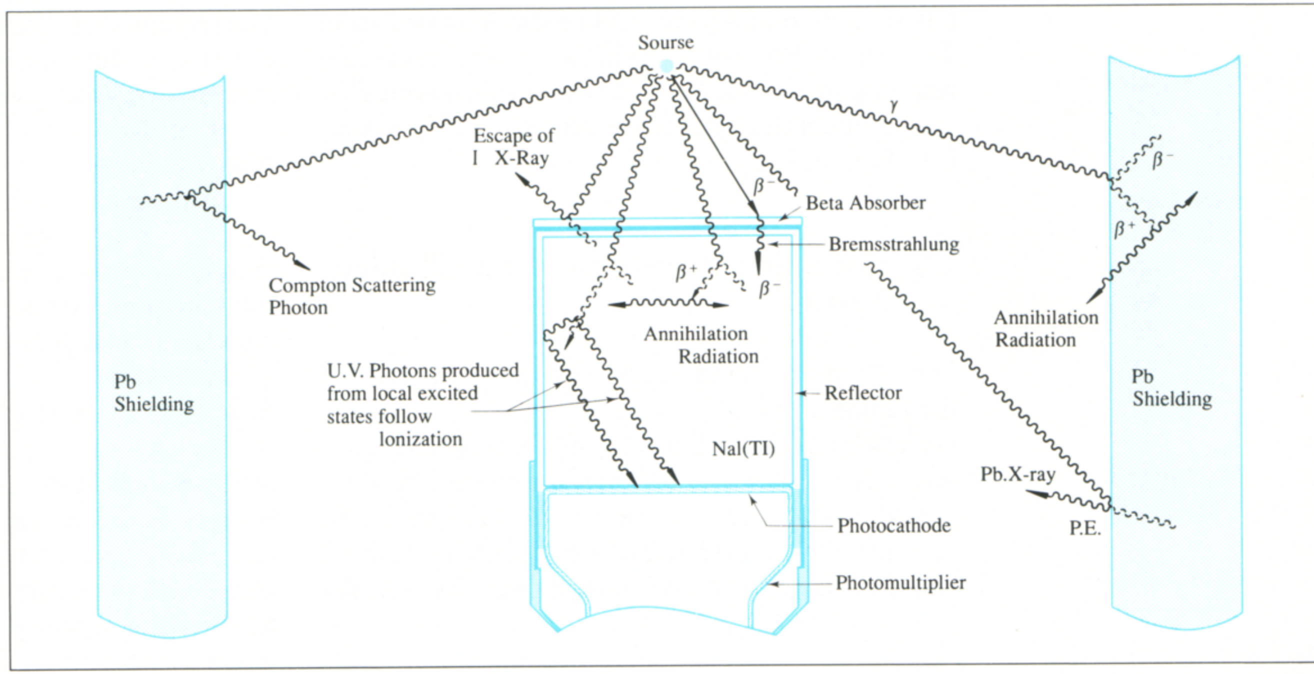
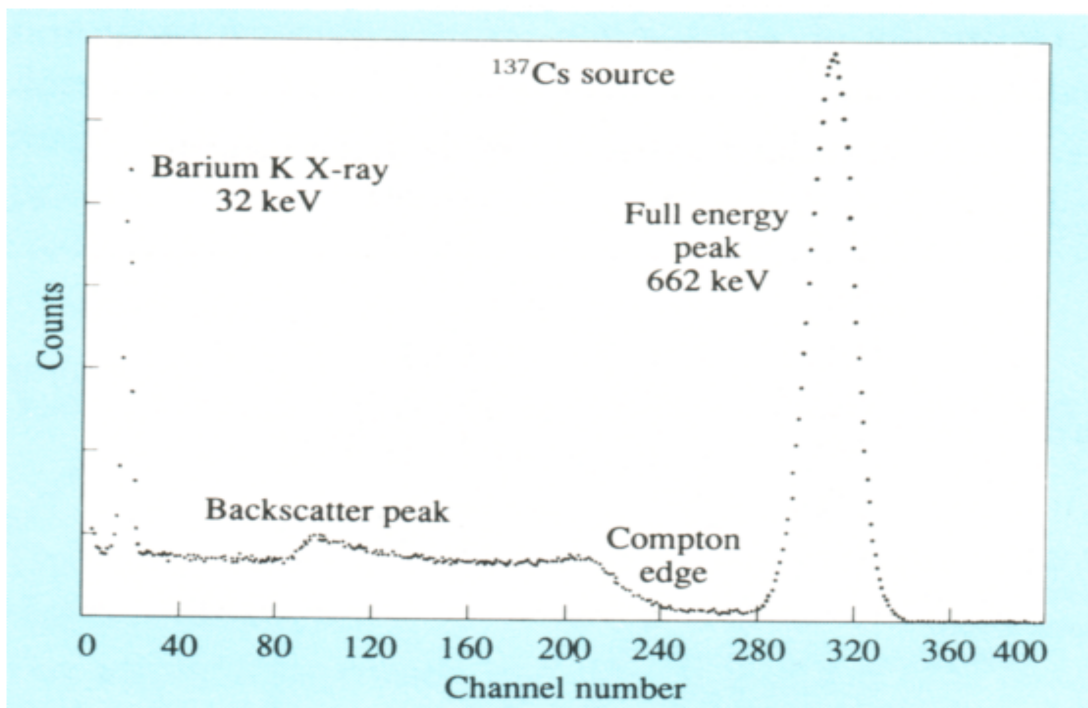
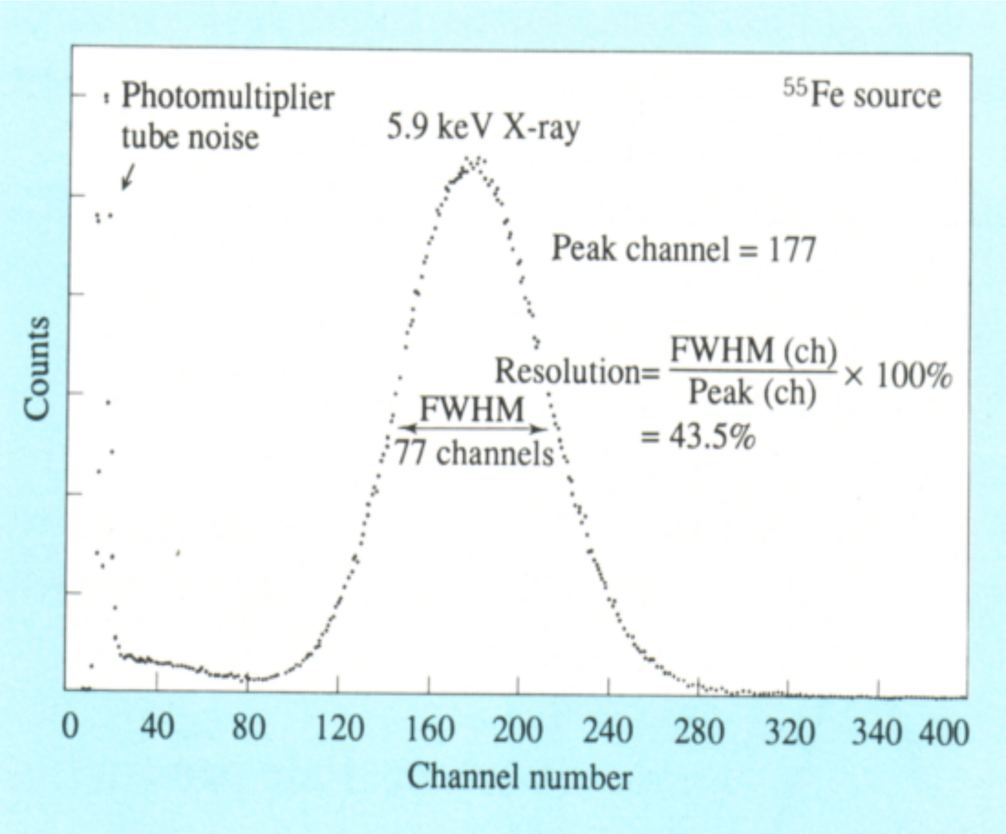


Fig. 1.6.

<u>Pulse height spectrometry:</u>

Typical pulse height spectrum from scintillation crystal.





Energy resolution:

the number of channels between the two points at half the maximum intensity of the photopeak, divided by the channel number of the peak mid-point, multiplied by 100%.

Influenced by:

1. Intrinsic effective line width (non proportionality)
2. Photoelectron statistics
3. Light collection uniformity + PMT effects

$$\left(\frac{\Delta E}{E}\right)^2 = \underbrace{\left(\frac{\Delta E}{E}\right)^2_{sci,\ intr}}_{1} + \underbrace{\left(\frac{\Delta E}{E}\right)^2_{stat,\ N}}_{2} + \underbrace{\left(\frac{\Delta E}{E}\right)^2_{PMT,\ sci}}_{3}$$

For low energies (e.g. 140 keV), contribution 2 and 3 most important.

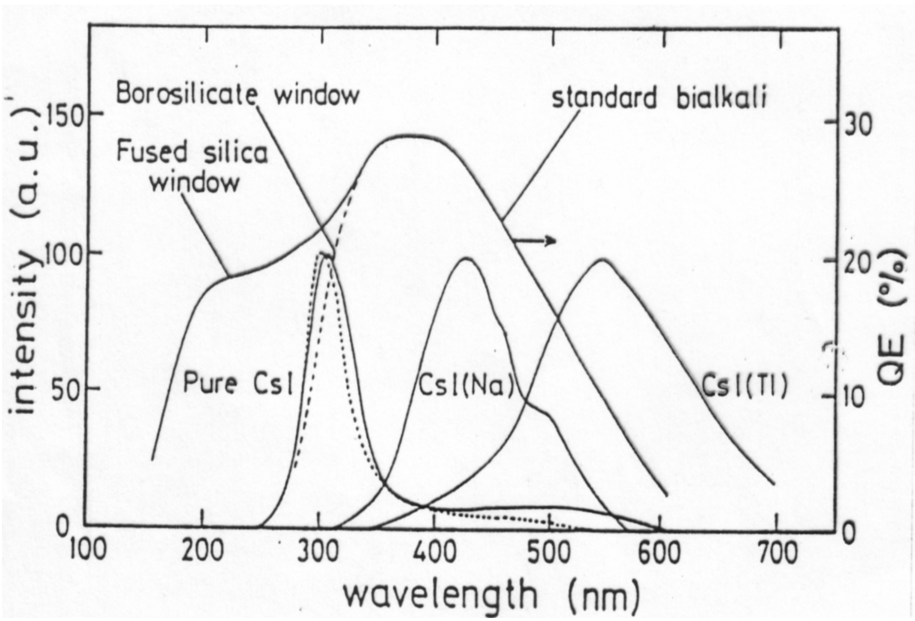
Physical Properties
of the most
Common Scintillation Materials

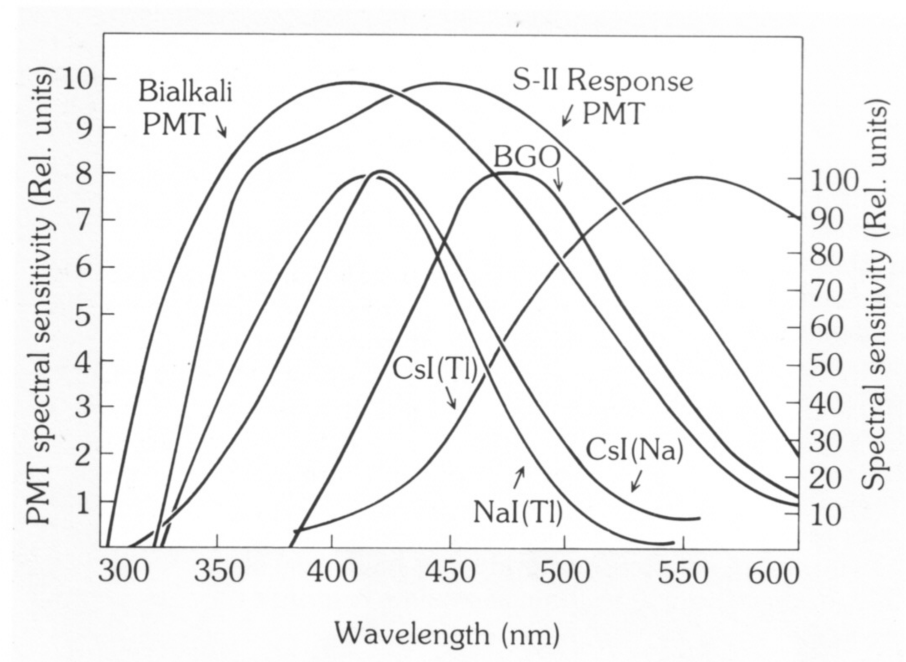
Material	Density [g/cm³]	Emission Maximum [nm]	Decay Constant (1)	Refractive Index (2)	Conversion Efficiency (3)	Hygroscopic
NaI(TI)	3.67	415	0.23μs	1.85	100	yes
CsI(TI)	4.51	550	0.6/3.4 μs	1.79	45	no
CsI(Na)	4.51	420	0.63 μs	1.84	85	slightly
CsI(undoped)	4.51	315	16 ns	1.95	4 - 6	no
CaF_2(Eu)	3.18	435	0.84 μs	1.47	50	no
^{6}Li - glass	2.6	390/430	60 ns	1.56	4 -6	no
^{6}LiI(Eu)	**4.08**	**470**	**1.4 μs**	**1.96**	**35**	**yes**
CsF	4064	390	3 - 5 ns	1.48	5 -7	yes
BaF_2	4.88	315 220	0.63 μs 0.8 ns	1.50 1.54	16 5	no
YAP(Ce)	5.55	350	27 ns	1.94	35 - 40	no
GSO(Ce)	6.71	440	30 - 60 ns	1.85	20 - 25	no
BGO	7.13	480	0.3 μs	2.15	15 - 20	no
$CdWO_4$	7.90	470/540	20/5 μs	2.3	25 - 30	no
$PbWO_4$	8.28	420	7 ns	2.16	0.10	no
Plastics	1.03	375/600	1 -3 ns	1.58	25 - 30	no

(1) Effective average decay time for γ-rays.
(2) At the wavelength of the emission maximum.
(3) Relative scintillation signal at room temperature for γ-rays when coupled to a Photomultiplier Tube with a Bi-Alkali Photocathode

Important characteristics of scintillators

- Density and Atomic number (Z)
- Light output intensity and wavelength
- Decay time (duration of light pulse)
- Mechanical and optical properties
- Cost





Often broad emission bands (mechanism)

Fig. I.1. NaI(Tl), CsI(Tl) and CsI(Na) and BGO emission spectra. The emission curves have been normalized to 100% for illustrative purposes. Harshaw/Filtrol Research Laboratory Report.

Some principles and criteria :

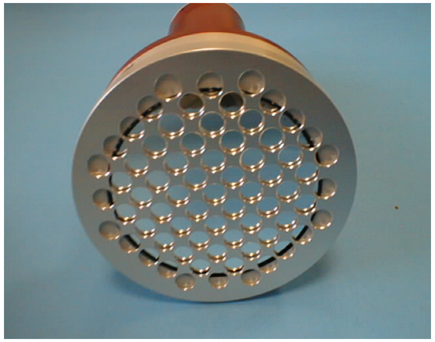
Photon detection :

Density (mass) to allow certain efficiency

1. Spectroscopy requires photo-electric effect (higher Z)
2. Dynamic range in relation to decay time of scintillator : NaI(Tl) < 500 kHz

   YAP:Ce ~ 4 MHz

   Higher count rates problematic in counting mode → DC current mode



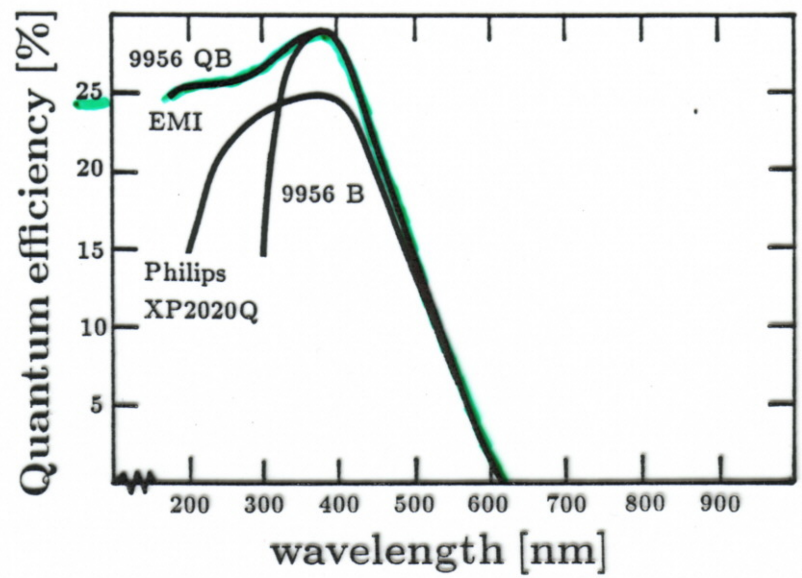
Particle detection (alphas/betas – heavy ions)

1. Optical window thickness ! (mylar windows required)
2. Total absorption of heavy ions will provide peaks
3. Energy per MeV less than for photons, scintillator dependent (0.1 - 0.95)

Detection of scintillation light:

A. 1. Photomultiplier Tubes

2. Semiconductor devices (photodiodes, APDs)



1. PMTs

Photoelectron production

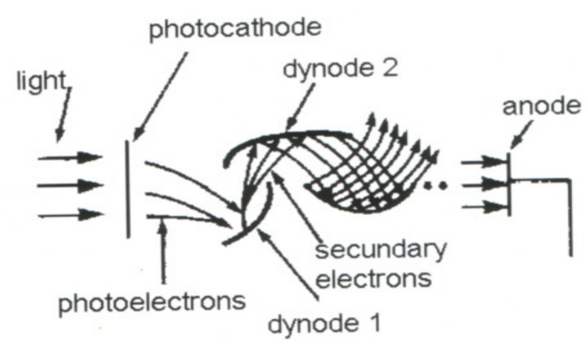
In thin photocathode layers

(e.g. Cs/Sb/K/Se)

+ electron mulitplication on

Structure of dynodes via secundary emission.

(Dynodes CuBe or Cs/Sb)



Focussing of electrons very important.

- venetian blind (standard)
- linear focuses (fast)
- circular cage (inexpensive)
- teacup (good PHR)
- box-and-grid (simple)
- proximity mesh (magnetic immunity)

Choice depends on application.

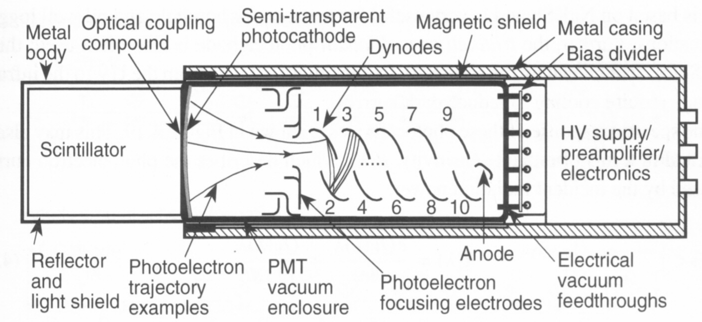
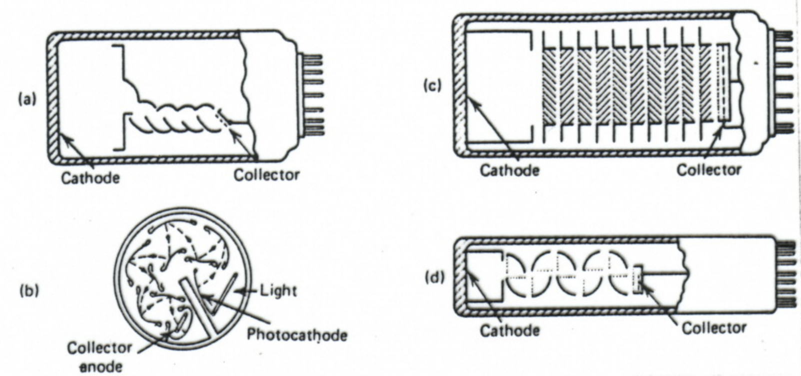


Figure 4.20 Schematic representation of a complete scintillation detector comprising a scintillator, a head-on photomultiplier tube, a bias divider for the dynode voltages and an electronics unit with preamplifier and possibly a high-voltage supply



Temperature drifts of PMTs

Gain drift of order 0.2% per degree K.

Gain of a PMT not 100 % reproducible

Max. gain or order 10^6

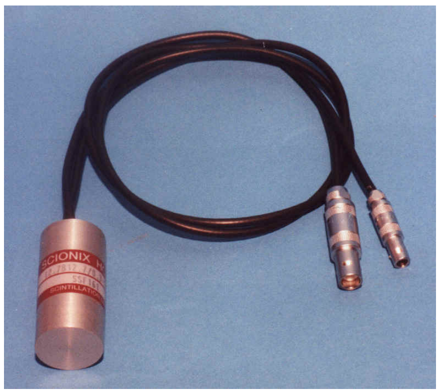
Table 2.1. Properties of different photomultiplier structures

Type of structure	size smallest volume	gain maximum overall	timing fastest	linearity highest pulsed current	magnetic immunity best
Venetian blind	3	2	3	3	3
Circular cage	1	4	2	2	1
Box and grid	2	3	4	4	2
Linear focussed	4	1	1	1	4

Note: the numbers indicate the order of preference for a certain application; 1 = best, 4 = worst.

Advantages of PMTs:

- **high gain => large signal**
- **standard devices**
- **fast reponse**



Disadvantages of PMTs:

•fragile & bulky / recently: - low profile

- miniature

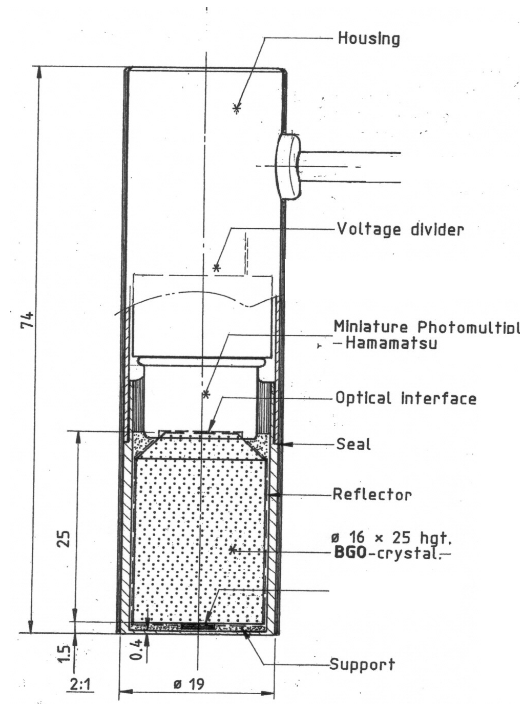
•high voltage reguired (kVs) / recent developm. I integrated HV.suppl.

• magnetic field sensitive

• 40K backgroud from glass

• gain drifts

•Only sensitive < 600 nm

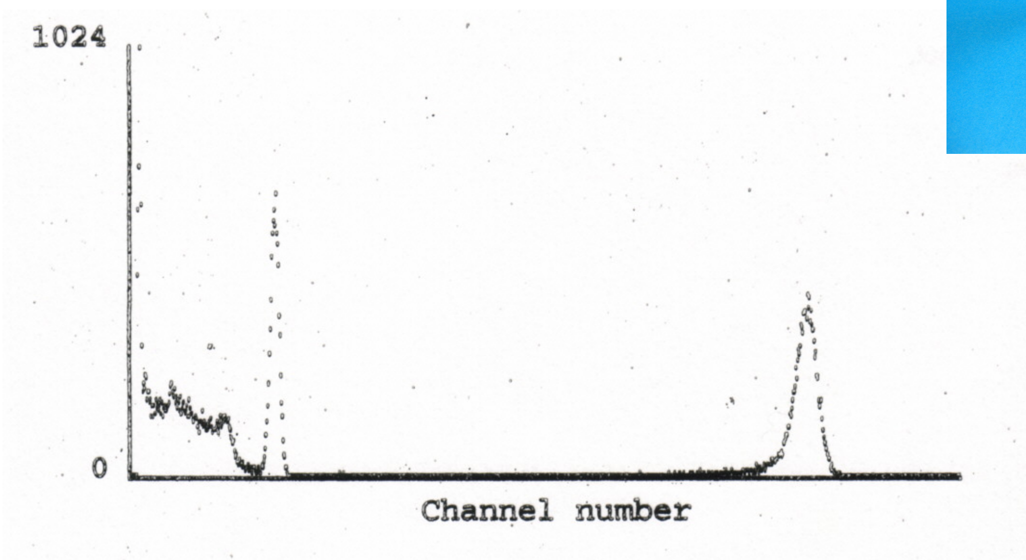


Detector gain drift due to temperature effects :

- Crystal
- light detection device

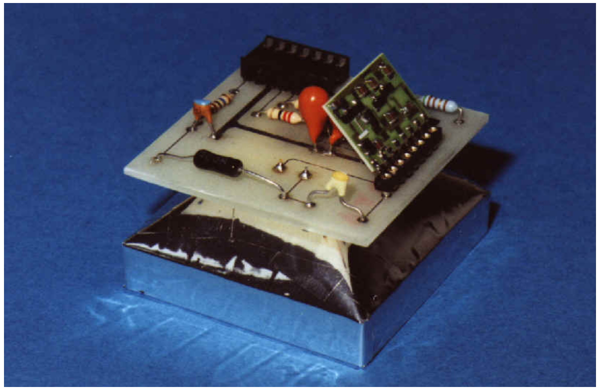
Stabilisation:

- Radioactive pulsers (Alpha emitters)
- LED pulsers
- hardware stabilisation on peak
- software stabilisation on peak



Detector with 241-Am source providing a peak at 3.2 MeV

SEMICONDUCTOR DETECTORS



- PIN photodiodes (standard)
- Avalanche photodiodes (new in large areas)
- Drift photodiodes (getting better and larger)
- Silicon PMTs

All above devices:

compact, rugged and insensitive to magnetic fields

Si High quantum efficiency in 500 nm area

Overlaps well with emission CsI(TI), CdWO4.

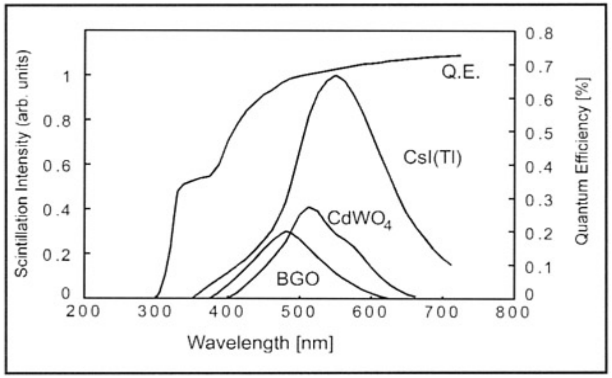


Fig. 4.3 Quantum efficiency curve of a silicon photodiode together with the emission spectrum of CsI(Tl), $CdWO_4$ and BGO.

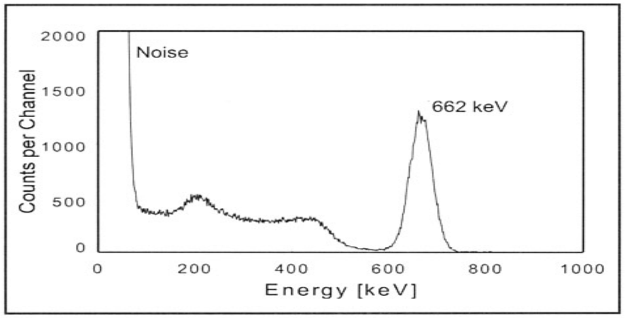
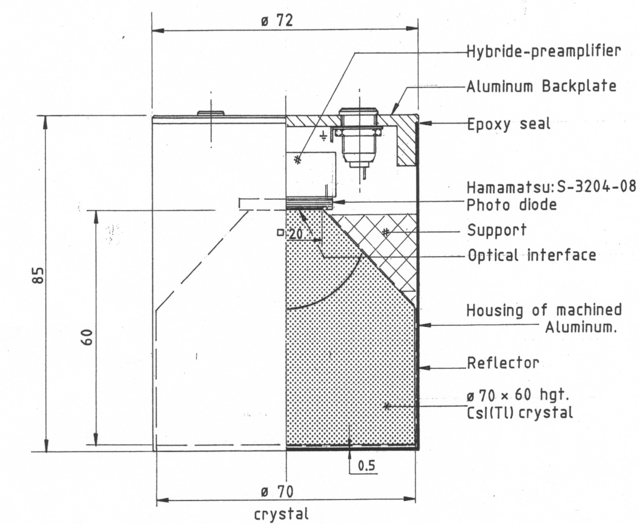


Fig. 4.4 Example of a pulse height spectrum of 662 keV gamma rays absorbed in a photodiode scintillation detector equipped with an 18x18x25 mm^3 CsI(Tl) scintillation crystal.

<u>Example</u> pulse height spectrum of 662 Kev *y*-rays absorbed in an 18 x 18 x 25 mm CsI(TI) crystal coupled to an 18 x 18 mm^2 photodiode.

Noise determines low energy limit e.g.:

10 x 10 x 10 mm CsI(Tl) + 10x10 mm PIN diode has lower energy limit of about 37 keV.

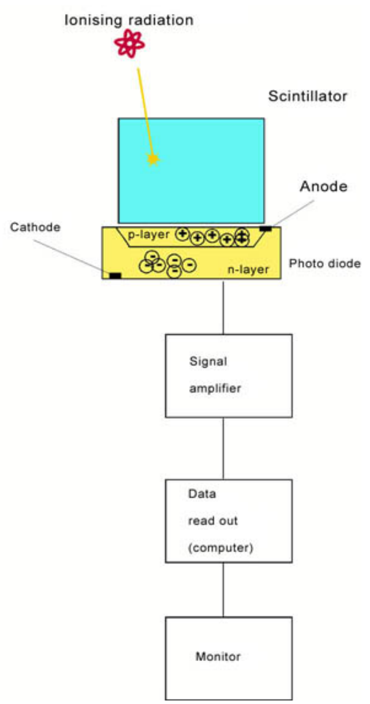


Most important advantage of PIN photodiodes is their *stability* (calibration + resolution!)

Noise is limiting factor for application

Optimum wafer thickness is 200 – 300 μm

Main contribution to energy resolution (cm size diodes) is *Capacitive noise diode/preamp*



Max. usable surface 28 x 28 mm

high resistivity silicon + good quality / low noise preamps

=> low noise combination Si-photodiode/preamp.

Typical noise:	10 x 10 mm	390 ENC (900 electrons)
	18 x 18 mm	550 ENC (1300 electrons)
	28 x 28 mm	1050 ENC (2500 electrons)

Very few crystals with high light output $\geq$ 500 nm

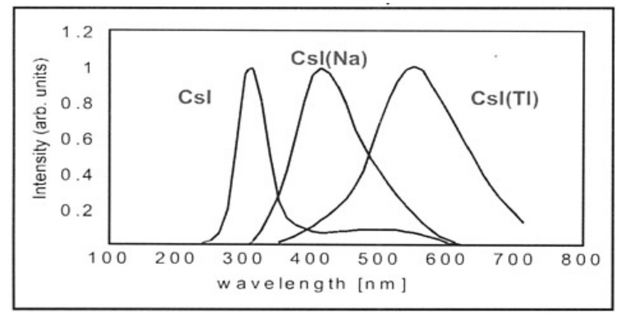


Fig. 3.2 ***Emission spectra of CsI, CsI(Na) and CsI(Tl) scaled on maximum emission intensity. Also a typical quantum efficiency curve of a bialkali photocathode is shown.***

scintillator with the highest light yield

$\geq$ 500 nm is CsI(Tl).

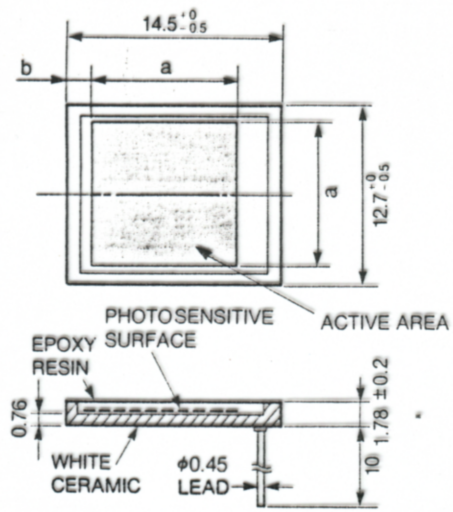
=> 3 – 4 . 10^4 e-h pairs per MeV *y*-rays

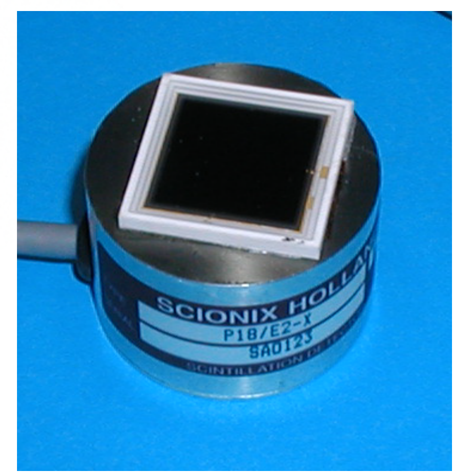
PIN SILICON PHOTODIODES.

Properties:

- No amplification (unity gain device)

  (therefore) Very stable signal
- Low voltage operation
- noisy
- *u*s filtering necessary





Exercises

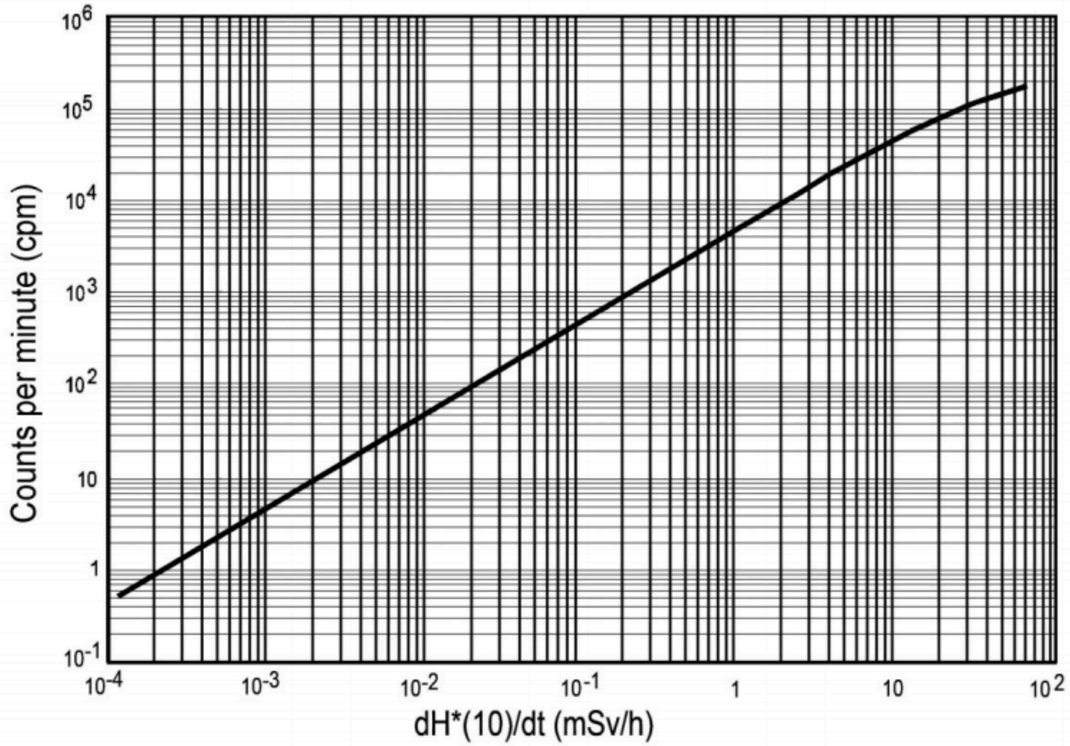
- Is this detector ok to use?

Teviso BG51

Radiation Sensor BG51

- Nuclear Beta and Gamma Radiation Sensor
- Ultra Low Power Requirement

BG51 Sensor Linearity



dH*(10) / dt = Radiation dose equivalent rate for Cs-137 and Co-60 (mSv/h)

Exercises

- What's the dose?

bGeigie Nano (LND 7317)

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ELECTRICAL SPECIFICATIONS

RECOMMENDED OPERATING VOLTAGE (VOLTS)	500
RECOMMENDED ANODE RESISTOR (MEG OHM)	4.7
OPERATING VOLTAGE RANGE (VOLTS)	475-675
MAXIMUM PLATEAU SLOPE (%/100 VOLTS)	10
MINIMUM DEAD TIME (MICRO SEC)	40
GAMMA SENSITIVITY CO60 (CPS/MR/HR)	58
TUBE CAPACITANCE (PF)	3
WEIGHT (GRAMS)	125
MAXIMUM BACKGROUND SHIELDED 50MM PB + 3MM AL (CPM)	30
MAXIMUM STARTING VOLTAGE (VOLTS)	425
MINIMUM ANODE RESISTOR (MEG OHM)	3.3

bGeigie Nano (LND 7317)

Feature	Description
Dual use modular design	main unit can be taken out of case for α-, β-detection, for careful use as surface contamination spot meter
Operating range	µSv/h: .000 to 1,000 ; mR/hr: .000 to 100 ; CPM: 0 to 350,000
Accuracy	+/- 10% typical, +/- 15% maximum [* as with Onyx ?]
Temperature range	-20 to +50 C, -4 to +122 F [* as with Onyx ?]
Calibration	Cesium-137 (gamma from daughter metastable Barium)
Gamma sensitivity	334 CPM per uSv/h (3340 CPM per mR/hr) referenced to Cs-137
Certifications	(in progress, TBA*)

Exercises

- How do we set up a spectrometer with an energy range of 1.2 & 2.4MeV
  - How would we cut off the energy to 2MeV
  - For a strong source how could we cut the counting rate?

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ReNuAL Renovation of the Nuclear Applications Laboratories

Department Nuclear Sciences & Applications

Division Physical & Chemical Sciences

Physics Section

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Thank you!