Examples of Cerenkov radiators

Radiator		**n**	θ_{max} $\beta = 1$	**N_0 (cm^{-1})** $200 < \lambda < 750$nm
He	gas	1.000035	0.48°	0.11
Air	gas	1.000283	1.36°	0.94
Isobutane	gas	1.001270	2.89°	4.3
Aerogel	solid	1.025-1.075	12.7-21.5°	81-226
Freon	liquid	1.233	35.8°	575
Water	liquid	1.33	41.2°	729
Quartz	solid	1.46	46.7°	892
BGO	solid	2.15	62.3°	1319

Exotics

- Transition radiation

radiation emitted when charged particle crosses dielectric boundary

signals in x-ray region (~ few keV)

very weak radiation - multiple boundaries required to generate measurable signal

but amplitude ~ $\gamma = 1/(1-\beta^2)^{1/2}$ *particle ID at very high energy*

- Bolometers

large fraction of ionisation energy does not appear as electrical signal

in crystals, eg silicon, excites phonons in crystal = heat

quantum of measurement = energy per phonon ~ meV (10^{-3}eV!)

potential for very high energy resolution

measure change in T $\Delta T = E_{deposit}/C$ C = heat capacity of sensor

C ~ mass so need small sensor and low T (near 0K)

nevertheless, some good results ΔE_{FWHM} = 17eV at 0.05K for 6keV x-ray

- Superconducting sensors - several types

two metal superconductors separated by thin insulator layer

under bias, QM tunneling of ionised excited states through insulator

ε *~ meV gives potential for high resolution*

Application: particle identification

- A common requirement in nuclear and particle physics is to identify which type of particle is being observed
- stable **neutral** particles - γ, n

  very different types of interaction so easy to distinguish- discuss later

- stable or long-lived **charged** particles: e^-, p^+, $\pi^\pm$, $K^\pm$, d, He^+, other ions

  typically momentum measurement is made by bending charged particle in B field

  Force = $q\mathbf{v}x\mathbf{B} = mv^2/r$ => $r = qB/p$ if motion in plane perpendicular to **B**

  direction of bend indicates if charge is + or -

- p and charge are not enough to identify particle, need measurement of m or E

  $E^2 = m^2 + p^2$ (c = 1 units , m = MeV/c^2, E = MeV, p = MeV/c)

  Two common methods : Time of Flight & Cerenkov

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Time of Flight

- Simply measure time taken between two measurement points, separation L

$t_1 = L/v_1$ $\quad t_2 = L/v_2$ $\quad 1/\beta = E/p \approx 1+m^2/2p^2$ for $p \gg m$

$\Delta t = t_1 - t_2 = (L/c)(1/\beta_1 - 1/\beta_2) \approx 3.3\text{ns}(1/\beta_1 - 1/\beta_2)$ for L = 1m

Since $\beta \sim 1$, good measurement accuracy required

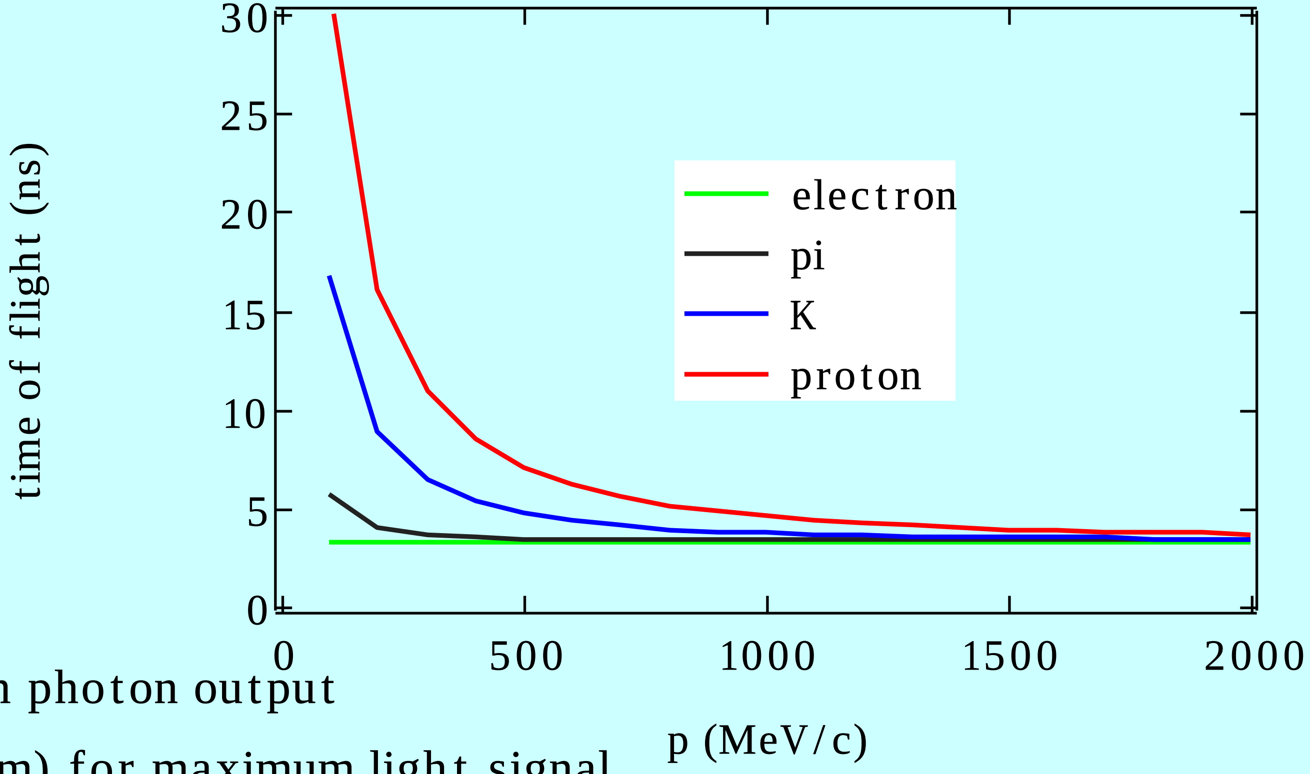
$\Delta t = (L/2p^2c)(m_1^2 - m_2^2)$

$m_e = 0.511$ MeV/c^2

$m_\pi = 140$ MeV/c^2

$m_K = 494$ MeV/c^2

$m_p = 938$ MeV/c^2



- Requirements

fast scintillator with high photon output

thick scintillator (~few cm) for maximum light signal

fast response photodetector

Cerenkov identification

- $\cos\theta = 1/\beta n$ so $\beta > 1/n$ for light emission

- light output $N_\gamma = N_0 L \sin^2\theta = N_0 L(1-1/\beta^2 n^2)$

a good figure of merit $N_0 \approx 100\text{cm}^{-1}$

depends on details of construction and photosensors

for gaseous radiator L > 1m

still expect small Nγ

- threshold counters

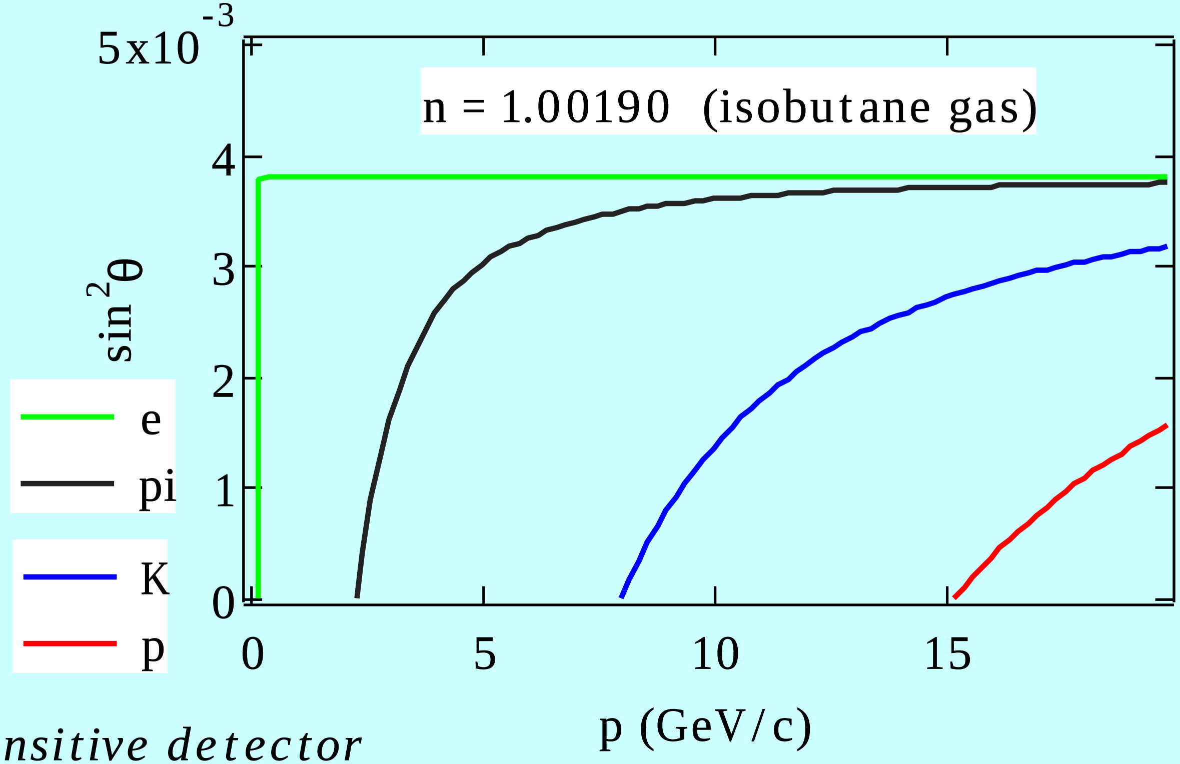
binary 0/1 signal

- ring imaging detectors

focussing mirror

cone -> ring

count photons with position sensitive detector



Photodetection

- Many examples of light signals

  sensors such as scintillators, Cerenkov radiation, ...

  lasers for telecommunications, cable TV, local or wide area optical network

  optoelectronic technology is rapidly growing field with innumerable applications, eg:

  optical computing
  holographic memories
  consumer electronics and data storage (CDs, etc)

- What types of sensor are available for photonic measurements?
- What are the requirements?
- What properties and limitations do they have?

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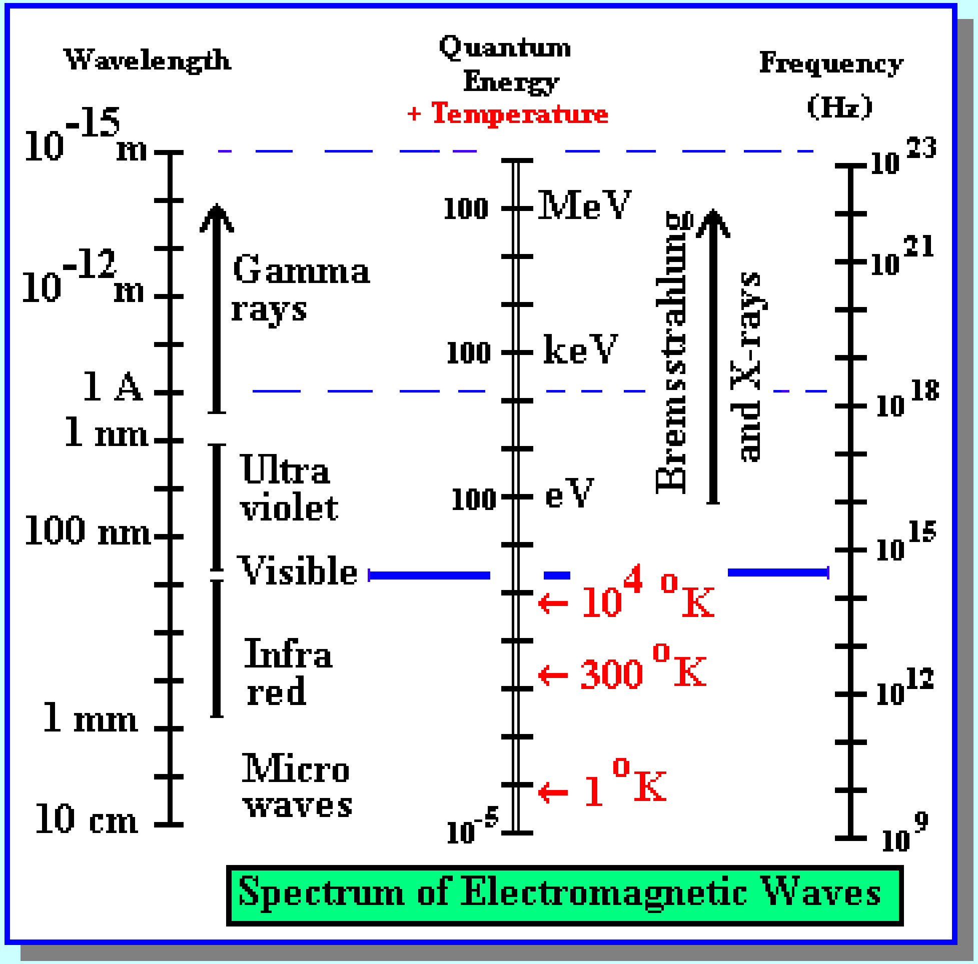
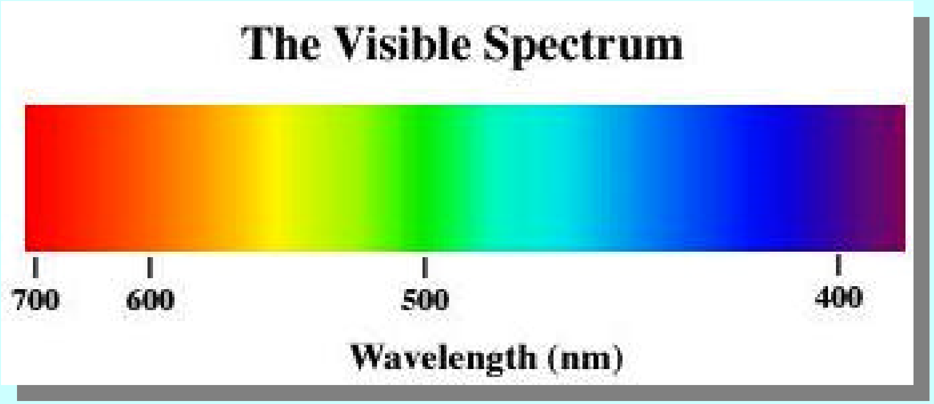
Reminder - Electromagnetic spectrum



Spectrum of Electromagnetic Waves



- $\lambda = c/\nu = hc/E$ $\lambda\,[\mu\text{m}] = 1.24/E\,[\text{eV}]$

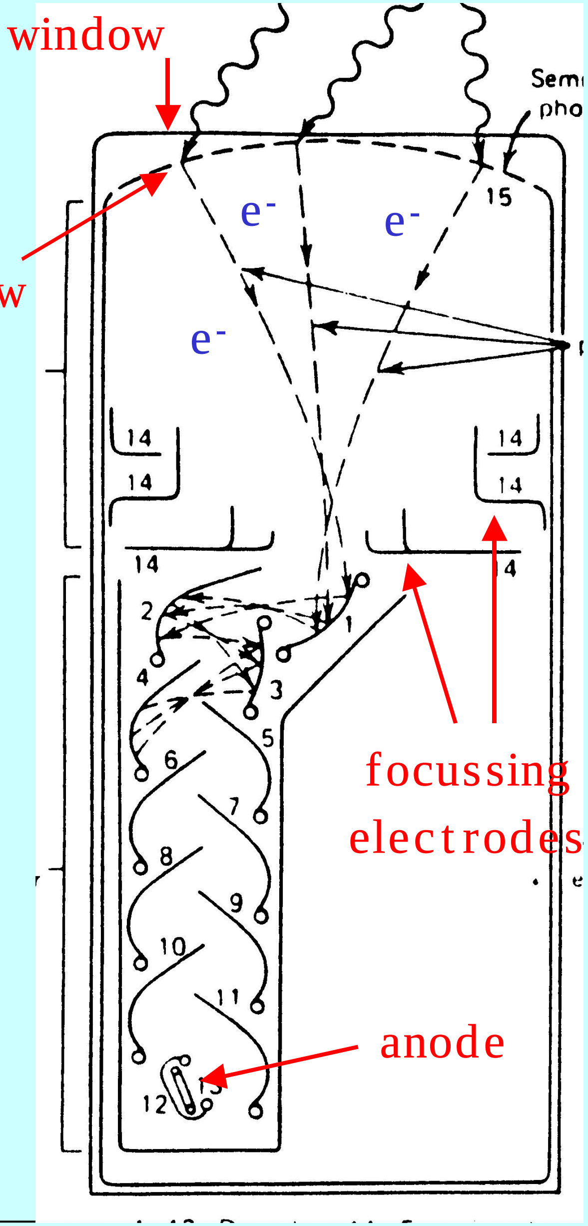
$0.2\mu\text{m} = 6\text{eV}$	ultra-violet
$0.5\mu\text{m} = 2.4\text{eV}$	visible
$1\mu\text{m} = 1.24\text{eV}$	infra-red
$10\mu\text{m} = 0.12\text{eV}$	far-IR

- Wide range of photon wavelengths and energies to be covered!

  should not expect a single sensor for all applications

Photomultiplier

- Most common light sensor - simple structure
  - electrodes enclosed, in vacuum, in glass envelope
    - *many sizes and shapes*
- Photocathode - thin metal coating on inside of entrance window
  - semi-transparent (& fragile)
  - photon absorbed and converted to electron, small k.e.
  - e^- diffuses to surface and escapes
- Electron capture region
  - E field shaped to transport e- to first dynode
- Dynodes - electron multiplier chain
  - e^- accelerated in E field
  - strikes dynode and ke. releases more e^- = amplification
- Anode
  - after several amplification stages, -> current signal



Photomultipliers

Photomultiplier operation

- Bias dynodes by applying voltages

  typically ~100V stage

  G_{stage} ~ ke of incident electron

- simplest arrangement: resistor potential divider

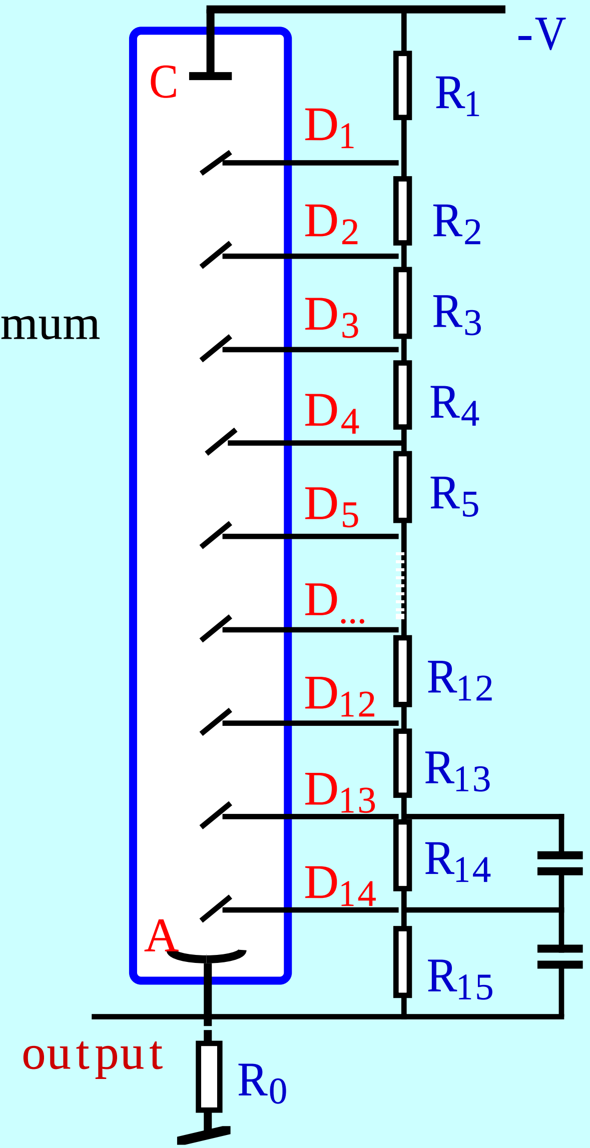
  usually add capacitors in final stages, where current is maximum

  can add Zener diodes for stability

- Choice of components

  first stage is often largest ΔV for maximum gain

  $I_{chain} \gg I_{peak\ signal}$



Characteristics

- photocathode- determines wavelength sensitivity and quantum efficiency

QE = N_e/incident photon

3-4 eV alkali metals

1.5-2eV bi-alkali

photocathode type	$\Delta\lambda$ (nm)	λmax (nm)	QE (%)	name
Ag-O-Cs	300-1100	800	0.4	S1
Bi-Ag-O-Cs	170-700	420	6.8	S10
Cs_3-Sb-O	160-600	390	19	S11
Na_2-K-Sb-Cs	160-800	380	22	S20
K_2-Cs-Sb	170-600	380	27	bialkali

Signal = G_{total} x QE x ε_{photon} x $\varepsilon_{electron}$

ε_{photon} = fraction of photons reaching cathode

$\varepsilon_{electron}$ = electron collection efficiency

- try to match sensitivity to source, eg scintillator spectrum

- very sensitive to magnetic field

electrons are low energy and E field is limited

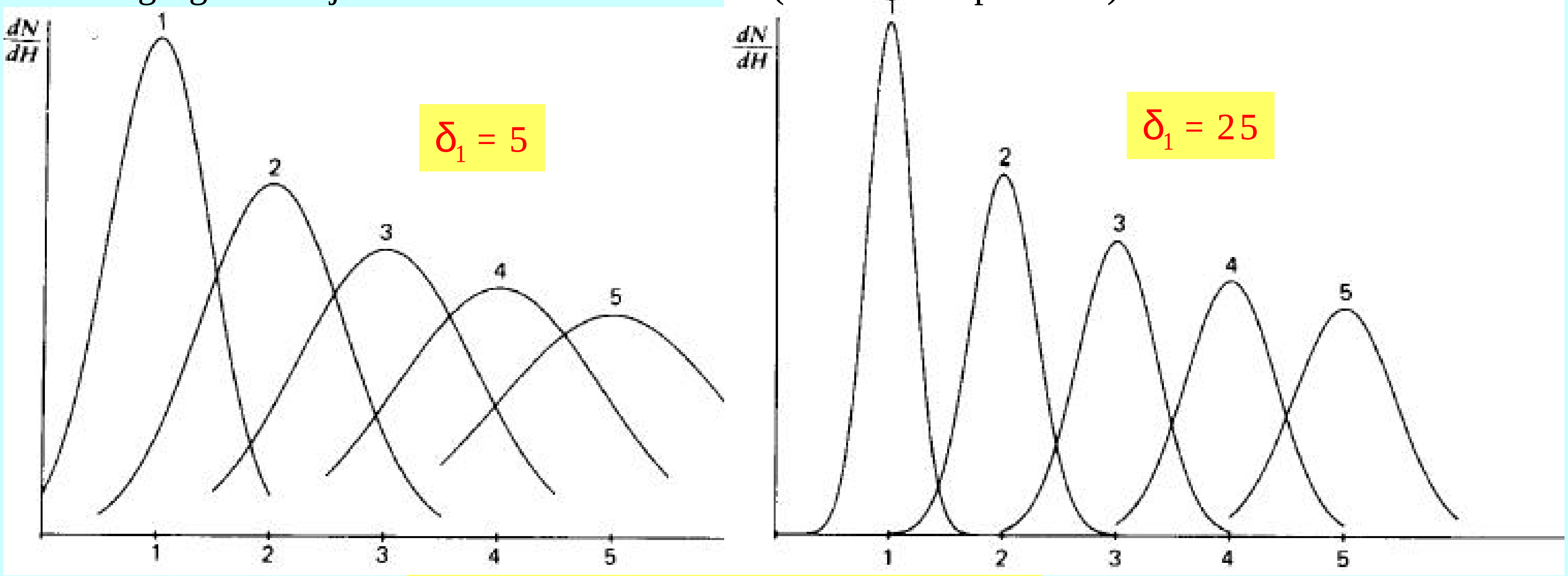
- stable high voltage required

since gain $G_{total} \sim G_{stage}^{N} \sim \Delta V^{N} \sim (V/N)^{N}$

Sensitivity

- Approximate picture - each stage increases signal by factor δ_{stage}

  Single and multiple electron signals can be distinguished depending on dynode gain stage gain subject to Poisson statistics (ie. random process)



signal in photoelectron equivalents

- if gain is high, first stage dominates

  Signal = $N_e\delta_1\delta_2\delta_3\delta_4\ldots\ \delta_N$

Noise

- Photomultipliers often described as noiseless sensor - but…

  noise arises from thermionic emission of electrons from cathode and dynodes

  dark count rates of ~kHz or more possible - can be minimised in several ways

  if signal can be observed in coincidence with another signal

    very often possible, eg particle crosses several detectors

  cooling tube

    minimise dark current

  discriminating amplitude of signal -

    noise pulses generated after first stage will be smaller amplitude

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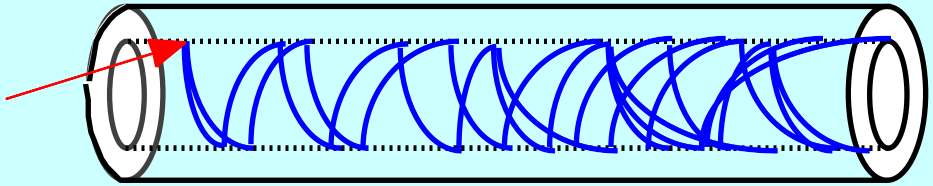
Channel plate

- Hollow tube of high resistivity glass coated internally with secondary electron emitter

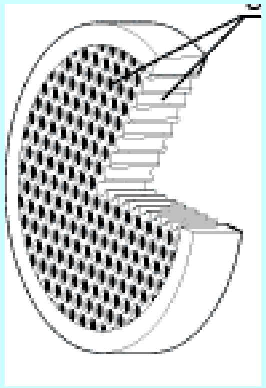
  apply potential difference along tube -> multiplication

  pack series of tubes as bundle ~ few cm^2



- Intrinsically spatially sensitive

  to avoid too many channels read out with resistive anodes, strips or CCD



- Use "chevron" arrangement to avoid positive ion feedback

  could damage tube

- Applications

  image intensifier - very compact low light detection

  spatial imaging - β isotopes

  fast timing - transit time short, and dispersion smaller