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Radiation Detection and Measurement

Lecture 9

Chapter 4: General properties of radiation detectors

Simplified detector model

- Must have one of the interactions (CH 2) to determine a radiation event.
- Detectors measure a build-up of charge (Q) at time t and translate this to an electrical signal.
- Generally, accomplished through the imposition of an electric field within the detector, where the ion pair formed from an interaction flow in opposite directions.

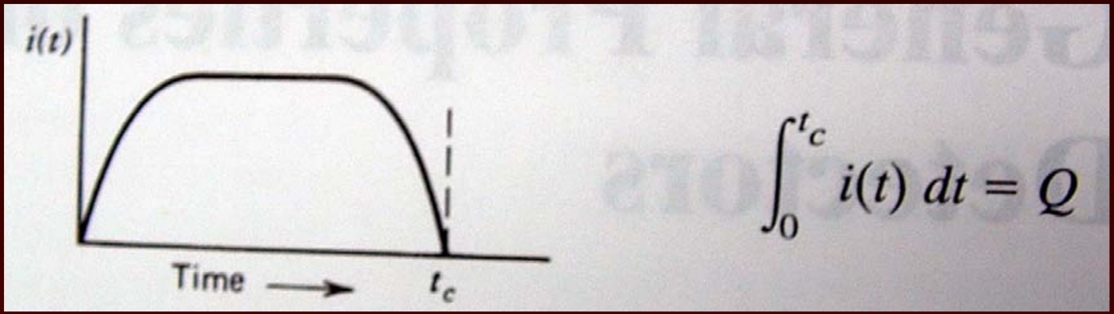
Simplified detector model

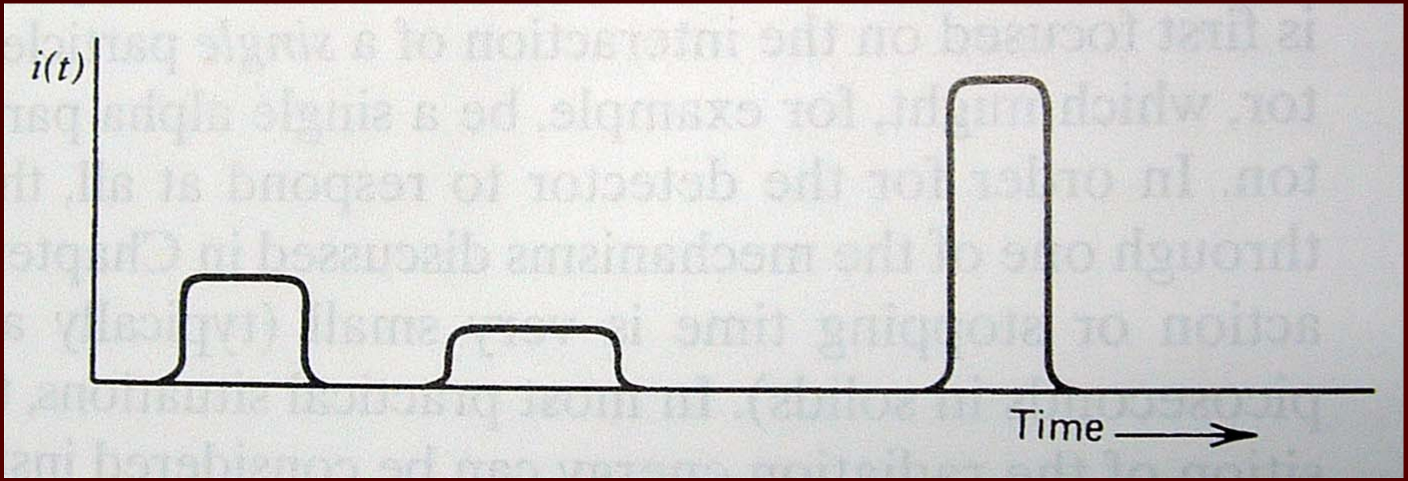
- Charge is collected over time: from the current of ion flow.

$$Q = \int_0^t i(t) \quad dt$$

- Collection times vary with the detector: ion chamber~10^{-3} s; semiconductor~10^{-9} (These reflect the average distance the electrons must travel to reach the electrodes)

Charge and random pulse sequences

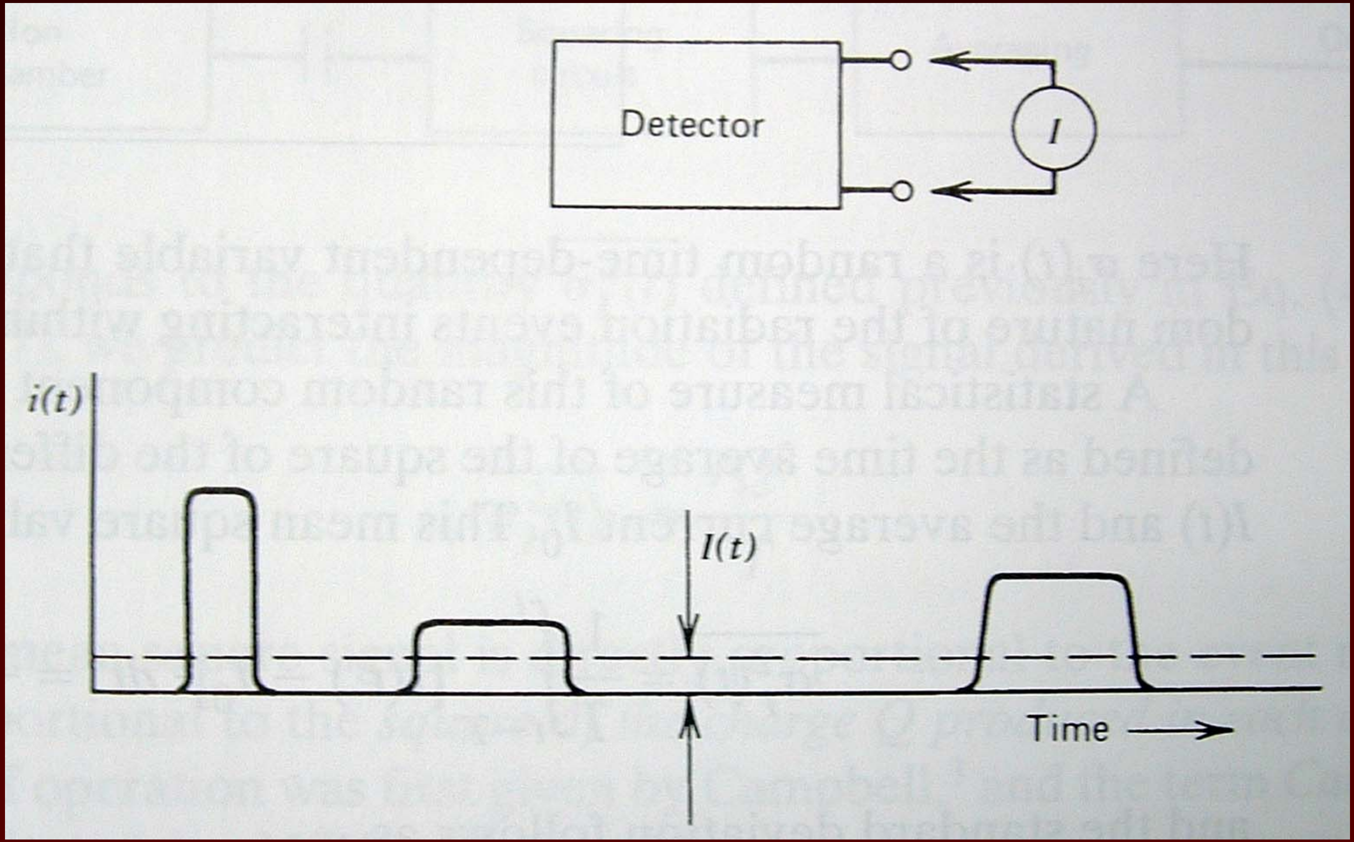




Modes of operation

- These are 3 mode of operation: current mode; pulse mode; and mean square voltage mode (MSV or Campbelling mode).
- Pulse mode is designed to record each individual quanta, where the total charge (Q) is related to the energy of each quanta, the mode is categorized as radiation spectroscopy.
- When energy information is not required the number of pulses may be counted (only) in pulse counting.
- At high rates the practicality of using pulse mode may no longer be an option and current or MSV mode may be employed.

Current mode



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Current mode

- We assume the measuring device has a fixed response time T, then the response will be a time dependent current:

$$I(t) = \frac{1}{T} \int_{t-T}^{t} i(t') \quad dt'$$

- Given T is long compared to the short bursts, the effect is to average out the individual events.

Current mode

- This mode will tend to average out statistical noise, but also will be slow to respond to rapid changes of events for a large T.
- The average current is given by the average event rate (r) and the charge produced per event Q: $I_o = rQ = r(E/W)q$. *E* is the energy deposited per event, *W* is the average energy to produce a charge pair, and *q* = 1.6x10-19 C.

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Current mode

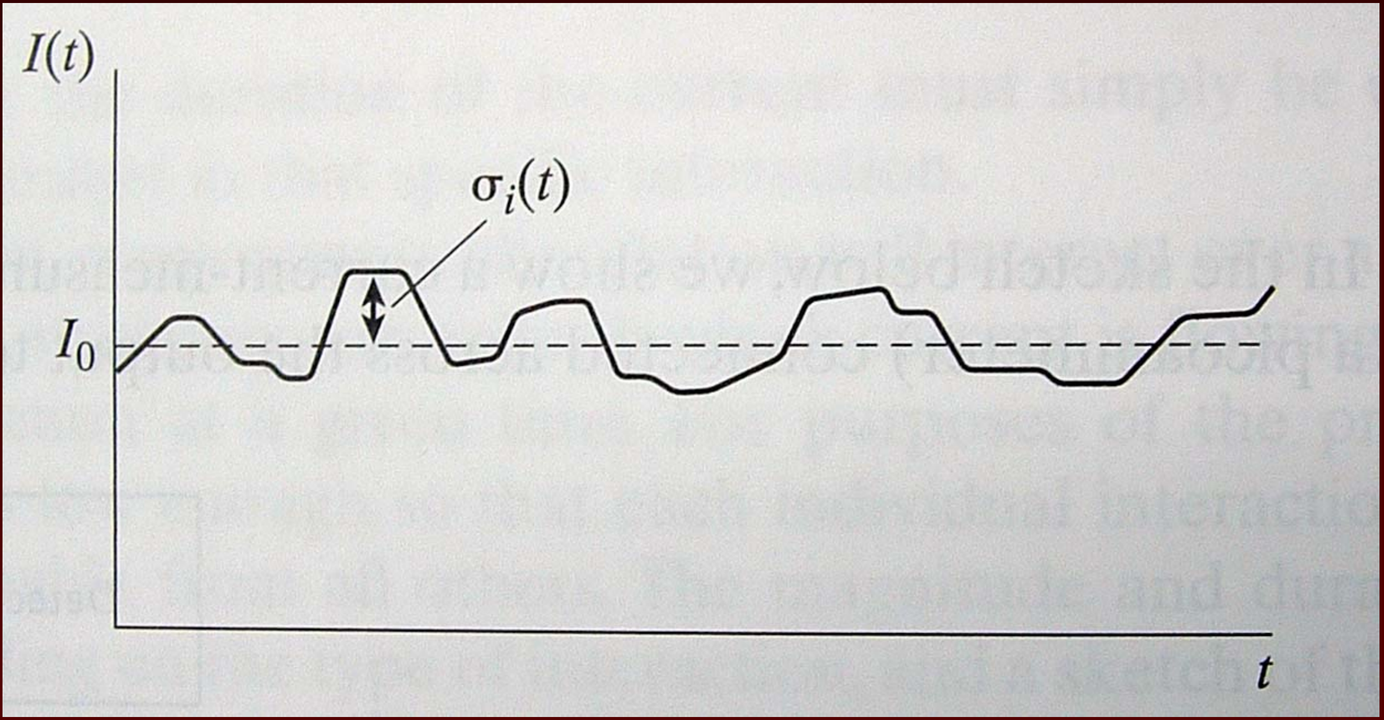
- For steady state the current can be expressed as a sum of a constant rate plus the fluctuations:

$$I(t) = I_o + \sigma_i(t).$$

- The variance or mean square value (as a measure of $\sigma_i(t)$):

$$\overline{\sigma_I^2} = \frac{1}{T}\int_{t-T}^{t}[I(t') - I_o]^2 \quad dt' = \frac{1}{T}\int_{t-T}^{t}\sigma_i^{\,2}(t') \quad dt$$

Current mode: fluctuations about a steady current



Current mode

- The time averaged standard deviation ($\sim 10^{-12}$ A):

$$\overline{\sigma}_I = \sqrt{\overline{\sigma}_I^{\,2}(t)}, \quad recall \quad \sigma_n = \sqrt{n} = \sqrt{rT}$$

- For each similar pulse the fractional standard deviation will then be:

$$\frac{\overline{\sigma}_I}{I_o} = \frac{\sigma_N}{n} = \frac{1}{\sqrt{rT}}$$

Current mode

$$\frac{\overline{\sigma}_I}{I_o} = \frac{\sigma_N}{n} = \frac{1}{\sqrt{rT}}$$

- So is the time average of the standard deviation of the measured current, T is the response time of the meter, Io is the average current read on the meter and one can estimate the error in current mode.

Mean square voltage mode

- We filter out the DC component (I_o) and measure $\sigma_i(t)$.
- Next we compute the time average of the amplitude squared of $\sigma_i(t)$ which is:

$$\overline{\sigma_I^2(t)} = \left(\frac{I_o}{\sqrt{rT}}\right)^2 = \left(\frac{rQ}{\sqrt{rT}}\right)^2 = \frac{rQ^2}{T}$$

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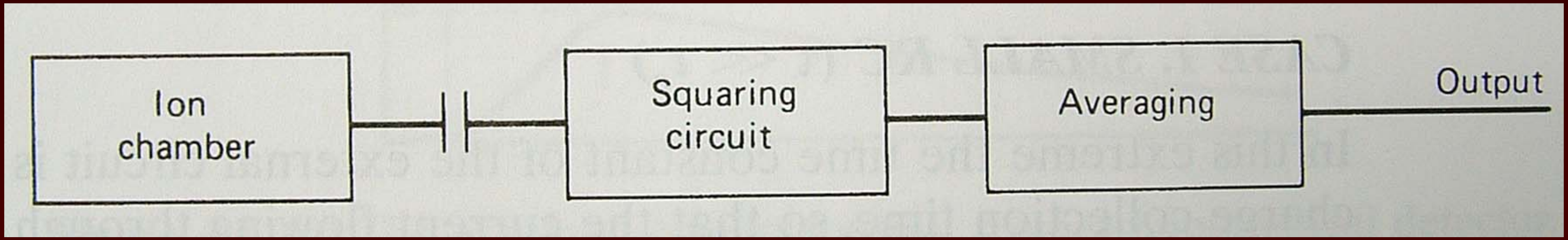
MSV schematic



Mean square voltage mode

$$\overline{\sigma_I^2(t)} = \left(\frac{I_o}{\sqrt{rT}}\right)^2 = \left(\frac{rQ}{\sqrt{rT}}\right)^2 = \frac{rQ^2}{T}$$

- $\overline{\sigma_I^2(t)}$ is proportional to the rate and the square of the charge for each event.
- This is useful when measuring mixed radiation sources which weights more heavily the radiation delivering more energy.

Pulse mode

- Employs an equivalent to a parallel RC circuit where R is the input resistance of the measuring circuit (pre-amp); C is the capacitance of the detector and measuring circuit (cable, input capacitance of pre-amp) with a circuit time constant τ=RC.
- Selecting long or short time constants can skew data to smoothing noise or missing fast input changes (Fig. 4.1)

Pulse mode

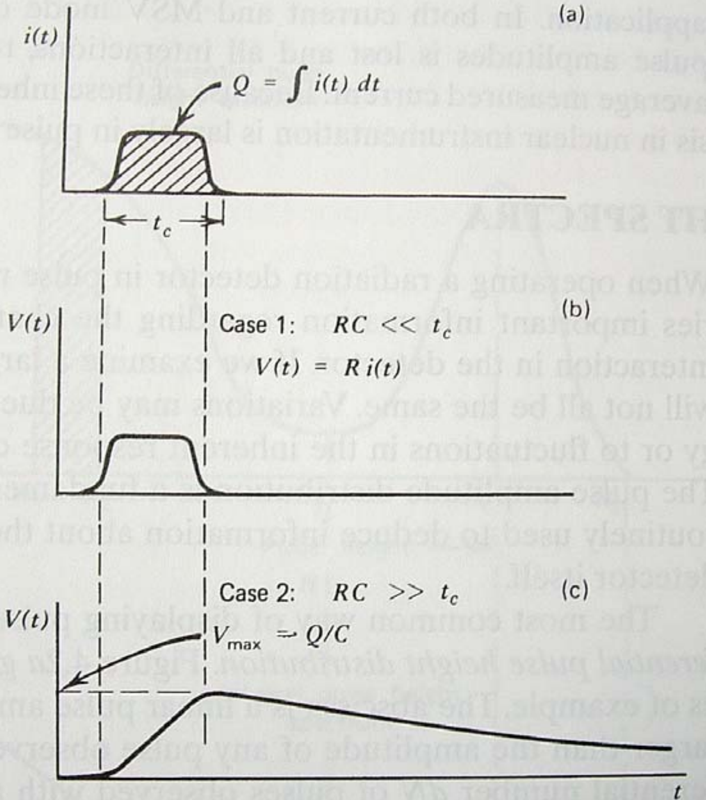


Figure 4.1 (*a*) The assumed current output from a hypothetical detector. (*b*) The signal voltage $V(t)$ for the case of a small time constant load circuit. (*c*) The signal voltage $V(t)$ for the case of a large time constant load circuit.

Pulse mode

Case 1:

$\tau << t_c$ (t_c is the charge collection time)

- The current flowing through the load resistance is essentially equal to the charge flowing through the detector.
- The output signal voltage looks like the shape of the current in the detector ($V(t)=R_i(t)$).

Pulse mode

Case 2: $\tau >> t_c$

- The rise time of the signal is dependent on the rise time of the charge in the detector itself.
- The time for the signal to reset to 0 is a function of the circuit time constant only.
- The leading and trailing edge traits of the signal is common to all detectors with $\tau>>t_c$.

Pulse mode

- Assuming C is a constant (semiconductors is an exception) the basic physics relation holds that the voltage out is proportional to the charge in the detector $V_{max}=Q/C$

Pulse height spectra

- In pulse mode the pulse height carries information about the charge generated in the detector.
- Pulse height is displayed in two ways: differential and integral pulse height distribution.
- Differential is a display of the differential number of pulse heights *dN* observed within a differential pulse height increment *dH* divided by the measurement, *dN/dH*.

Pulse height spectra

- One can then get the total number of pulses between two height values:

$$N_{H_1 - H_2} = \int_{H_1}^{H_2} \frac{dN}{dH}\, dH$$

- And the total number of pulses:

$$N_o = \int_0^{\infty} \frac{dN}{dH}\, dH$$

Pulse height spectra

- The total number of pulses given per pulse height is the integral pulse height distribution.
- Both descriptions convey the same information where the differential distribution is the absolute slope of the integral distribution.

Pulse height spectra plots

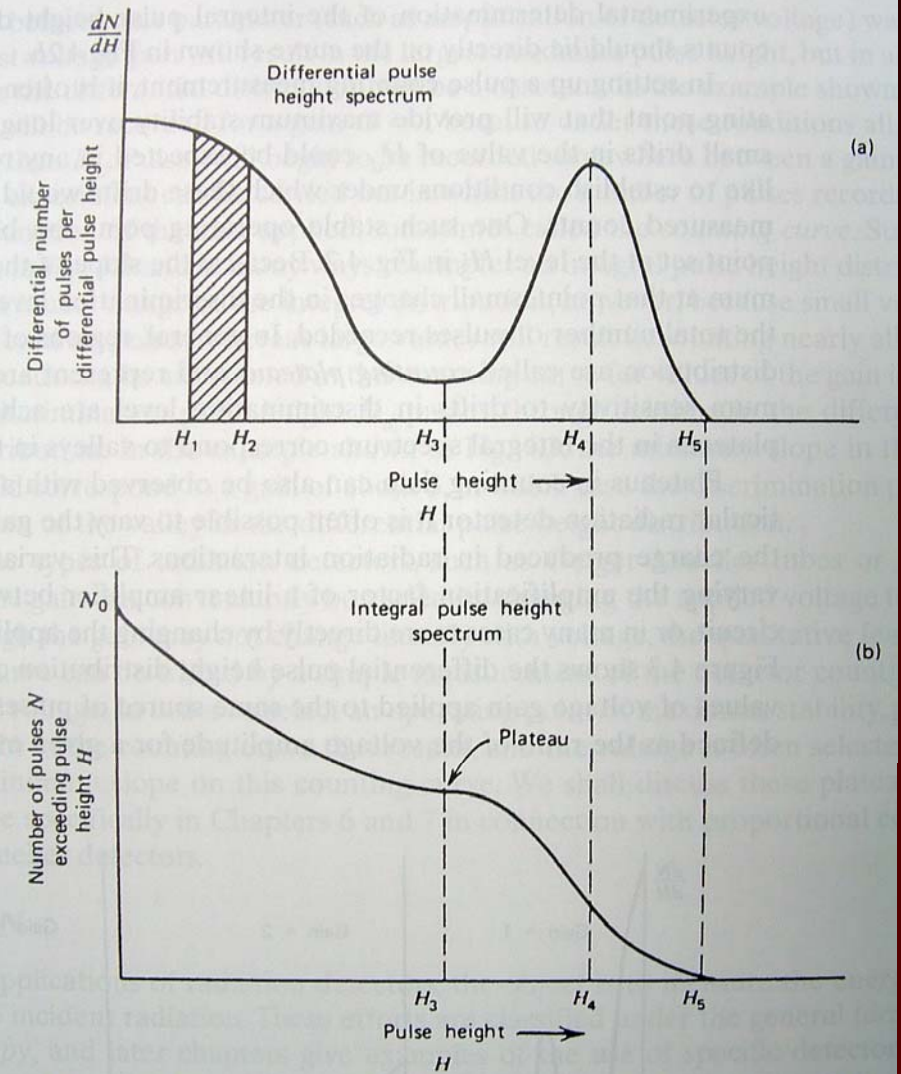


Figure 4.2 Examples of differential and integral pulse height spectra for an assumed source of pulses.

Counting curves and plateaus

- The information from the pulse height distribution is fed to a discriminator which selects signal above a minimum H_d before being counted by the counting circuit.
- Therefore the integral pulse height distribution shows the number of signals accepted as you vary H_d.
- One can also change the number of events counted by varying the gain.

Counting curves and plateaus

- Gain is a change in the detector voltage or a change in the amplifier setting.
- A counting curve is the number of signal pulses counted as a function of the gain.
- Some counting curves may show a plateau, which may be an indicator of the best setting on a detector system to minimize fluctuations.

Counting curve generated from varying gain

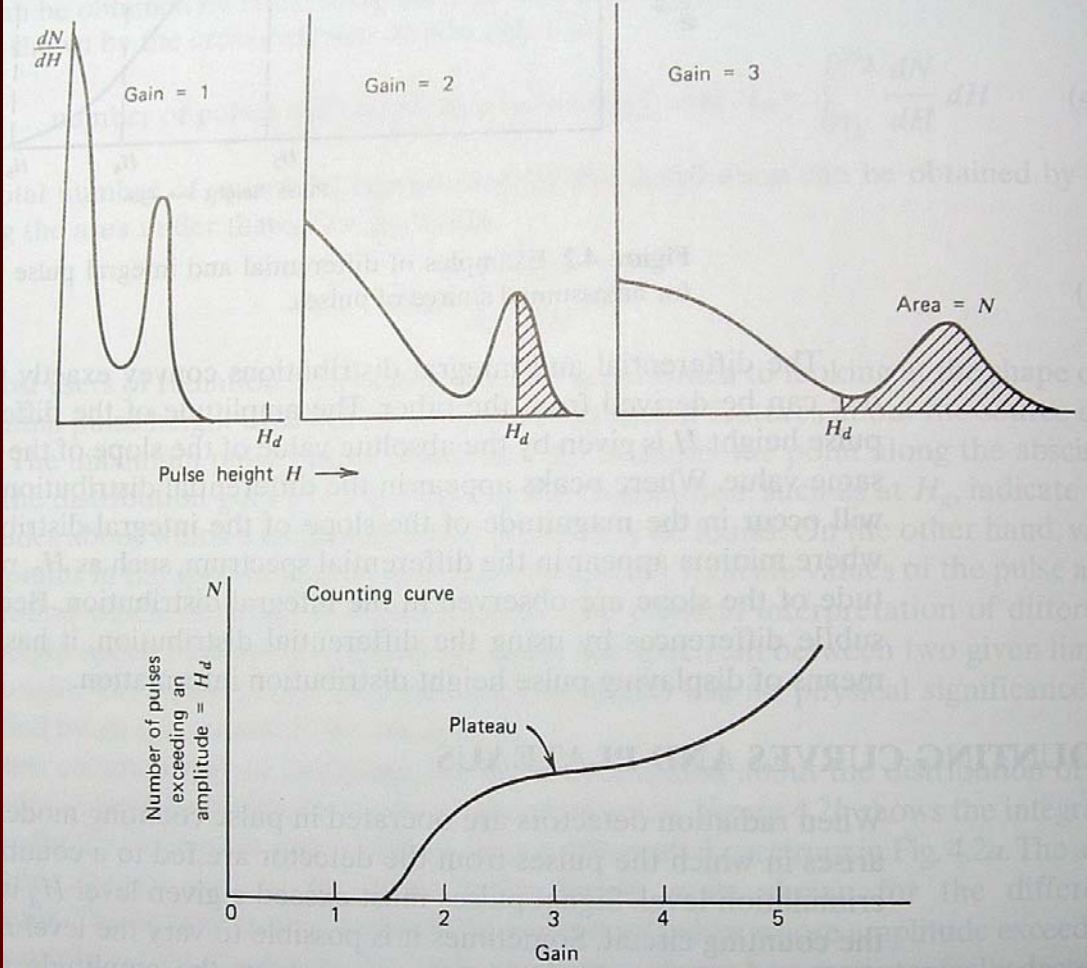


Figure 4.3 Example of a counting curve generated by varying gain under constant source conditions. The three plots at the top give the corresponding differential pulse height spectra.

Energy resolution

- In the application where one is interested in the energy distribution of the incident radiation (radiation spectroscopy).
- One important property of a detector in radiation spectroscopy is its response to a mono-energetic source or its response function.
- The response function is the ability to resolve the energy of the source, or more generally the energy resolution.

Energy resolution

- Resolution is the spread of the detector response over the energy of the source. The spread is defined as the FULL WIDTH at HALF MAXIMUM (FWHM) of the peak:
  - (H_o is the source energy)

$$R = \frac{FWHM}{H_o}$$

  - For peaks with a Gaussian shape FWHM = 2.35 σ

Energy resolution

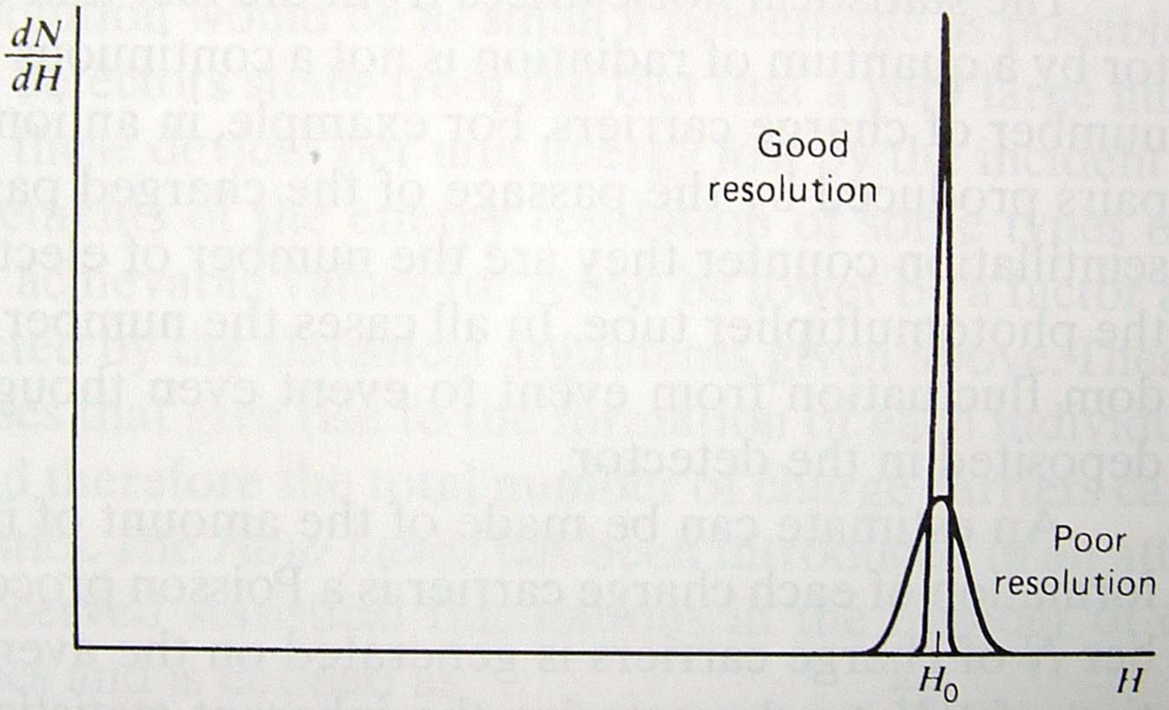


Figure 4.4 Examples of response functions for detectors with relatively good resolution and relatively poor resolution.

Energy resolution

- Smaller R is better, semiconductor for α~1% and scintillation detectors in γ-ray spectroscopy ~ 5% -10%.
- Potential sources of fluctuation which diminish the detector response include: detector operating characteristic drift; random noise in the detector and instrumentation; discreet noise in the signal itself – which puts a minimum on the noise level of the detection.

Energy resolution

- An estimation of the inherent noise from a Poisson distributed signal: $\sigma = \sqrt{N}$
  - where N is the number of charge carriers.
- With large N the distribution becomes Gaussian:

$$G(H) = \frac{A}{\sigma\sqrt{2\pi}} e^{-(H-H_o)^2/2\sigma^2}$$

  - Where σ determines the FWHM, H_o is the centroid, and A is the area.

Energy resolution

- Assume a linear response, so the average pulse amplitude:

$$H_0 = KN$$

$$\sigma = K\sqrt{N}$$

$$FWHM = 2.35K\sqrt{N}$$

$$R\Big|_{Poisson\ \ Limit} = \frac{2.35\mathrm{K}\sqrt{\mathrm{N}}}{KN} = \frac{2.35}{\sqrt{N}}$$

Energy resolution

- Which gives us:

$$R\Big|_{Poisson\ \ Limit} = \frac{2.35\mathrm{K}\sqrt{\mathrm{N}}}{KN} = \frac{2.35}{\sqrt{N}}$$

- For some systems it has been shown that an *R* of 3-4 times better may be achieved, showing the coupled nature of the charge carriers do not follow Poisson.

Detector resolution

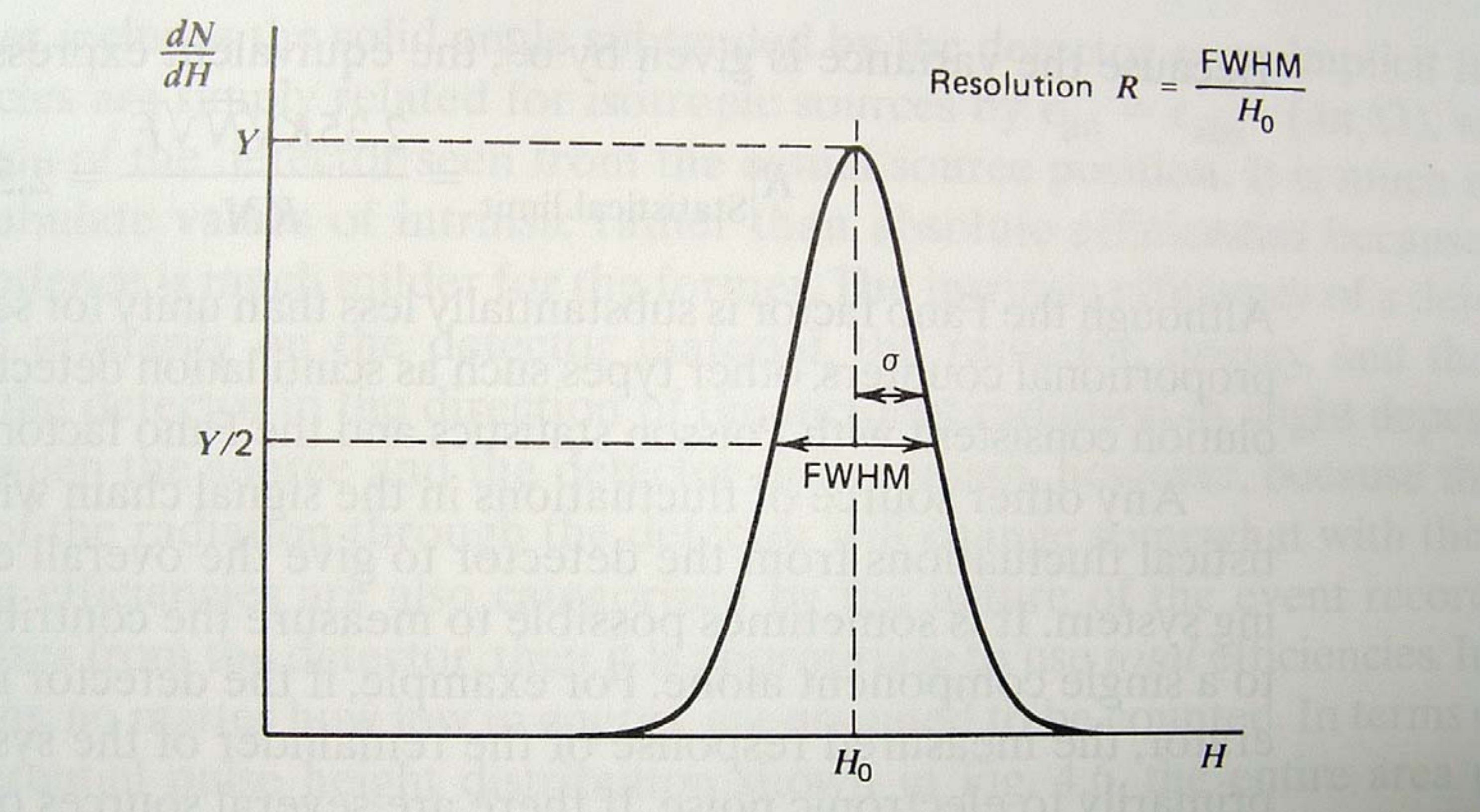


Figure 4.5 Definition of detector resolution. For peaks whose shape is Gaussian with standard deviation σ, the FWHM is given by 2.35σ.

Energy resolution

- The Fano factor is an intended measure of the departure from Poisson:

$$F \equiv \frac{observed \quad \mathrm{var}\,iance \quad in \quad N}{Poisson \quad predicted \quad \mathrm{var}\,iance(=N)}$$

  - or *NF* = observed variance.

Energy resolution

- Since the variance is given by $\sigma^2 = KN_{observed}$ we now get:

$$R\Big|_{Statistical\ \ Limit} = \frac{2.35K\sqrt{N}\sqrt{F}}{KN} = 2.35\sqrt{\frac{F}{N}}$$

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Energy resolution

- If several sources of fluctuation are present and each is symmetric and independent, statistical theory predicts the overall response will tend towards a Gaussian shape, even if the independent sources are not Gaussian shaped.
- The total FWHM fluctuation is the found by the quadrature sum of all the FWHM contributions. Each FWHM contribution would then be the fluctuation contribution if all other fluctuations were 0:

$$(FWHM)^2_{overall} = (FWHM)^2_{statistical} + (FWHM)^2_{noise} + (FWHM)^2_{drift} + \ldots$$

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