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.
- Charge is collected over time: $Q = \int_0^t i(t) \quad dt$, from the current of ion flow.
- 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).

Modes of Detector 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:

- 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.
- 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 $q = 1.6\times10^{-19}$ C.

- 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 $\sigma_i(t)$):

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

- The time averaged standard deviation (~10^{-12} A):

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

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

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

- So $\bar{\sigma}_I$ is the time average of the standard deviation of the measured current, T is the response time of the meter, I_o is the average current read on the meter and one can estimate the error in current mode.

Mean Square Value 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:

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

- $\overline{\sigma_I^2(t)}$ 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)
- Case 1 $\tau << t_c$ (t_c is the charge collection time)
  - o The current flowing through the load resistance is essentially equal to the charge flowing through the detector.
  - o The output signal voltage looks like the shape of the current in the detector ($V(t)=R_i(t)$).
- Case 2 $\tau >> t_c$
  - o 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 $\tau >> t_c$.
- 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*.
- 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:

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

- 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.

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.
- 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.

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.
- 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:

$$R = \frac{FWHM}{H_o}$$, (H_o is the source energy)

  For peaks with a Gaussian shape FWHM = 2.35 σ.
- 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.
- 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.
- Assume a linear response, so the average pulse amplitude $H_0 = KN$, $\sigma = K\sqrt{N}$, and $FWHM = 2.35K\sqrt{N}$ 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.
- 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.
- Since the variance is given by $\sigma^2 = KN_{\mathrm{observed}}$ we now get:

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

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