Week 4: Chap. 4 Basic Detector Principles

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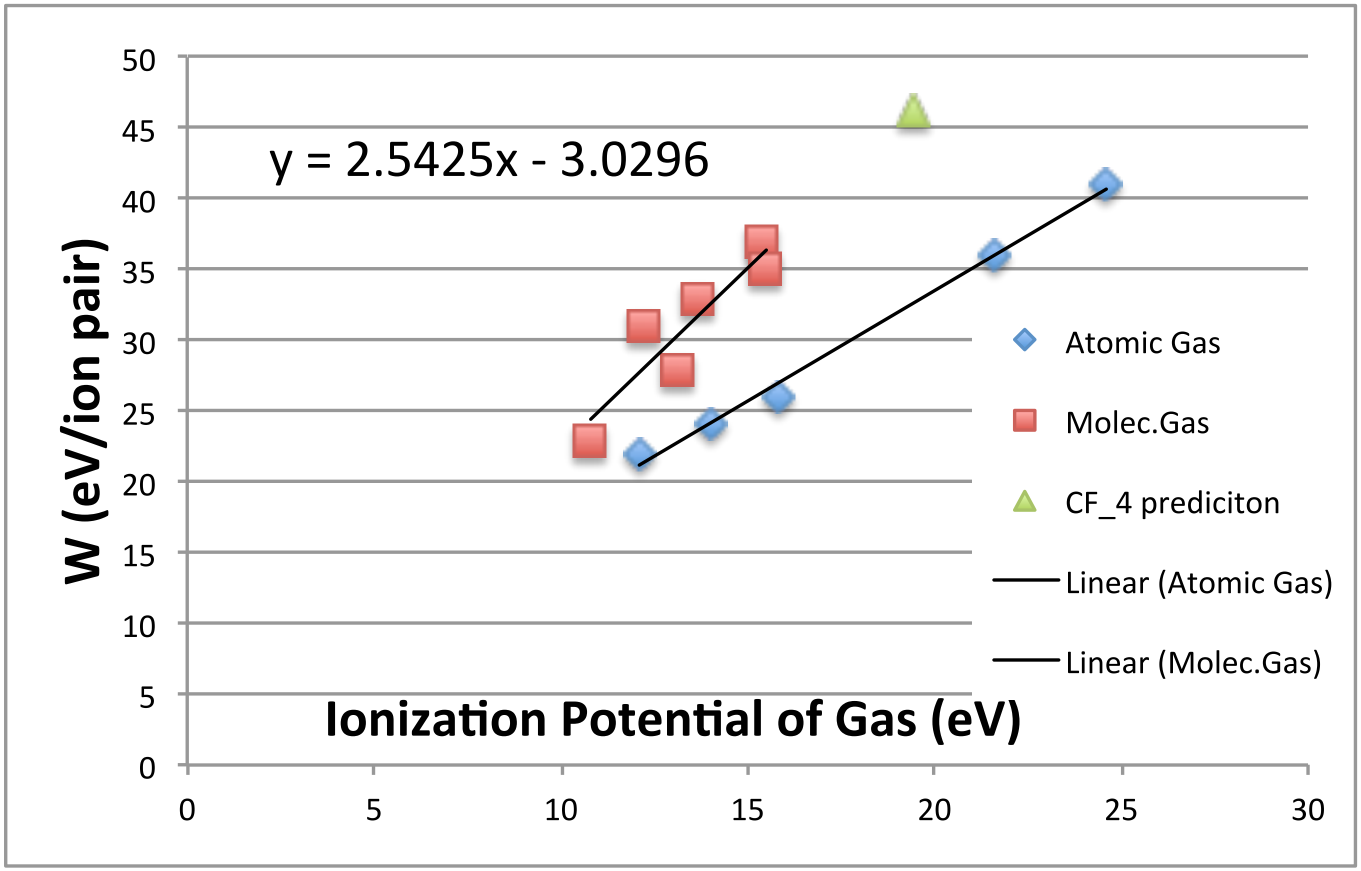
General use of Statistical Distributions

Basic Detector Principles

-- Current Mode
-- Pulse Mode
--- resolution
---- Fano Factor
--- efficiency
--- dead time

Ion Chambers



Chap. 4 General Features of Detectors

Primary Ionization is created by the interaction of the primary radiation in the bulk material of the ‘detector’ – then what?

Rate	Technique	Device	Energy Proportionality?	Temporal Information?	Position Information?
Low	Collect ions	Ion Chamber	Can be Excellent	Poor	Average
	Multiply & Collect ions	Proportional Chamber	Very good	Average	Good
	Convert into photons	Scintillation Detector	Acceptable	Good to Excellent	Poor
	Create discharge	Geiger-Mueller Ctr. PPAC Spark chamber	No	Good to Excellent	Excellent
High	Collect current	Ion Chamber	Radiation Field	None	None

General Features of Detectors – High Rates

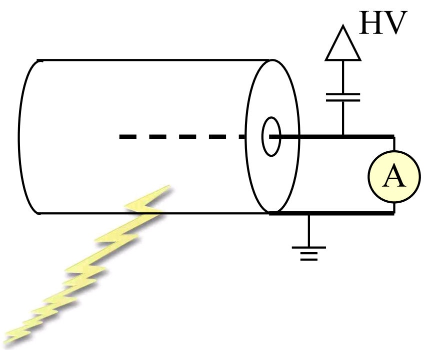
Ion Chamber: the individual pulses are summed in a system that has a long time-constant. $I = r\,(E / w)\,q_e = r\,Q$

where I is the current,

r is the rate of the incident radiation,

E is the energy deposited in the sensitive volume ~ 10's keV

w is the "effective work function" for bulk material ~ few tens of eV



For example: 0.01 MeV deposited in an air-filled ion chamber
w = 34 eV/IP for *fast electrons* [Table 5.1 in text]
whereas the ionization potentials for O_2 =12.1 eV , N_2 =15.6 eV

Values from NIST

$$N_{IP} = E / w = 10^4 eV / \left(34 eV / IonPair\right)$$

$$N_{IP} = 3x10^2 \quad \rightarrow \quad \sigma_{N_{IP}} / N_{IP} = \sqrt{N_{IP}} / N_{IP} = 6x10^{-2}$$

for a *statistical* distribution
(more on this in a moment)

$$I = r\,(E / w) q_e$$

$$I = r\left(3x10^2 IP\right) 2x\,1.602x10^{-19} coul / IP$$

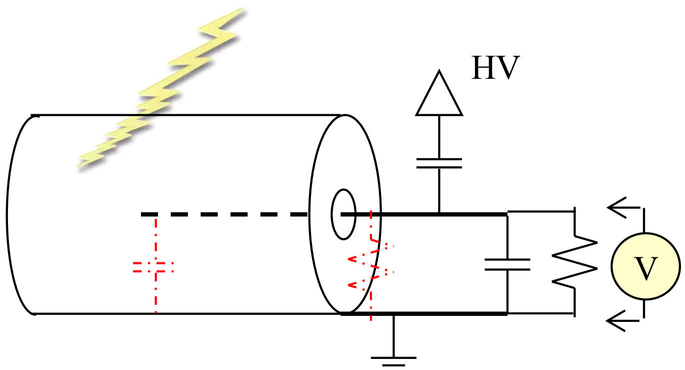
$$I = r\,(1x10^{-16})\,coul$$

General Features of Detectors – Single Pulse

<u>Single Pulse</u>: the electronics have to be sensitive enough to process the signal and not lose it in the noise (low noise electronic amplifiers, physical amplification of primary ionization occurs in proportional chambers & a few other devices).

a) Circuit is fast enough to follow the collection of the ionization and one has a current pulse.

b) Circuit is slower than the collection time and one gets a voltage pulse.



Characteristic time, $\tau = RC$

Typical $R \sim 50\ \Omega$

If typical $\tau = 1$ ns $\rightarrow C \sim 20$ pF

Note: $V_{max} \sim Q/C$

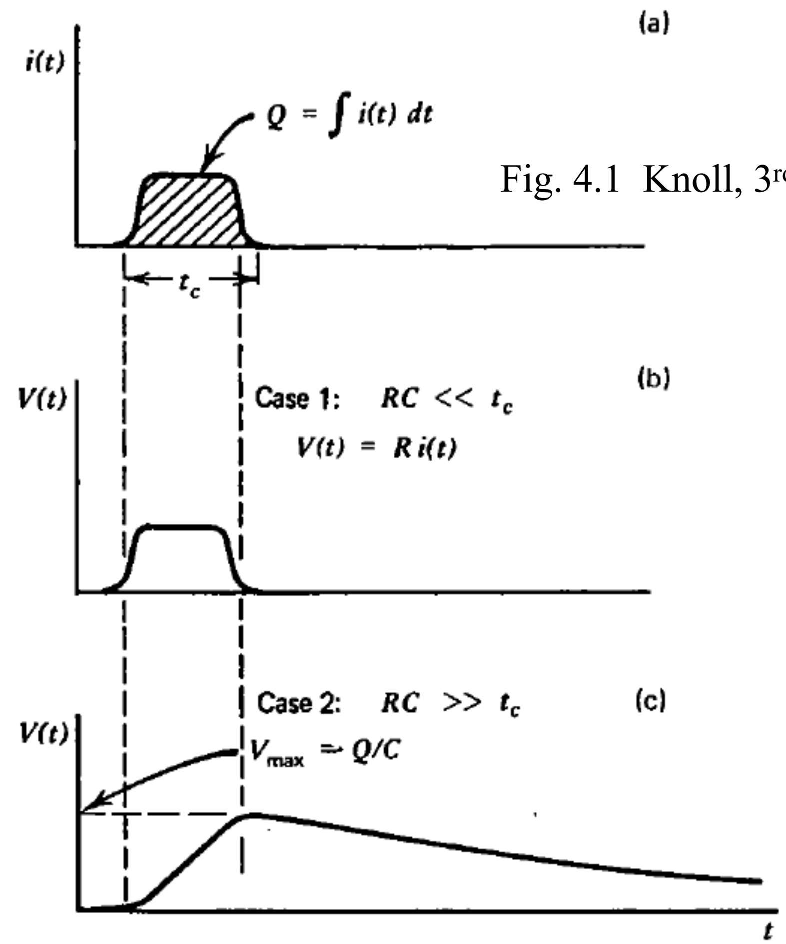
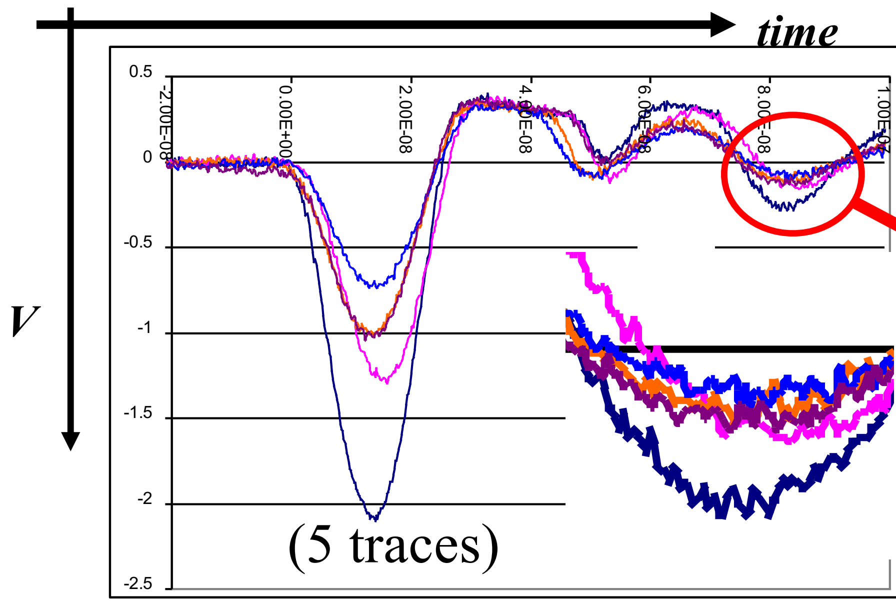
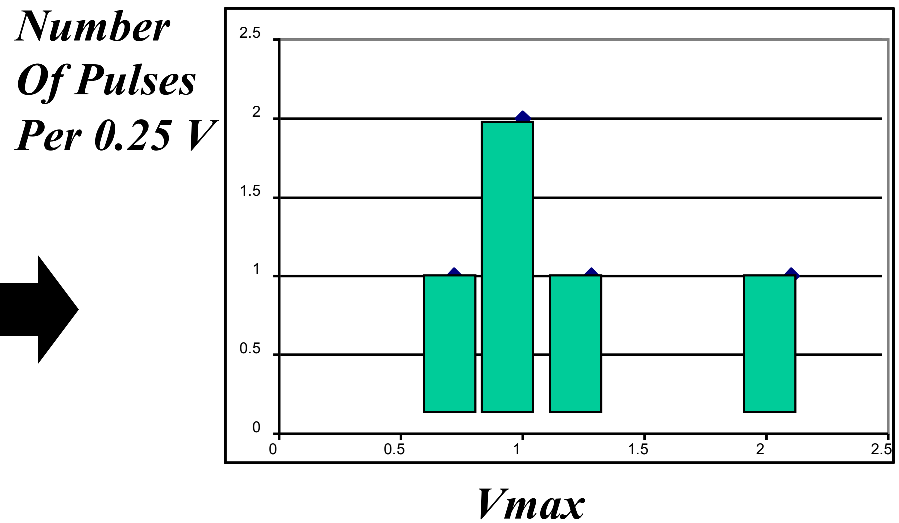


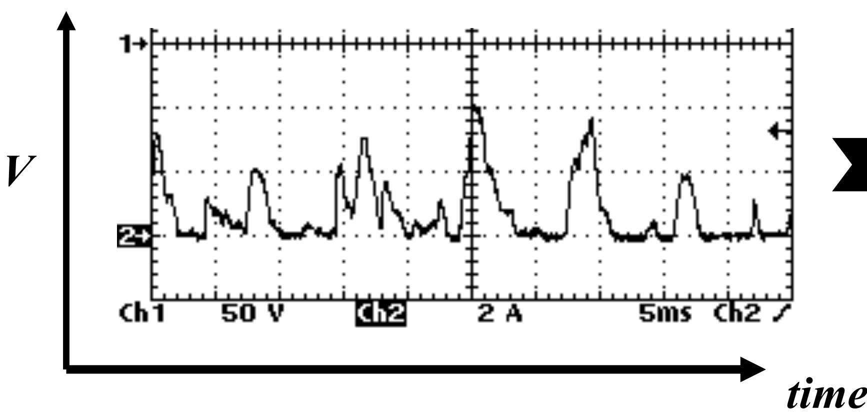
Fig. 4.1 Knoll, 3rd,4th Eds.

General Features of Detectors – Pulse Heights

Pulse Height Distribution: the detector usually produces a distribution of pulses even from a monoenergetic source due to statistical fluctuations, incomplete charge collection, geometrical path-length differences, or sometimes various interactions of the radiation in the bulk material.







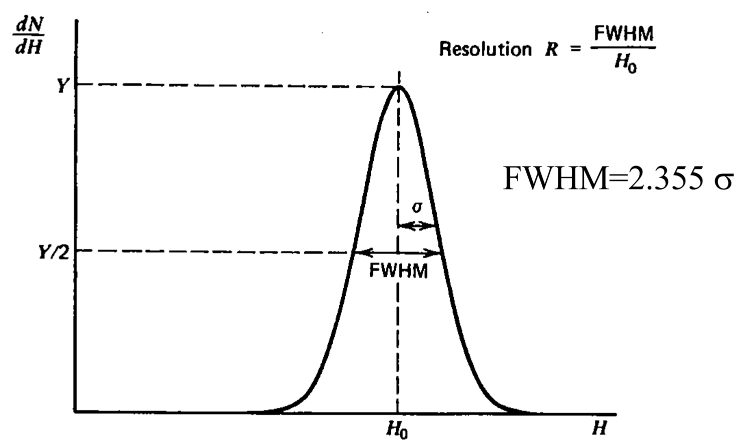


Fig. 4.5 Knoll, 3rd ,4th Eds.

General Features of Detectors – Resolution

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Pulse Height Resolution: a detector that is used to determine an energy signal must produce a signal that is proportional to the initial number of ion pairs. If the number of pairs is random, then for a system with a linear gain, κ:

$$R_{Poisson} = \frac{FWHM}{\bar{x}} = \frac{\kappa(2.355\sigma)}{\kappa\, N_{IP}} = \frac{\left(2.355\sqrt{N_{IP}}\right)}{N_{IP}} = \frac{2.355}{\sqrt{N_{IP}}}$$

$$N_{IP} = \frac{E}{w} \qquad \therefore \qquad R_{Poisson} \propto \frac{1}{\sqrt{E}} \qquad \left\{2.355 = 2\sqrt{2\ln 2}\right\}$$

Recall that the total number of IP's is not truly random, e.g. if "w" has a small range of values (very pure or single crystal materials), the energy deposited by a stopping particle will be an exact number. Thus, the resolution of the system can be "better" than statistical. $s^2 = \sigma^2 F$ where 'F' is the *Fano factor.*

U.Fano, Phys. Rev. 72 (1947) 26

Phys. Rev. 70 (1946) 44

$$R_{observed} = \frac{FWHM_e}{\bar{x}_e} = \frac{\left(2.355\sqrt{N_{IP}F}\right)}{N_{IP}} = 2.355\sqrt{\frac{F}{N_{IP}}}$$

Silicon, CdTe	F ~ 0.1 to 0.15
Pure gas	F ~ 0.2 to 0.4
Scintillator	F ~ 1

General Features of Detectors – Resolution –2–

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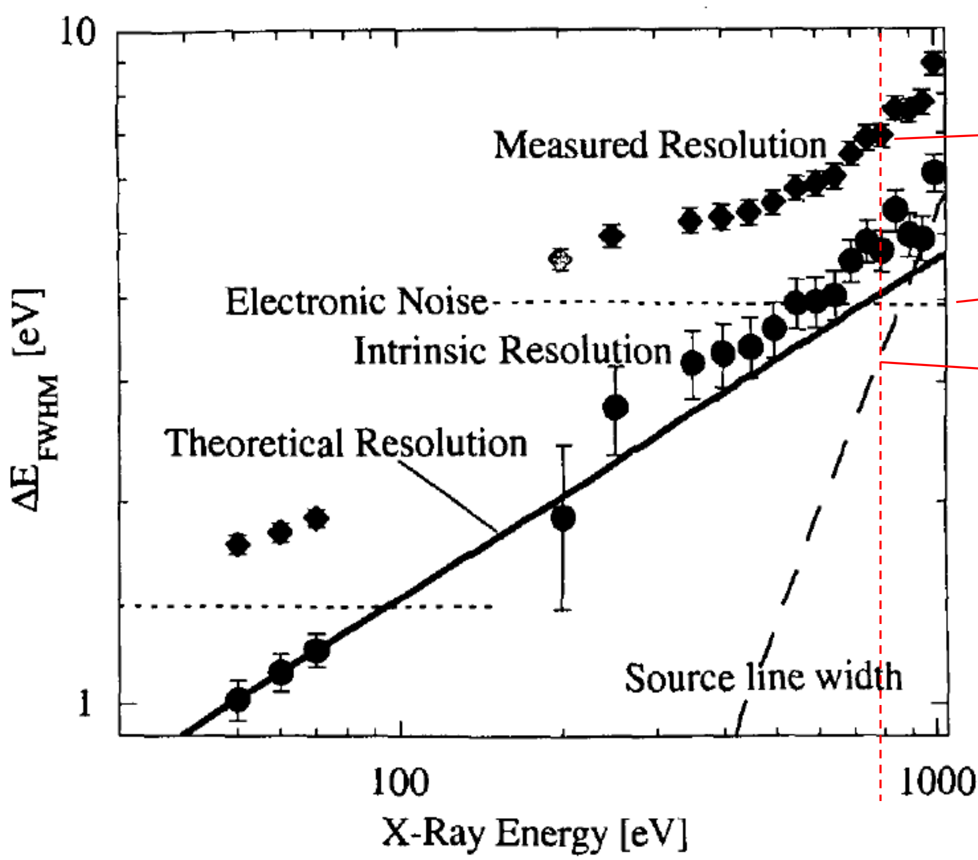
Pulse Height Resolution: The Resolution will be made up from several parts added together in quadrature. For example,

$$R^2_{observed} = R^2_{source\,lineshape} + R^2_{intrinsic} + R^2_{electronic\,noise} + \cdots$$



Example for data point at 800 eV

$R^2_{obs} = (7)^2$

$R^2_{noise} = (4)^2$

$R^2_{lineshape} = (3.3)^2$

Leaving $R^2_{intrinsic} \sim (4.7)^2$ at 800 eV

$R^2_{intrinsic}$ is to be compared to
$R^2_{theory} \sim F\,(w/E)$

Results for a Superconducting Tunnel-Junction Device by
Friedrich, et al. IEEE Trans. App.Supercon. 9 (1999) 3330

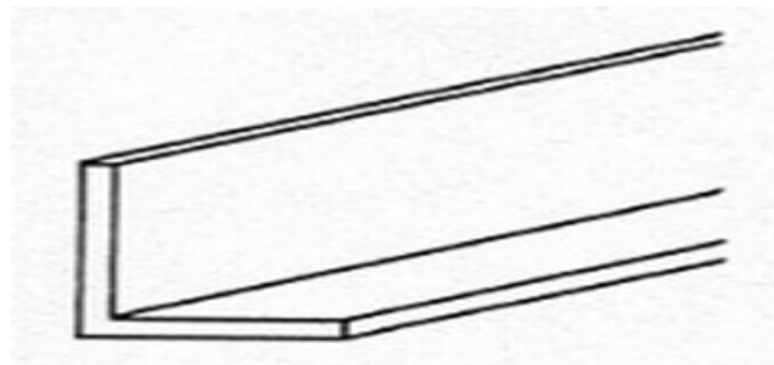
General Features of Detectors – Efficiency

Efficiency: total detection efficiency (a dimensionless quantity) is usually broken into three terms times an angular distribution function:

$$N_{obs} = N_{absolute}\,\varepsilon_{total} = N_{absolute}\,W(\Theta,\Phi)\,\varepsilon_{geo}\,\varepsilon_{intrinsic}\,\varepsilon_{electronic}$$

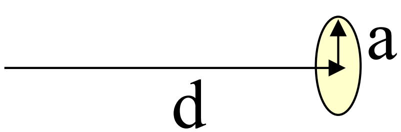
- the first three terms depend on the detector configuration and are *static* for a given detector configuration and radiation source.
- the electronic term is *rate dependent* and is due to the 'dead-time' of the system

$$\varepsilon_{geo} = \frac{\Omega}{4\pi} \leftrightarrow \Omega = 4\pi\,\varepsilon_{geo}$$



E.g., thin circular detector at a distance 'd'

$$\varepsilon_{geo} = \frac{1}{2}\left(1 - \frac{d}{\sqrt{d^2 + a^2}}\right)$$



With d=1	$\Omega = 4\pi\,\varepsilon_{geo}$	$\Omega \sim \pi\,a^2/d^2$
a= 0.01	0.000314 sr	0.000314 sr
a=0.05	0.00784	0.00785
a=0.1	0.0312	0.0314
a=0.5	0.663	0.785
a=1	1.84	3.14

General Features of Detectors – Dead Time – 1

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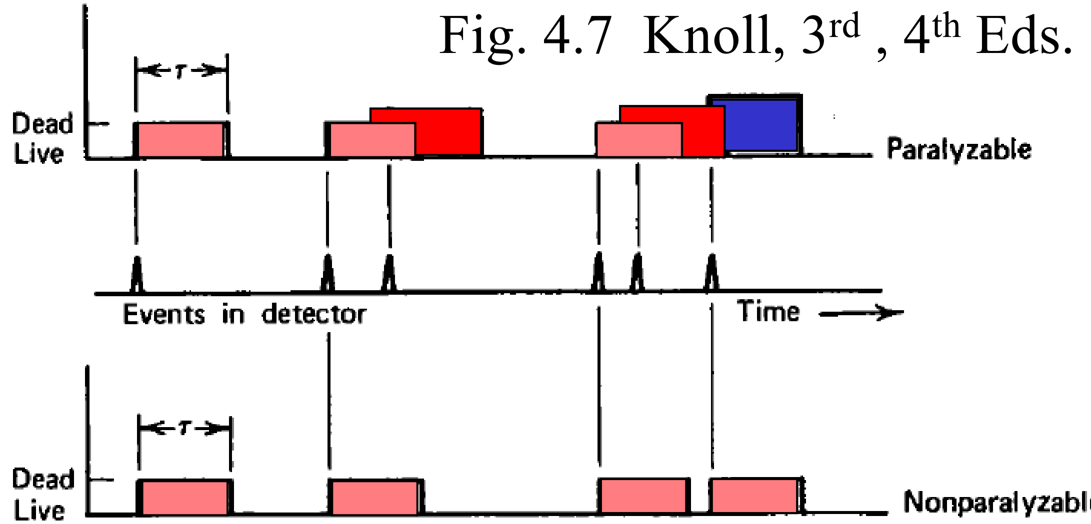
The ability (efficiency) of a system to measure and record pulses depends on the time taken up by all components of the signal processing. There are two classes of systems, those that require a fixed recovery time and those that don't.

Dead Time Models:

a) Paralyzable – detector system is affected by the radiation even if the signal is not processed. (a "slow" detector system)

b) Nonparalyzable – fixed dead-time

Fig. 4.7 Knoll, 3rd, 4th Eds.



True rate: r or n (in text)
Obs. rate: r_{obs} or m (in text) Dead-time: τ

a) Paralyzable – if the time gap between two events is larger than τ then both events will be recorded. If not, the second event will be lost. The observed rate is equal to the rate at which time intervals occur that exceed τ.

$$I_1(t)dt = r\, e^{-r\,t}\, dt \rightarrow P(\tau) = \int_{\tau}^{\infty} r\, e^{-r\,t}\, dt = e^{-r\,\tau}$$

$$r_{obs} = r\, e^{-r\,\tau} \qquad [m = n e^{-n\tau}]$$

N.B. True rate, r, is unknown.

General Features of Detectors – Dead Time – 2

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Dead Time Models:

b) Nonparalyzable – detector system is not affected if the signal is not processed. (a "fast" detector system)

Loss rate = $r - r_{obs}$ or $n - m$ (in text) : r is unknown

Fraction dead = $r_{obs}\,\tau$ or $m\,\tau$

Fraction live = $(1 - r_{obs}\,\tau)$ or $(1 - m\,\tau)$

$r_{obs} = r$ * Fraction live

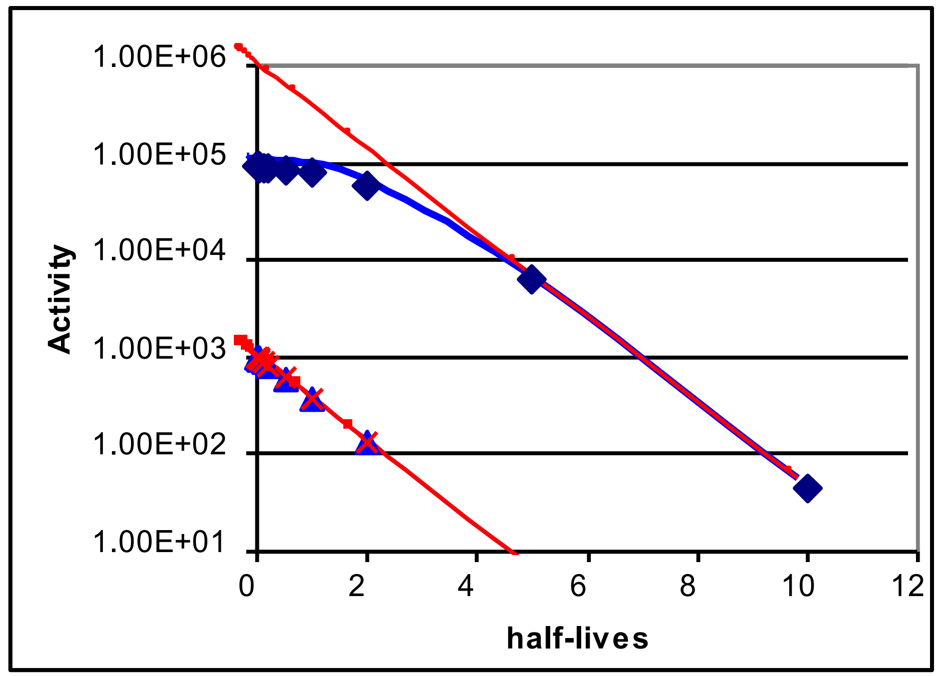
$r_{obs} = r\,(1 - r_{obs}\,\tau) \quad \rightarrow \quad r = r_{obs} / (1 - r_{obs}\,\tau)$

Decay example:

$A = A_0\, e^{-\lambda t}$

$A_0 = 10^6 \quad \tau = 10^{-5}$

$A_0 = 10^3 \quad \tau = 10^{-5}$



Deadtime in a non-paralyzable system leads to a depression of the decay curve of a source at short times (high rates) relative to that at long times (low rates).

General Features of Detectors – Dead Time – 3

Dead Time Models:

a) Paralyzable: $r_{obs} = r\, e^{-r\tau}$

b) Nonparalyzable: $r = r_{obs} / (1 - r_{obs}\, \tau)$

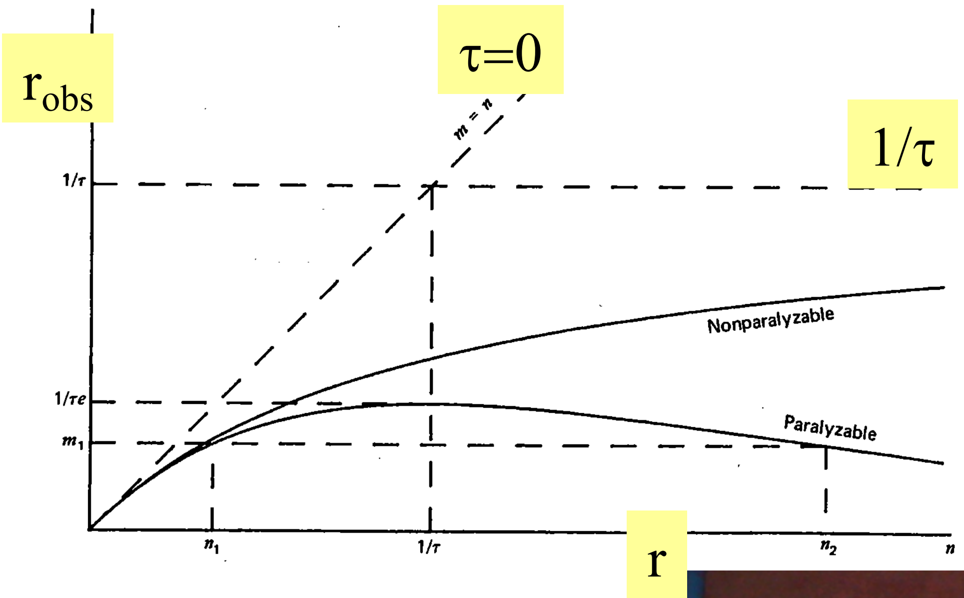


Fig. 4.8 Knoll, 3rd , 4th Eds.

General Features of Det. – Instantaneous Rate -1

Accelerated Beams:

a) Electrostatic machines – true "DC", use *Interval Distribution* of times

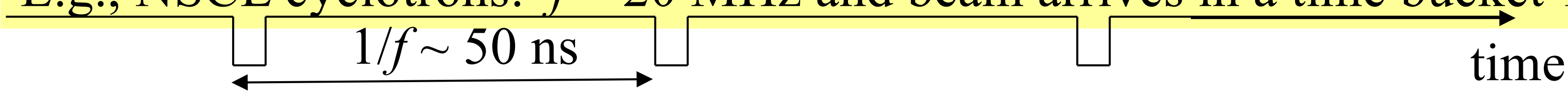
b) Rf-based machines – quantized arrival times & duty factor

  a) Cyclotrons – rf-micropulses appear as continuous current above tens of ns
    duty factor = 1 (accelerator is on), duty factor = 0 (accel. is off)

  b) Linacs – rf-micropulses (few ns) inside a macropulse (few ms)
    duty factor = macropulse time in ms / 1000

  a) Synchrotrons – rf-micropulses (few ns) inside a macro-spill (~ s)
    duty factor = 1 during spill, = 0 outside spill

E.g., NSCL cyclotrons: $f \sim 20$ MHz and beam arrives in a time bucket T< 2ns



$$f = 20\ MHz \rightarrow 2x10^7\ buckets/s$$

$$I = 16\ enA \rightarrow \Phi = \frac{16.x10^{-9}\ A}{q * 1.602x10^{-19}\ coul/part} = \frac{10^{11}}{q}\ part/s$$

E.g., reaction with a typical Be target in the A1900

General Features of Det. – Instantaneous Rate -2

E.g., NSCL cyclotrons: $f \sim 20$ MHz and beam arrives in a time bucket of T (ns)

Accelerated Beams and system deadtime, τ :

α) $\tau << T$, bucket much longer than deadtime, no effect on rate. (rare situation)

β) $\tau < T$, Knoll writes: "this is beyond the scope of the present discussion" Fortunately this is not applicable to cyclotrons and similar accelerators.

c) $T < \tau < [(1/f) - T]$ -- maximum of one event processed per bucket, first event of every bucket is processed

e.g., T=2 ns, $[(1/f) - T = 50 - 2]$ for NSCL requires $\tau < 48$ ns

d) $[(1/f) - T] < \tau$, event rate appears continuous, generally first event of random bucket is processed

Probability that at least one event occurs in a bucket is:

$$P_{x>0} = \sum_{i=1}^{\infty} P_i$$

$$P_{x>0} = 1 - P_{x=0} = 1 - e^{-\overline{X}}$$

$$P_{x>0} = 1 - e^{-r/f}$$

Observed rate per bucket:

$r_{obs} / f = 1 - e^{-r/f}$

Observed total rate:

$r_{obs} = f\,(1 - e^{-r/f}) \quad \rightarrow \quad r = f \ln(f/ f - r_{obs})$

Week 5: Chap. 5 Ion Chambers

Basic Detector Principles

Ion Chambers
-- Current Mode
-- Pulse Mode
--- signal shape
-- Grids
-- Examples

Proportional Counters