Part III:

Detection of ionizing radiations

Chapter 7: General properties of radiation detectors

Contents

- Basic principles of the detection
- Simplified detector model
- Operations modes
- Radiation spectroscopy
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- Dead time

Detector definition

A detector is an instrument that measures one of the quantities characterizing a particle. Attention is focused on particles that originate from direct or indirect nuclear phenomena → the domain of energies considered is restricted. Particle detection is a complex process → the questions must be answered are:

- Is a particle present?
- Which is its energy, its quantity of motion?
- In which direction is emitted the particle?
- Which is its nature?
- ...?

→ No universal detector can answers to all these questions

Types of measurements

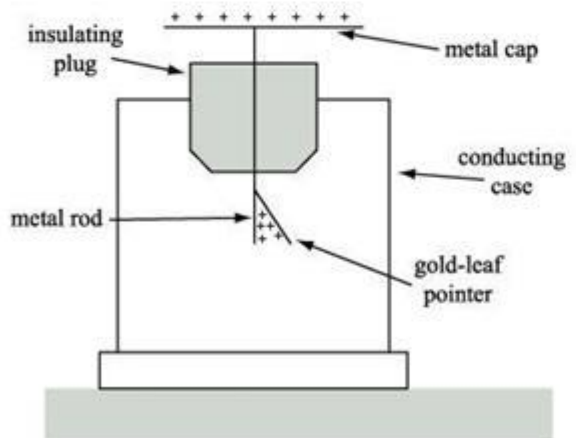
- Detector for instantaneous measurements of dose → dose rate → **monitor** → called « dosimeter » (ex: ionization chamber)

- Detector for integrated dose measurement (on a period of time) → **dosimeter** → called « integrating dosimeter » (ex: films, thermoluminescent dosimeters,…)

- Detector for the identification of incident particles → **spectrometer**

Basic principles of the detection: the electroscope

All detectors are based on the same fundamental principle:
the transfer of part or all of the radiation energy to the detector mass where it is converted into some other form that can be apprehended.



The electroscope rod is charged (suppose + charges) → the gold-leaf pointer moves away from its equilibrium position due to the repulsive force between positive charges on the pointer and on the rod. If the air in the box is ionized by radiation → the leave reaches back to its equilibrium position because of the production of negative and positive pairs of charges inside the box. Negative charges are attracted by the rod and the leave → smaller deviation of the leave.

Detection of N_i

An electroscope is then sensitive to the total amount N_i of negative and positive charges Q produced in the box

$$N_i = \frac{E_{abs}}{W}$$

Modern detectors are based on the same principle → the directly or indirectly measure of the number of ionizations produced by radiations inside a non-conductive medium and to transform it into electrical impulses

Importance of W!

Gas:	30 eV for one electron-ion pair
Scintillator:	between 20 and 500 eV for one photoelectron
semiconductor	between 3 and 10 eV for one electron-ion pair

Detection methods

All detection methods are based on the detection of charged particles (direct measurement), neutral particle must first interact and produce charged particles before they can be detected (indirect measurement)

3 principal detection methods:

- Gas ionization detectors
- Semiconductor detectors
- Scintillators

Other methods exist but are less used

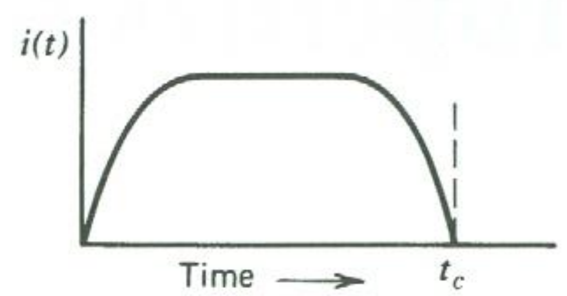
Simplified detector model (1)

- Consider a hypothetical detector subject to the interaction of a single particle or radiation quantum in its active volume through one of the mechanisms discussed in part I
- Interactions time is short → the energy deposition is **instantaneous**
- Appearance of an electric charge Q within the active volume of the detector at time t = 0
- This charge is collected to form the basic electric signal
- Collection of the charge is accomplished through the imposition of an electric field → migration of + and - charges in opposite directions

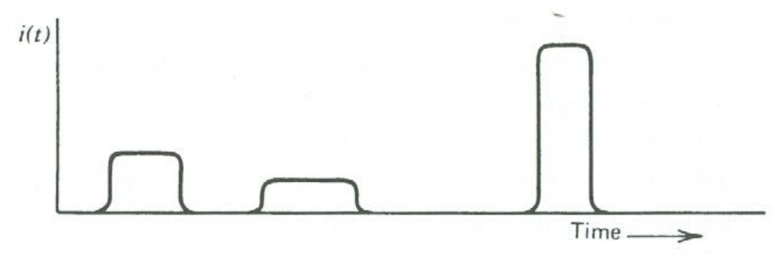
Simplified detector model (2)

- Time required to fully collect the charge (charge collection time t_c) is variable from one detector to another (1 ns < t_c < 100 μs) ↔ charge mobility, traveled distance,...
- Response of the detector:

$$\int_0^{t_c} i(t)dt = Q$$



- Magnitude and duration of each current pulse depend on the type of interactions



Simplified detector model (3)

- The probability to observe radiations follows Poisson statistics → the time between 2 pulses follows the Erlang distribution

- If 2 individual pulses deposit their energy at the same time in the active volume of the detector → the measured current will be the sum of the currents due to both particles → the particles are indistinguishable

- We always assume that *a*, the mean number of disintegrations per time unit is « small » enough to have one individual pulse for each individual incident particle

Operation modes

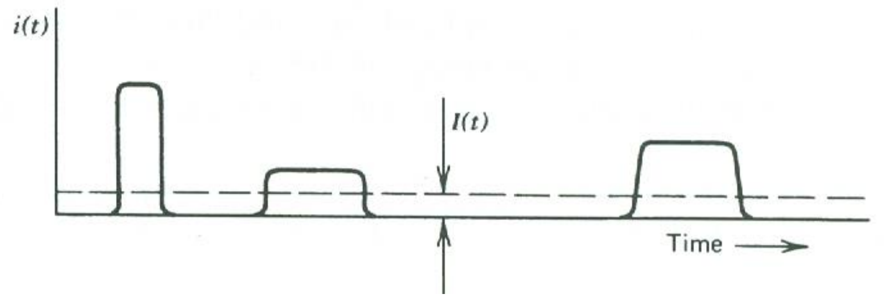
3 operations modes:

- Pulse mode: most common use
- Current mode: used when event rates are very high
- Mean square voltage mode (MSV): used when charges produced by two type of radiations differ a lot

Current mode

A current-measuring device (a picoammeter) is connected to the detector:

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



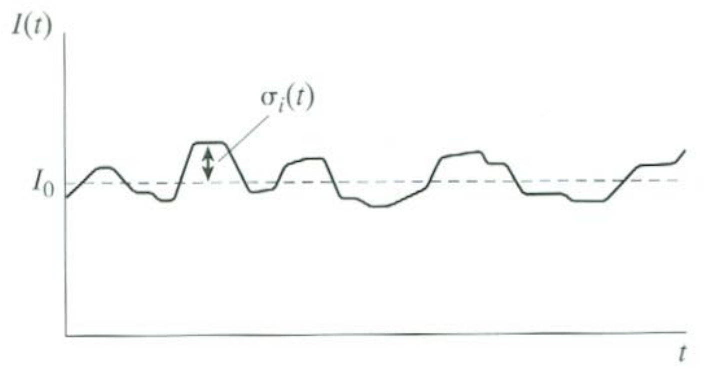
with T the response time of the measuring device , long compared with the average time between individual pulses → an average current I_0 is recorded such as $I_0=rQ$ (r: interaction rate and Q: charge per interaction → $Q = E_{abs}e/W$) →

$$I_0 = r\frac{E_{abs}}{W}e$$

used when current pulses from successive events overlap in time

Fluctuation mode (1)

- Developed by Campbell in 1946 → also called Campbell mode or mean square voltage mode
- The average current I_0 is blocked and only current fluctuations $\sigma_I(t)$ are measured →



- The variance is given by →

$$\overline{\sigma_I^2(t)} = \frac{1}{T}\int_{t-T}^{t} [I(t') - I_0]^2 dt' = \frac{1}{T}\int_{t-T}^{t} \sigma_i^2(t')dt'$$

Fluctuation mode (2)

- Poisson statistics (with *n*, the mean number of events recorded during time *T*) → the mean deviation of the number of recorded events is →

$$\sigma_n = \sqrt{n} = \sqrt{rT}$$

- If each pulse corresponds to the same charge *Q* →

$$\frac{\overline{\sigma_I(t)}}{I_0} = \frac{\sigma_n}{n} = \frac{1}{\sqrt{rT}}$$

- With the definition of $I_0 = rQ$ →

$$\overline{\sigma_I^2(t)} = \frac{rQ^2}{T}$$

Fluctuation mode (3)

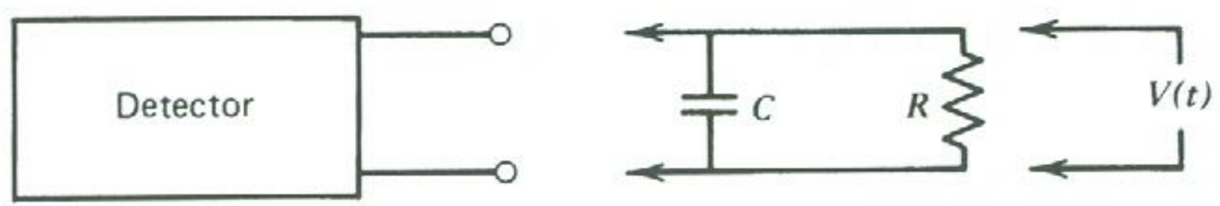
- In practice → the mean current is blocked → fluctuations are measured → squaring the result → response $\propto$ to r and Q^2

- Response in Q^2 → when we have a mixed radiations environment which produce very different charges Q → the radiation giving the greater charge Q is weighted → discrimination of the radiations producing very different charges (example: mixed radiations: neutron-γ)

- In practice → not very often used

Pulse mode (1)

- The detector is designed to record each individual radiation that interacts in its active volume.
- The nature of one signal pulse depends of the input characteristics of the circuit to which the detector is connected (usually a preamplifier)



- C: equivalent capacitance of both detector and measuring circuit
- R: input resistance of the external circuit
- V(t): measured time-dependent voltage

Pulse mode (2)

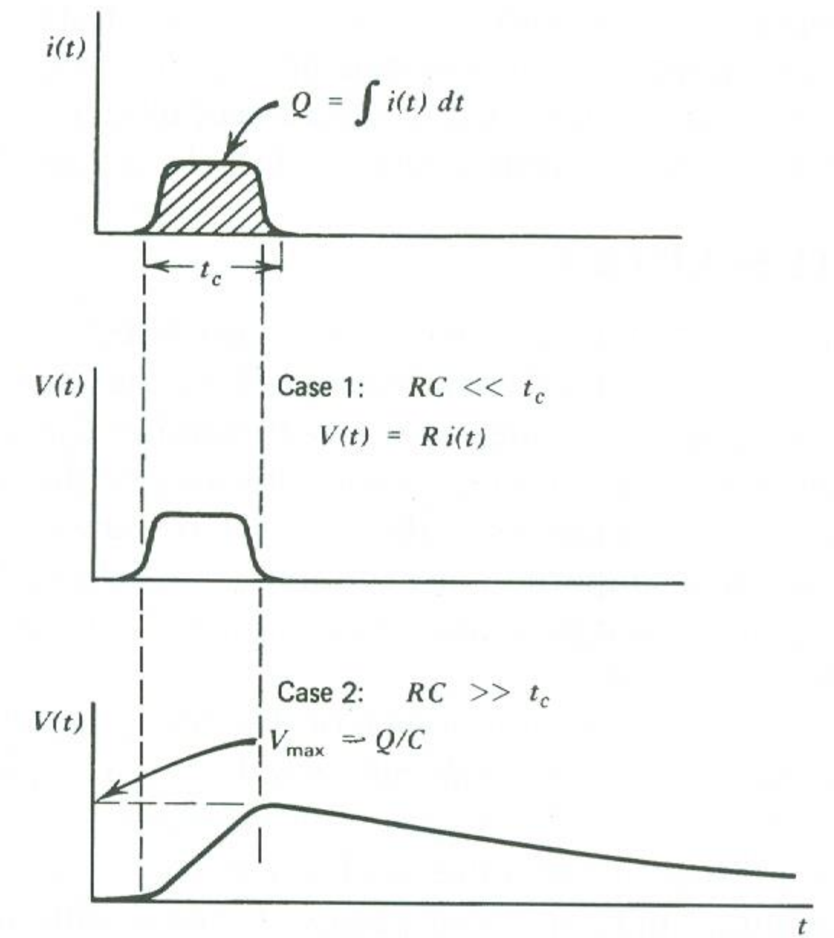
Two separate extremes of operation depending on the time constant τ= RC of the measuring circuit:

1. $\tau \ll t_c$: V(t) has a shape identical to the current from the detector → used when high event rate is more important than accurate energy information
2. $\tau \gg t_c$: the amplitude of the signal pulse V_{max} is determined by V_{max}=Q/C

   Rising time ↔ detector

   Falling time ↔ external circuit

   → most common



Pulse mode (3)

The pulse mode is the most used mode because

1. The sensitivity of the detector in pulse mode is largely better than the sensitivity for the 2 other → each pulse is individually detected → the pulse is easily separated from the noise of the background while in current mode the level of noise can be high
2. In pulse mode → each pulse gives useful information while in current mode a mean current is measured → loss of information

Radiation spectroscopy

- Operating in pulse mode (generally with $\tau \gg t_c$)
- Large numbers of pulses
- Different amplitudes of the pulses because
  - each interaction do not imply the total absorption of the energy of the incident particle in the detector
  - not a constant signal for a given energy due to the inherent response of the detector

⇨ The pulse amplitude distribution is a fundamental property of the detector output and is used to deduced information about the incident radiation

⇨ **Radiation spectroscopy**

Pulse amplitude displaying

The most common way is the differential pulse height distribution:

→ The abscissa is a linear pulse amplitude scale in volts or analog to digital converter (ADC) counts

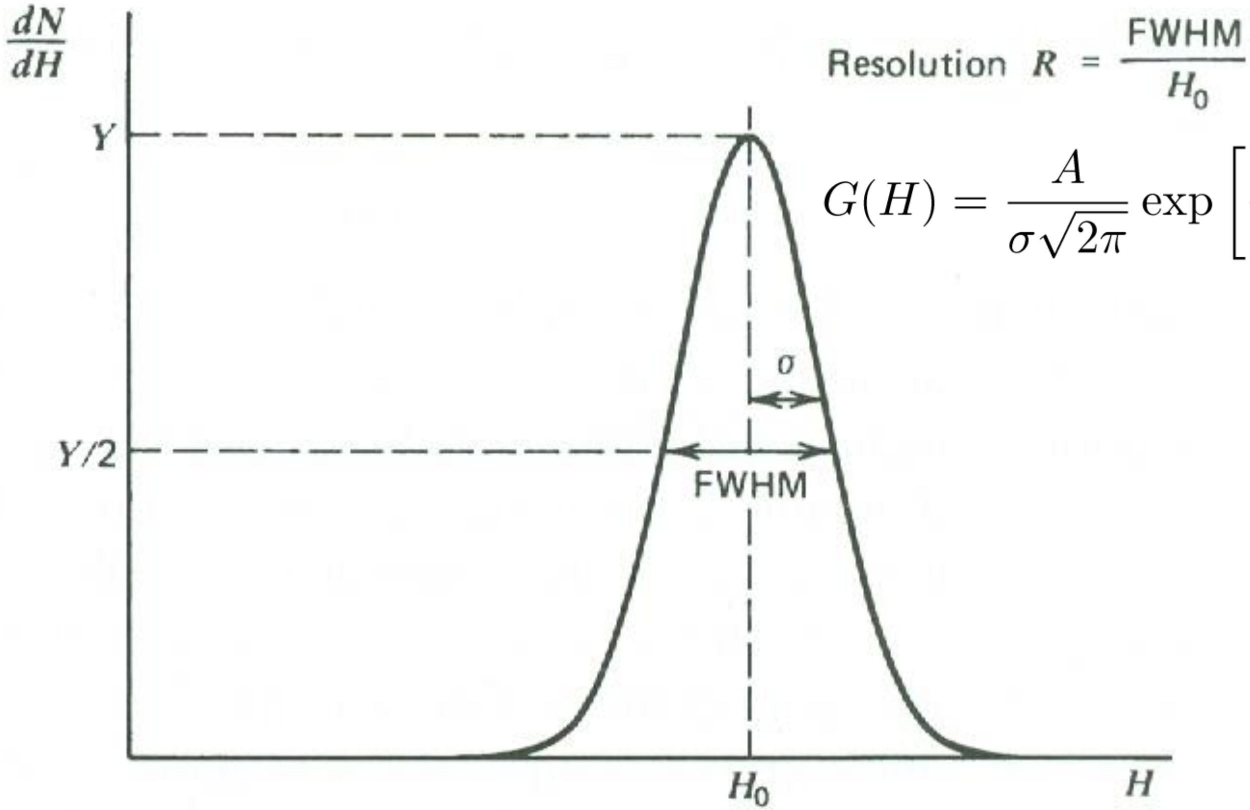
→ The ordinate is the differential number dN of pulses observed with an amplitude within the differential amplitude increment dH divided by that increment: dN/dH

→ The number of pulses with amplitude between two values is obtained by integrating the area between those two limits

→ Presence of peaks (H_0) in the distribution → indicates the detection of an incident particle with a precise energy

→ In many detectors: linear response → $H_0=KN_i$

Example of differential pulse height distribution



$$G(H) = \frac{A}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(H - H_0)^2}{2\sigma^2}\right]$$

The energy resolution R of the detector is conventionally defined as the full width at half maximum (FWHM) divided by the location of the peak centroid H_0 generally associated with a Gaussian

Detector resolution (1)

- Different processes are involved → complex determination

- If the number of ionizations is Poisson distributed → the standard deviation of the peak $\sigma(H_0)$ is obtained from $\sigma^2(H_0)=\sigma^2(KN_i)=K^2\sigma^2(N_i)$ → $\sigma(H_0)=K(N_i)^{1/2}$

- The resolution R is (we recall FWHM $= 2\sqrt{2\ln 2}\,\sigma$):

$$R = \frac{\mathrm{FWHM}}{H_0} = \frac{2.355\sigma}{H_0} = \frac{2.355K\sqrt{N_i}}{KN_i} = \frac{2.355}{\sqrt{N_i}} = 2.355\sqrt{\frac{W}{E_{abs}}}$$

- We observe that the resolution is improving (i.e. ↘) when N_i ↗ or equivalently when W ↘

Detector resolution(2)

- We have

Gas:	30 eV for one electron-ion pair
Scintillator:	between 20 and 500 eV for one photoelectron
semiconductor	between 3 and 10 eV for one electron-ion pair

- $R_{\text{semiconducteur}} < R_{\text{gas}} < R_{\text{Scintillator}}$

Resolution with Fano factor

- However fluctuations are not well described by Poisson statistics → introduction of the empirical Fano factor F → it includes all differences from Poisson statistics
- With Fano factor →

$$R = 2.355\frac{\sqrt{FN_i}}{N_i} = 2.355\sqrt{\frac{FW}{E_{abs}}}$$

- If F = 1 → Poisson statistics
- For many detectors such semiconductors or gases: F<1

Detection efficiency (1)

- Charged particles → immediate interaction with the detector → the detector detects each particle who goes inside its active volume
- Non-charged particles → the particle can enter inside the active volume of the detector abd comes out without interaction → no detection
- Necessity to define a notion of efficiency
- We define two classes of efficiencies → absolute efficiency and intrinsic efficiency

Detection efficiency (2)

1. Absolute efficiency (dependent on the detector properties and on counting geometry):

$$\epsilon_{abs} = \frac{\text{number of pulses recorded}}{\text{number of radiation quanta emitted by the source}}$$

2. Intrinsic efficiency (dependent on the detector properties):

$$\epsilon_{int} = \frac{\text{number of pulses recorded}}{\text{number of radiation quanta incident on detector}}$$

If the source is isotropic → $\epsilon_{int} = \epsilon_{abs}(4\pi/\Omega)$

Ω is the solid angle of the detector seen from the source position

Detection efficiency (3)

- We can also define efficiencies as a function of the nature of the recorded event
- If we accept all pulses from the detector without discrimination on the deposited energy → we have the total efficiency ϵ_{tot}
- If we consider only pulses such as all the energy is deposited in the detector → we have the peak efficiency ϵ_{peak}
- Example of incident photons on the detector → spectrum with a Compton edge and a total absorption peak → ϵ_{tot} corresponds to the total spectrum and ϵ_{peak} corresponds to the total absorption peak
- We sometimes define the ratio peak-on-total $r = \epsilon_{peak} / \epsilon_{tot}$

Detection efficiency (4)

- We can also combine the 2 types of probabilities → for instance → an efficiency often tabulated is the intrinsic efficiency of the peak, ϵ_{ip}

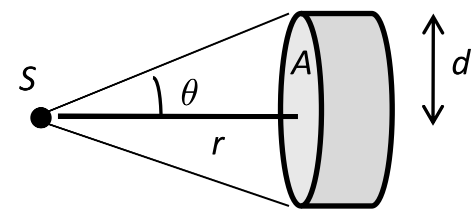
- For a source of photons isotropic and monenergetic emitting *S* radiations during a time *T* and N_p, the number of events corresponding to the total absorption peak recorded during time *T* →

$$S = N_p \frac{4\pi}{\epsilon_{ip}\Omega}$$

Solid angle

- The solid angle is defined by →

$$\Omega = \int_A \frac{\cos\theta}{r^2} dA$$



- For a source on the axis of the cylinder depicting the detector →

$$\Omega = 2\pi \left(1 - \frac{r}{\sqrt{r^2 + d^2}}\right)$$

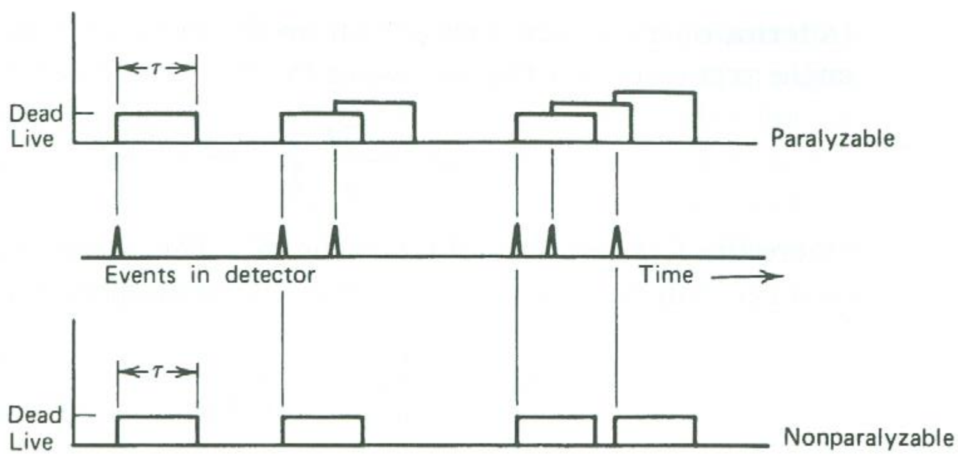
- For $r \gg d$ →

$$\Omega \simeq \frac{\pi d^2}{r^2}$$

Dead time

Minimum amount of time that must separate two events in order that they be recorded as two separate pulses → Two models of dead time:

1. paralyzable response (also called cumulative)
2. nonparalyzable response (also called noncumulative)



→ Real counting systems are intermediate

Response detector: Nonparalyzable

n: true interaction rate, m: recorded count rate, τ: dead time

Nonparalyzable: fraction of time for which the detector is dead is $m\tau$ → rate at which true events are lost is $nm\tau$ → but rate of losses is also $n-m$ → $nm\tau = n-m$ →

$$n = \frac{m}{1 - m\tau} \quad \Longleftrightarrow \quad m = \frac{n}{1 + n\tau}$$

Response detector: paralyzable

Paralyzable: dead periods are not always of fixed length → distribution of time intervals between events at a rate n is

$$P(t) = n \exp(-nt)$$

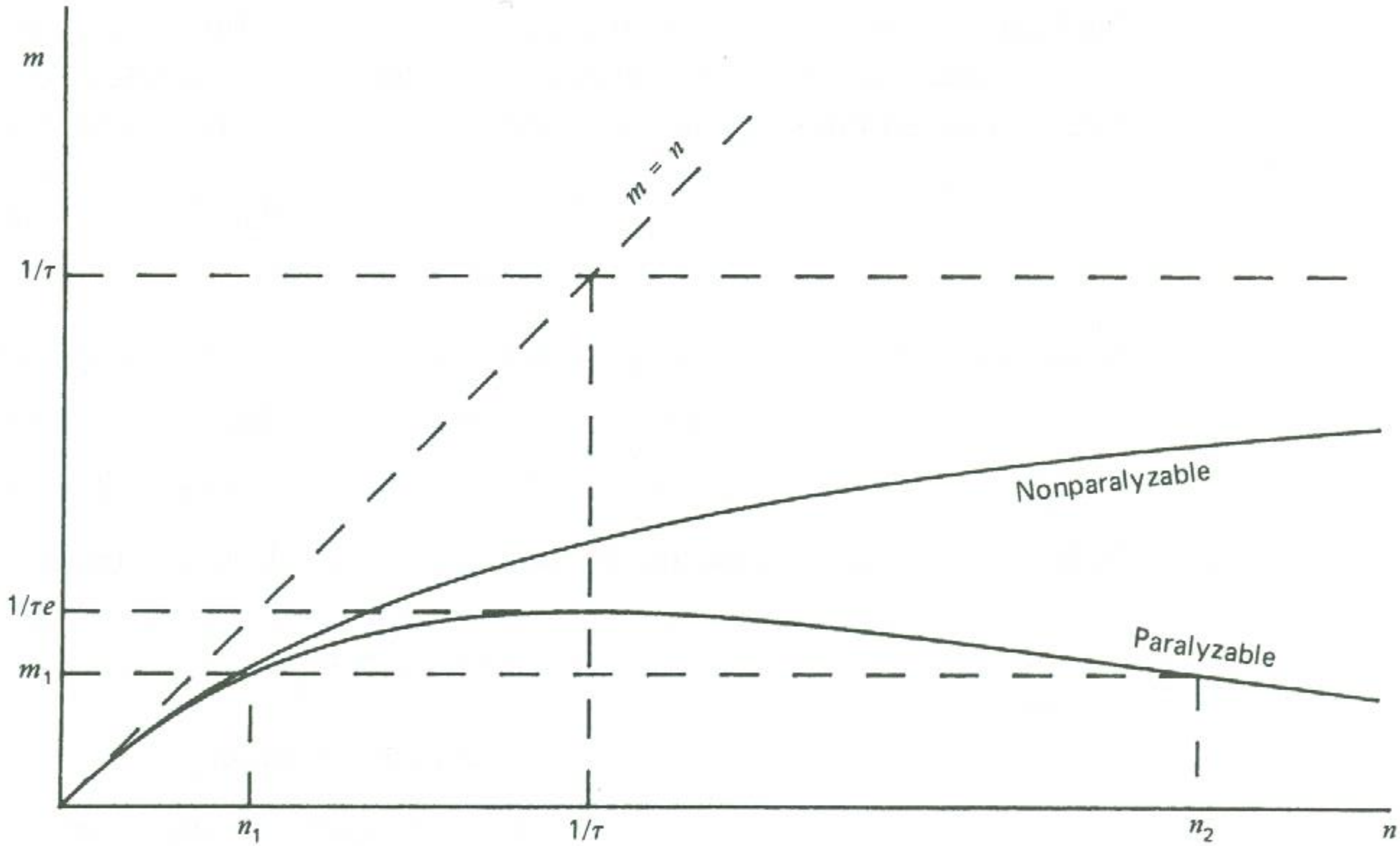
The probability that t >τ is then

$$P(t > \tau) = n \int_{\tau}^{\infty} \exp(-nt) dt = \exp(-n\tau)$$

The rate of occurrences of such intervals is obtained by multiplying this expression by the true rate n to obtain

$$m = n \exp(-n\tau)$$

Plots of observable rates m



For low rates n → $m \cong n(1 - n\tau)$