Queen Mary
University of London
Science and Engineering

Radiation Detectors (SPA 6309)

Lecture 4

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What is this lecture about?

- The principles of detection of ionising radiation
  - Interaction of charged and neutral particles with matter
  - Gaseous sensors
  - Semiconductor sensors
  - Scintillators
- Sensor systems used in particle and nuclear physics
  - Calorimeters
  - Tracking detectors
  - Neutrino detectors

Key points from previous lecture

- The interactions of photons and scattering
- Variety of interactions for photons
  - Photoelectric dominates below ~ 100 keV, important for gamma ray spectroscopy using high-Z scintillators.
  - Compton scattering (inelastic scatter) important in the range 100 keV to ~ 10 MeV
  - Above 1.02 MeV (twice the electron rest mass) pair production is possible. Above ~10 MeV this is the dominant interaction for photons.
- Scattering
  - Elastic scattering (Rutherford) and inelastic (Coulomb)
  - Scattering can provide a flux of (low energy) particles coming back out of a material exposed to an incident beam.

Neutrons

- Uncharged particles.
- Interact with nuclei but only when in close proximity.
- Interaction probability very dependent on energy and (to some extent) nucleus.

Thermal neutrons:

E < 1/40 eV (thermal energy at 300 K), slow diffusion, nuclear capture

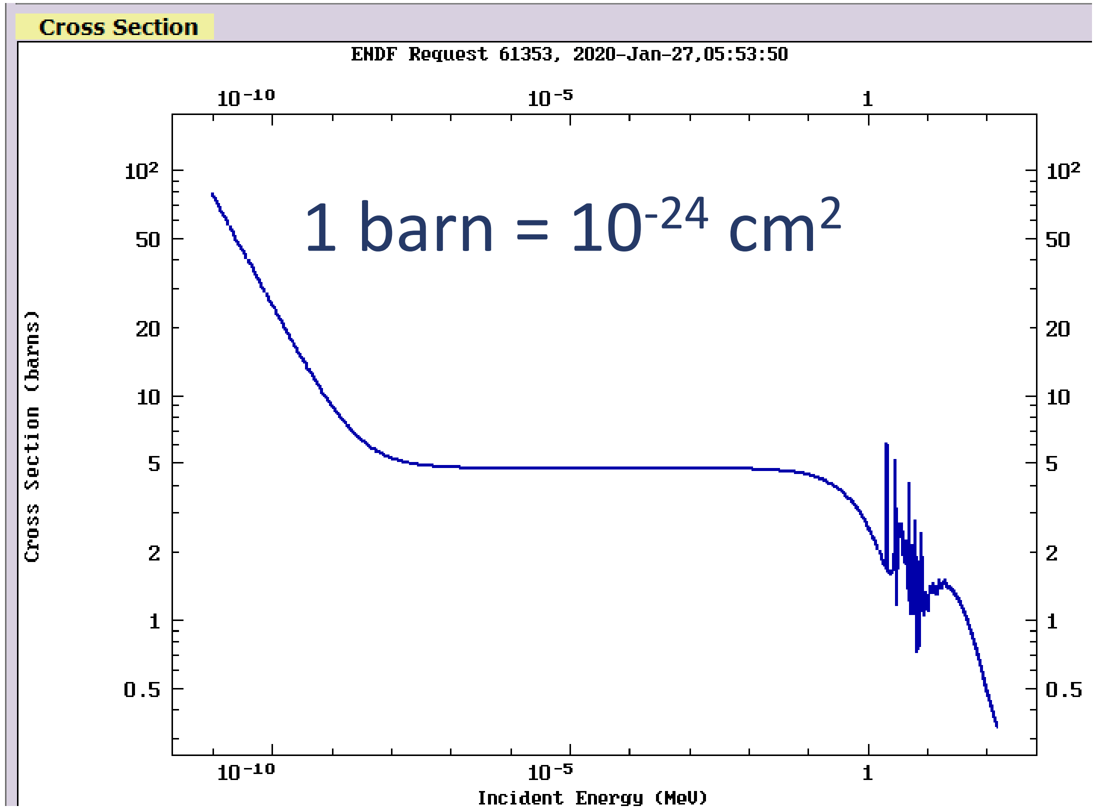
Intermediate energy neutrons:

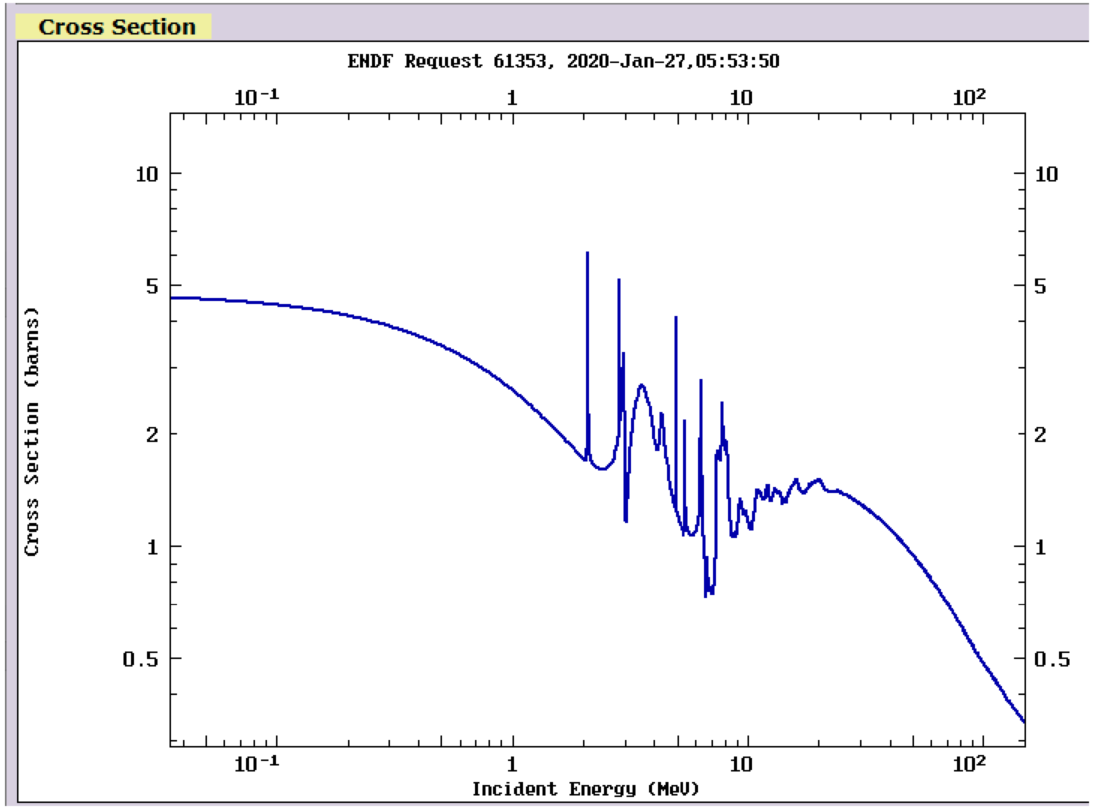
E < 10 MeV, mainly elastic scattering and capture processes [the range 0.1 eV to 100 keV is called *epithermal*]

Fast neutrons:

E > 10 MeV, inelastic scatter, nuclear reactions

Neutrons





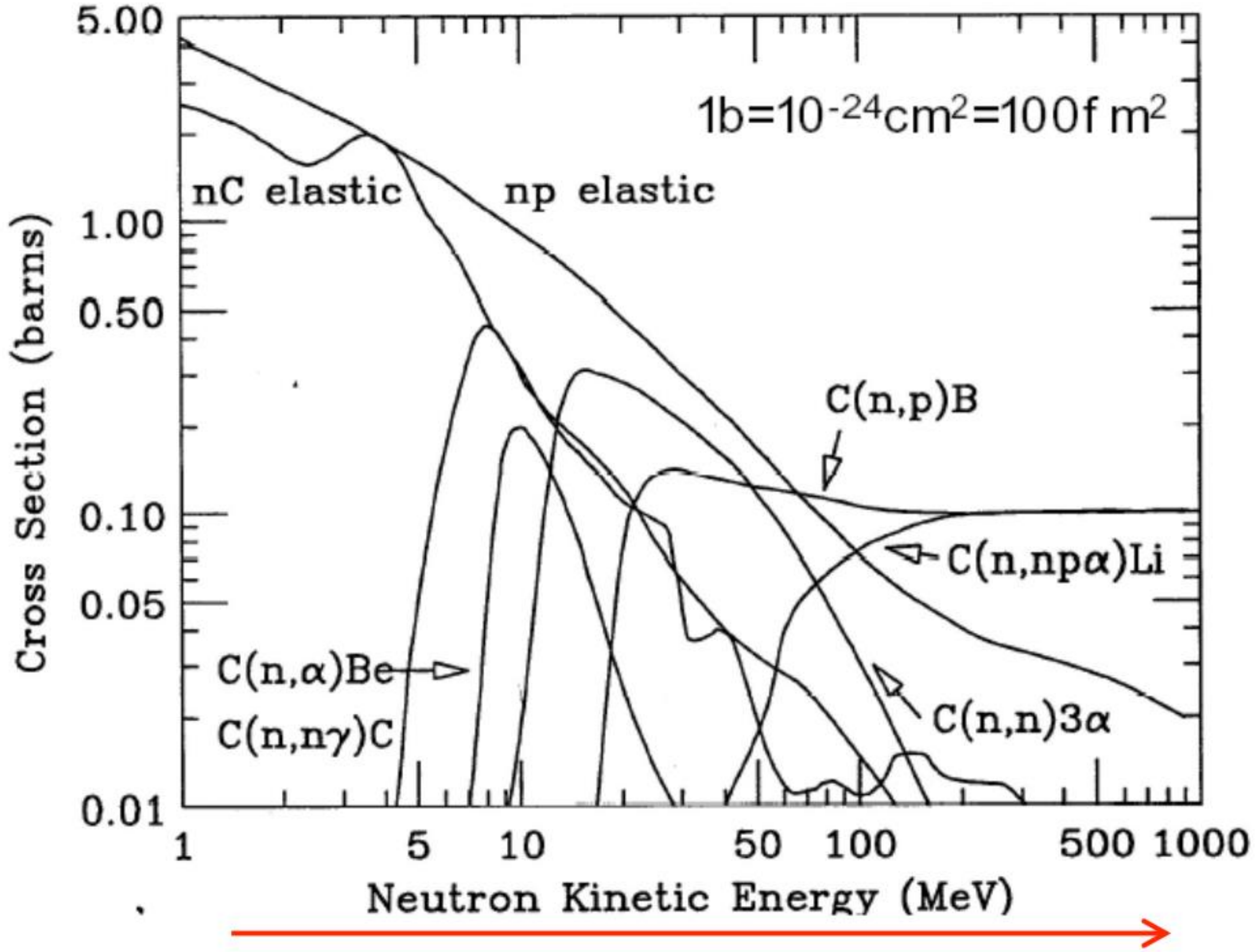
Total cross-section for ^{12}C. Data from National Nuclear Data Center https://www.nndc.bnl.gov/

Neutrons

Characteristic secondary particles

- Gamma rays
- Protons, alphas, tritons
- Neutrons
- Nuclear fragments (fission)

Neutrons



Cross-section for ^{12}C.

Cherenkov effect

A charged particle radiates if its velocity is greater than the local phase velocity of light (Cherenkov radiation) or if it crosses suddenly from one medium to another with different optical properties (transition radiation). Neither process is important for energy loss, but both are used in high-energy and cosmic-ray physics detectors.

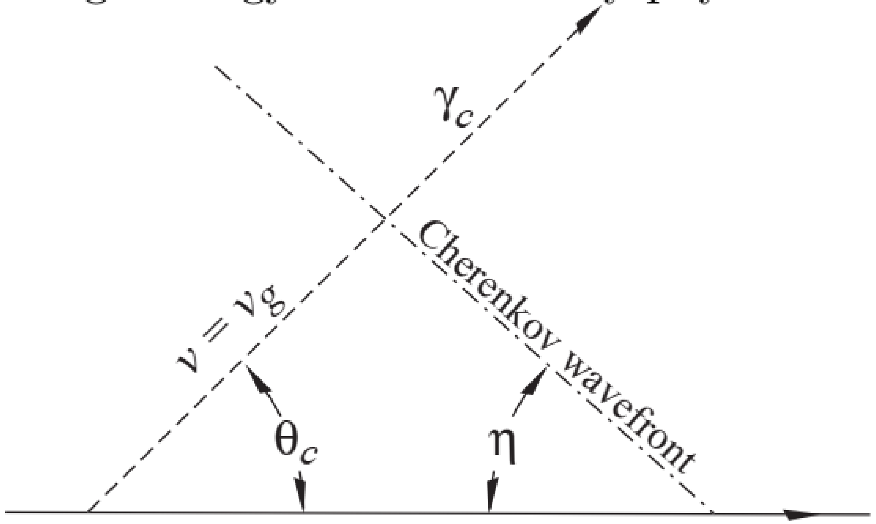


Figure 33.26: Cherenkov light emission and wavefront angles. In a dispersive medium, $\theta_c + \eta \neq 90^0$.

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

Cherenkov effect

There is a threshold, dependent on the refractive index and the particle velocity below which no light is emitted.

The angle θ_c of Cherenkov radiation, relative to the particle's direction, for a particle with velocity βc in a medium with index of refraction n is

$$\begin{aligned} \cos\theta_c &= (1/n\beta) \\ \text{or} \quad \tan\theta_c &= \sqrt{\beta^2 n^2 - 1} \\ &\approx \sqrt{2(1 - 1/n\beta)} \quad \text{for small } \theta_c, \textit{e.g.} \text{ in gases.} \end{aligned} \tag{33.43}$$

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

Cherenkov effect

The amount of light emitted, per cm, is very small so not in any way significant as an energy loss mechanism but is used in a number of practical particle detectors (see later lectures).

Note the $1/\lambda^2$ dependence on $dN/d\lambda$

The number of photons produced per unit path length of a particle with charge ze and per unit energy interval of the photons is

$$\frac{d^2N}{dEdx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e\, m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$
$$\approx 370 \sin^2\theta_c(E)\ \mathrm{eV^{-1}cm^{-1}} \qquad (z = 1)\ , \tag{33.45}$$

or, equivalently,

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) . \tag{33.46}$$

α is the "fine structure constant"

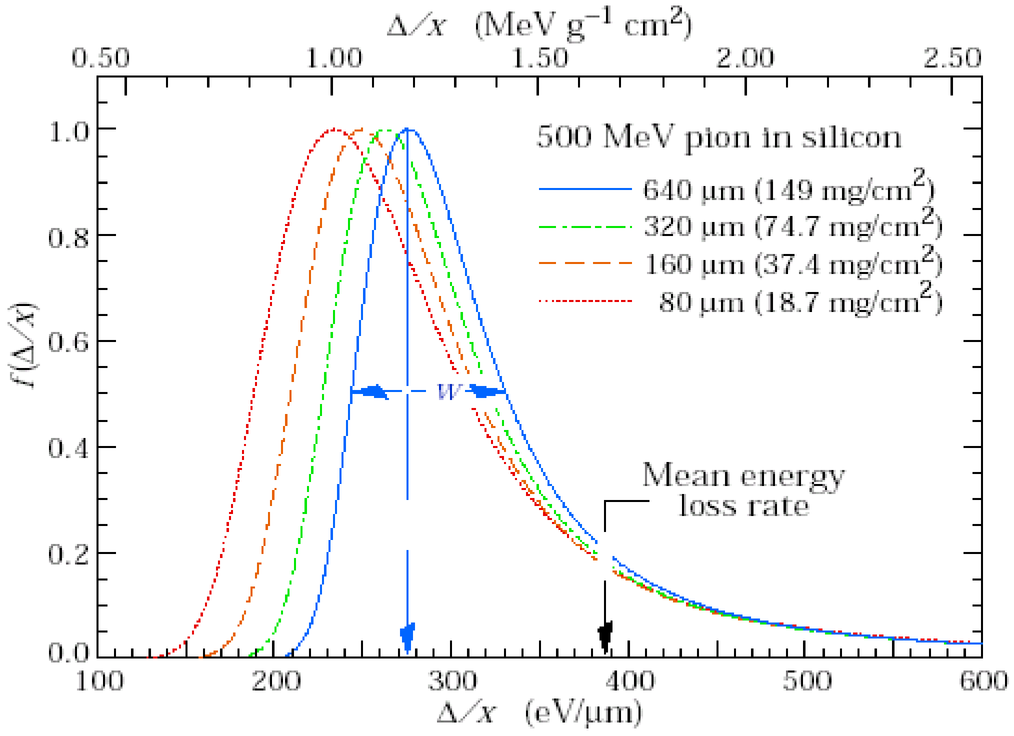
$\alpha = e^2/4\pi\epsilon_0\hbar c$

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

Energy loss in "thin" absorbers

- In "thin" materials the energy loss is dominated by a small number of interactions each with a wide range of energy transfers allowed.
- Thus we get the *Landau* distribution which has a **very long high energy tail and is very far from a Gaussian**.
- Thus energy resolution is poor, and signals have a large dynamic range (affects design of electronics).
- To *measure dE/dx* (for particle ID for example) we need to have a large number of independent samples.

Thin absorbers



500 MeV pions in silicon. *W* = FWHM

Gaseous detectors

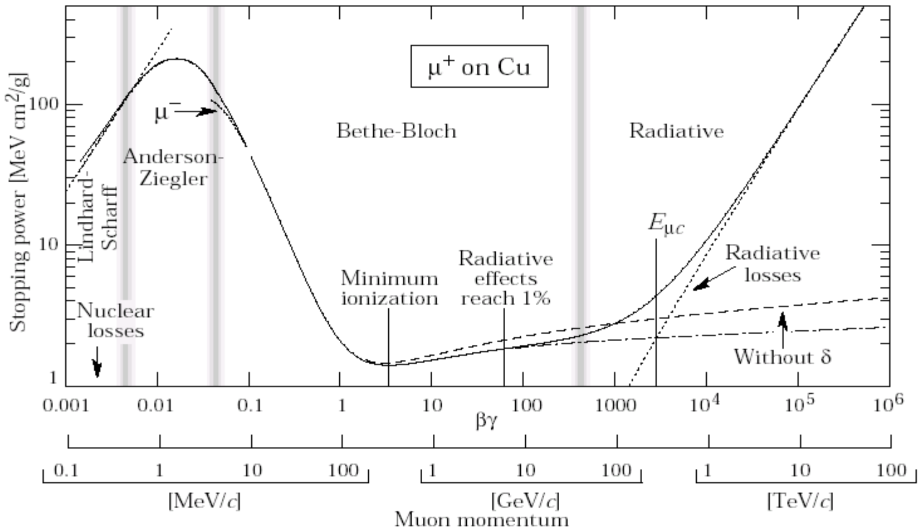
- Relatively small amounts of energy can ionise a gas atom/molecule. Typically 25 – 35 eV to produce one ion-pair.
- In the absence of an electric field the ions rapidly lose energy by collisions with gas molecules.
- The diffusion follows a Gaussian distribution with an rms given by

$$\sigma_x = \sqrt{2Dt} \quad \text{linear}$$

$$\sigma_V = \sqrt{6Dt} \quad \text{volume}$$

D is the diffusion coefficient (0.34 $cm^2.s^{-1}$ for H_2 and 0.04 $cm^2.s^{-1}$ for Ar)

Gaseous detectors



Note the rapid fall until a minimum is reached at about $\beta \approx 0.97$.
Then there is a slow "relativistic rise" as the velocity approaches c.
In most materials the energy loss at the minimum is close to 2 $MeV.g^{-1}cm^2$ (hydrogen is an exception).

Gas	Z	A	$MeVg^{-1}cm^2$	$keV.cm^{-1}$
H_2	2	2	4.03	0.34
Ar	18	40	1.47	2.44
CO_2	22	44	1.62	3.01
C_4H_{10}	34	58	1.86	4.50

Gaseous detectors

- When an external electric field is applied a net movement along the field direction is observed.
- The *average* velocity is called the drift velocity *w* and is proportional to the reduced field *E/P* (up to quite high fields). It is useful to define the mobility $\mu = w/E$.
- The mobility depends on the ion and the gas.

Gas	Ion	Mobility ($cm^2.V^{-1}.s^{-1}$)
Ar	Ar^+	1.7
Ar	CH_4^+	2.26
CO_2	CO_2^+	1.09
He	He^+	13.0

Electron drift

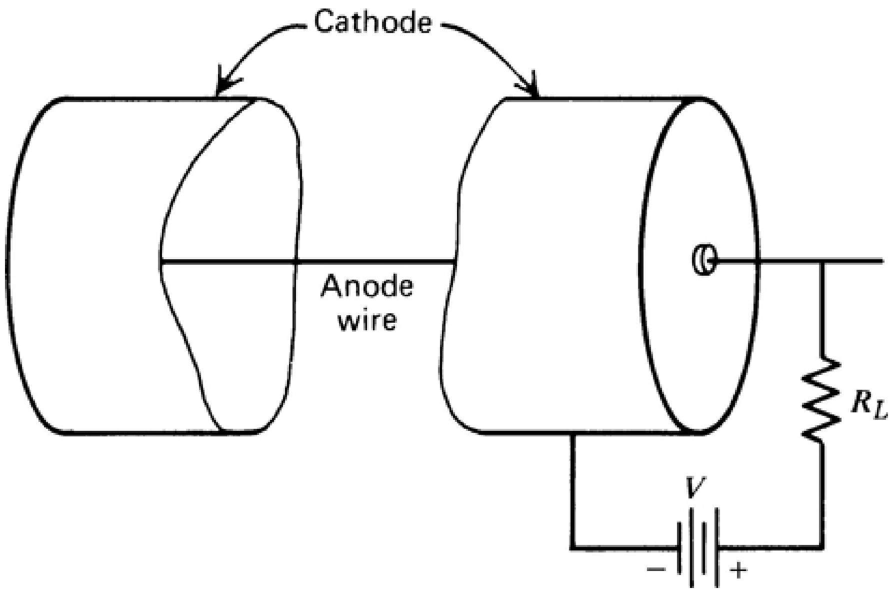
- When an external electric field is applied a net movement along the field direction is observed.
- The mobility of electrons is *not* constant with field.
- Electrons drift **much more rapidly than ions**. At high fields, velocities of order 5 cm/μs are typical which is about 1000 faster than typical ion drift velocities.

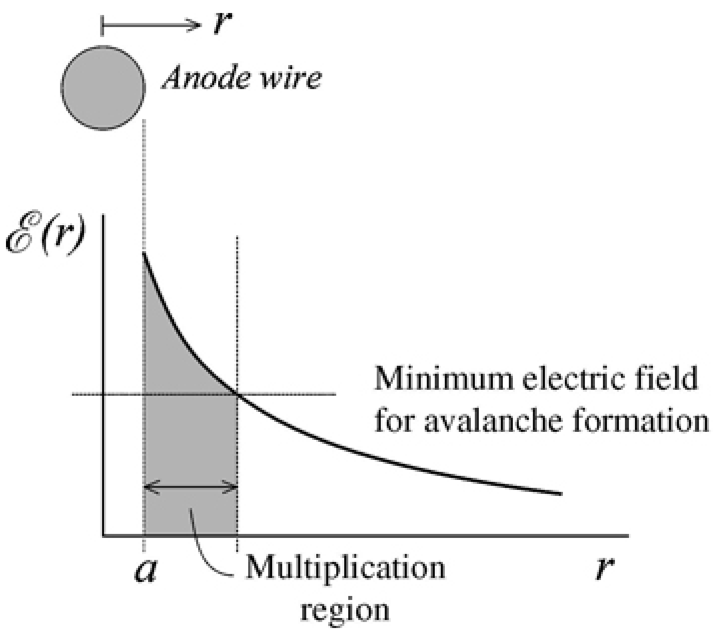
Electron impact ionisation

- Electrons can acquire enough energy between collisions to produce *inelastic* phenomena (for fields above a few kV/cm).
- The process of ionisation by collision is the basis of *avalanche multiplication* in proportional counters.
- High gains can be achieved, but getting stable operation requires mixtures of gases and the maximum practical gain is of order 10^6.

The proportional counter

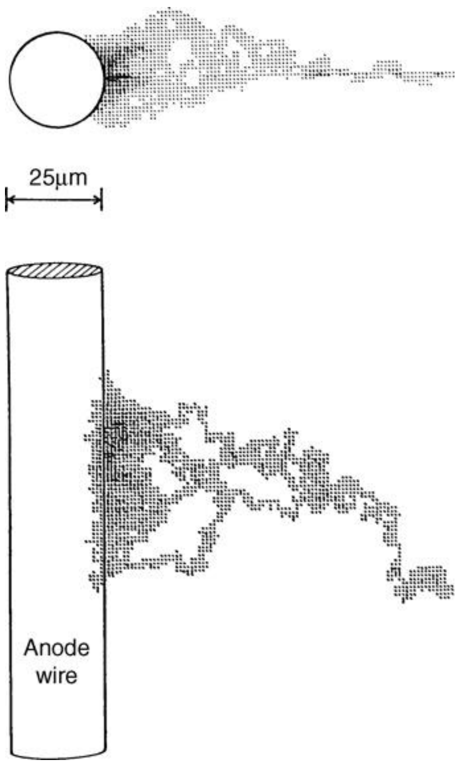
- Consider a co-axial detector consisting of a gas (or mixture of gases) between two cylinders.
- Apply a potential between the cylinders. The field is a maximum at the surface of the anode and decreases as 1/r towards the cathode.





The proportional counter

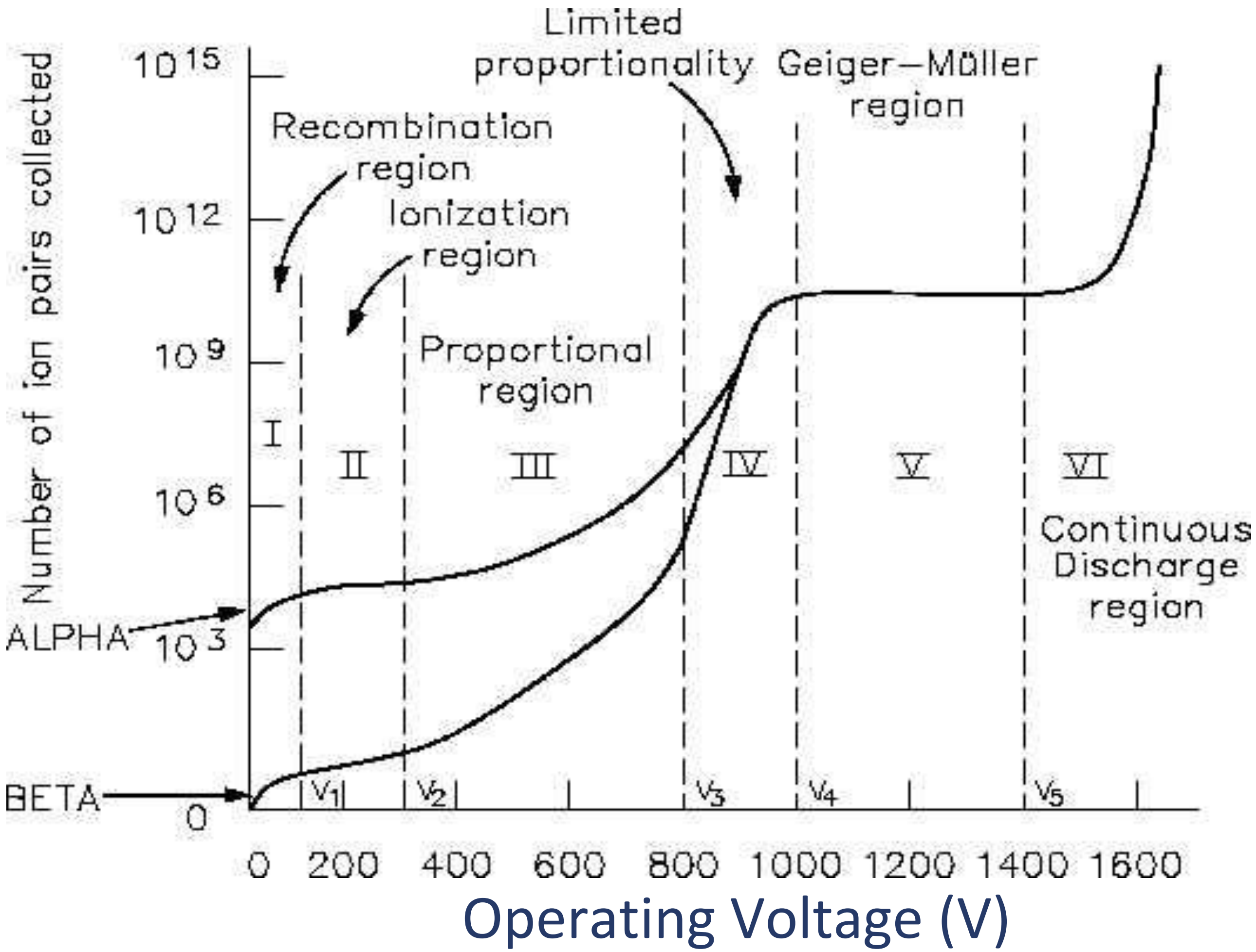
- Produced charges drift towards the cathode and anode.
- Close to the anode the field can be strong enough to allow significant gas multiplication (via the avalanche process).
- The electrons are rapidly collected and the ions drift back to the cathode.
- For gains up to about 10000 the collected charge is *proportional* to the charge originally deposited.
- At very high gains, the gain becomes independent of the deposited charge – this is the Geiger-Muller region.



Avalanche arising from one electron (Monte Carlo simulation)

Gas ionisation

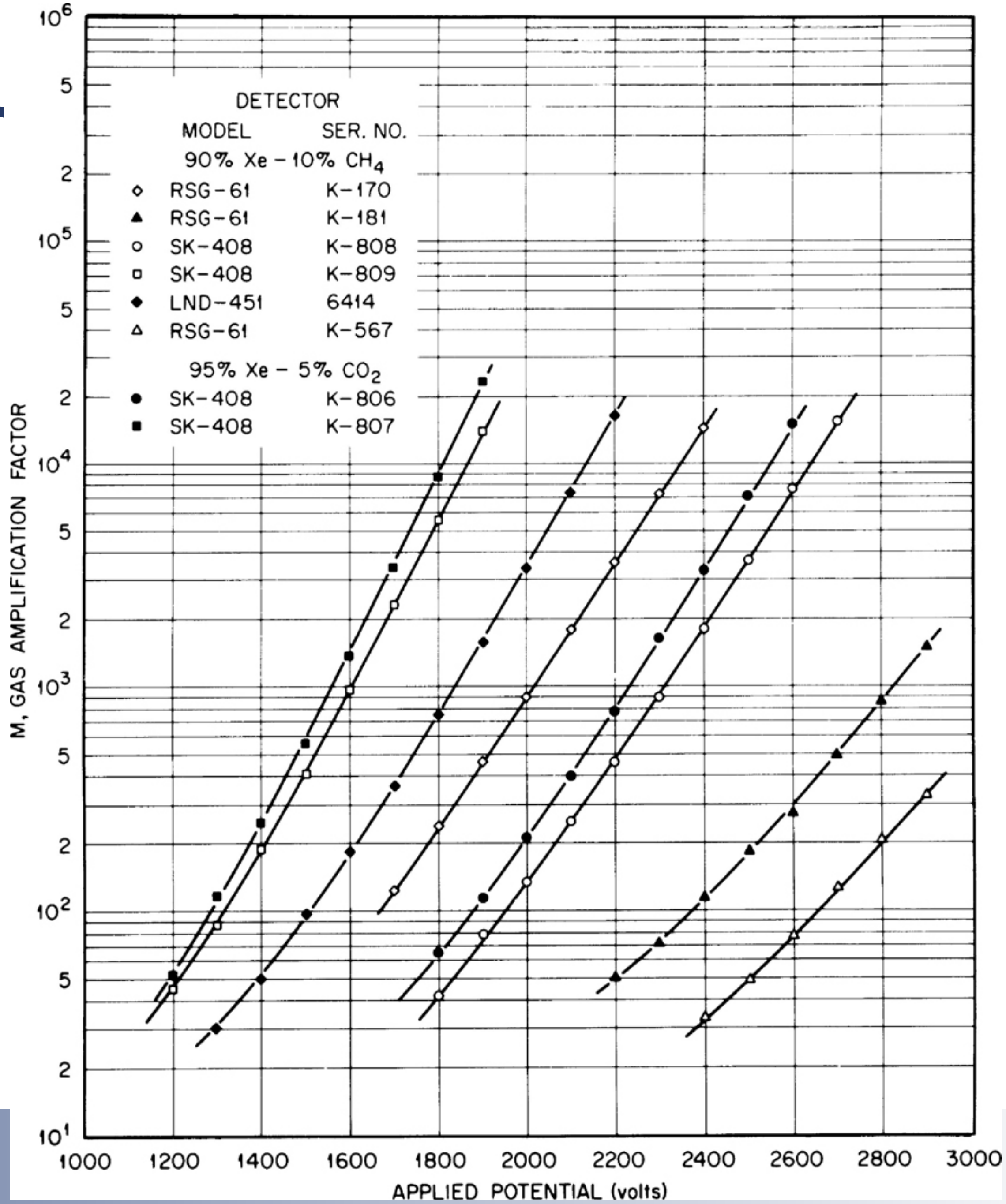
- I Some recombination of the ions at $V < V_1$ due to slow drift velocity
- II No *gas amplification* but full collection
- III Gas amplification is proportional to operating voltage
- IV Townsend avalanche begins to spread along the anode wire
- V Geiger-Muller region: pulse height is now independent of particle type.



Gas multiplication factor

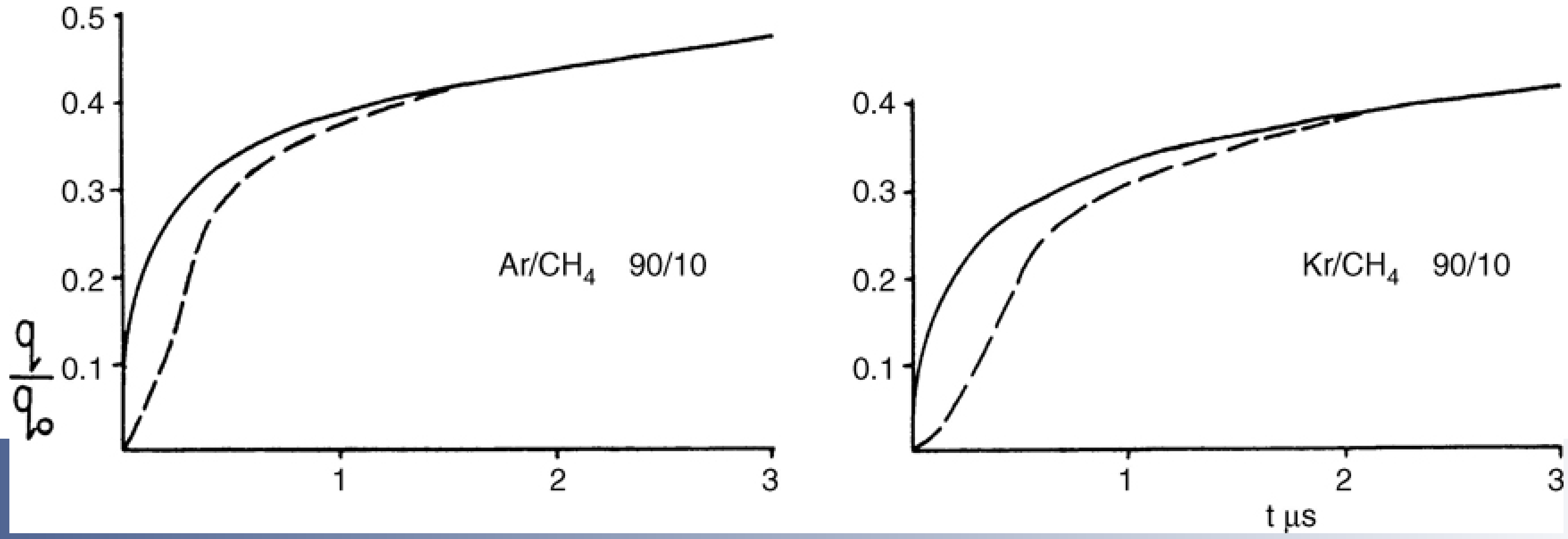
The figure (from Knoll) shows the gas multiplication factor for various proportional counters.

Note the rapid change with voltage.



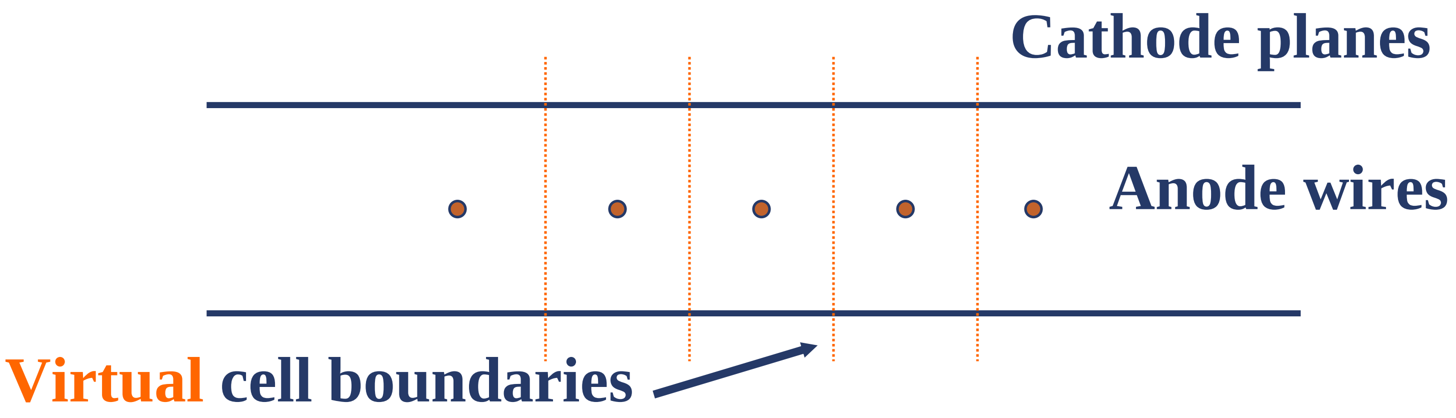
Signal

- Essentially **all the signal is due to the positive ions**.
- This is because the induced signal for the electrons is tiny since they are produced very close (of order 1 µm) to the anode. The positive ions drift back across almost the whole diameter of the proportional counter.
- The maximum signal is thus achieved when all the positive ions are collected (of order 0.5 ms for typical geometries), however ~ 35% of the signal is collected in about 500 ns.
- Normally terminate the counter with a resistance to quickly differentiate the signal with a time constant *RC*. A small value of R gives a good high rate capability.



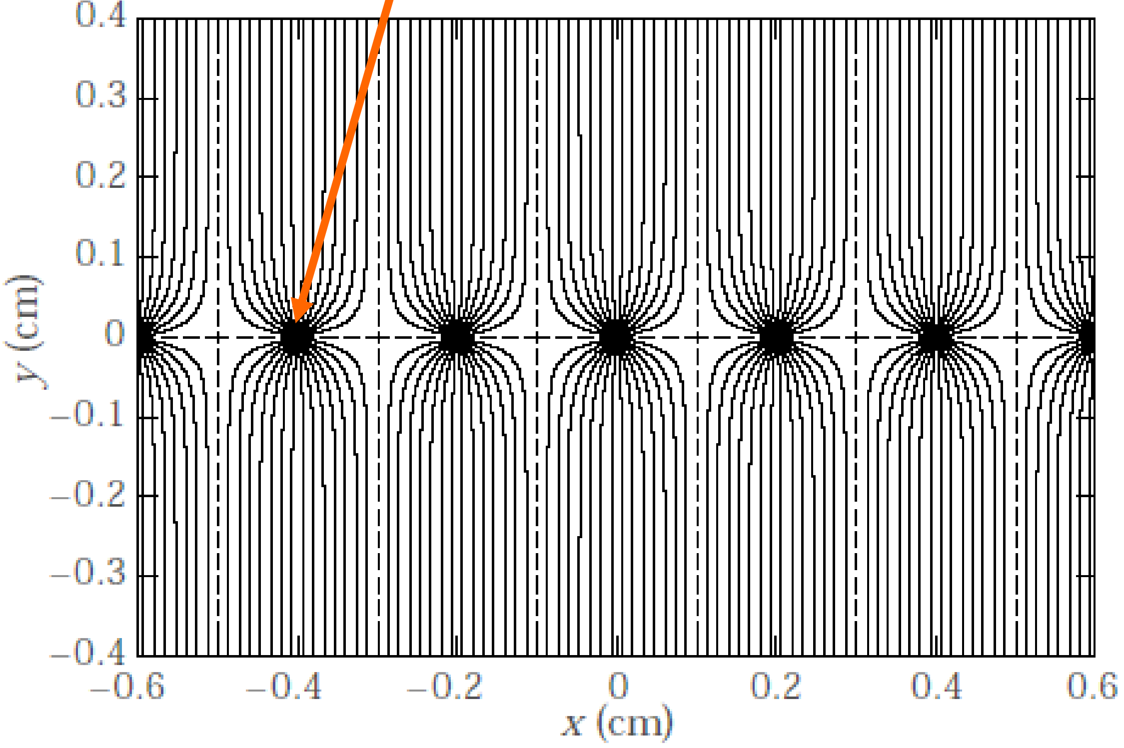
Multi-wire proportional counter

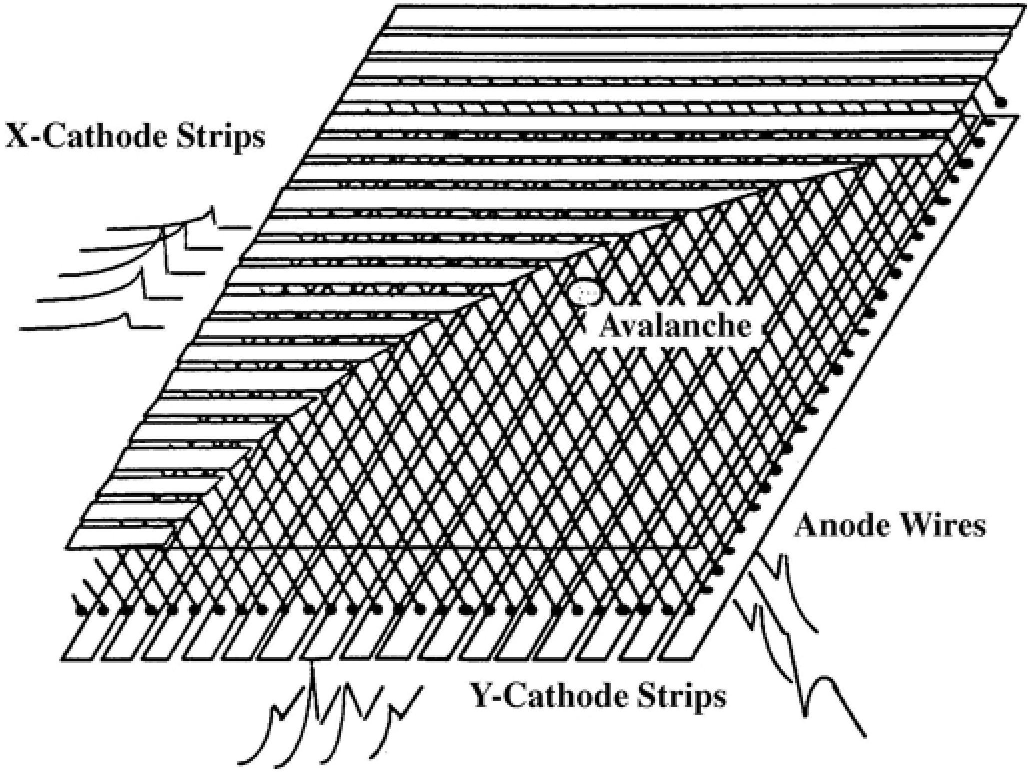
- Multi-wire proportional counters (MWPC) collect deposited charge in a large number of electrically isolated cells – position resolution
- By using planes of MWPC with orthogonal (and often diagonal) wire planes you get 2D hit resolution.



MWPC

Anode wires





2D position sensing using induced charges on cathode plane strips.