Lecture # 2

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The interactions of photons

- Behavior of photons (x-rays, γ-rays) → different from charged particles
- Photo electric effect
- Compton scattering
- Pair production
- x-rays and γ-rays are many times more penetrating
- Much smaller cross-section relative to electron inelastic collisions
- Beam of photons is not degraded → in energy but attenuated → in intensity

- Three process remove photons completely from beam → absorption or scattering
- Photon pass straight → retain orig. energy
- However total no. of photons → reduced
- Attenuation →

$$I(x) = I_0 \exp(-\mu x)$$

Incident beam intensity

Absorption coefficient

Absorber thickness

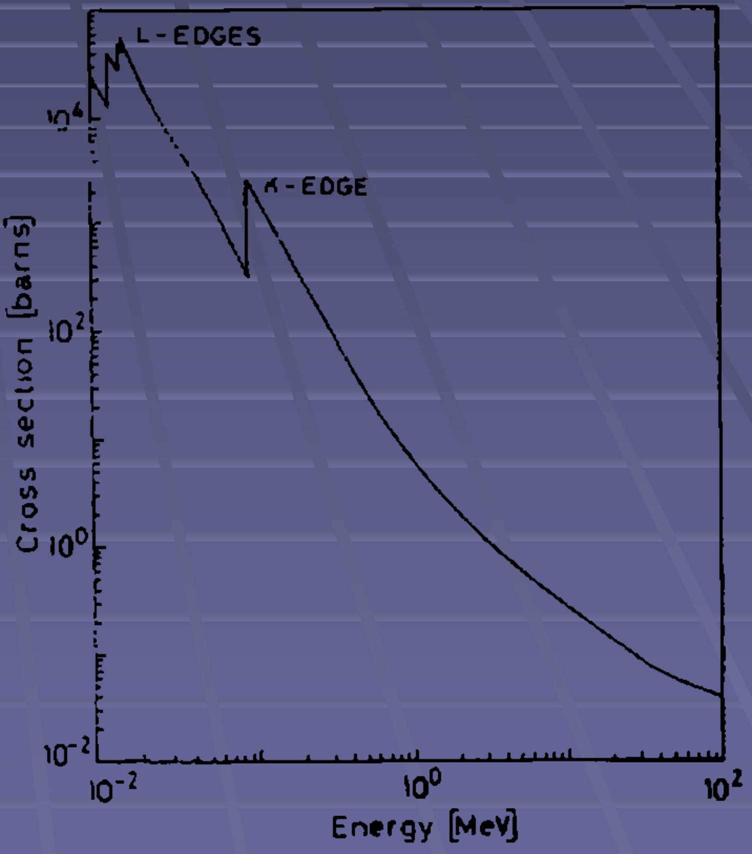
- Absorption coefficient → characteristic of absorbing material → related to total interaction cross-section

Photoelectric effect

- Photoelectric effect → absorption of photon by atomic electron → subsequent ejection of electron from atom
- Energy of electron → $E = h\upsilon - B.E$
- Photoelectric effect → always occur → on bound electrons
- Nucleus → absorb recoil momentum
- Energies above → highest electron B.E → relatively small
- Increases → as k-shell energy approached

- Drops → k-shell electron not available for P.E
- K-absorption edge
- Below this energy → cross-section rises
- L-abrption edge, M-absorption edge
- Energies above k-shell always k-electrons involved in P.E →
- Dependence on Z

Calculated photoelectric cross-section for lead



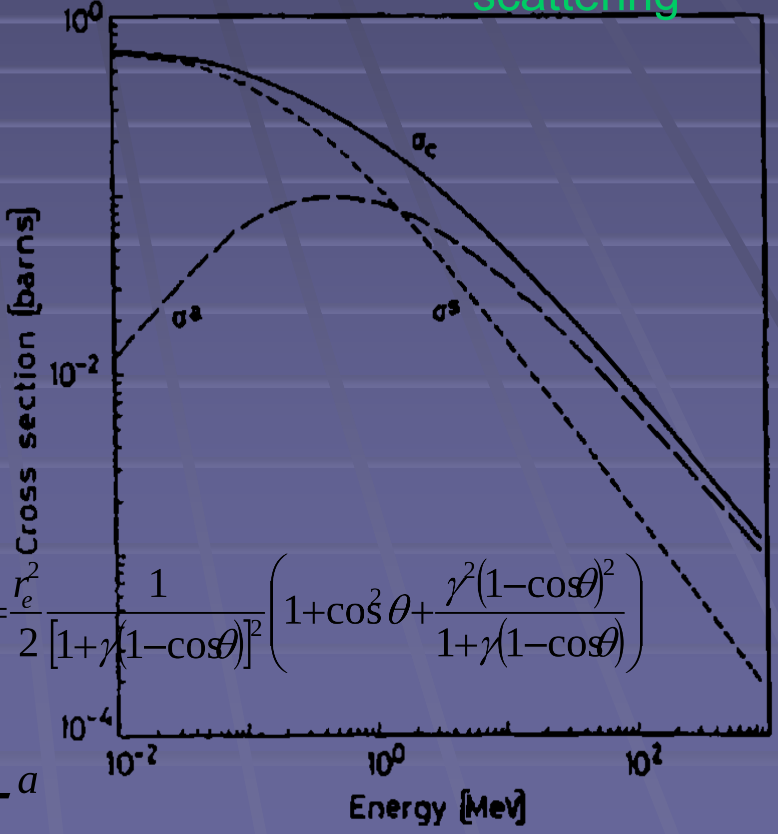
$$\Phi_{photo} = 4\alpha^4\sqrt{2}Z^5\Phi_0\left(m_ec^2/h\upsilon\right)^{7/2}$$

Cross-section by using Born approximation

Compton scattering

- Best understood → process in photon interaction
- Scattering of → photons on free electrons
- Klein-Nishina formula
- Compton scattered cross-section → average fraction of total energy contained in scattered photon
- Compton absorption cross-section → averag energy transferred to recoil electron

Kinematics of compton scattering



$$\frac{d\sigma}{d\Omega}=\frac{r_e^2}{2}\frac{1}{[1+\gamma(1-\cos\theta)]^2}\left(1+\cos^2\theta+\frac{\gamma^2(1-\cos\theta)^2}{1+\gamma(1-\cos\theta)}\right)$$

Average energy absorbed by material →

$$\sigma_c=\sigma^s+\sigma^a$$

Applying energy and momentum conservation, following relations are obtained

$$h\upsilon^{-} = \frac{h\upsilon}{1+\gamma\left(1-\cos\theta\right)}$$

$$T = h\upsilon - h\upsilon^{-} = h\upsilon\,\frac{\gamma\left(1-\cos\theta\right)}{1+\gamma\left(1-\cos\theta\right)}$$

$$\cos\theta = 1 - \frac{2}{\left(1+\gamma\right)^{2}\tan^{2}\phi + 1}$$

Thomson sca. → photon → free electron → classical

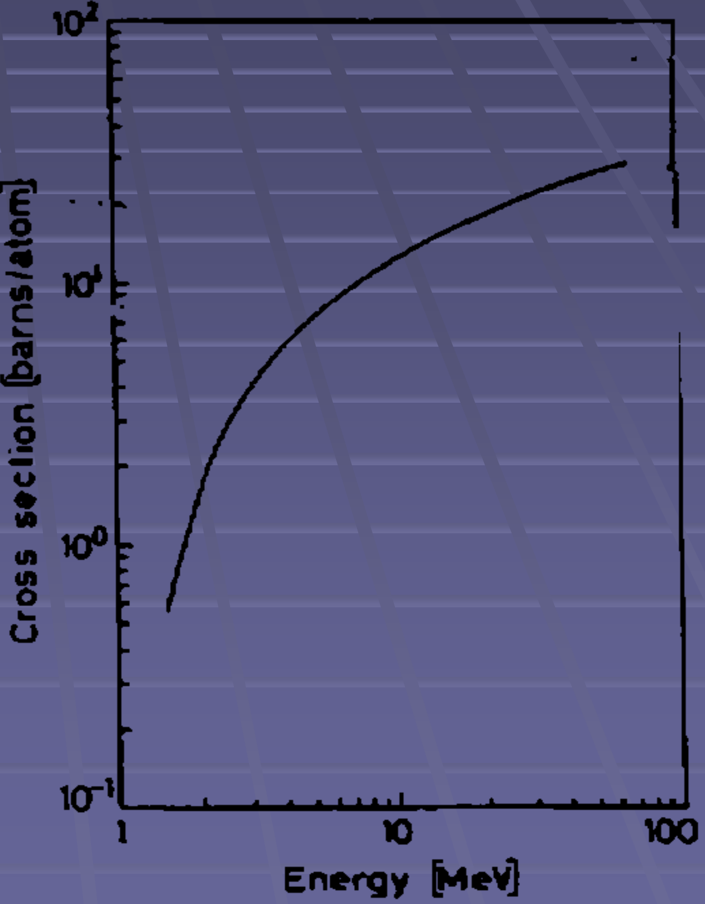
Rayleigh sca. → Photon by → atom as a whole

In both process → no energy transfer → to medium

No excitation → no ionization → only photon direction change

Pair production

- Transformation of photon → electron-positron pair
- To conserve momentum → in presence of nucleus
- Photon energy → 1.022 MeV
- Theoretically pair production → related to bremsstrahlung



Pair production cross-section in lead

Introduction

- General characteristics common to detectors
- Transfer of part or all of radiation energy to detector mass
- Charged particles produce direct ionization
- Neutral particles produce indirect ionization
- Form of converted energy depends on detector and its design
- Gaseous detectors are designed to directly collect ionization
- In scintillators both ionization and excitation contribute to induce molecular excitations, which results in emission of light

- In photographic emulsion, ionization induces chemical reactions
- Detectors are electrical in nature
- Informations are tranformed into electrical pulses
- Recordable information
- Specific data formats

General Characteristics of detectors

- Sensitivity
- Detector response
- Energy resolution: The Fano Factor
- The response function
- Response time
- Detector efficiency
- Dead time

Sensitivity

- The capability to produce a usable signal
- No detector can be sensitive to all radiations

1. The cross-section for ionizing reactions in the detector
2. The detector mass
3. The inherent detector noise
4. The protective material surrounding the sensitive volume

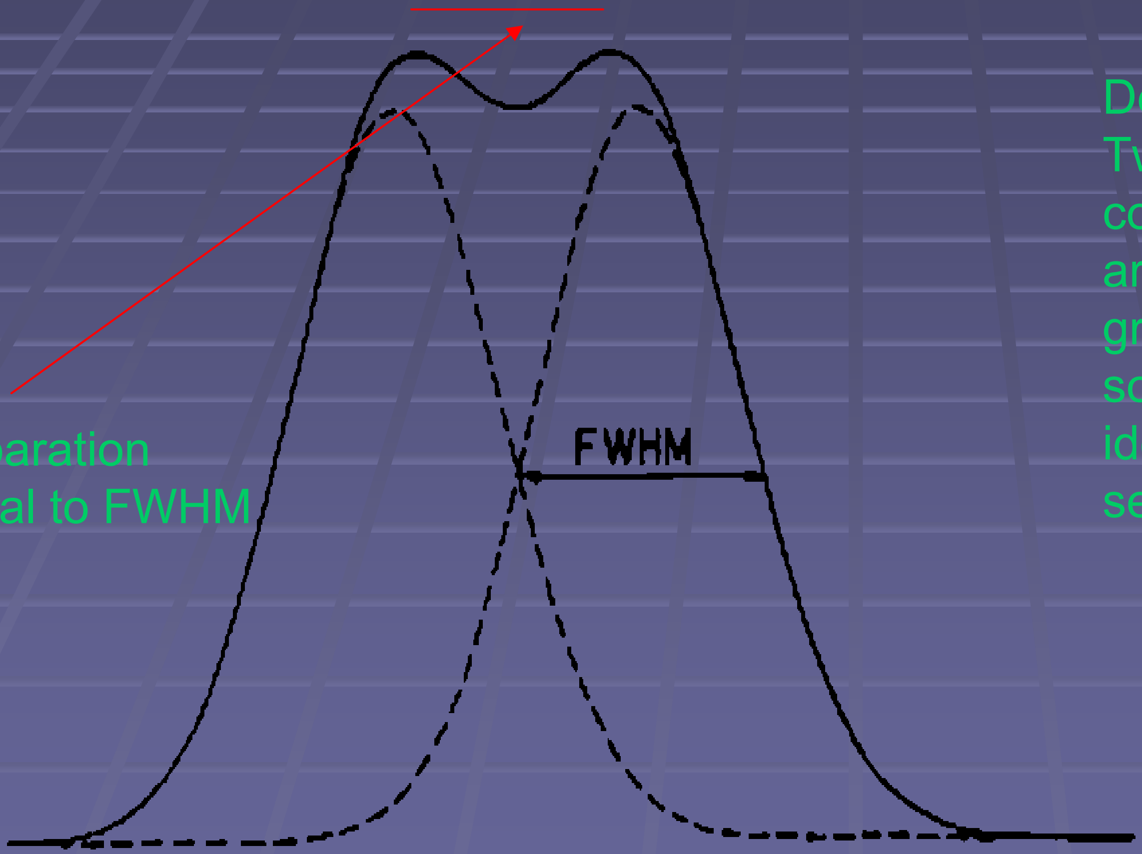
- Cross-section and detector mass → determine probability of energy conversion
- Charged particles → highly ionizing
- Neutral particles → indirect ionization
- The detector mass → depends on radiation type
- Lower limit is determined → by noise
- Material covering the entering window

Detector response

- Information of energy → the amount of ionization is proportional to energy loss
- Large detector volume completely absorb radiation → ionization gives energy information
- Information preserved or not, depends on design
- The amount of ionization → form of signal
- Signal: The integral of pulse with respect to time
- Relation between radiation energy and pulse height → response of detector
- Ideally this relation → linear
- A detector is linear for one radiation but not for other

Energy resolution

- For design consideration → energy resolution most → important factor
- Extent → to which a detector can distinguish two → close lying energies
- Resolution is measured → by sending a beam of monoenergetic particles
- Ideally a sharp delta function peak is expected
- Practically → a peak with finite width is observed, usually gaussian
- Width arises → because of fluctuations in the number of ionization and excitation



Separation equal to FWHM

Defenition of energy resolution. Two peaks are generally considered to be resolved if they are separated by a distance greater than their FWHM. The solid line shows the sum of two identical Gaussian peaks separated by just this amount

- The resolution usually → in Full Width at Half Maxima (FWHM)
- Energies closer than this interval → normally unresolvable

$$\mathrm{Re}\ solution = {\Delta E}/{E}$$

- NaI has 9% resolution for gamma particles of about 1 MeV
- Germanium detectors have 0.1%
- Generally → resolution is function of energy, with → ratio improving with higher energy

- Due to → Poisson or Poisson like statistics of ionization and excitation
- Average energy required to produce an ionization is a fixed number, w
- For deposited energy, E → Average ionization $J = E/w$
- Energy increase → ionization events increase → smaller relative fluctuations
- To calculate fluctuations → two cases

- Two cases
- Radiation energy is → not totally absorbed
- Thin transmission detector → dE/dx → number of signal producing reactions → Poisson dist.

variance → $\sigma^2 = J$

$$R = 2.35\sqrt{w/E}$$

- Full energy of radiation → absorbed
- Ionization events are not independent
- Poisson statistics is → not applicable

$\sigma^2 = FJ$

$$R = 2.35\sqrt{\frac{Fw}{E}}$$

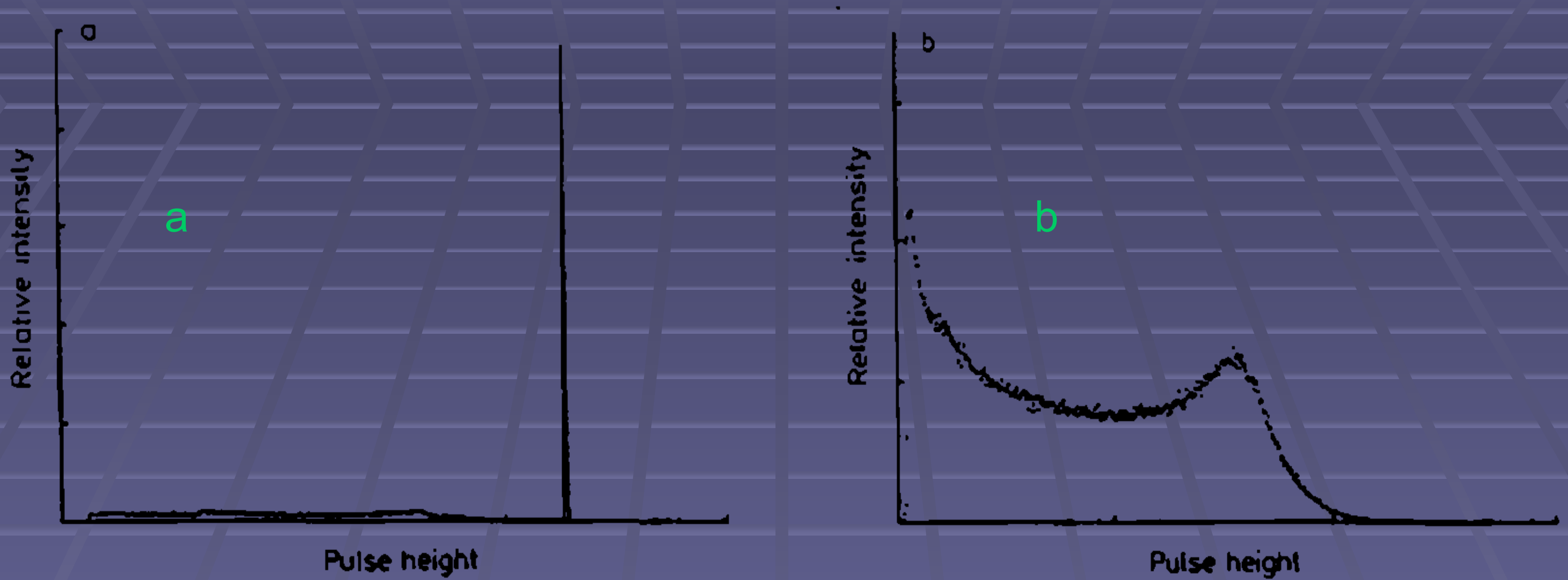
F = Fano Factor

The response function

- For the measurement of energy spectra , response function is crucial parameter
- Spectrum of pulse heights when bombarded by monoenergetic beam
- Dirac delta function
- Gaussian peak is not always realized, specially in case of neutral particles
- The response function is determined by interactions and design and geometry of detector

- Beam of monoenergetic electrons, incident on a detector, thick enough to stop particles.
- Some electrons will scatter out of detector
- Low energy tail
- Some electrons emit bremsstrahlung photons, which may escape from detector
- Events at a lower energy then peak
- Response function is Gaussian peak with low energy tail determined by amount of scattering and bremsstrahlung
- Response function can be improved by changing design and geometry

- A material of small Z, to minimize backscattering and bremsstrahlung
- Relative intensity of each structure in spectrum is determined by relative cross-section for each interaction mechanism
- Response function will be different at different energies for different detector media



- The response function of two different detectors for 661 keV gamma rays.
- a-) germanium detector which has large photoelectric effect cross-section relative to Compton scattering cross-section at this energy. A large photo peak with a small continuous Compton ditribution.
- b-)response of organic scintillator with low Z. Compton scattering is predominent and only this distribution is visible

Response time

- The time taken by detector to form the signal after the arrival of particle
- Duration of signal is very important
- During this time second event cannot be entertained
- This contribute to dead time
- Limits the count rate

Detector efficiency

- Absolute efficiency

$$\varepsilon_{tot} = \frac{events\ registered}{events\ \ emitted\ \ bysource}$$

- Function of detector geometry and probability of interaction

$$\varepsilon_{tot} = \varepsilon_{\mathrm{int}} \varepsilon_{geom}$$

- Intrinsic efficiency

$$\varepsilon_{\mathrm{int}} = \frac{events\ registered}{events\ impinging\ on\ \det ector}$$

- Intrinsic efficiency is function of radiation type, energy and detector material
- For charged particles generally intrinsic efficiency is good
- Problem of efficiency is important for neutral particles
- ε_{geom} is fraction source radiation which is geometrically intercepted by detector
- Angular distribution of incident radiation

Dead time

- Finite time to process the event
- Usually related to duration of pulse height
- Detector may or may not sensitive
- Insensitive detector → events lost
- Sensitive → events pileup
- Distortion and subsequent loss of information from both events
- Affect observed count rate
- Distort time distribution between arrival of events
- To avoid large dead time, rate should be small
- RPC, rate capability 1 kHz/cm2, dead time ≈ 1 ns
- Probability of another event is small

Introduction

- Gaseous detectors
- Greater mobility of electrons
- Obvious medium
- Charged particles detection
- Particle information easily transformed
- Efficiency
- Time resolution
- Rate capability
- cheap

Ionization mechanisms

- Energy loss → excitation, ionization

$$X + p \rightarrow X^{*} + p$$

- Excitation, → resonant reaction, exact amount of energy transfer
- Cross-section → $\delta = 10^{-17}$ cm^2
- No free electron-ion pai

$$X + p \rightarrow X^{+} + p + e^{-}$$

- Primary ionization, secondary ionization
- Penning effect → metastable states spin-parity difference → unable to deexcite → immediately
- Molecular ion → interacts nuetral atom

- Ionization reactions → statistical in nature
- Two particles → not same → electron-ion par
- For gases 1 e-i pair → 30 eV
- Average energy determines efficiency and time resolution of detector
- Recombination and electron attachment
- Electron affinity

$$R = 2.35\sqrt{Fw/E}$$

Energy resolution of a particle

Working principle

- Ionization mechanism
- Working under different voltage conditions
- Exploiting different phenomenon
- Gas cylinder
- Noble gas
- Mean number of electron-ion pair created
- Recombination and electron attachment

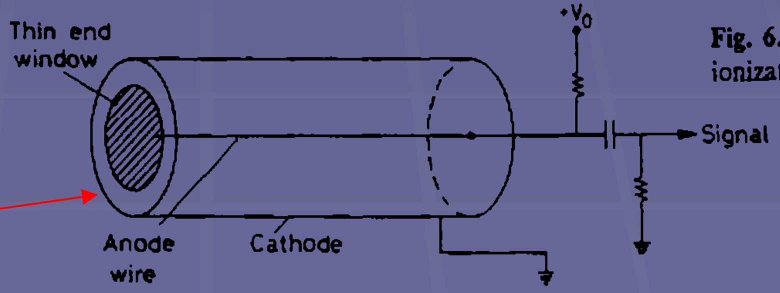


Fig. 6.1. Basic construction of a simple ionization detector

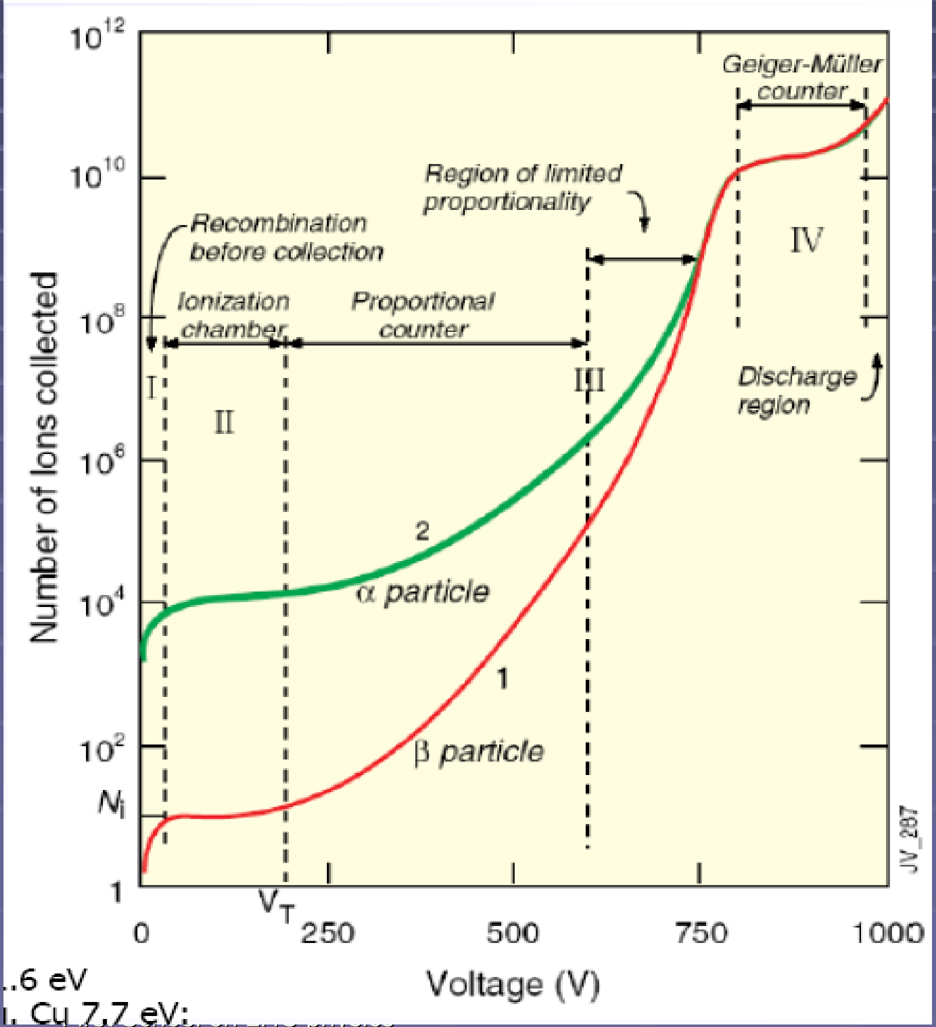
Simple gaseous detector

- Radial electric field $E = \frac{1}{r}\frac{V_0}{\ln\left(b/a\right)}$
- Electron-ion pair produced
- Direct ionization
- Indirect ionization
- Mean number of pair produced directly proportional to energy deposited by particle
- At zero voltage, recombination
- Recombination forces overcome, current increase
- All created pair collected, voltage increase no effect

- Detector working in this range → ionization chamber
- Voltage increase beyond region II
- Strong electric field → accelerate freed electrons → ionization
- Electrons liberated in secondary ionization accelerate → more ionization
- Ionization avalanche or cascade
- Strongest electric field near anode wire
- Number of electron-ion pair directly proportional to primary electrons

- Proportional amplification → as high 10^6
- Working in this range → Proportional chamber
- Further voltage increase
- Space charge distorts electric field about anode
- Proportionality begins to lost
- Region of limited proportionality
- Further V increase → discharge
- Chain reaction of many avalanche
- Secondary avalanche caused by → photons emitted by deexciting molecules

- Output current completely saturated
- Same amplitude regardless of particle energy
- To stop discharge → quench gas
- Working is this range → Geigger-Muller or break-down
- Further voltage increase → continuous breakdown



The total charge collected as function of V

Conclusions

- Interaction of photons with material
- Detector parameters
- Sensitivity
- Detector response
- Energy resolution: The Fano Factor
- The response function
- Response time
- Detector efficiency
- Dead time
- Tried to understand basic → particle-material interactions
- Working principal of gaseous detectors