Instrumentation for Particle Physics – in four lectures

Lecture I: Interactions of Particles and Radiation with Matter, and Properties of Detectors

Sally Seidel
University of New Mexico

African School of Physics 2021

A reference that has been valuable to me in preparing these lectures is “Particle Detectors,” by C. Grupen and B. Shwartz, Cambridge Monographs Series Number 26.

Other useful texts include:

“The Physics of Particle Detectors,” by Dan Green, Cambridge Monographs Series Number 12

“Calorimetry: Energy Measurement in Particle Physics,” by Richard Wigmans, Oxford Science Publications

“Semiconductor Radiation Detectors: Device Physics,” by Gerhard Lutz, Springer

“Particle Detection with Drift Chambers,” by W. Blum, W. Rieger, and L. Rolandi, Springer

“Handbook of Particle Detection and Imaging,” by C. Grupen and I. Buvat, Springer

Interactions of particles and radiation (photons) with matter (the detector):

- Electromagnetic interactions of charged particles with matter

- Electromagnetic interactions of photons with matter

- Strong interactions of hadrons with matter

- Diffusion and drift of particles in the detector

Particles can only be detected through their interaction with matter. These interactions are the basis for all the detection methods and instruments described in these lectures.

Charged particles interact with matter through:

- *ionization*
- *excitation*
- (if they are relativistic) *bremsstrahlung* radiation.
- pair production
- photonuclear interaction
- radiation losses (Cherenkov, transition radiation, and synchrotron)

Neutral particles must produce charged particles that are then detected.

Photons are detected through

- *Compton scattering*
- *photoelectric effect*
- *pair production*

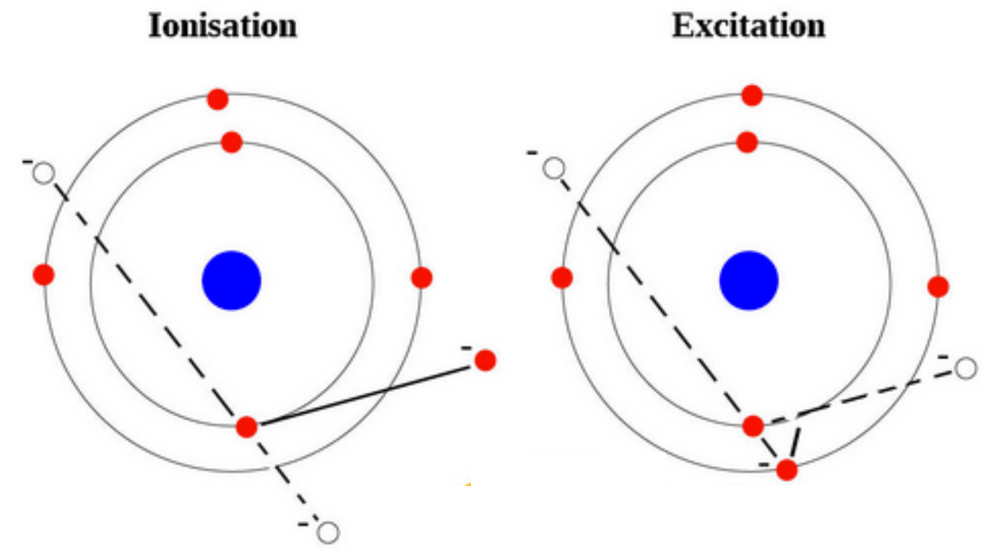
and then the electrons that are produced in these interactions are observed.

Electromagnetic interactions of charged particles with matter

1). ***Excitation*** of bound electrons, ***followed by*** de-excitation and photon emission: this is ***luminescence*** and is used in wavelength shifters

$$e^- + atom \rightarrow e^- + atom^*$$
$$\searrow$$
$$atom + \gamma$$

2). ***Ionization*** of bound electrons. If the incident charged particle energy is high enough, it can liberate the electron from the target atom.



The foundational equation:
The average energy loss *dE* per path length *dx* in matter, for a particle heavier than an electron – due to ionization and excitation - is given by **the Bethe-Bloch formula**:

This (in red) is the maximum transferable energy, call it κ

$$-\frac{dE}{dx} = 2 \cdot \boxed{2\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2}} \left(\ln \frac{2 m_e c^2 \gamma^2 \beta^2}{I} - \beta^2 - \frac{\delta}{2} \right)$$

Avogadro's number

"classical electron radius": $r_e = \frac{1}{4\pi\varepsilon_0} \cdot \frac{e^2}{m_e c^2}$

electron mass

charge of the incident particle

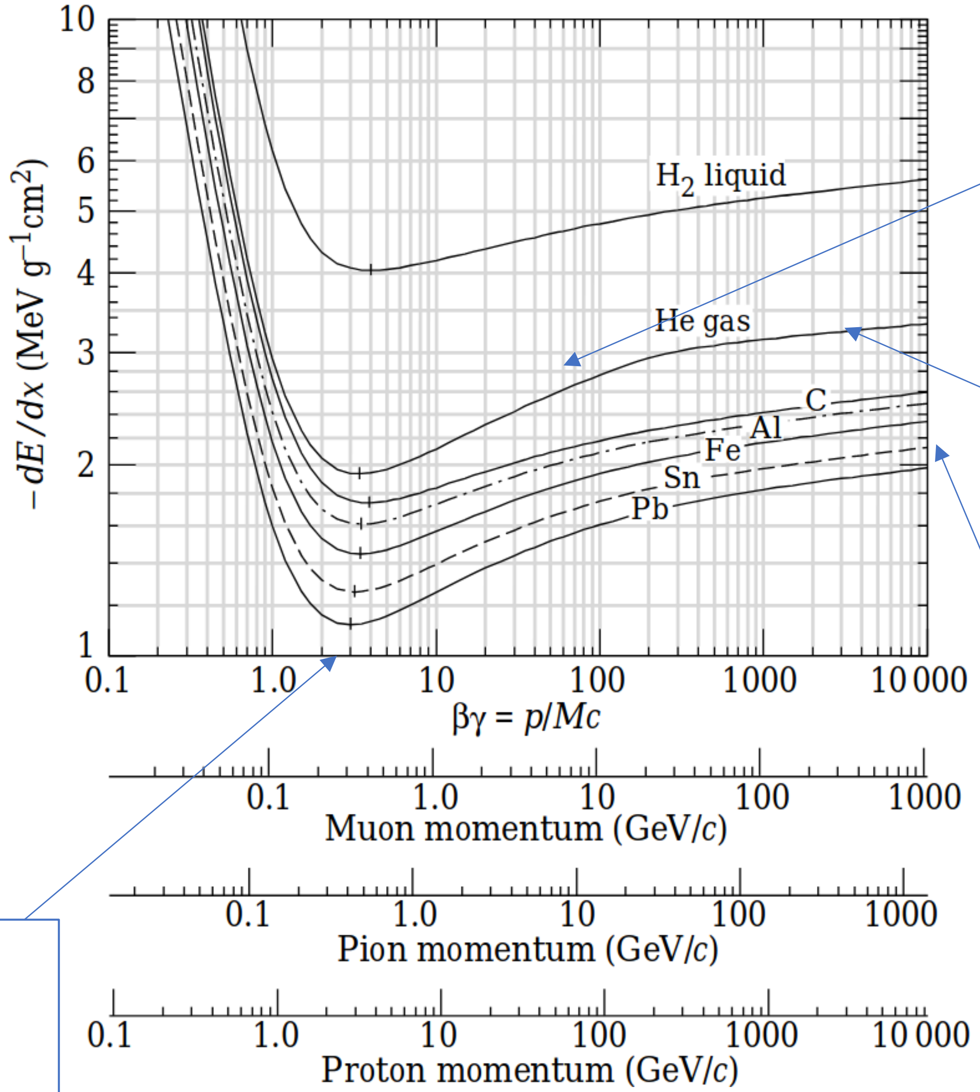
atomic number Z, atomic weight A of target

mean excitation energy, characteristic of the absorber material, approximately $I = 16Z^{0.9}$ eV

δ characterizes how much the transverse electric field of the incident particle is screened by the charge density of target electrons: the "density effect"

c is speed of light
β is v/c
γ is Lorentz factor

This formula is valid to a few % up to energies of hundreds of GeV. It does not apply to particles with velocities comparable to those of the atomic electrons.



logarithmic rise due to large energy transfers to a few electrons ("delta rays" or "knock-on electrons") in the medium

saturation due to the density effect: as particle energy increases, the electric field extends so that collisions from distant particles increase, but the medium polarizes, truncating the effect.

The decrease with increasing atomic number comes from the Z/A term.

Relativistic particles in the regime of this minimum are called **Minimum Ionizing Particles, MIPs**. In almost all modern detector materials,

$$-\left.\frac{dE}{dx}\right|_{\min} \approx 2\,\frac{\text{MeV}}{\text{g/cm}^2}$$

For particles passing through ***thin absorbers***, there are strong fluctuations around the average energy loss. This phenomenon is described by a ***Landau distribution:***

$$L(\lambda) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\lambda + e^{-\lambda}\right) \right]$$

$$\lambda = \frac{\Delta E - \Delta E^W}{\kappa \rho x}$$

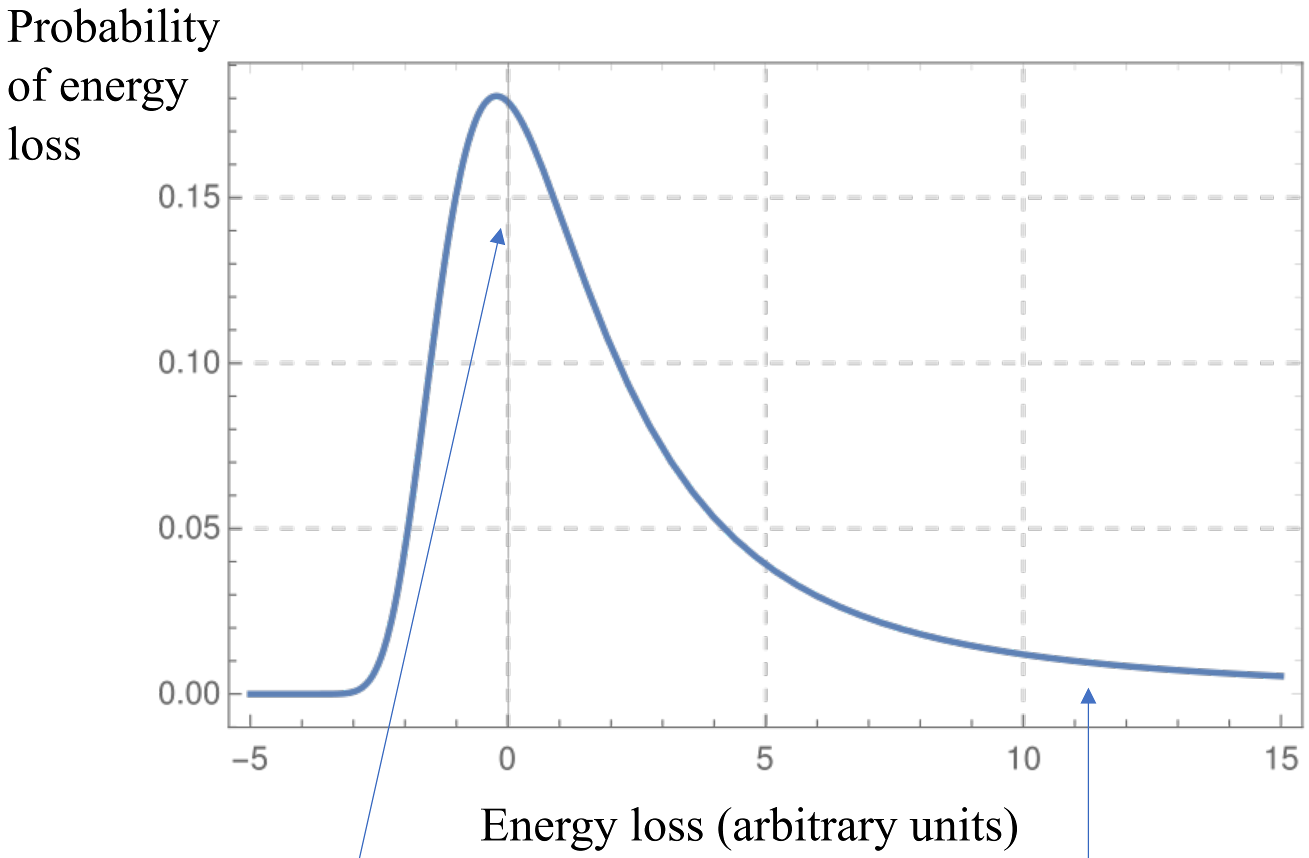
ΔE : actual energy loss in layer of thickness x

ΔE^W : most probable energy loss in layer of thickness x

κ : maximum transferable energy

ρ : density

x : absorber thickness



Approximately Gaussian

Knock-on electrons (delta rays) receive such large energy transfers that they stimulate further ionization.

As absorber is thickened, the tail reduces, leaving an approx. Gaussian distribution

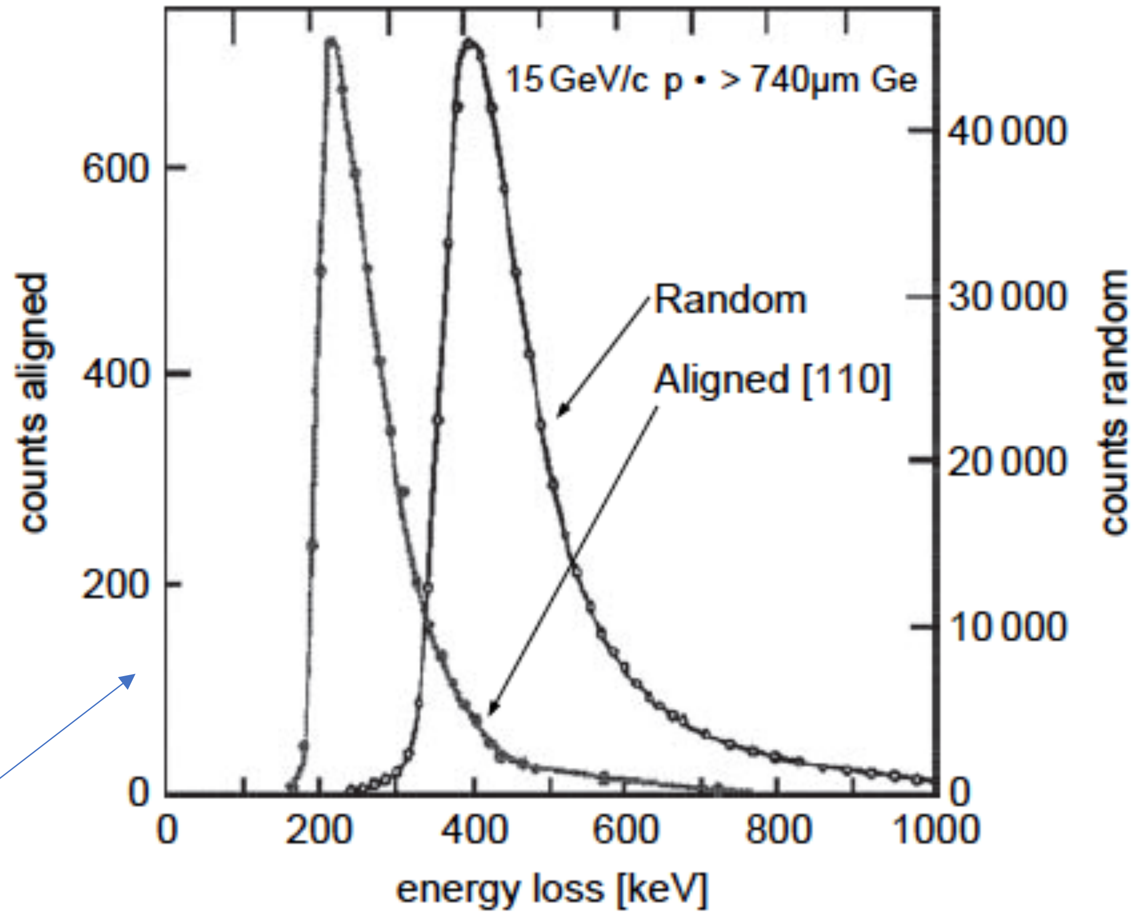
Modifications to the Bethe-Bloch formula

1. *in the case of electrons*, because the primary (incident) and secondary (target) electrons cannot be distinguished after the collision

2. *positrons* – similar correction to that of electrons, plus positron can annihilate in flight with a target e^-

3. cases where the energy is truncated because some *energy is deposited outside the sensitive volume*

4. *"channeling":* when the incident particle travels *along certain crystal directions* of a regular crystal lattice, its motion is governed by coherent scattering on strings and planes rather than individual scattering from single atoms; this produces anomalous energy loss relative to other directions or to amorphous materials



Ionization yield: number of signal products due to collisions by the incoming charged particle with atomic electrons

- *In a gas*: this is the **number of produced electron-ion pairs**

  (Average energy W needed to produce a pair) > (ionization potential)
  because

  (1) inner shells can participate in ionization
  (2) some collisions produce excitation without ionization

  W in gases is generally around 22 eV (Xe) to 41 eV (He) – but depends strongly on the purity of the gas.

- *In a solid state detector*: this is the **number of electron-hole pairs**.

  Typical values: 3.6 eV for Si, 2.85 eV for Ge

  The number of charge carriers produced is much higher in solid state, so statistical fluctuations are smaller

Continuing the list of energy loss mechanisms for charged particles:
3) Energy loss by bremsstrahlung

When relativistic charged particles decelerate in the Coulomb field of a nucleus, they emit photons in a process called bremsstrahlung ("braking radiation")

$$-\frac{dE}{dx} \approx 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0}\cdot\frac{e^2}{mc^2}\right)^2 \cdot E \ln\left(\frac{183}{Z^{1/3}}\right)$$

target particle
atomic number Z,
atomic weight A

incident particle
charge z, mass m,
energy E

Note brem loss is $\propto E$ and $\propto 1/m^2$, so especially significant for incident electrons.

Recall again the formula for brem:

$$-\frac{dE}{dx} \approx 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0} \cdot \frac{e^2}{mc^2} \right)^2 \cdot E \ln\left(\frac{183}{Z^{1/3}} \right)$$

for incident electrons ($z = 1$, $m = m_e$), **define radiation length X_0:**

$$X_0 = \left[4\alpha N_A \frac{Z^2}{A} \left(\frac{1}{4\pi\varepsilon_0} \cdot \frac{e^2}{m_e c^2} \right)^2 \cdot \ln\left(\frac{183}{Z^{1/3}} \right) \right]^{-1}$$

then

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

Integrate this to get:

$$E = E_0 e^{-x/X_0}$$

Thus radiation length is **the mean path length required to reduce the energy of a relativistic particle by 1/e, due to radiation loss.** Note that this is attenuation of energy of *particles.* Later we will discuss attenuation of intensity of photons.

Corrections to the brem equation:
(1) brem due to target electrons, in addition to nuclei
(2) Screening of the atomic nucleus charge by the atomic electrons

When we include those corrections, we get:

$$\boxed{X_0 = \frac{716.4 \cdot A\left[g/mol\right]}{Z(Z+1)\ln\left(287/\sqrt{Z}\right)} \text{g/cm}^2}$$

Resolution is degraded by **multiple scattering**: small deflections of the incoming charged particle in the Coulomb field of target nuclei plus larger deflections due to collisions with nuclei.

Projected scattering angle distribution (i.e, in 2 dimensions, as in the surface of a detector), approximately:

$$\boxed{\Theta_{rms}^{projected} = \frac{13.6 \text{ MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln(x/X_0)\right]}$$

Notice multiple scattering ∝ *1/p* so it is worst for the lowest momentum particles.

Continuing the list of energy loss mechanisms for charged particles:

4. When a high energy incident particle approaches the nuclear Coulomb field, associated photons can produce electron-positron pairs ("**direct pair production**"):

$$-\left.\frac{dE}{dx}\right|_{pair} = b_{pair}\left(Z,A,E\right)\cdot E \approx 0.3\ \frac{\text{MeV}}{\text{g/cm}^2}\quad \text{for 100 GeV muons in iron}$$

5. **Photonuclear interactions**: incident charged particles can initiate nuclear interactions by exchanging photons with the nucleus of the target:

$$-\left.\frac{dE}{dx}\right|_{photonuclear} = b_{photonuclear}\left(Z,A,E\right)\cdot E \approx 0.04\ \frac{\text{MeV}}{\text{g/cm}^2}\quad \text{for 100 GeV muons in iron}$$

6. Charged particles deflecting from a straight path (e.g. due to a magnetic field) emit **synchrotron radiation**

Radiated power $P = \frac{1}{6\pi\varepsilon_0}\frac{2e^2}{3c^3}\frac{\gamma^4 v^4}{r^2}$.

Note $\gamma = \frac{E}{mc^2}$

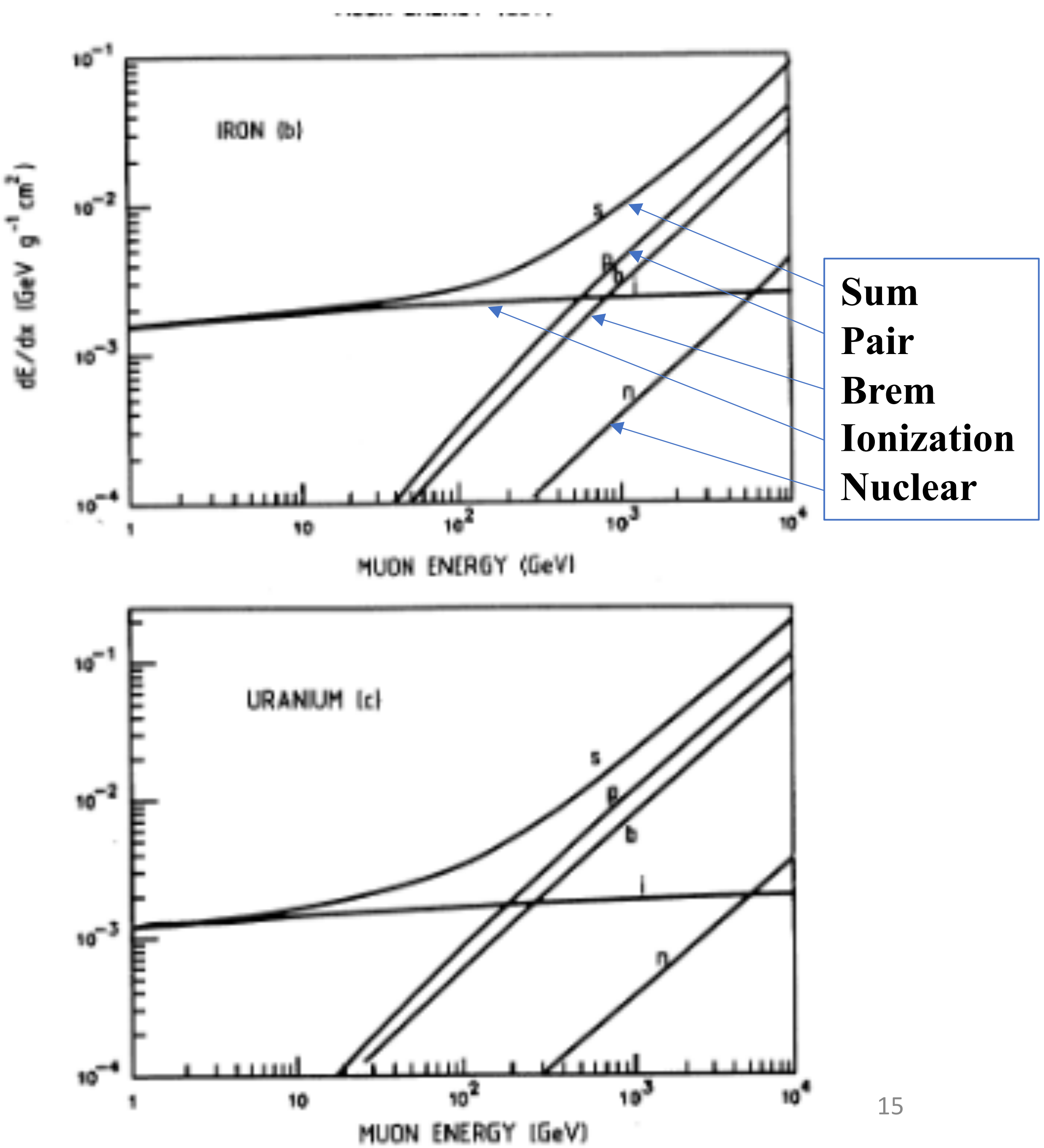
So loss is highest for low incident mass m, tight radius of curvature r.

Synchrotron radiation is emitted in a forward cone with opening angle $\propto \frac{1}{\gamma}$. Sometimes this is a desired effect.

We temporarily neglect energy loss due to excitation, and postpone discussion of Cherenkov radiation and transition radiation. Considering just the **four leading mechanisms** of energy loss:

$$-\frac{dE}{dx}\Big|_{total} = \underbrace{-\frac{dE}{dx}\Big|_{ionization} - \frac{dE}{dx}\Big|_{brem}}_{a(Z,A,E)} + \underbrace{-\frac{dE}{dx}\Big|_{pair} - \frac{dE}{dx}\Big|_{photonuclear}}_{b(Z,A,E)\cdot E}$$

Notice that **above a few TeV, the pair production dominates**. Since it is proportional to energy, this makes it possible to measure muon energies by sampling energy loss in that regime.



Now we set aside the topic of charged particles, to discuss:
electromagnetic interactions of photons with matter

- This concerns *primary photons*, not luminescence as a stage in detection of charged particles.

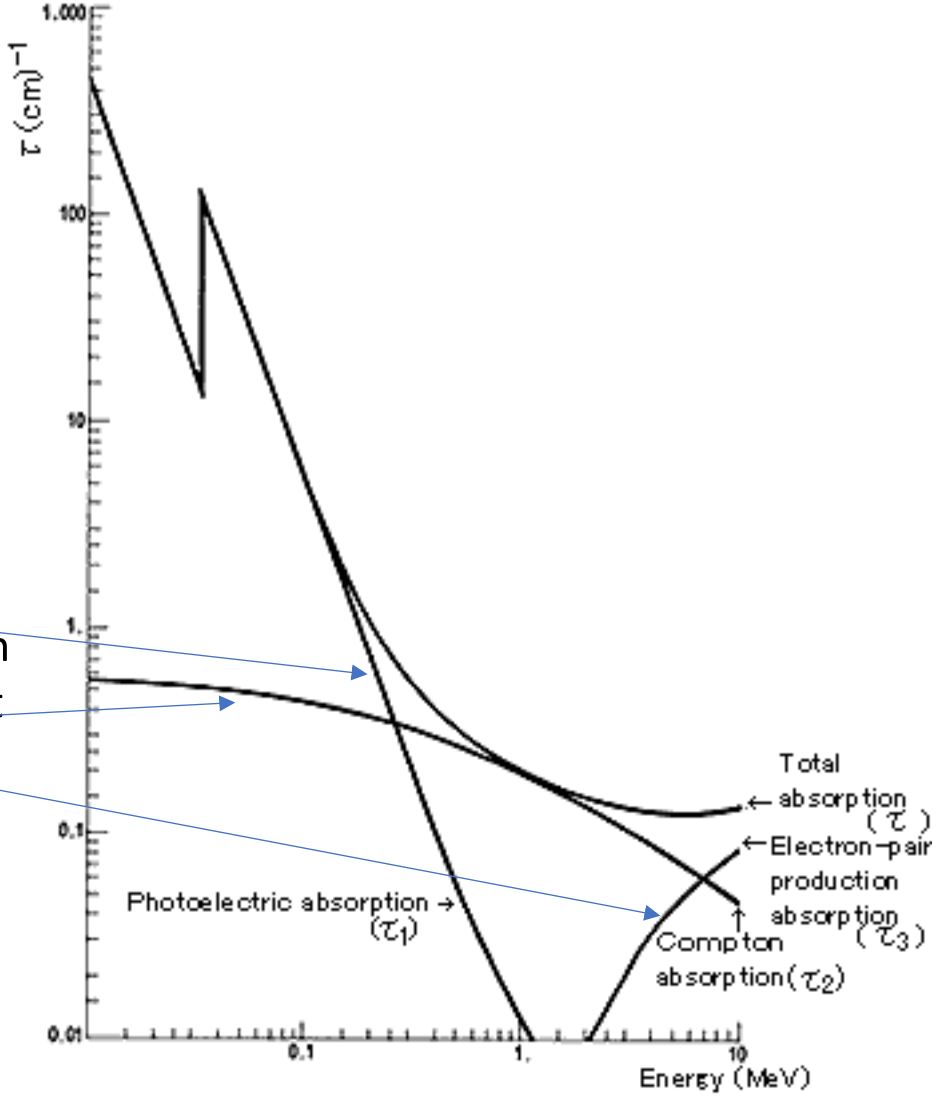
- The primary photon produces charged particles in the medium, and those particles ionize

- The photons are either completely absorbed:
  -photoelectric effect
  -pair production

  or scattered:
  -Compton effect

- Which process dominates depends on the photon energy.

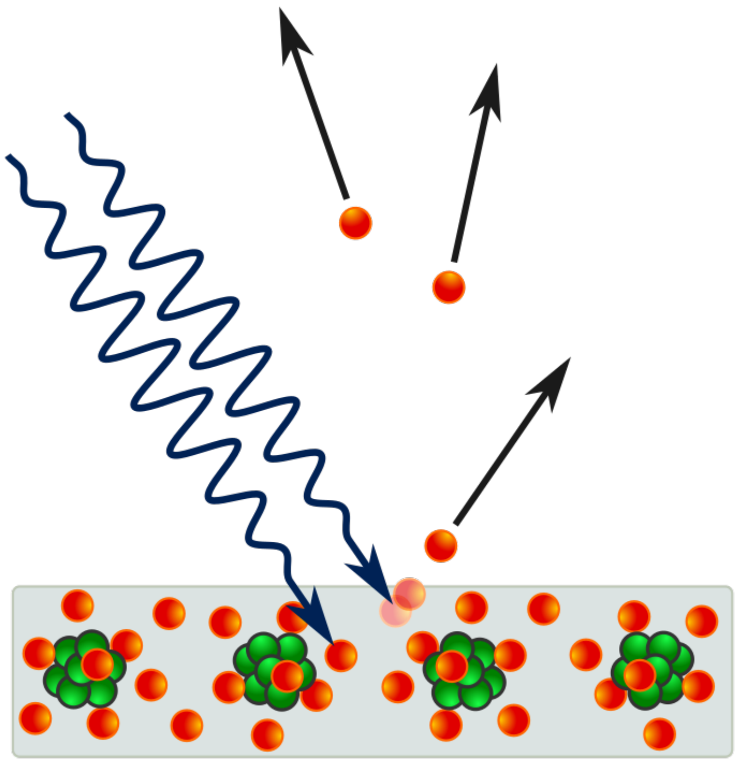
absorption
coefficient



Photoelectric effect

Atomic electrons can absorb photons because the nucleus is nearby to absorb recoil momentum. This is not possible for free electrons.

The approximate formula for the cross section depends on the photon energy E_γ relative to the rest energy $m_e c^2$ of the electron.



Let $\varepsilon \equiv \dfrac{E_\gamma}{m_e c^2}$.

Define $\sigma_{Th}^{e} \equiv \dfrac{8}{3}\pi r_e^2 = 6.65\times 10^{-25}\ \text{cm}^2$, the "Thomson cross section"

For $\varepsilon \le 1$, $\sigma_{photo}^{K-shell} = \left(\dfrac{32}{\varepsilon^7}\right)^{1/2} \alpha^4 Z^5 \sigma_{Th}^{e}$ [cm^2 / atom]

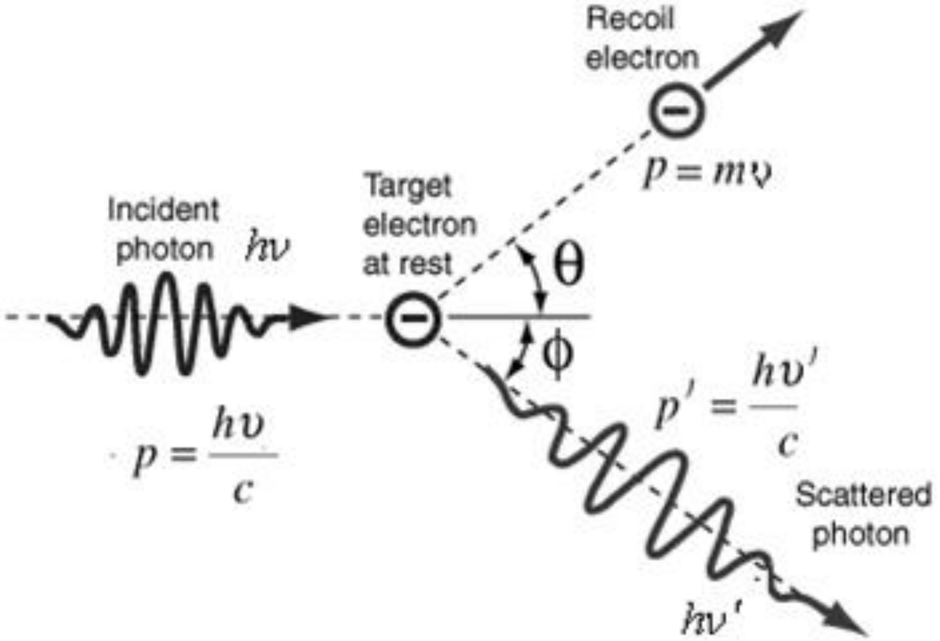
For $\varepsilon >> 1$, $\sigma_{photo}^{K-shell} = \left(\dfrac{1}{\varepsilon}\right) 4\pi r_e^2 \alpha^4 Z^5$

If the electron is liberated from an inner shell, an outer-shell electron can transition down into the hole. The energy released by that process is radiated as X-rays ("Moseley's Law") or transferred to another electron which is ionized ("Auger electron").

Compton effect: the scattering of a photon off an atomic electron

$$\sigma_{Compton}^{e-\text{target}} = 2\pi r_e^2 \left[\left(\frac{1+\varepsilon}{\varepsilon^2} \right) \left\{ \frac{2(1+\varepsilon)}{1+2\varepsilon} - \frac{1}{\varepsilon} \ln(1+2\varepsilon) \right\} + \frac{1}{2\varepsilon} \ln(1+2\varepsilon) - \frac{1+3\varepsilon}{(1+2\varepsilon)^2} \right] \text{ [cm}^2 \text{ / electron]}$$

This is the "Klein-Nishina formula."



- The binding energy of the electron is ignored.
- If the photon scatters off the atom, use

$$\sigma_{Compton}^{atomic-\text{target}} = Z \cdot \sigma_{Compton}^{e-\text{target}}$$

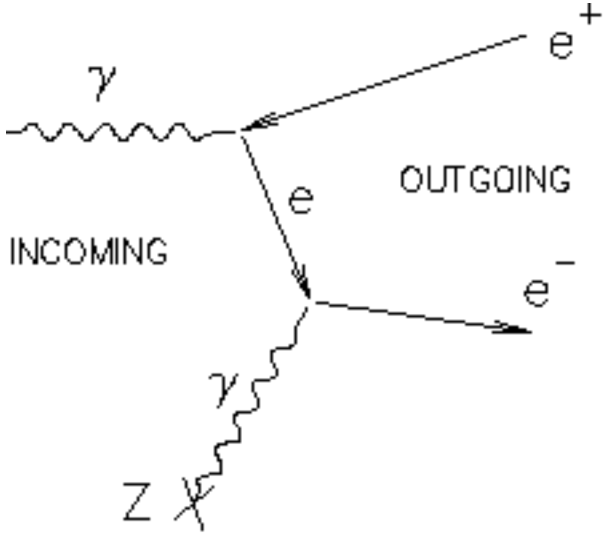
- Note **inverse Compton scattering** can also occur, in which an energetic electron collides with a low-energy photon, transfers energy to it, blue-shifting the photon to higher frequency.

Pair production

Must occur in the Coulomb field of the nucleus to absorb recoil energy

For high energy photons ($\varepsilon >> \frac{1}{\alpha Z^{1/3}}$),

$$\sigma_{pair} = 4\alpha r_e^2 Z^2 \left(\frac{7}{9} \ln \frac{183}{Z^{1/3}} - \frac{1}{54} \right) \quad [\mathrm{cm}^2 / \mathrm{atom}]$$



Now we set aside electromagnetic interactions to discuss:
Strong interactions of hadrons with matter

This cross section is dominated by inelastic strong interactions between projectile and target, where secondary strongly interacting particles are produced.

These interactions lead to absorption of projectile hadrons. After travelling distance *x*, N_0 projectiles are reduced to *N* projectiles, according to:

$$N = N_0 e^{-x/\lambda_I} \quad \text{where}$$

atomic weight

$$\lambda_I = \frac{A}{N_A \rho \sigma_{inelastic}} \quad \text{is the } \textbf{interaction length}.$$

Avogadro's number, target density, cross section

Cross section depends weakly on energy and incident particle type.

$\lambda_I \cdot \rho$ [g/cm^2] for common materials:

hydrogen	50.8
aluminum	106.4
uranium	199

Once the primary particle has interacted with the medium, and produced signal particles, those particles will *drift and diffuse.*

This applies to *electrons and ions in gases*, and to *electrons and holes in solid state*.

Diffusion: statistically *disordered* displacement from position, due to mechanical collisions (Brownian motion).

Mean free path... $$\lambda = \frac{1}{N\sigma(\varepsilon)}$$ ...is about 10^{-5} cm for ions in common gases at STP

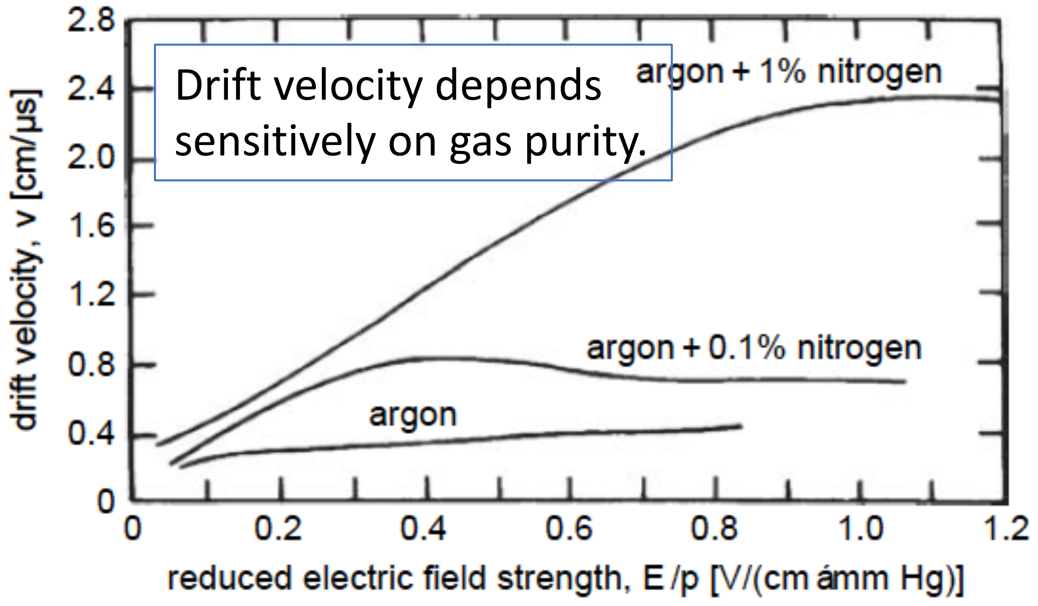
molecular density

collision cross section (energy-dependent)

Drift: *ordered* motion of charge carriers along electric field lines

Velocity $\vec{v}_{drift} = \mu \cdot \vec{E} \cdot \frac{p_0}{p}$, where the typical value is a few cm/μs.

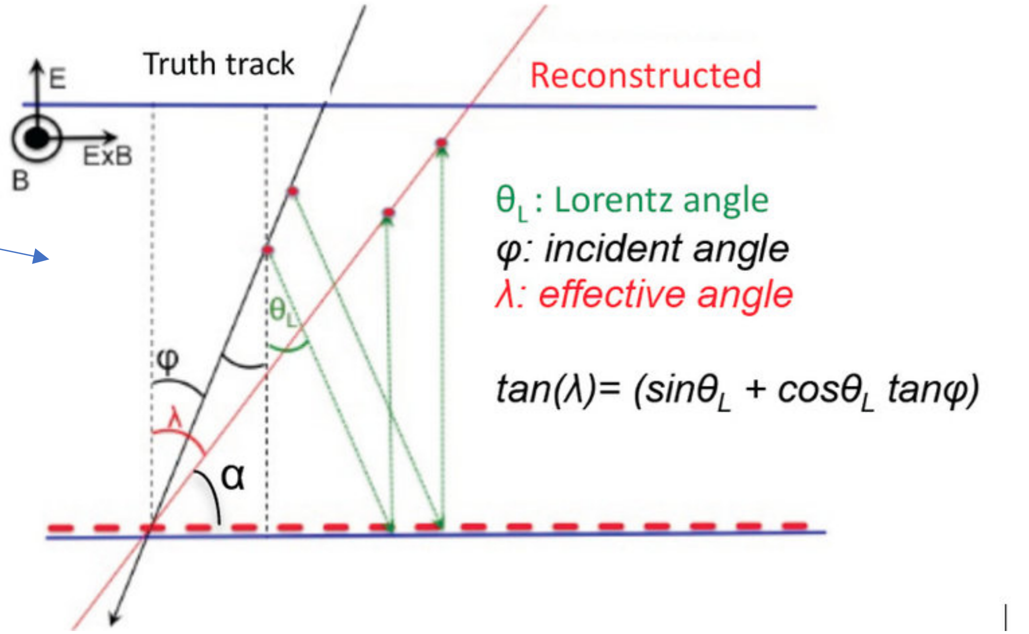
mobility, electric field, p/p_0 is pressure normalized to standard pressure (1 atm)



- Mobility is proportional to charge/mass or charge/temperature.

- If a magnetic field is also present, the drift responds to both E and B, leading to a Lorentz angle α between the drift velocity vector and the electric field vector:

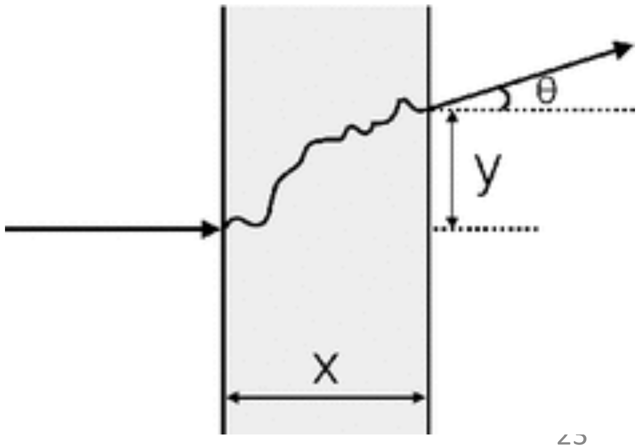
$$\boxed{\tan\alpha = v_{drift} \cdot \frac{B}{E}}$$



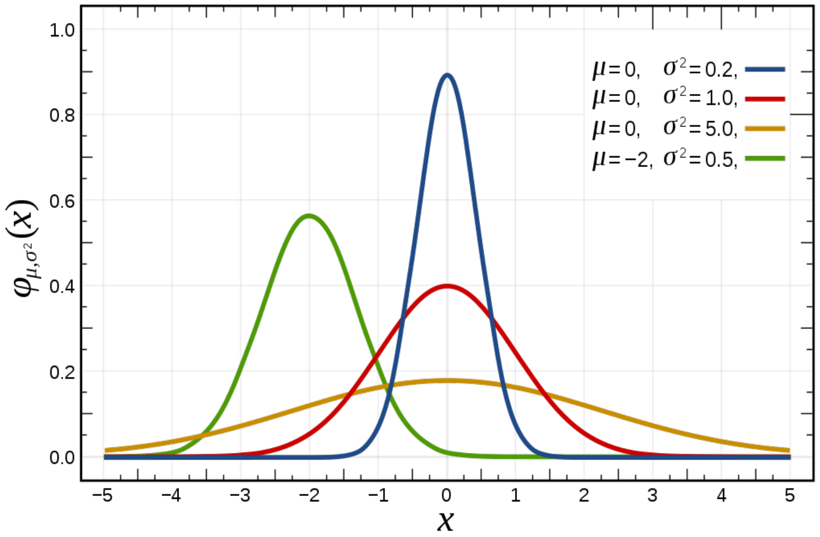
Characteristic properties of detectors

These are the properties that we use to answer the question:

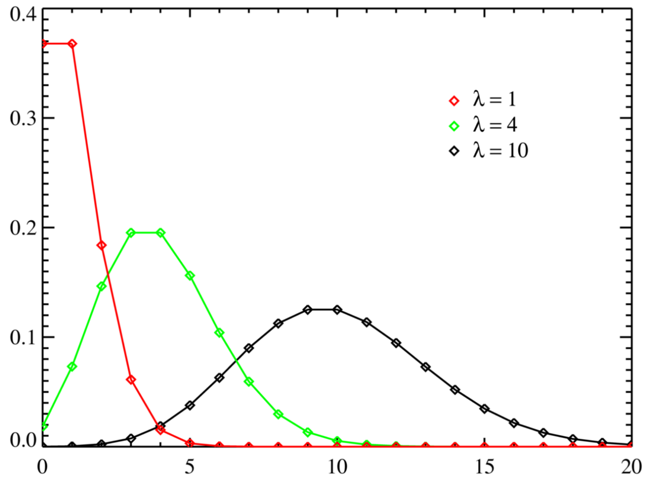
Is this detector good enough for the measurement I want to make?   Or, which of two detectors would be best for the measurement?



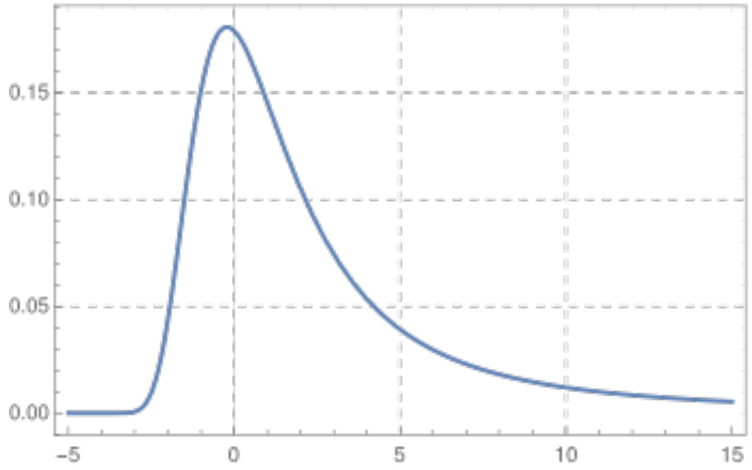
Consider a detector that provides measurements z. The measurements will be distributed about some true value z_0. The distribution D(z) is called the **probability density function (PDF)**, and often it is Gaussian:



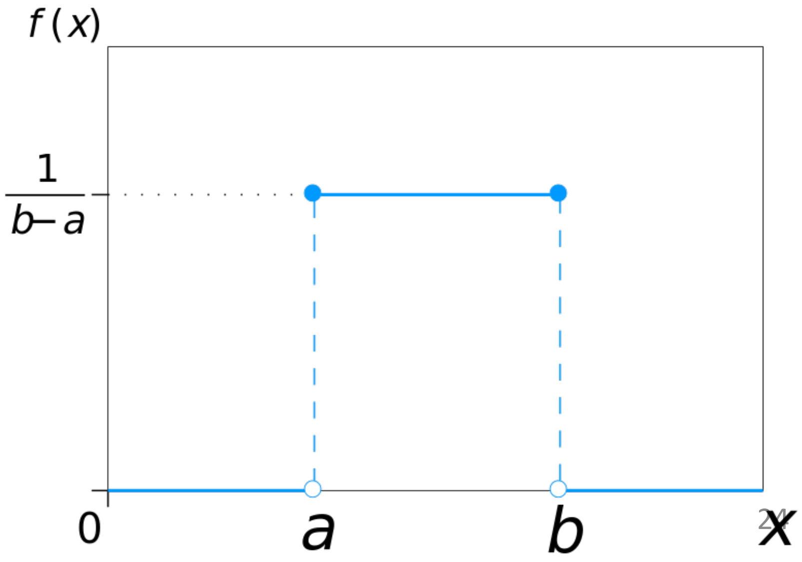
But it could instead be Poisson:



or Landau:



or rectangular:



A critical indicator of the quality of the measurement is the resolution. To find the *resolution in parameter z (where z could be energy, position, time...)*:

1) Calculate the expectation value: $$\langle z \rangle = \frac{\int z D(z)\,dz}{\int D(z)\,dz}$$

2) Calculate the variance: $$\sigma_z^2 = \frac{\int \left(z - \langle z \rangle\right)^2 D(z)\,dz}{\int D(z)\,dz}$$

3) For a gaussian, the resolution is often taken as the full width at half-maximum (FWHM). For a gaussian this is 2.35 σ_z.

4) For a rectangular distribution (e.g. discrete electrodes in a wire chamber or solid state detector), the resolution is often taken as the σ_z, which is (electrode spacing)/$\sqrt{12}$.

Besides its positional resolution, ***other indicators of the quality of a detector are*** its

Characteristic times

- ***dead time***: the interval that must pass between detection of one set of particles (“event”) and recovery of sensitivity to another

- ***readout time:*** the interval necessary to record the data, for example into electronic memory

Efficiency: the probability that a particle that passes through a detector is sensed by it.

Occupancy: number of particles traversing a detector cell, per event