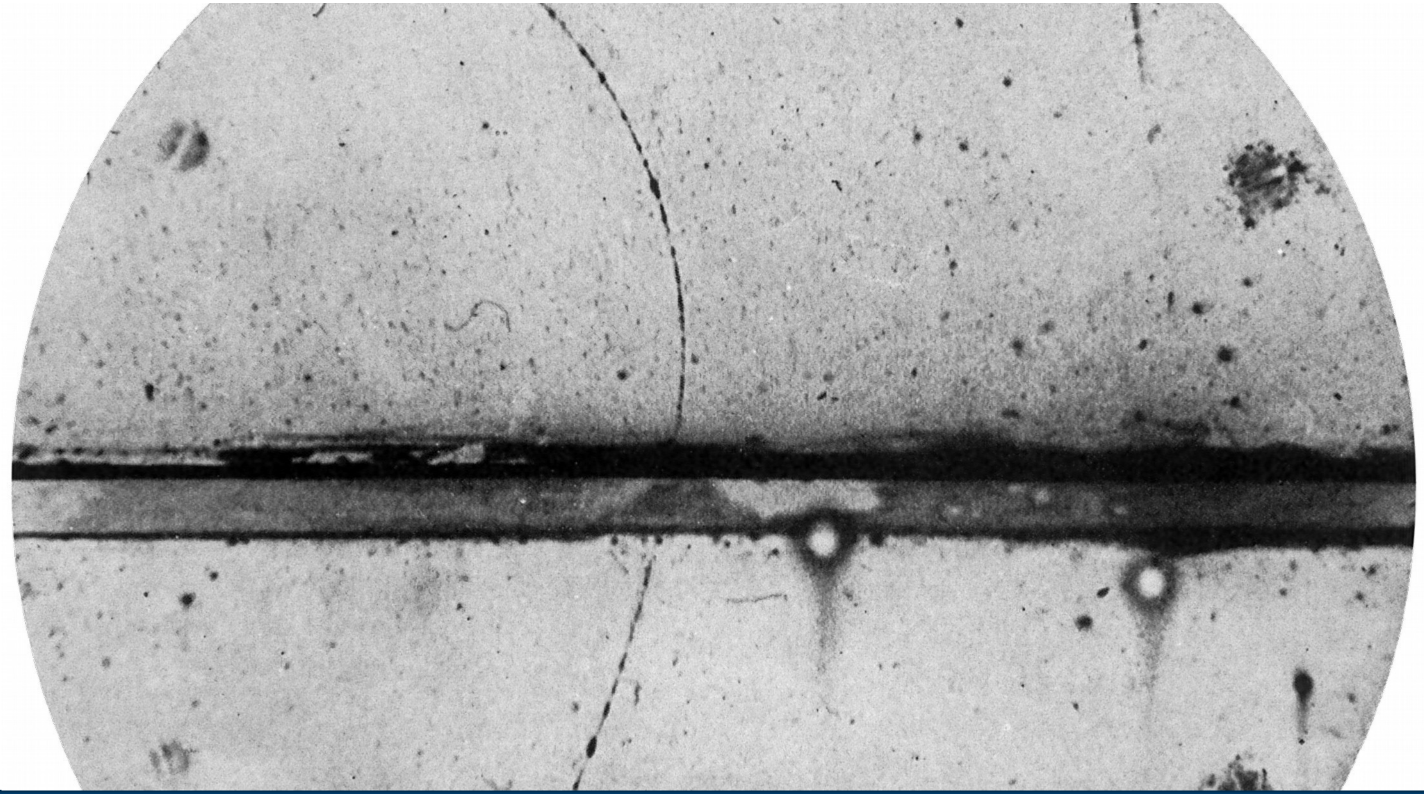

INTERACTION WITH MATTER

Particle Physics 2020

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JÜLICH Forschungszentrum

Use of Interactions

Interaction of:

- Photons with matter
  - Electrons/positrons with matter
    - Heavy (>m_e) charged particles with matter
      - Neutrons with matter

Ionization

- Particle production
  - Bremsstrahlung
    - Cherenkov radiation
      - Transition radiation

Important keywords

Bethe-Bloch Formula

Energy loss of heavy particles by Ionization

Multiple Scattering

Change of particle energy & direction in Matter

Cerenkov Radiation

Light emitted in medium cosed by
charged particles traveling in dielectric materials

Transition radiation

EM radiation emitted on traversing matter boundary

Fundamental Forces

How to detect particle?!

- it must interact with the material of the detector
- convert energy in some human recognizable pattern

- Strong : 1
- Electromagnetic: 1/137
- Week: 1/1'000'000
- Gravity: ~$1/10^{39}$

Characteristics

The interaction between particles and absorber material determines the energy loss of the particles and therefore the range of the particles in the absorber material.

Each interaction process leads to a certain amount of energy loss, since a fraction of the kinetic energy of the incoming particle is transferred to the body material by:
scattering, excitation, ionization or radiation loss.

The sum over all energy loss events along the trajectory of the particle yields the total energy loss.

Particle Species

1. Light charged particles (electrons/positrons)

- excitation and ionization of atoms in absorber material (atomic effects)
- interaction with electrons in material (collision, scatter)
- deceleration by Coulomb interaction (Bremsstrahlung)

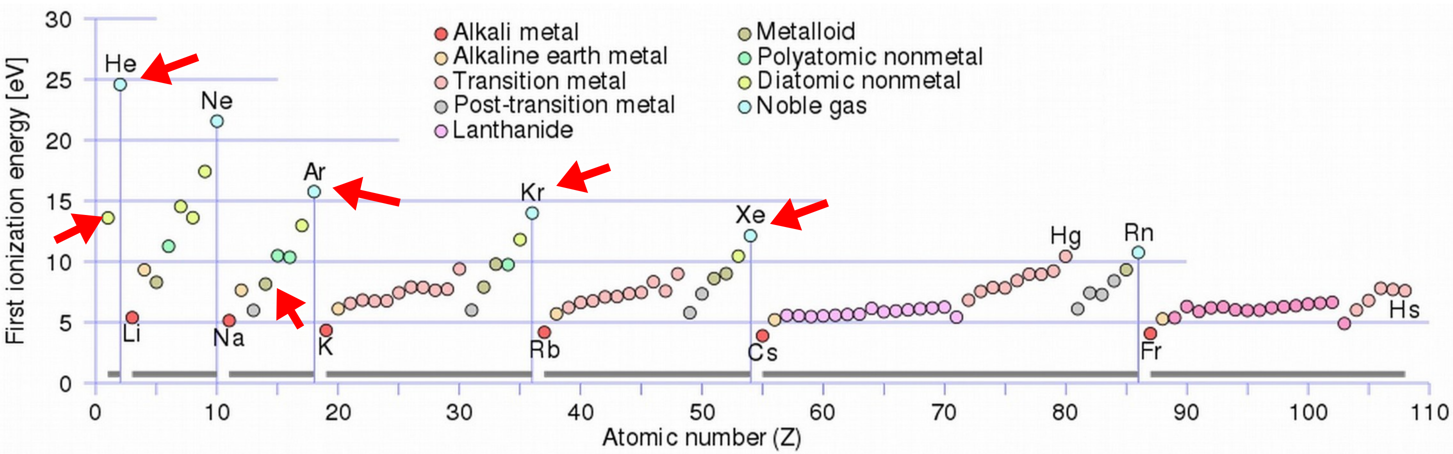
2. Heavy charged particles ($M \gg m_e$)

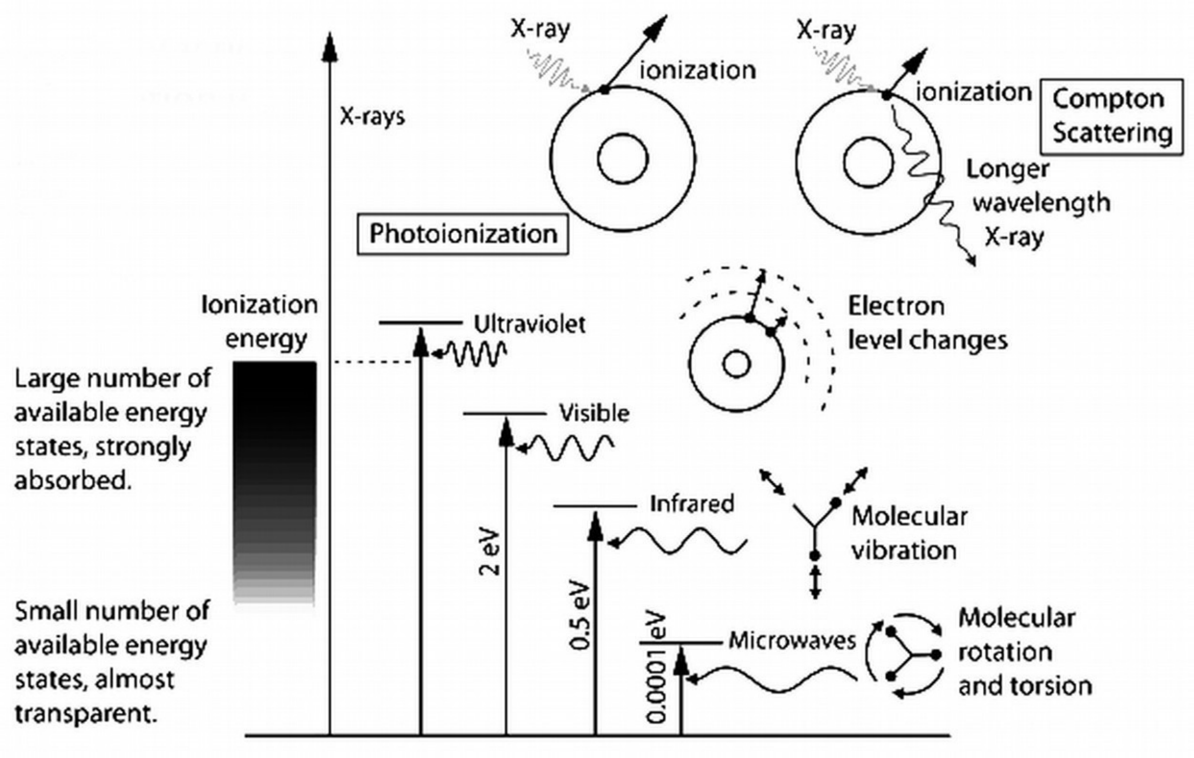
- excitation and ionization of atoms in absorber material (atomic effects)
- Coulomb interaction with nuclei in material (collision, scatter)
(long range forces)

3. Neutron radiation

- interaction by collision with nuclei in material (short range forces)

Energy Levels





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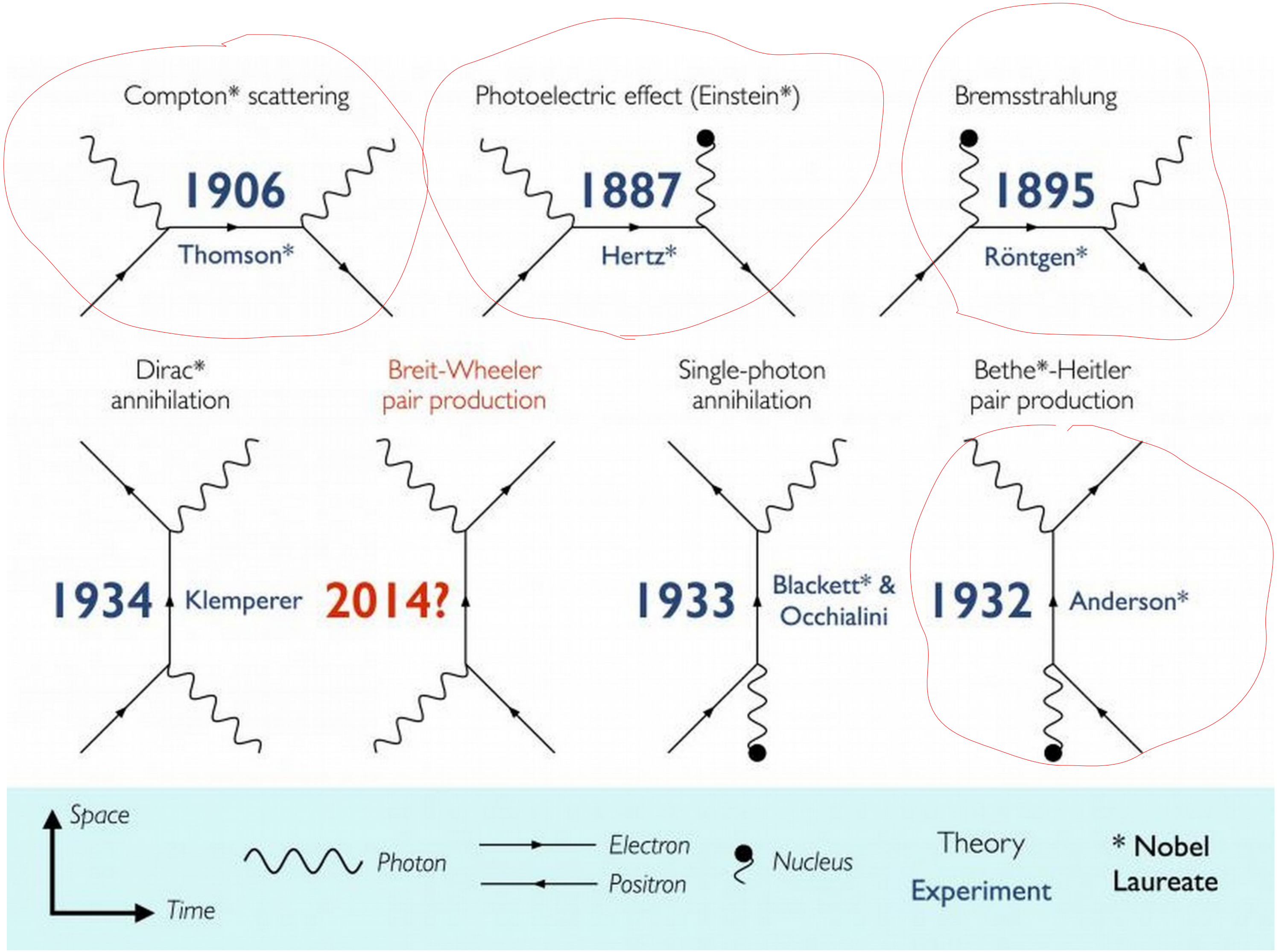
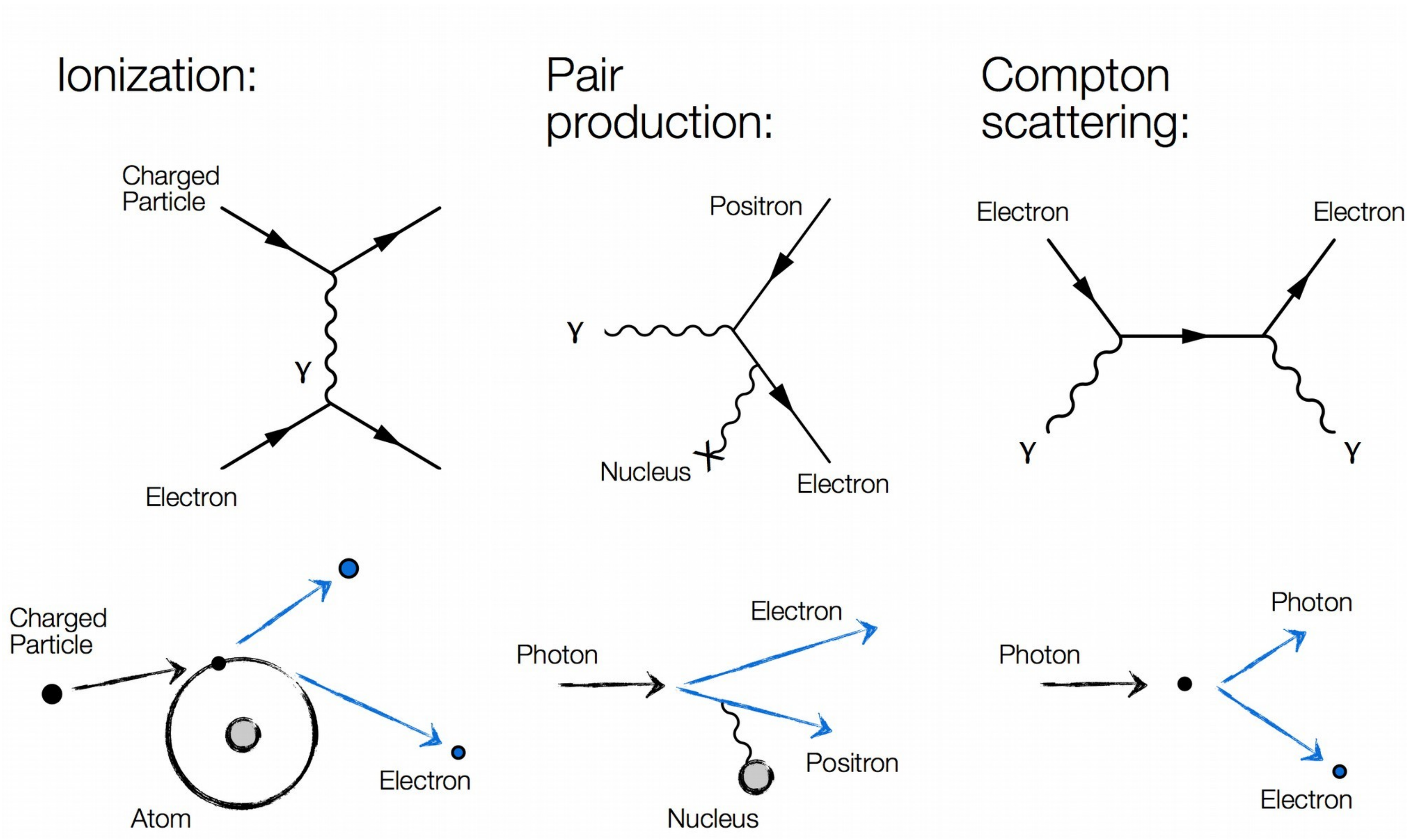
Important processes



Electrons and Photons



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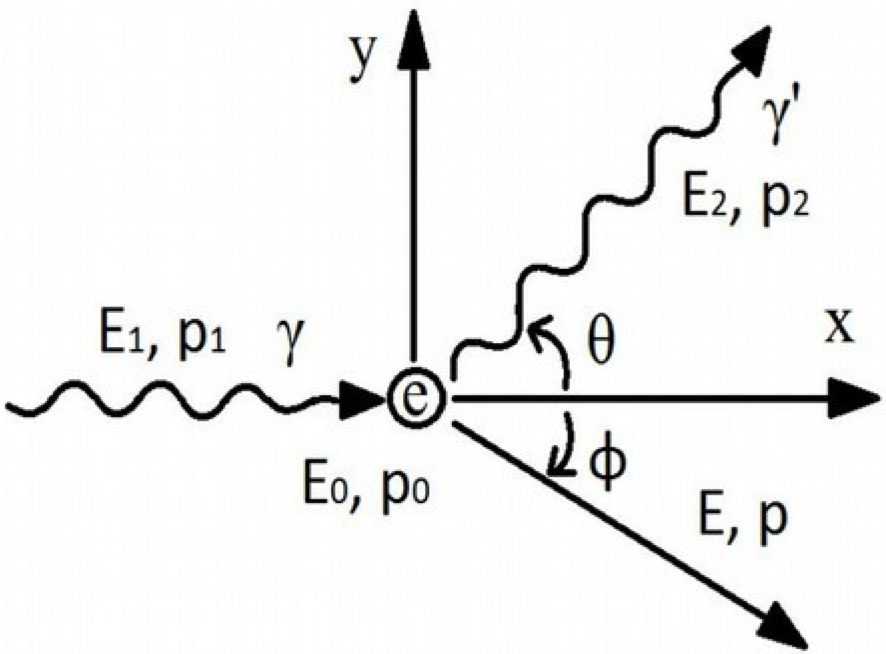
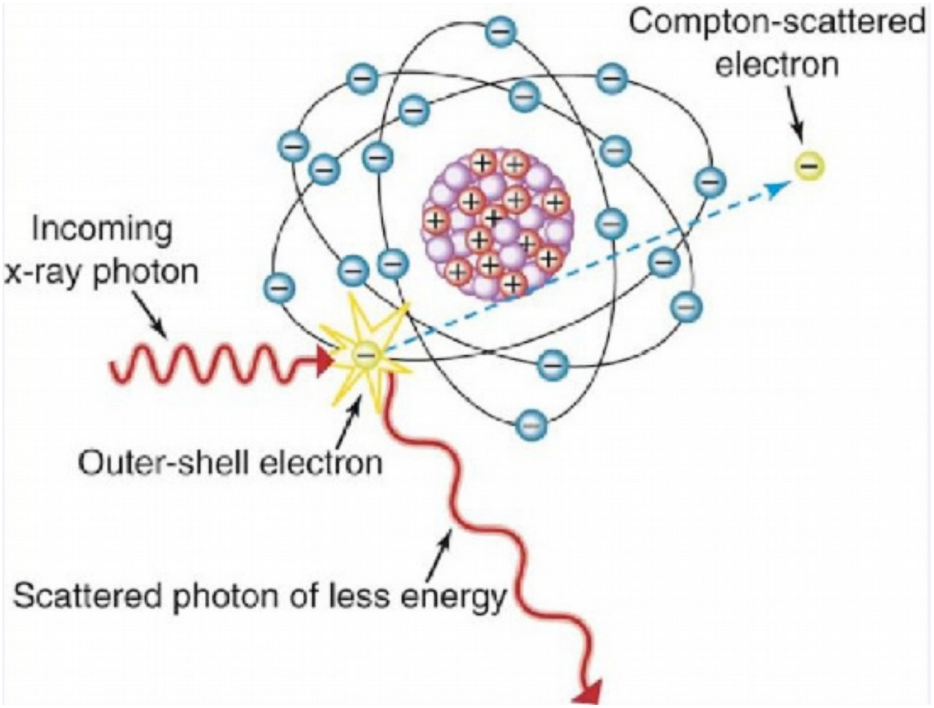
Compton Effect

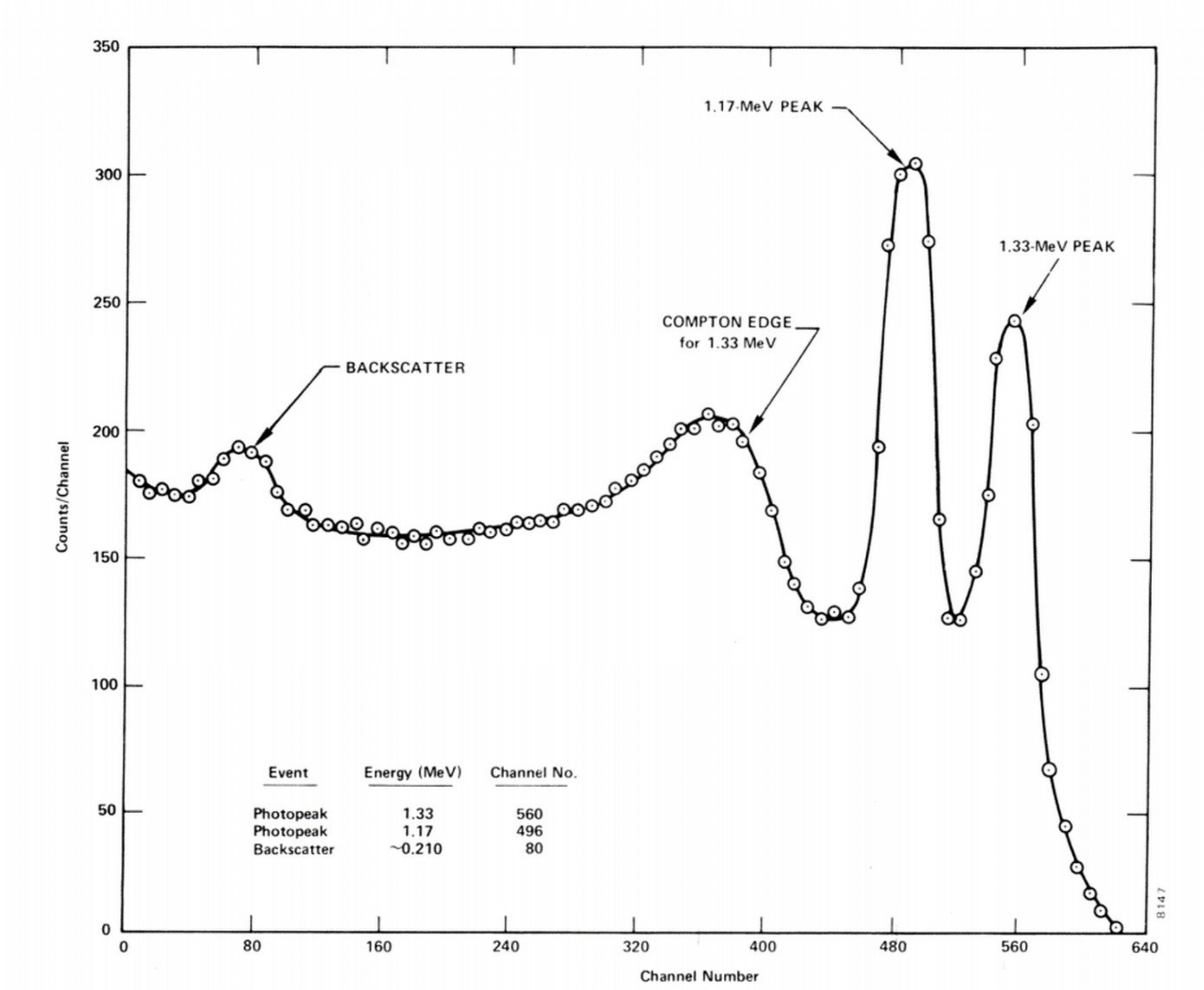




$$E_1 = \frac{E_0}{1 + \left(\frac{E_0}{m_0 c^2}\right)(1 - \cos\theta)}$$

Compton Edge

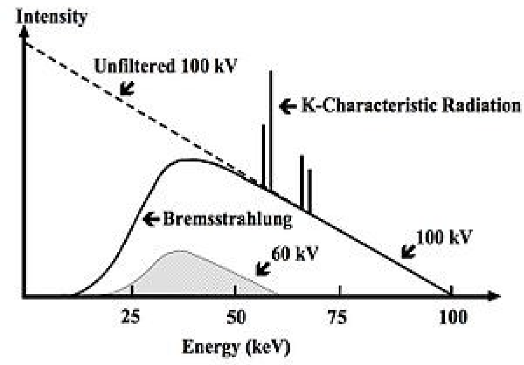
of ^{60}Co on gamma spectrometer Na(Tl).

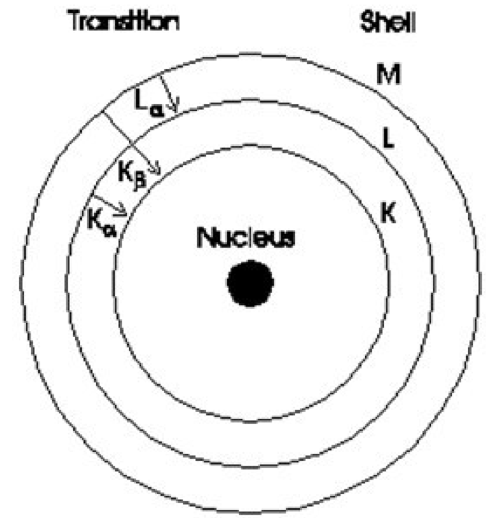


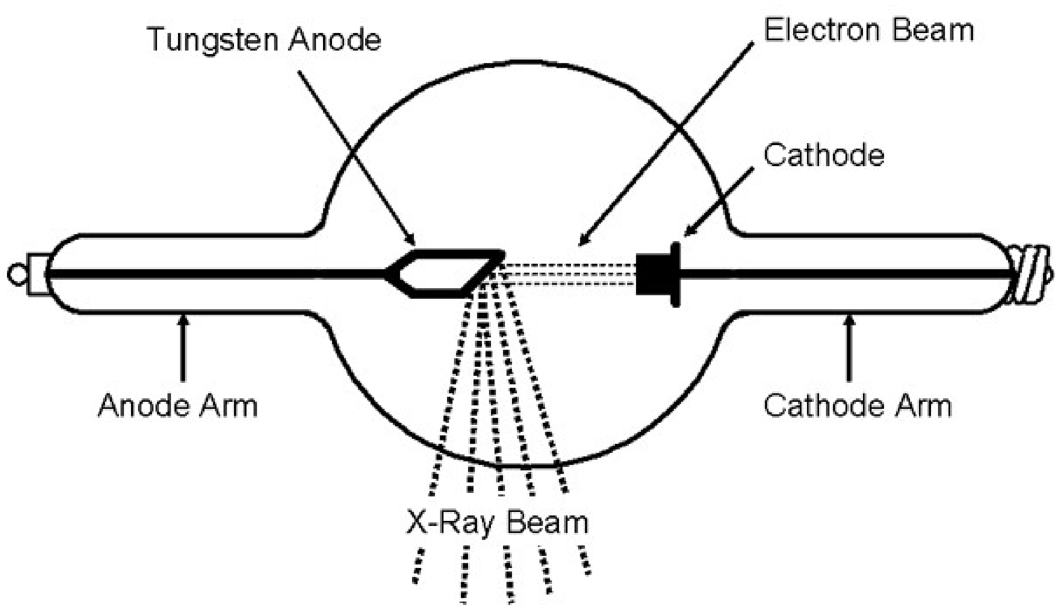
Characteristic X-Rays

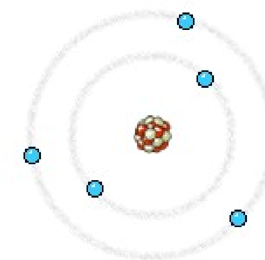
Tungsten 74
K – 70 keV
L – 12 keV
M – 2.8 keV

L → K	Kα	70-12=58 keV
M → K	Kβ	70-3=67 keV
M → L	Lα	12-3=9 keV



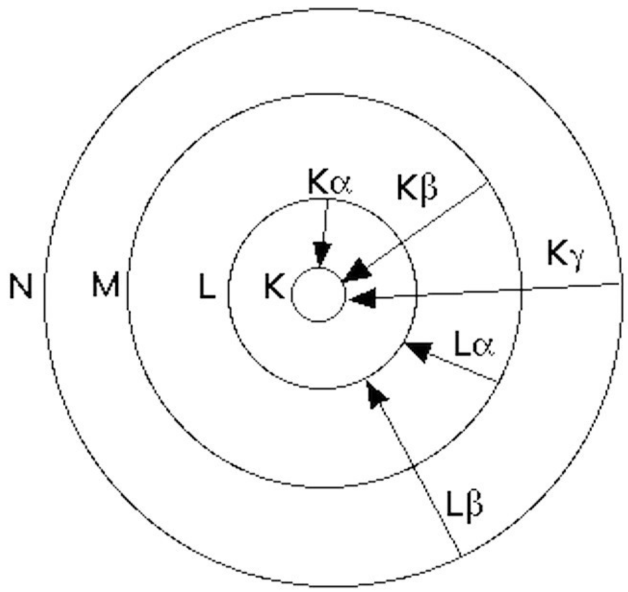




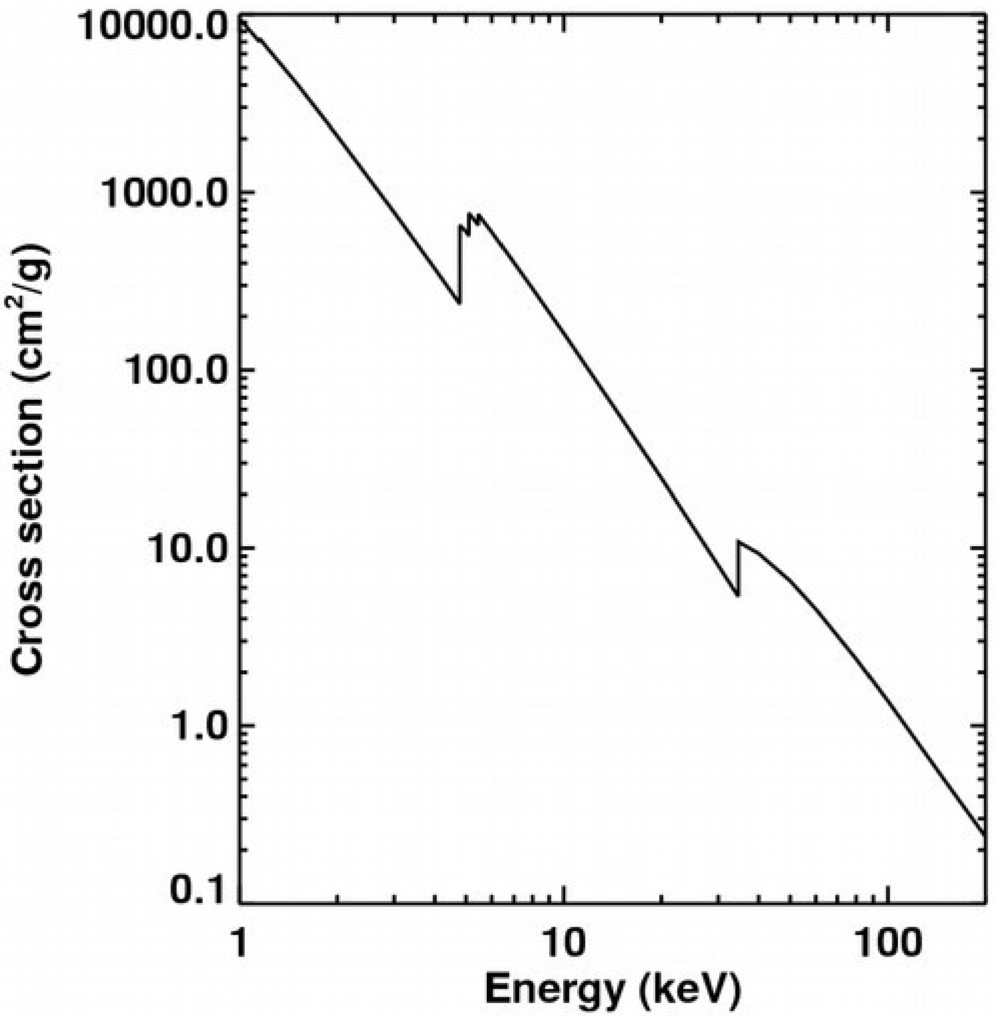


Xe Cross Section

"Edges" occur at the characteristic electronic transition energies

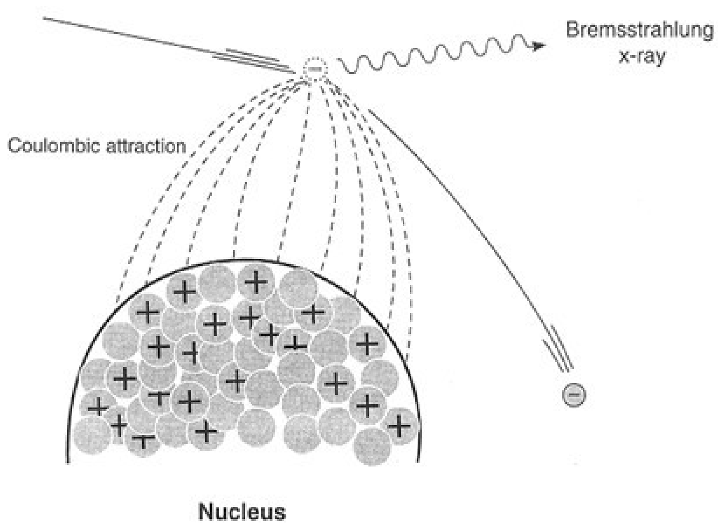


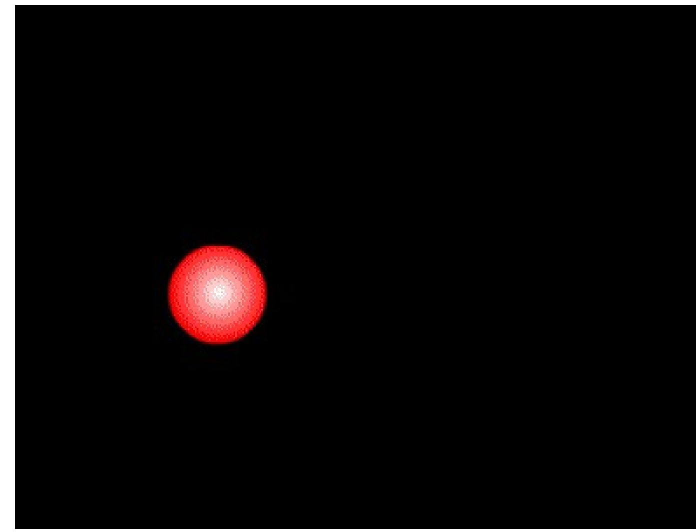
When in emission, elements produce characteristic lines at these energies



Bremsstrahlung

All charged particles scatter from the atomic nuclei when passing through a medium.
When a charged particle is accelerated it radiates, so scattering of charged particles produces radiation.
The radiation produced is know as "**bremsstrahlung**"





The mean bremsstrahlung energy loss of a charged particle (mass M, charge ze) is

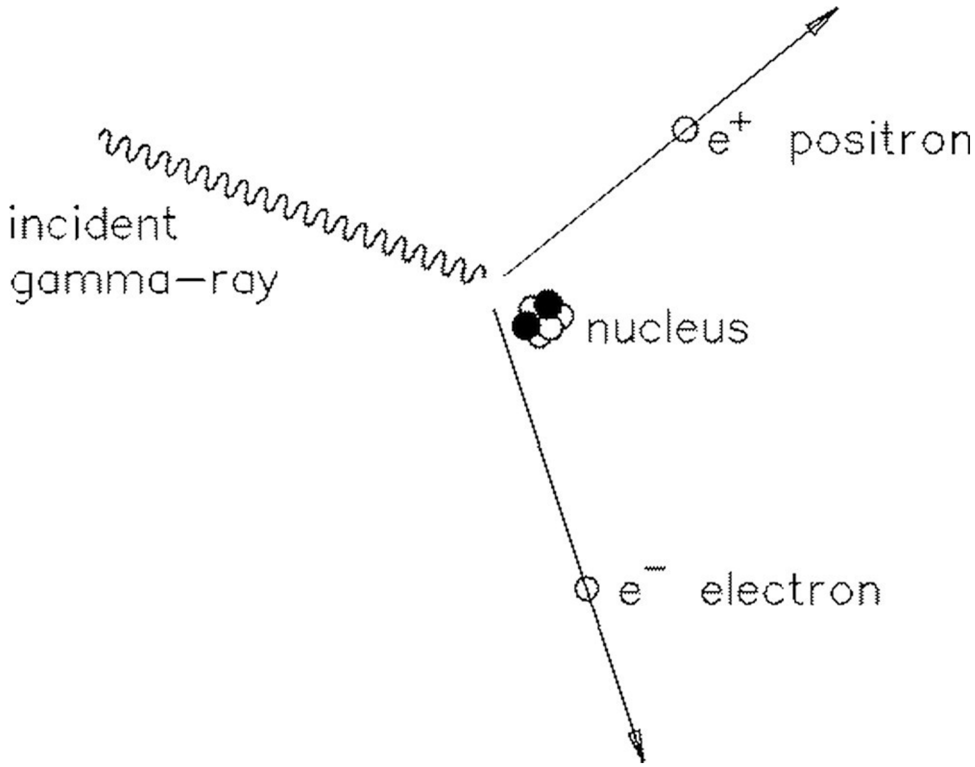
dE/dx = -E/X0

where the radiation length, X_0, for the medium (atom density na and atomic number Z) is approximately given by

$$X_0 = M^2/[4n_a e^6 z^4 Z(Z+1)\ln(183/Z^{1/3})]$$

it dominates the energy loss of electrons above **the critical energy, E_c**; ionization dominates at lower energies.

Pair Production



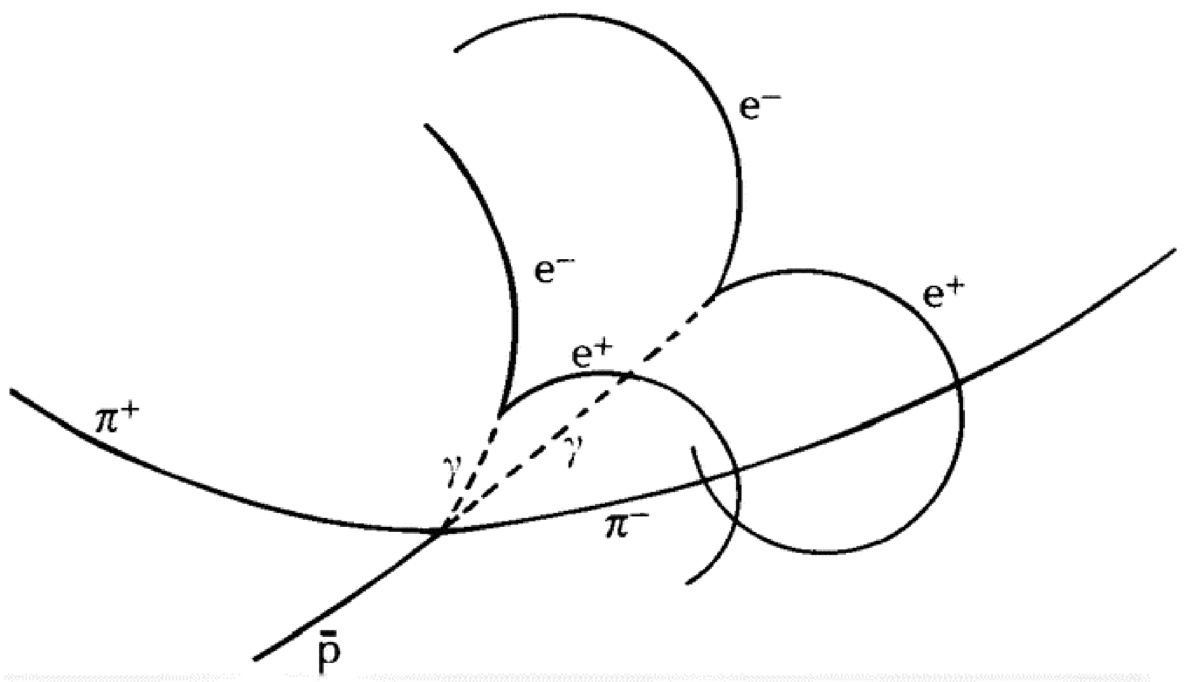
Nucleus is needed for process to converse momentum and energy

$$\sigma \propto Z^2$$

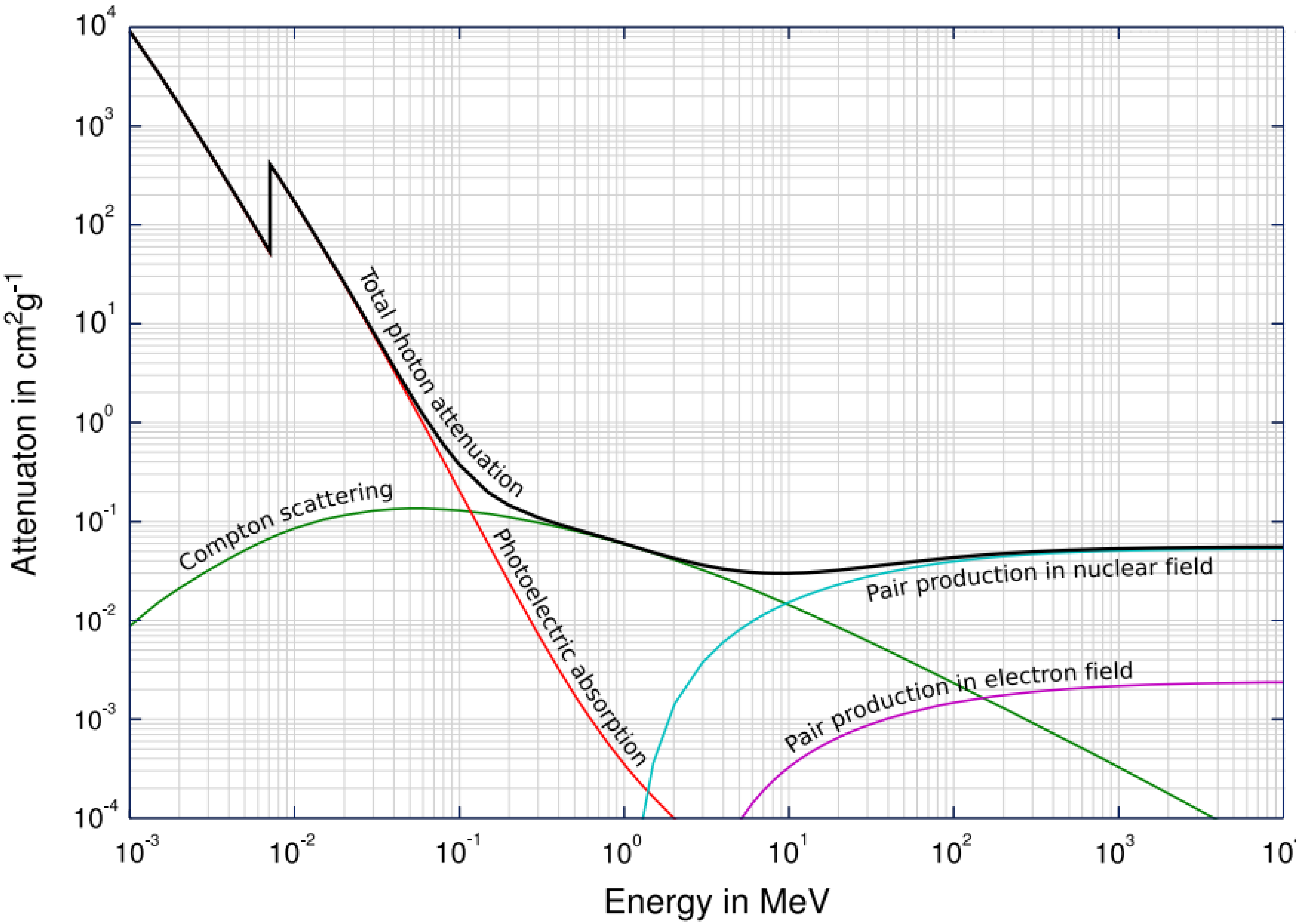
Only process with cross section which never decreases with energy, dominates at high energies

Pair Production

- Incoming photon must have an energy > 1.022 MeV
  twice of an e mass
- This process is a conversion of energy into matter
  and then matter back into energy



Attenuation

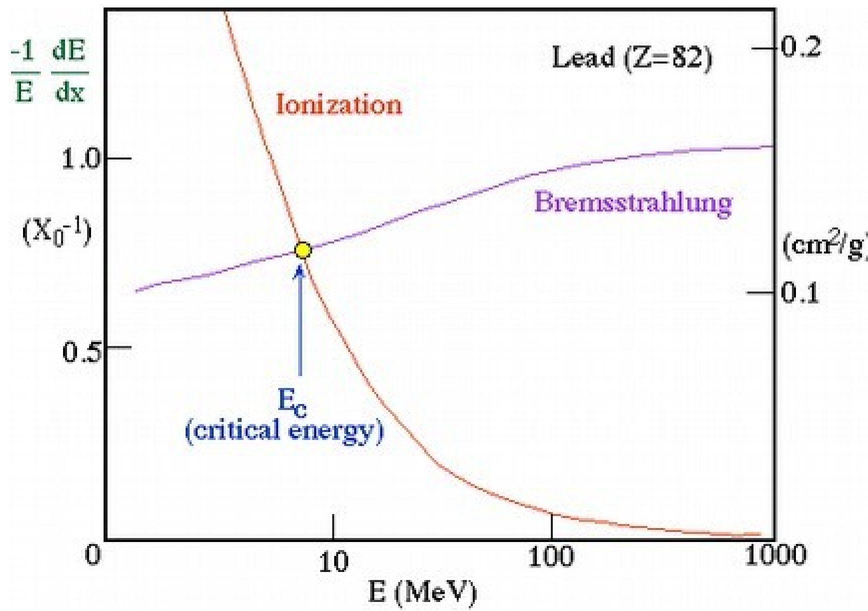


Energy loss of e in lead

The critical energy (in lead) of the electron is about 7 MeV;

the critical energy of the next lightest particle (the muon) is about half a TeV.

One can introduce the so-called radiation length X_0 defined as:



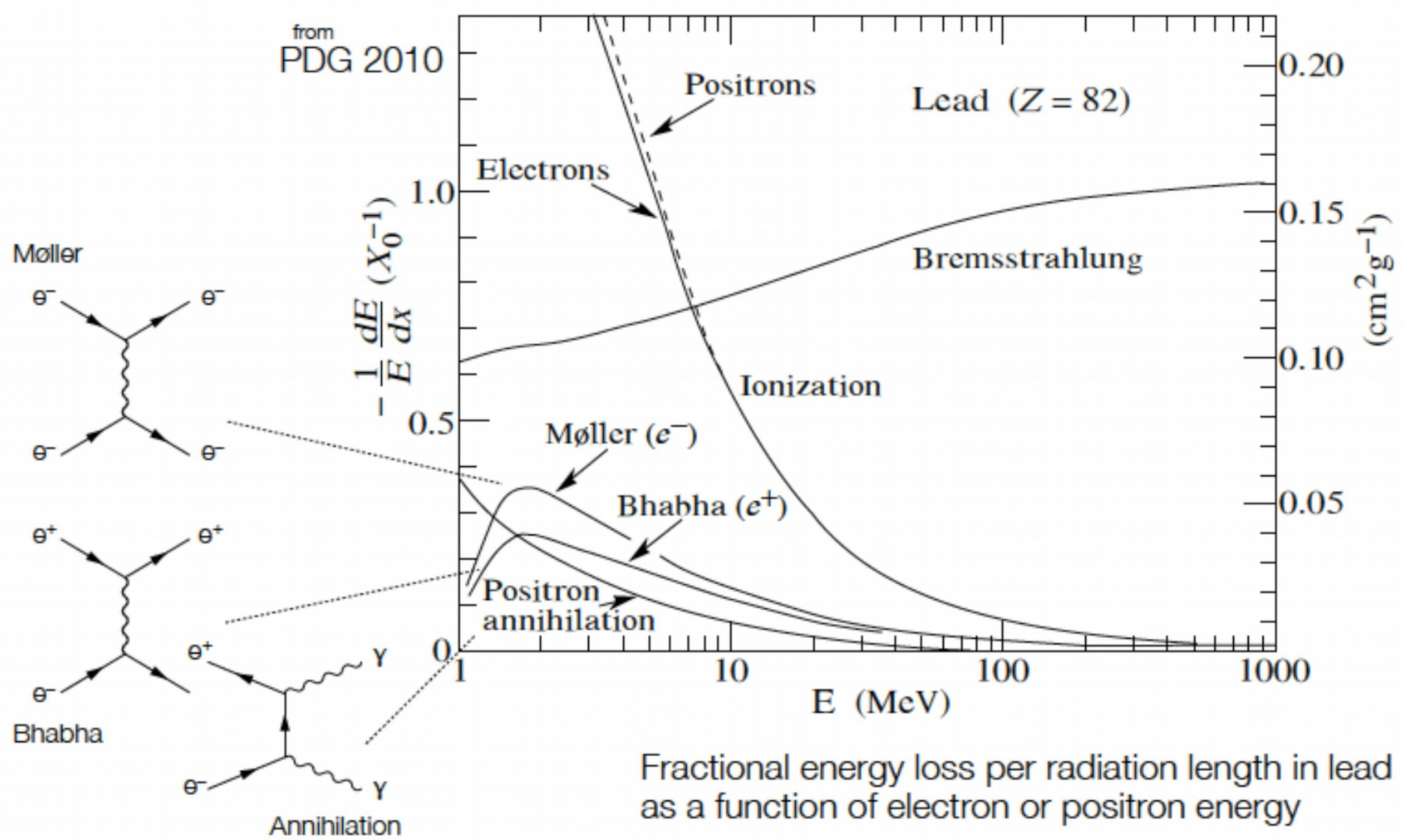
$$-\left.\frac{dE}{dx}\right|_{Brems} = 4\alpha N_A \left(\frac{e^2}{mc^2}\right)^2 \ln\frac{183}{Z^{1/3}} \frac{Z(Z+1)}{A} Q^2 E$$

$$\frac{1}{X_0} = 4\alpha N_A \left(\frac{e^2}{m_e c^2}\right)^2 \ln\frac{183}{Z^{1/3}} \frac{Z(Z+1)}{A}$$

$$-\left.\frac{dE}{dx}\right|_{Brems} := \frac{1}{X_0} E$$

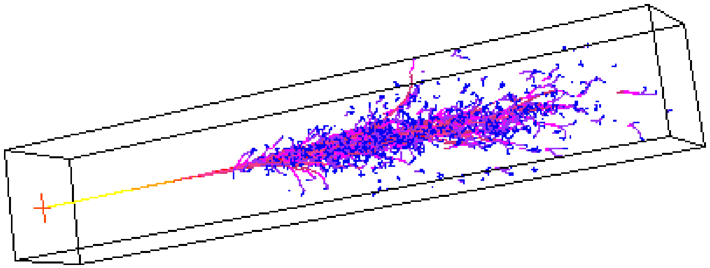
$$\left(\frac{dE}{dx}\right)_\mu \Big/ \left(\frac{dE}{dx}\right)_e \sim \frac{1}{40.000}$$

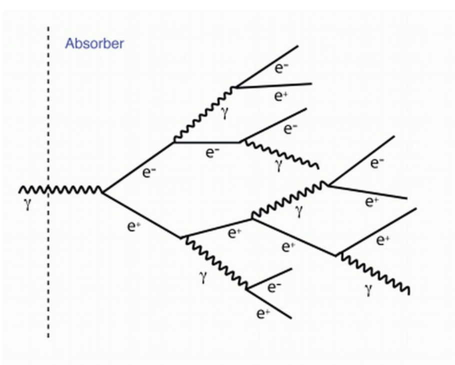
Energy loss for electrons



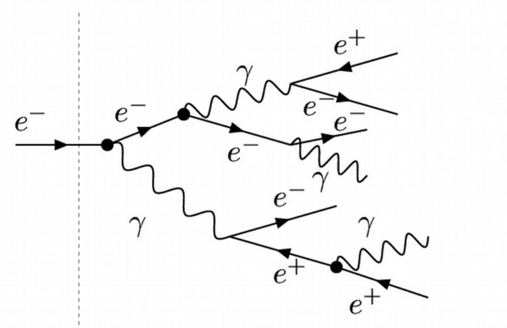
Fractional energy loss per radiation length in lead as a function of electron or positron energy

EM shower

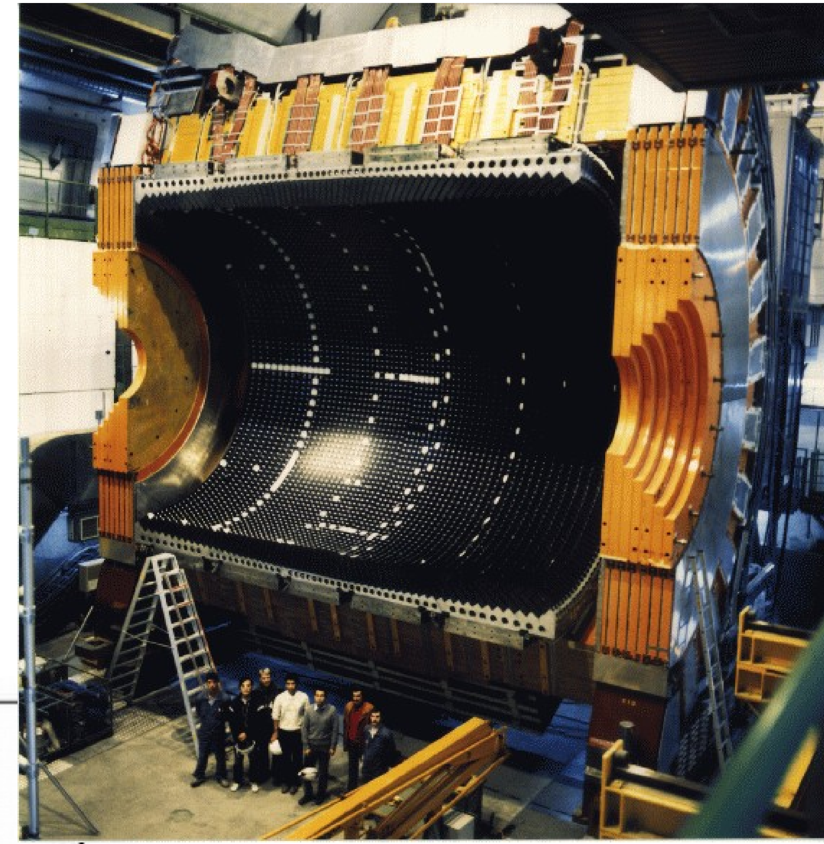


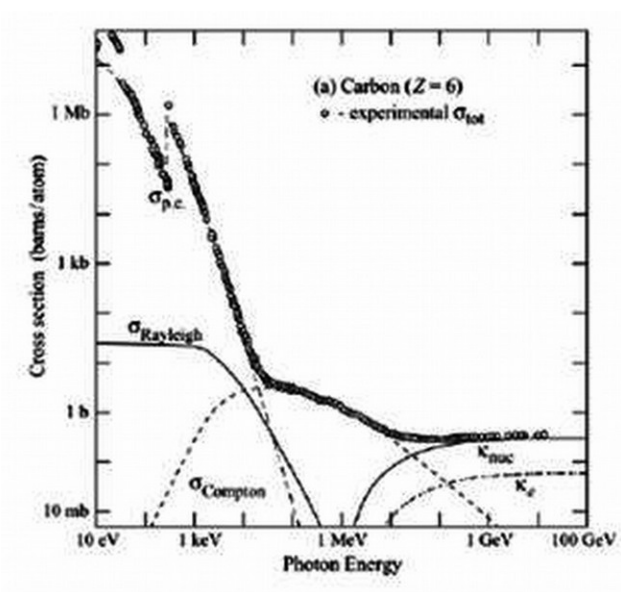


Absorber
γ
e⁻
e⁺

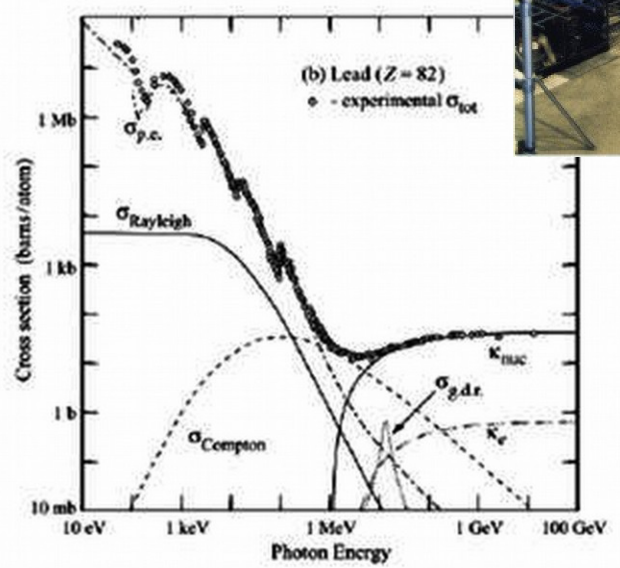


e^-
e^+
γ





(a) Carbon (Z = 6)
∘ - experimental σ_tot
Cross section (barns/atom)
1 Mb
1 kb
1 b
10 mb
σ_p.e.
σ_Rayleigh
σ_Compton
κ_nuc
κ_e
10 eV
1 keV
1 MeV
1 GeV
100 GeV
Photon Energy



(b) Lead (Z = 82)
∘ - experimental σ_tot
Cross section (barns/atom)
1 Mb
1 kb
1 b
10 mb
σ_p.e.
σ_Rayleigh
σ_Compton
σ_g.d.r.
κ_nuc
κ_e
10 eV
1 keV
1 MeV
1 GeV
100 GeV
Photon Energy

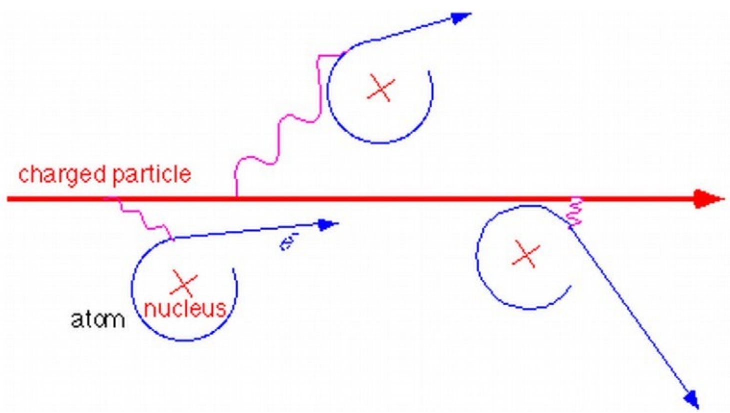
Interactions

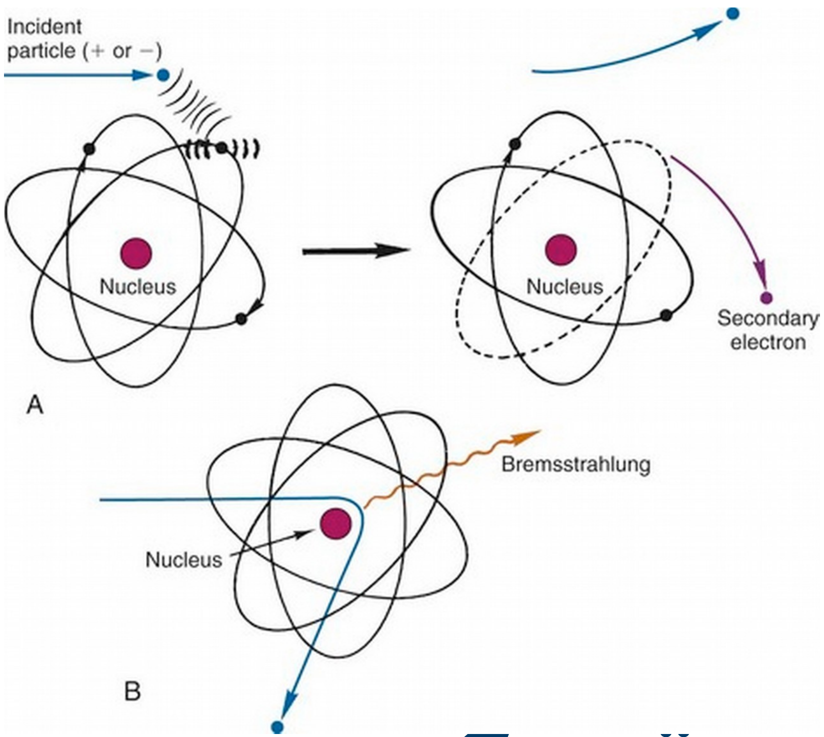
Fundamental interaction for charged particles:
electromagnetic interaction

Energy is mainly lost due to interaction of the particles with the electrons of the atoms of the medium

Cross sections are large: $\sigma \sim 10^{-17} – 10^{-16} cm^2$!!

Small energy loss per collision,
however, large number of them
in dense materials

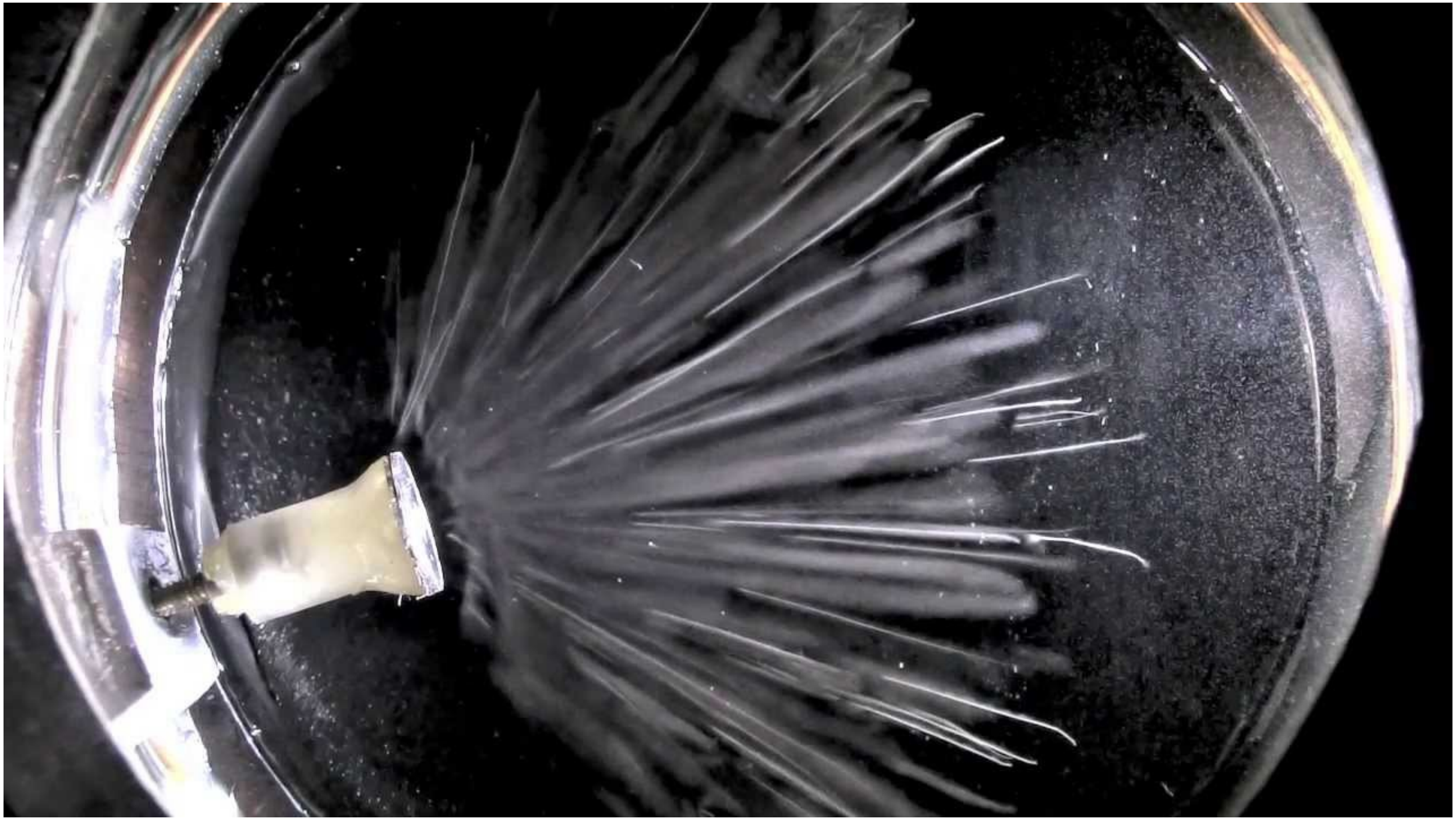




Bragg-Kleeman Rule

$$\frac{R_1}{R_2} = \frac{\rho_2}{\rho_1} \cdot \frac{\sqrt{A_1}}{\sqrt{A_2}} \; where \; \rho - density \, , A - effective \; atomic \; weight$$

Alpha Tracks in Cloud Chamber



History of E loss calculations

1915: **Niels Bohr**, classical formula, Nobel prize 1922.
1930: Non-relativistic formula found by **Hans Bethe**
1932: Relativistic formula by **Hans Bethe**

Bethe's calculation is leading order in pertubation theory, thus only z^2 terms are included.

- z^3corrections calculated by **Barkas-Andersen**
- z^4 correction calculated by **Felix Bloch** (**Nobel prize 1952**, for nuclear magnetic resonance). Although the formula is called **Bethe-Bloch formula** the z^4 term is usually not included.
- Shell corrections: atomic electrons are not stationary
- Density corrections: by **Enrico Fermi** (**Nobel prize 1938**, for the discovery of nuclear reaction induced by slow neutrons).

Hans Bethe (1906-2005)
Studied physics in Frankfurt and Munich, emigrated to US in 1933. Professor at Cornell U., **Nobel prize 1967** for the theory of nuclear processes in stars.

Formula

[see e.g. PDG 2010]

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\mathrm{max}}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$[\cdot \rho]$

density

$K = 4\pi N_A r_e^2 m_e c^2 = 0.307$ MeV g^{-1} cm^2

$T_{max} = 2 m_e c^2 \beta^2 \gamma^2 / (1 + 2\gamma\, m_e/M + (m_e/M)^2)$

[Max. energy transfer in single collision]

z : Charge of incident particle
M : Mass of incident particle

Z : Charge number of medium
A : Atomic mass of medium

I : Mean excitation energy of medium
δ : Density correction [transv. extension of electric field]

$N_A = 6.022 \cdot 10^{23}$
[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm
[Classical electron radius]

$m_e = 511$ keV
[Electron mass]

$\beta = v/c$
[Velocity]

$\gamma = (1-\beta^2)^{-2}$
[Lorentz factor]

Validity:

$.05 < \beta\gamma < 500$
$M > m_\mu$

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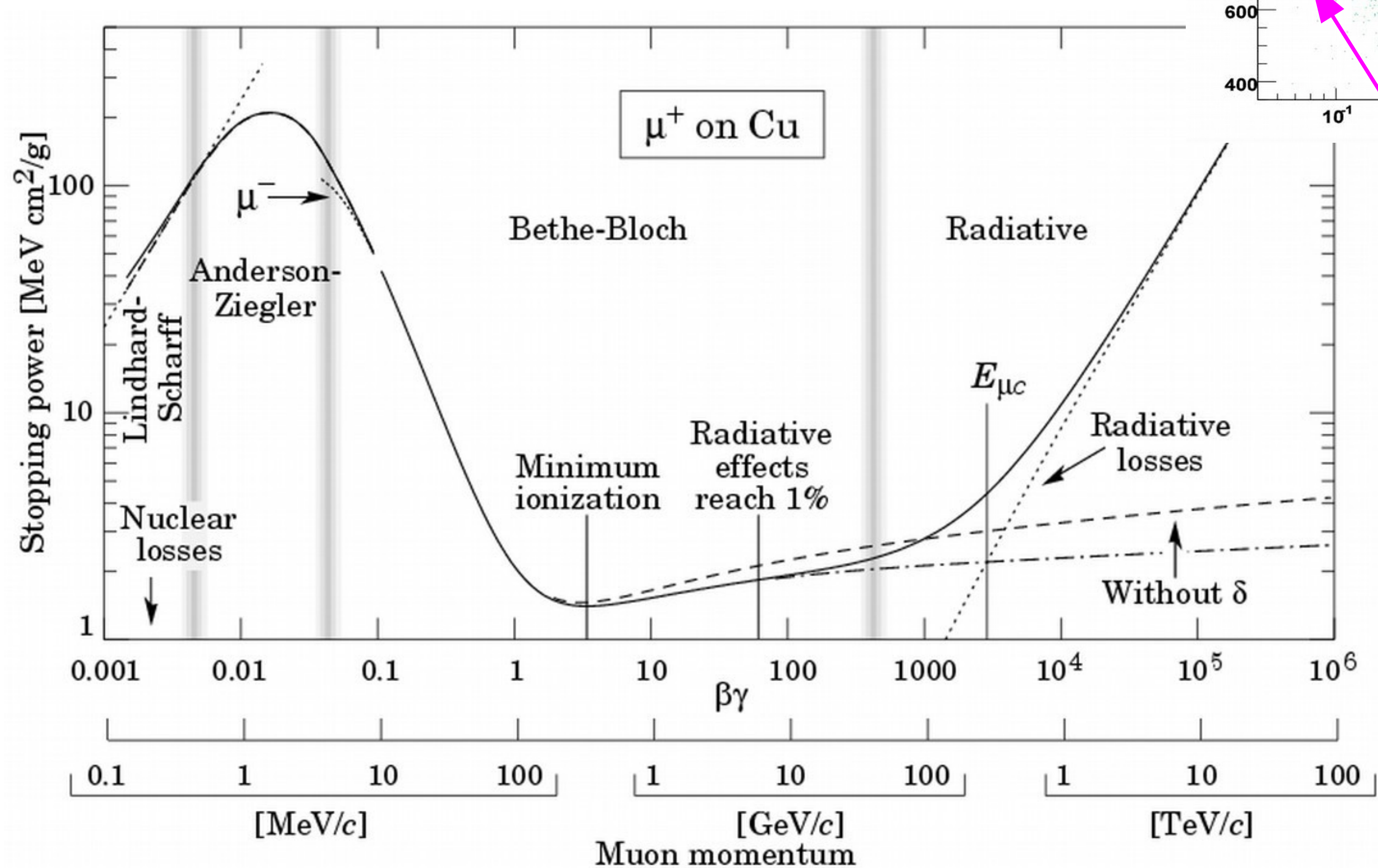
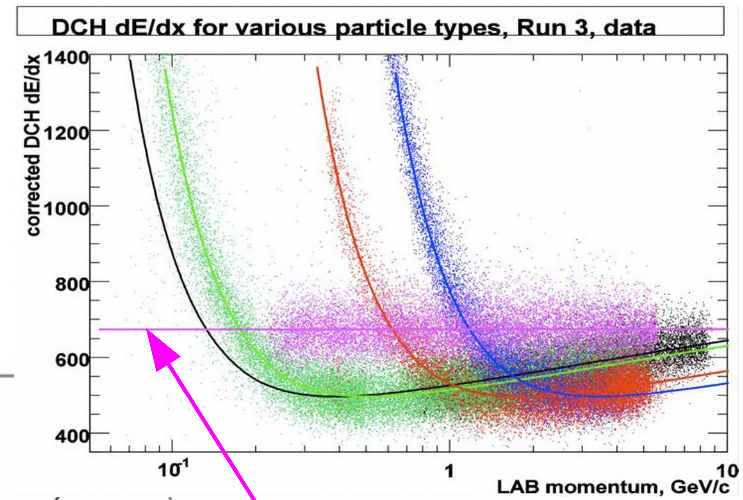
Bethe-Bloch stopping power plot

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln f(\beta) - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$





note: Bethe-Bloch formula is not valid for electrons (equal mass, identical particles)

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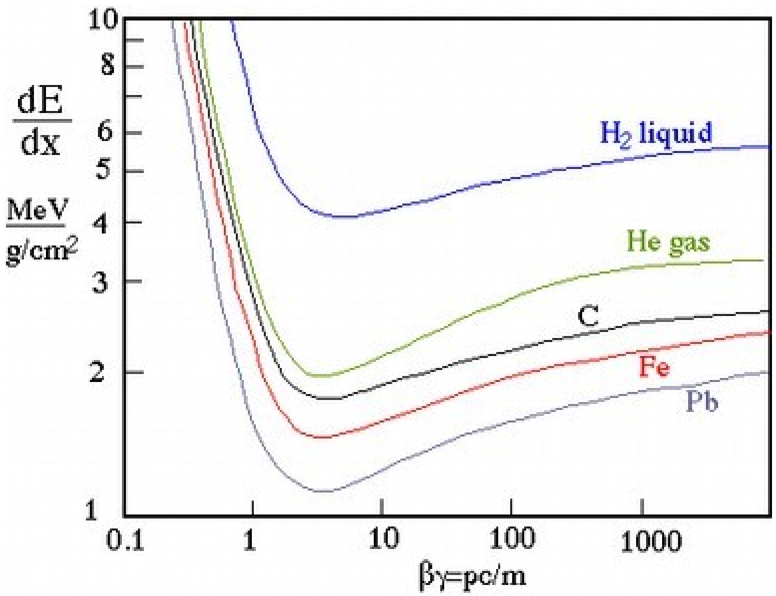
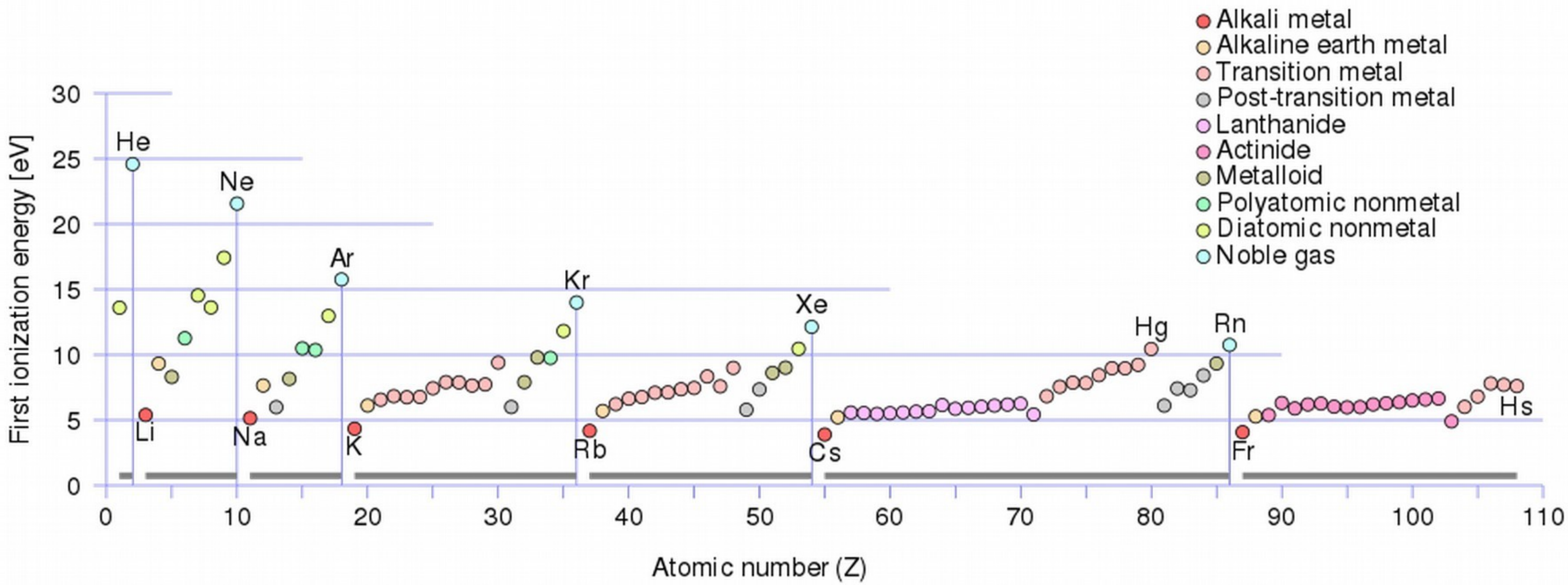
Ionization energies





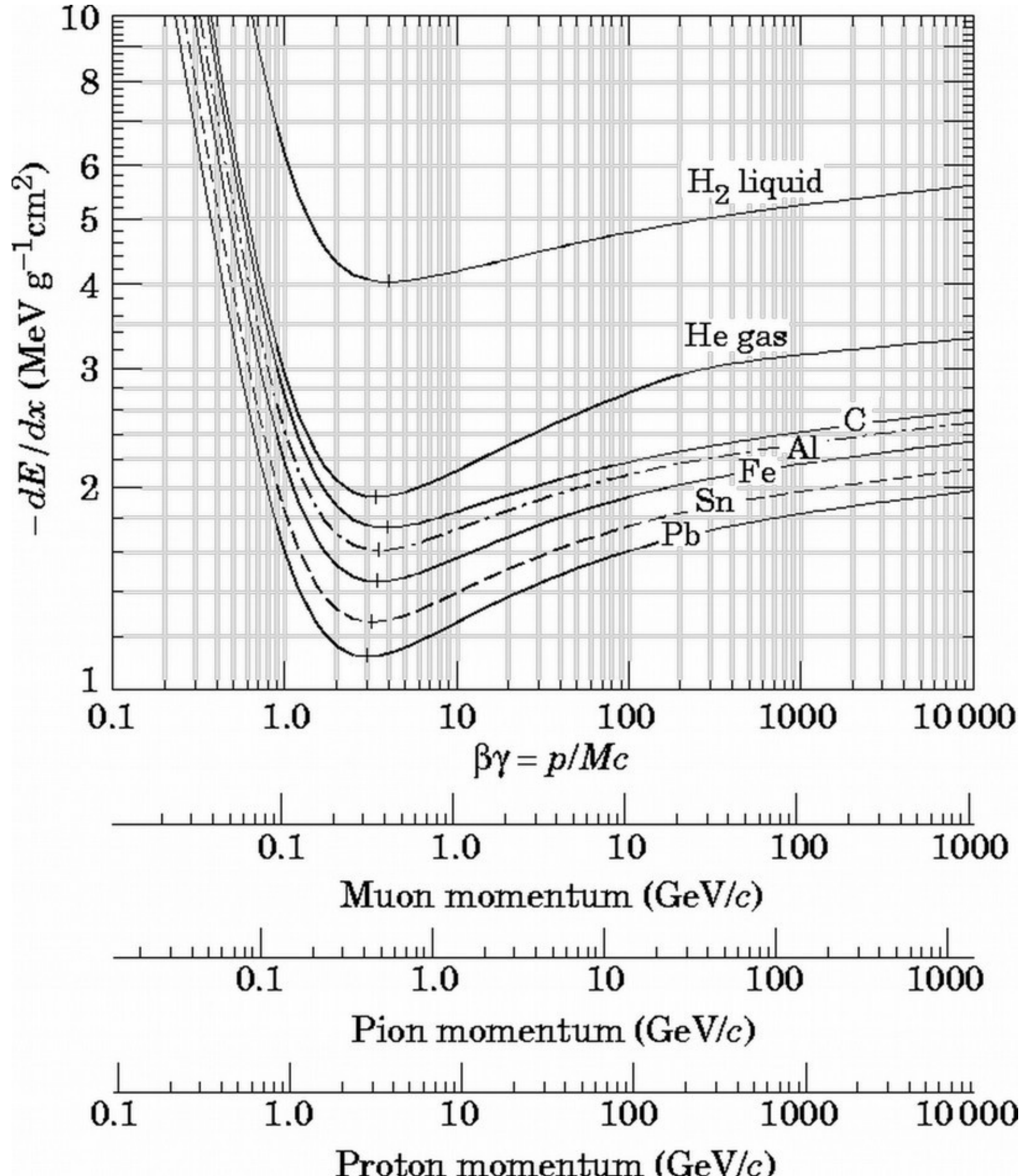
Important futures

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} [\frac{1}{2} \ln f(\beta) - \beta^2 - \frac{\delta(\beta\gamma)}{2}]$$

- Energy loss is independent of the mass

of the incoming particle-universal curve

- depends quadratically on the charge and velocity of the particle: ~ z^2/β^2
- dE/dx is relatively independent of the absorber (enters only via Z/A, which is constant over a large range of materials)
- Minimum for $\beta\gamma \approx 3.5$ energy loss in the "mimimum ionizing particle" MIP:
- Logarithmic rise for large values of $\beta\gamma$due to relativistic effects is damped in dense media $\delta(\beta\gamma)$



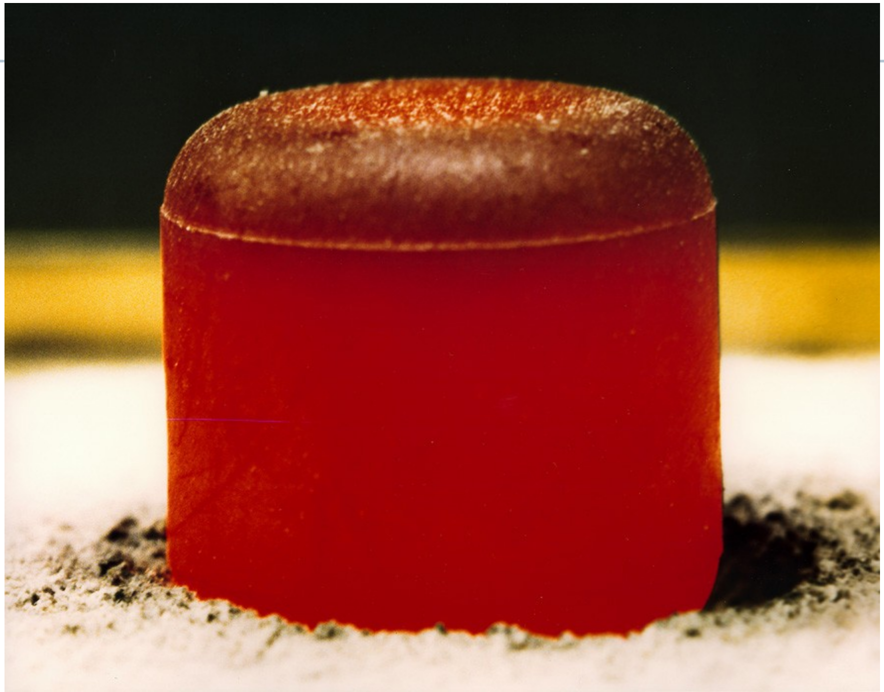
Practical Use

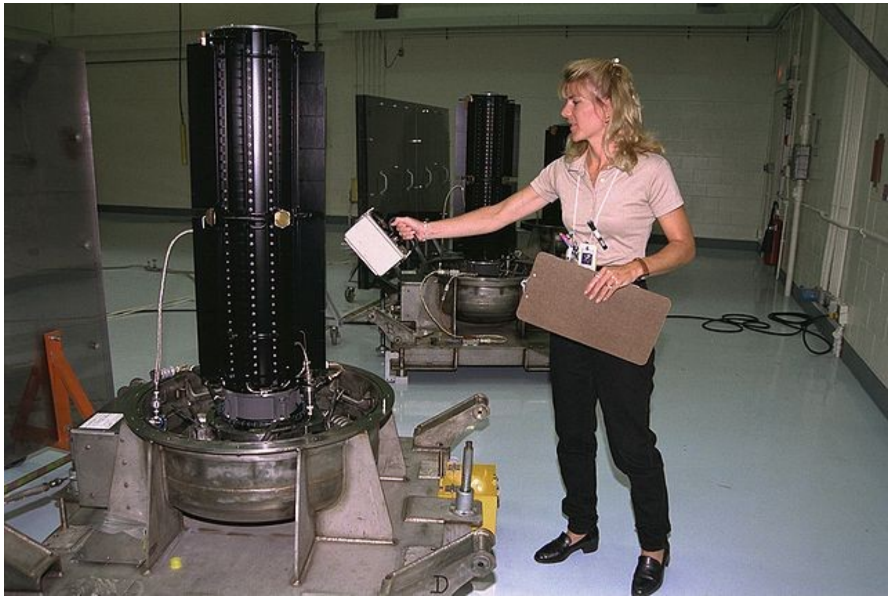
^{238}Pu – (PuO_2) alpha source

- half-life: 87.7y
- **power: 540 W/kg**
- shielding: 2.5mm lead
- high temperature

^{90}Sr – beta source

- half-life: 28.8y
- **power: 460 W/kg**
- shielding: few mm light material
- low temperature but cheap



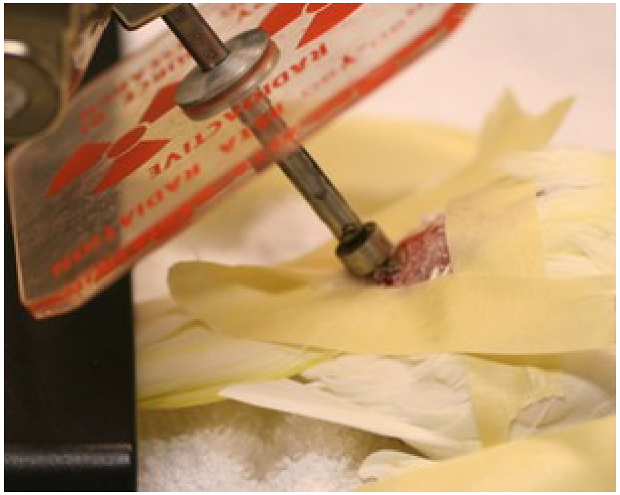


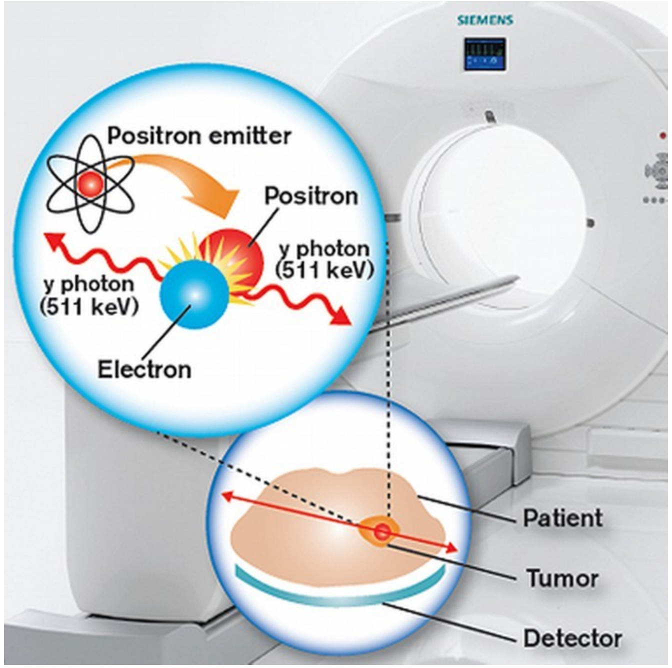
Therapy

Radiotherapy

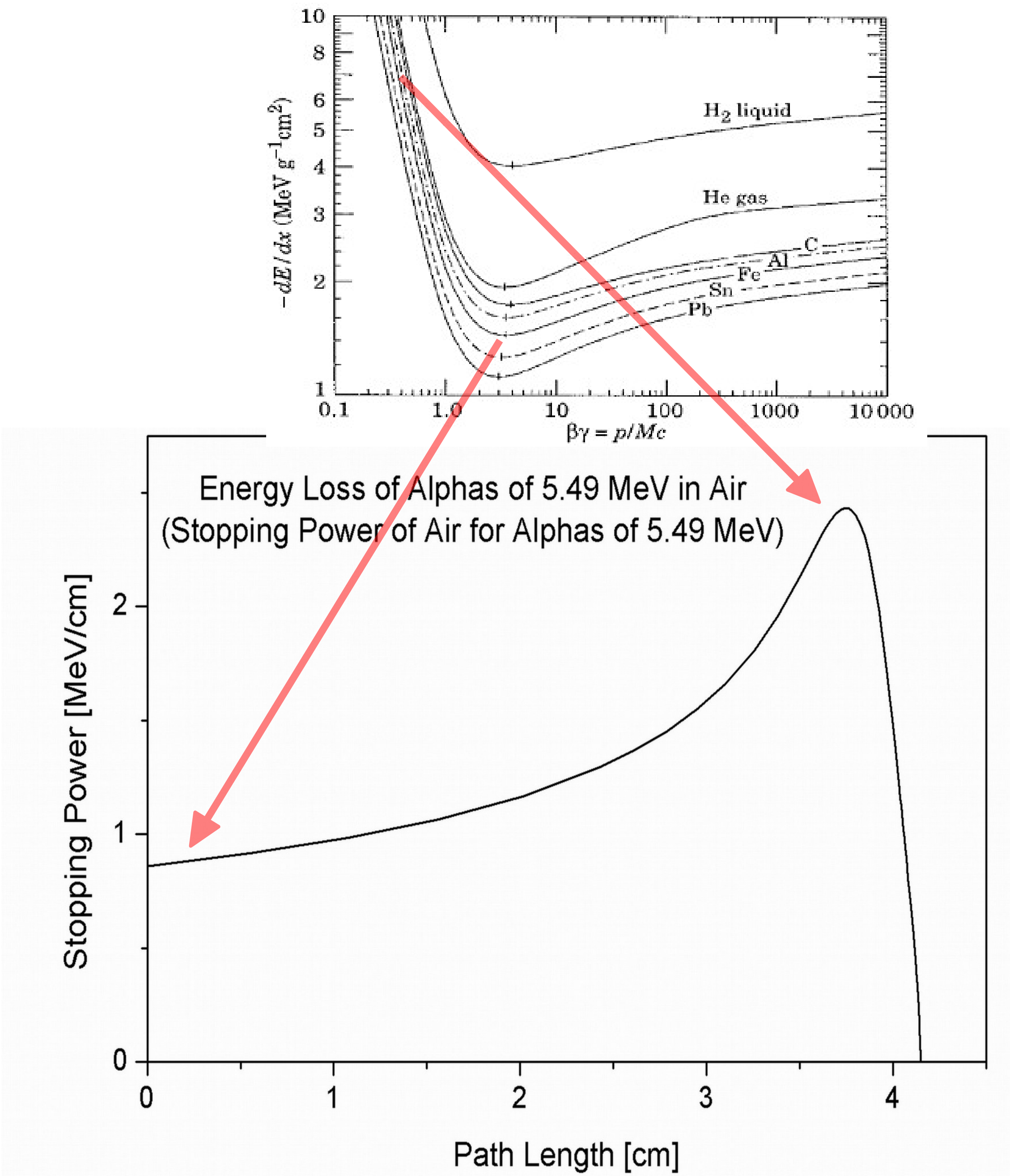
PET scanner

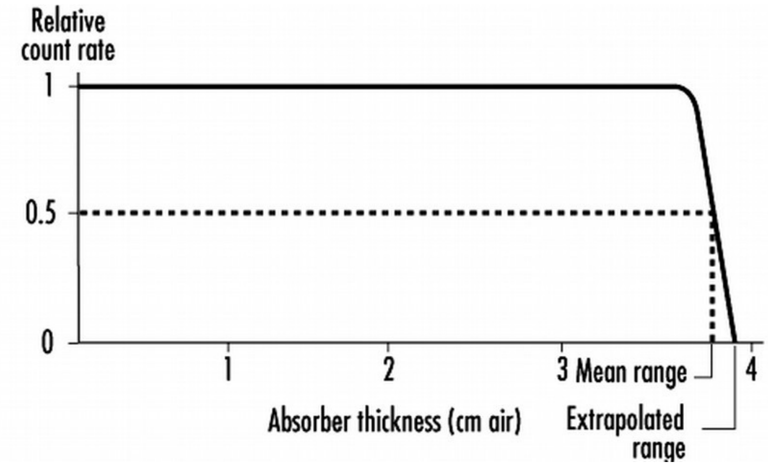
Brachytherapy with Radionuclides

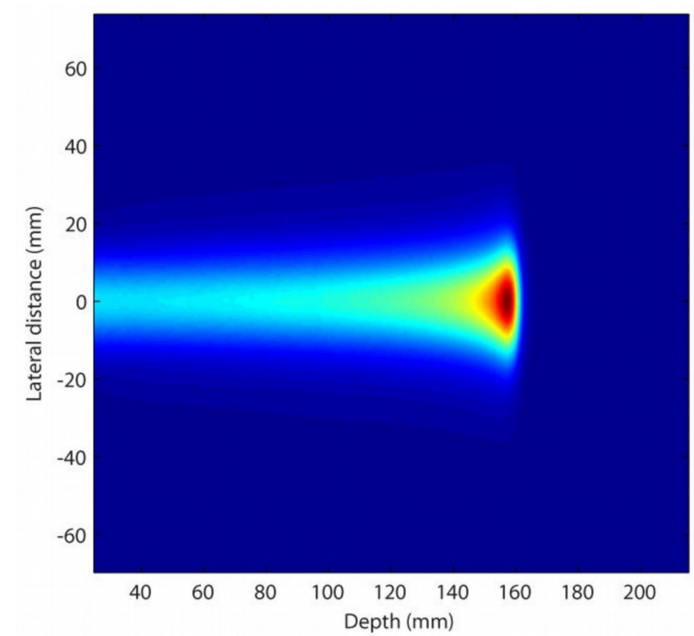




Bragg peak







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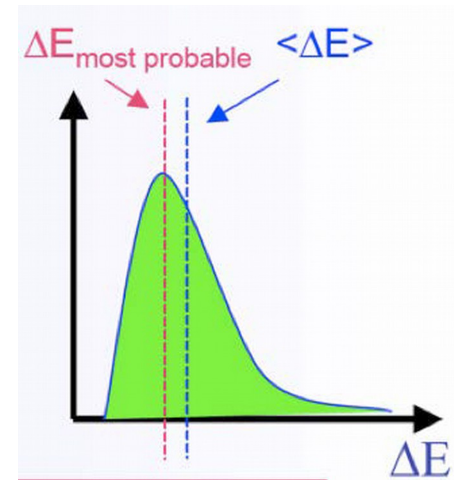
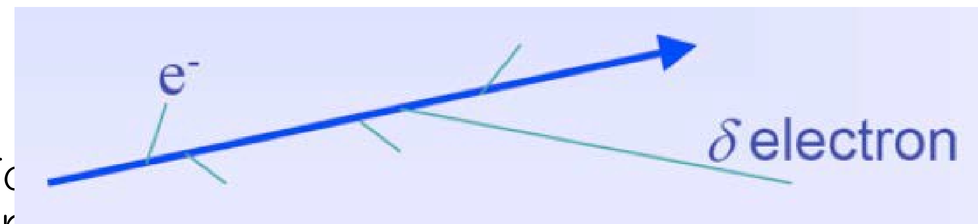
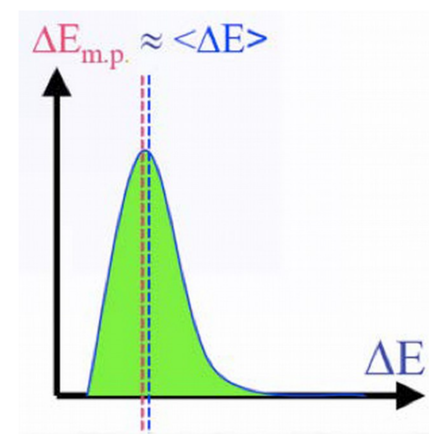
Fluctuations in energy loss

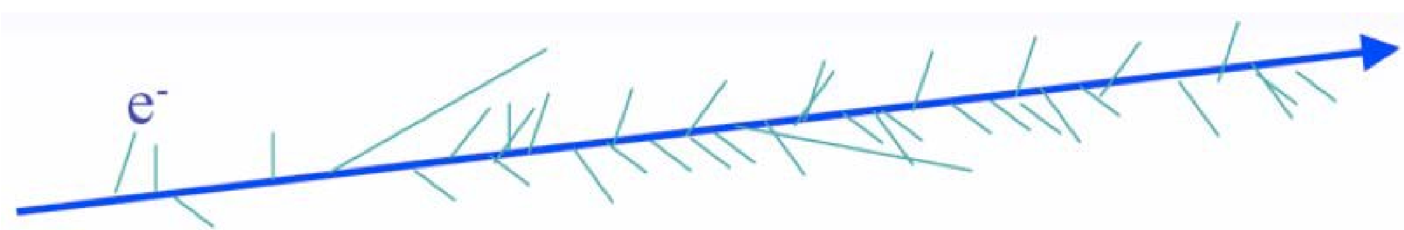
For thin layers or low density materials, the energy loss distribution shows large fluctuations towards high losses, so called **Landau tails**.





Fo
energy loss distribution shows a more **Gaussian-like** distribution (many collisions, Central limit theorem)

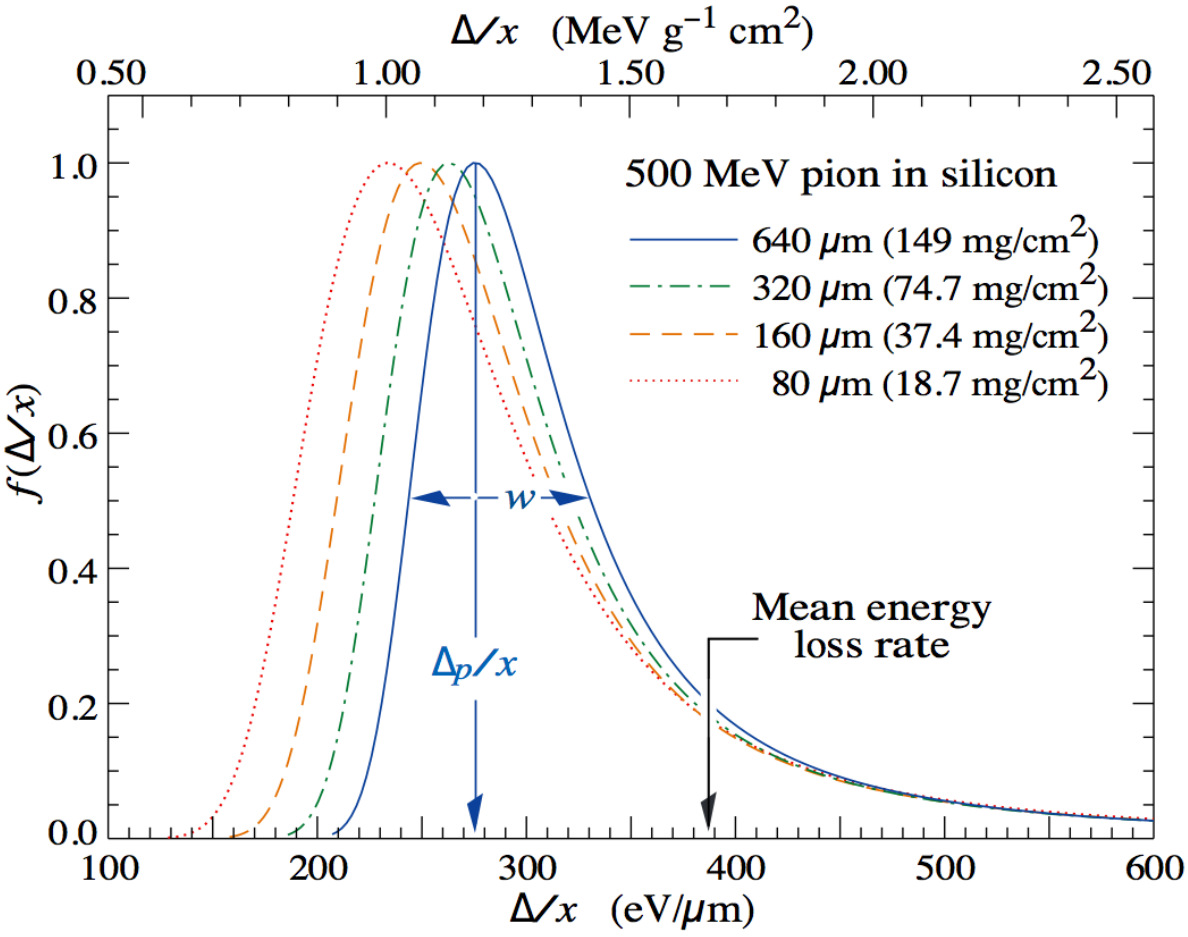




Landau Distribution

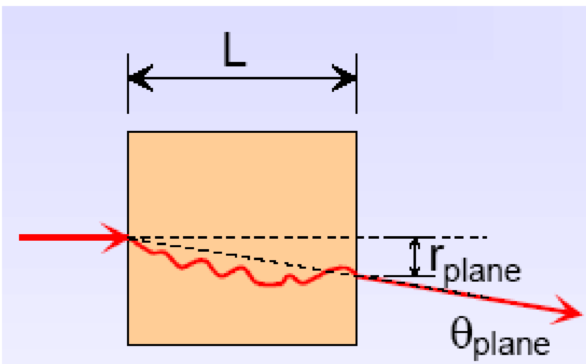
In a **thin** detector, a charged particle deposits a certain amount of energy (ionizes a certain number of atoms) described by a Landau distribution

Notice nice “gap” between zero charge and minimum, and long tail on high side.



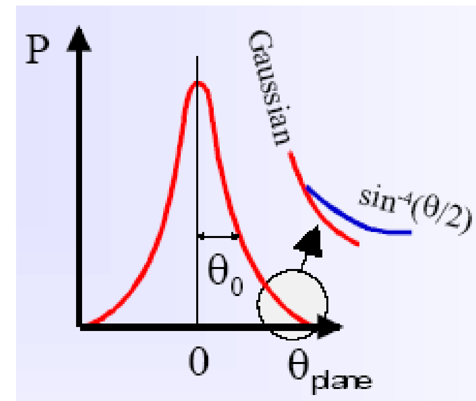
Multiple Scattering

For any observed angle θ of a particle, we don't know if it underwent a single scattering event or multiple small angle scattering. We determine distance for processes, so the probability of a process resulting in angle θ can be found.



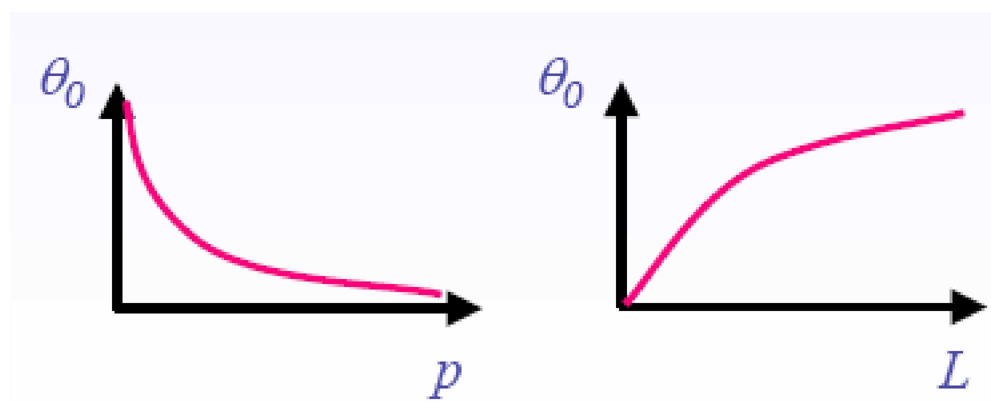
$$\theta_0^2 = L n_a \int \theta^2 \frac{d\sigma}{d\Omega} d\Omega$$

$$= \frac{4\pi}{\alpha} Z_1^2 \frac{m^2 c^2}{\beta^2 p^2} \frac{L}{X_0}$$

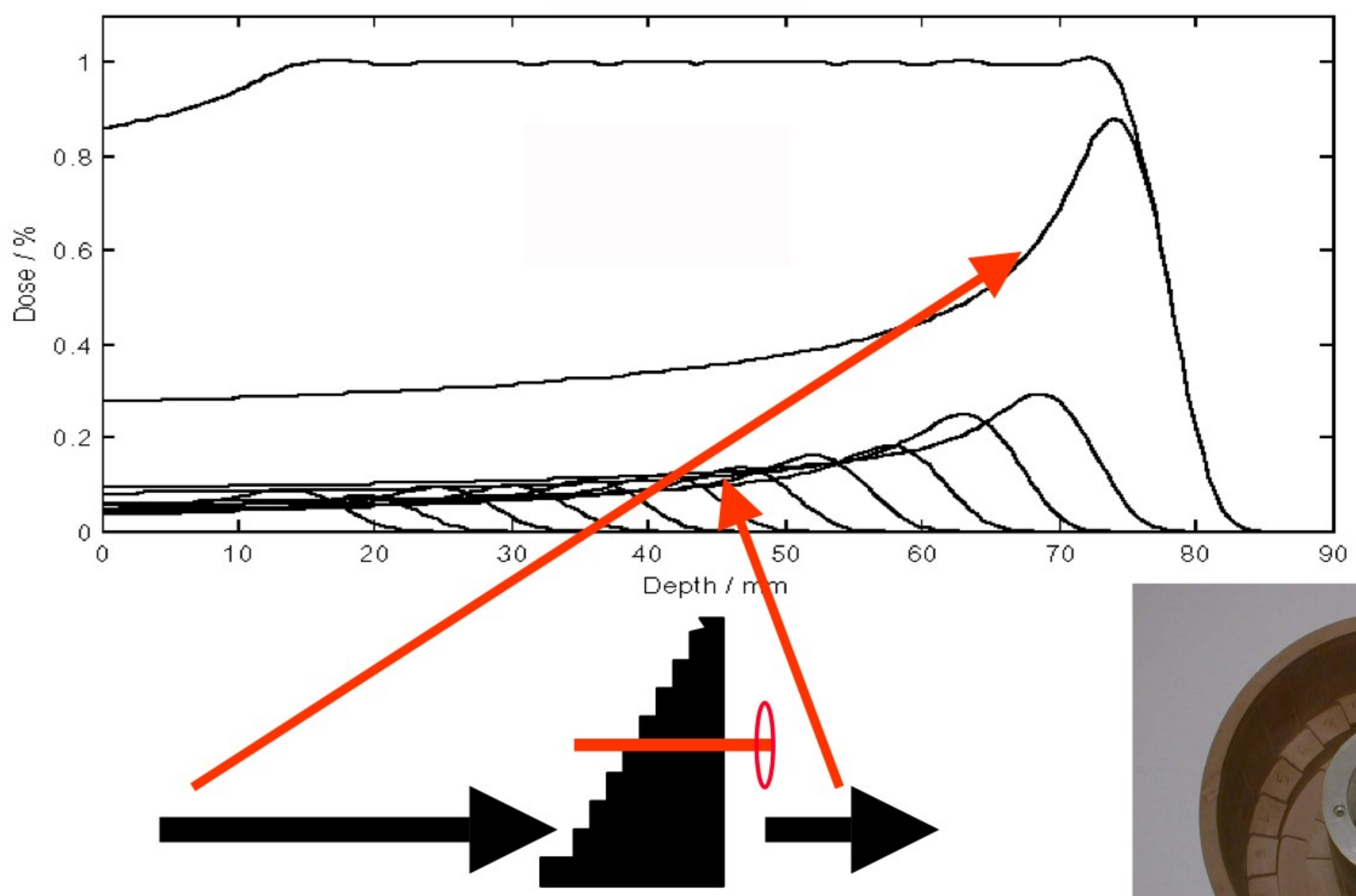


$$\theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$$ €

X_0 = "radiation length"

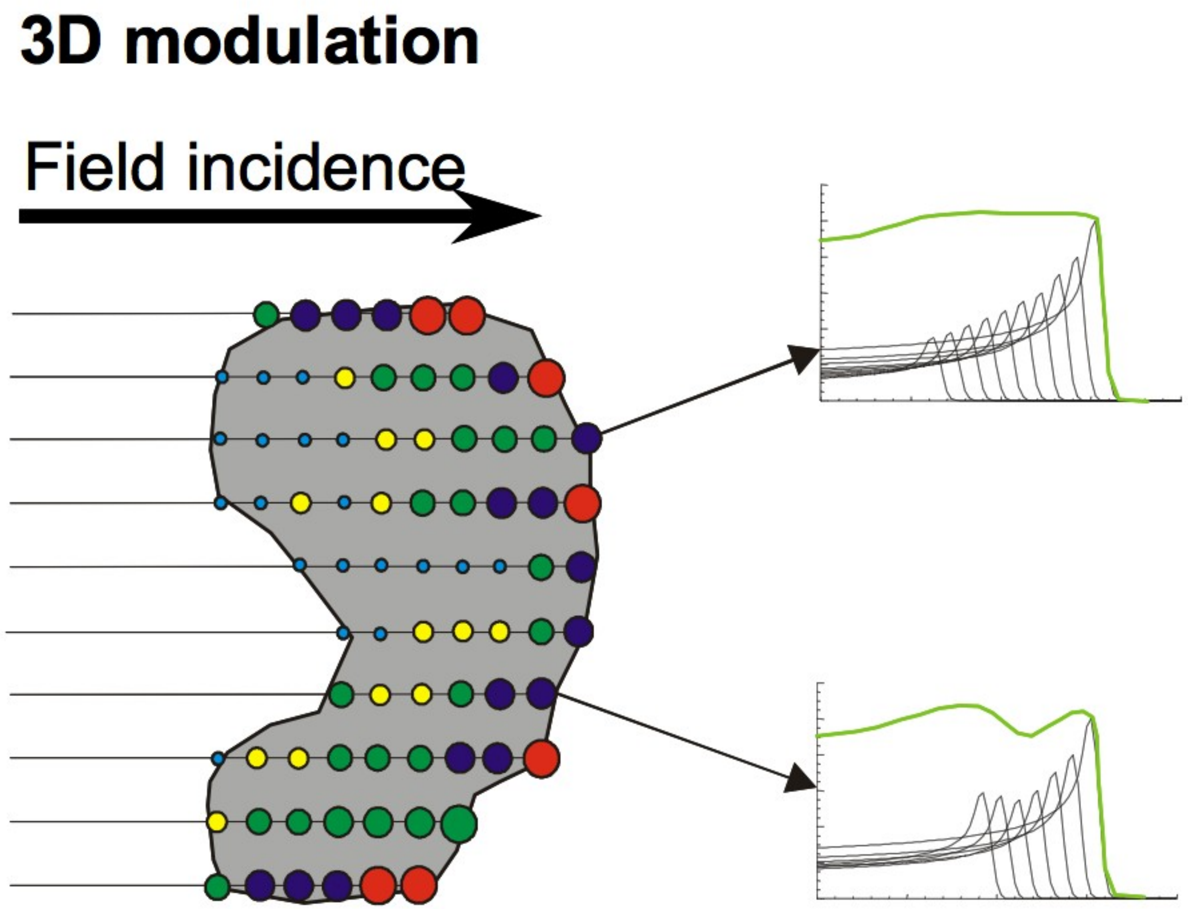


BB Practical Use

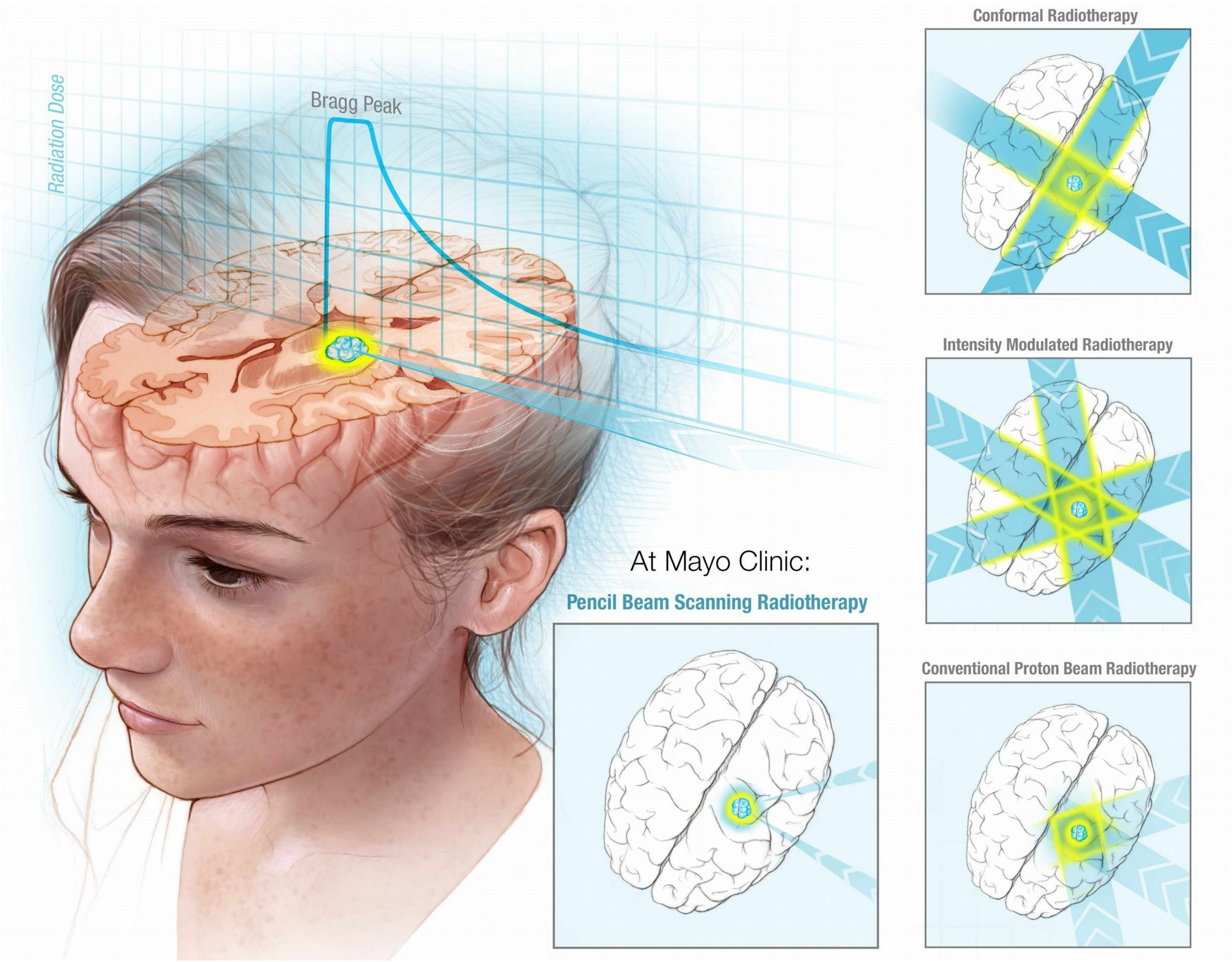


JÜLICH Forschungszentrum

Profile



Proton Beam Therapy



Cerenkov Effect

The Nobel Prize in Physics 1958
Pavel A. Cherenkov, Il´ja M. Frank, Igor Y. Tamm

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The Nobel Prize in Physics 1958

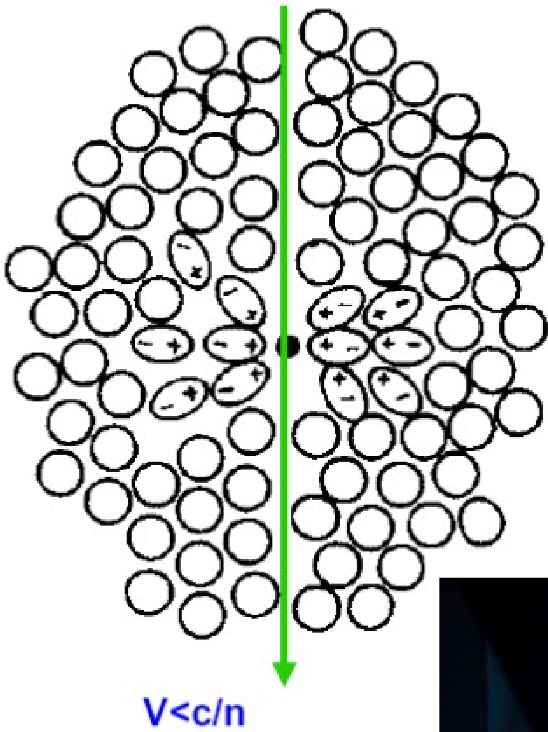
Pavel Alekseyevich Cherenkov
Prize share: 1/3

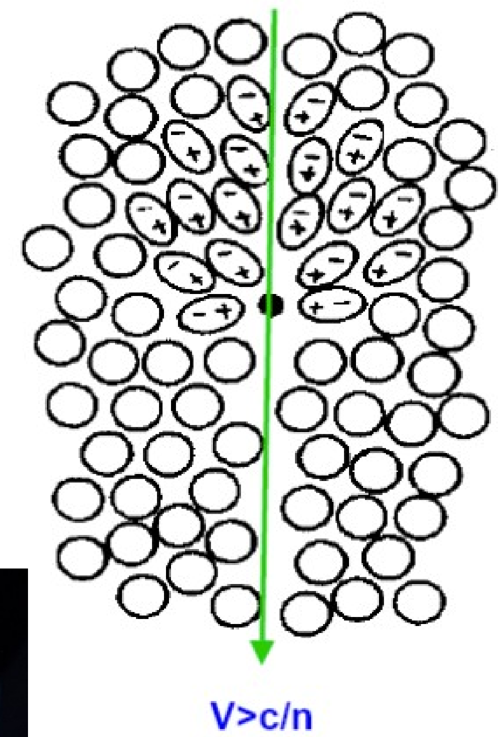
Il´ja Mikhailovich Frank
Prize share: 1/3

Igor Yevgenyevich Tamm
Prize share: 1/3

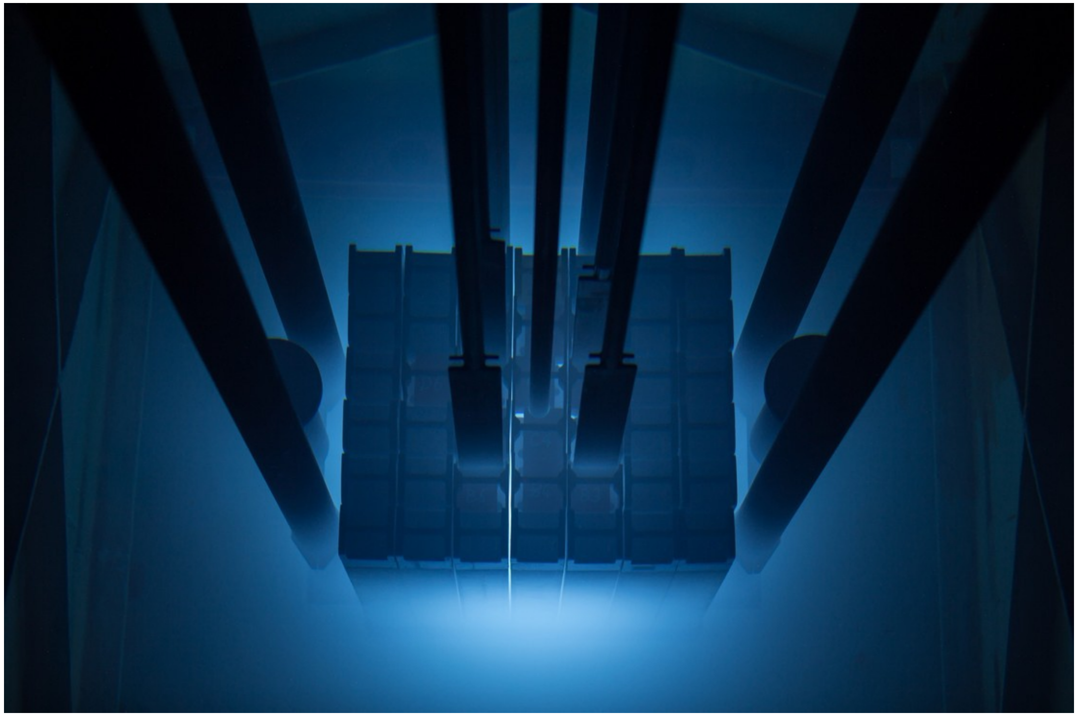
The Nobel Prize in Physics 1958 was awarded jointly to Pavel Alekseyevich Cherenkov, Il´ja Mikhailovich Frank and Igor Yevgenyevich Tamm *"for the discovery and the interpretation of the Cherenkov effect"*.

Cerenkov effect





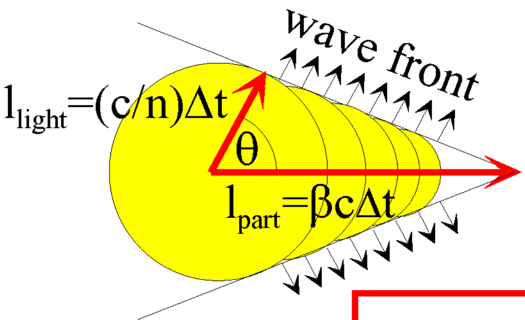
Small 2kW nuclear reactor
at university of Basel

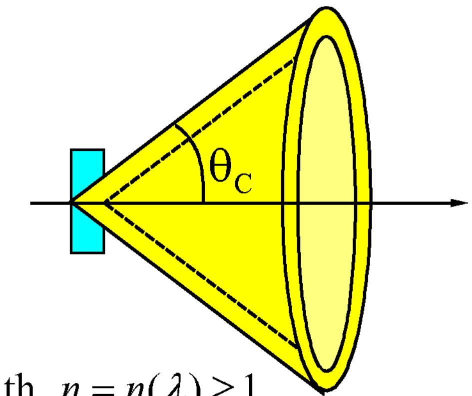


Properties of Cherenkov Radiation

Cherenkov radiation is emitted when a charged particle passes a dielectric medium with velocity > c/n

$$\beta \geq \beta_{thr} = \frac{1}{n} \quad n:$$ Refractive index

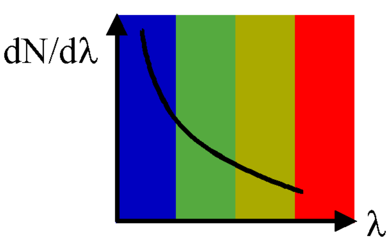


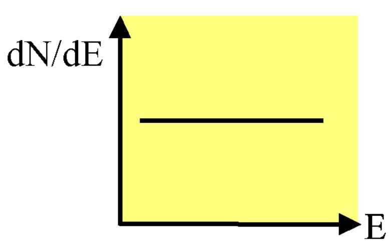


$$\cos\theta_C = \frac{1}{n\beta}$$ with $n = n(\lambda) \geq 1$

$$\beta_{thr} = \frac{1}{n} \rightarrow \theta_C \approx 0$$ threshold

$$\theta_{max} = \arccos\frac{1}{n}$$ 'Saturated' angle β=1





Number of emitted photons per unit length and unit wavelength interval

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

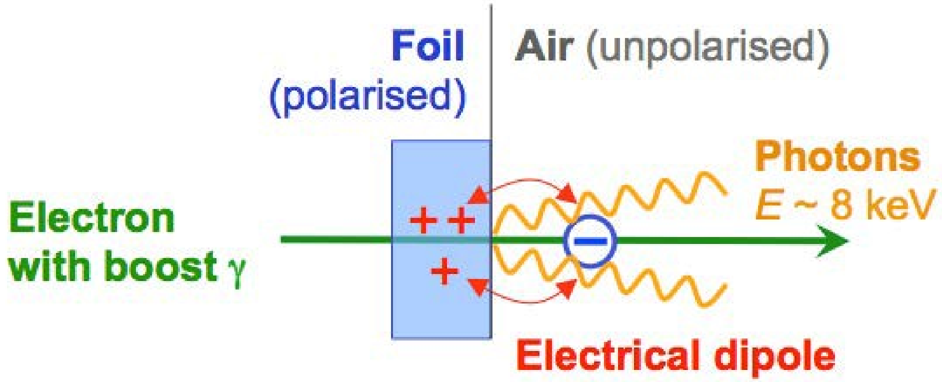
$$\frac{d^2N}{dxd\lambda} \propto \frac{1}{\lambda^2} \quad \text{with } \lambda = \frac{c}{\nu} = \frac{hc}{E} \quad \frac{d^2N}{dxdE} = const.$$

Transition radiation

When crossing boundaries of two media with different dielectrical constants,
a charged particles emits electromagnetic radiation, transition radiation

Reason: adaptation of the electric fields (ε1, ε2)

1946 Discovery and explanation by Ginsburg and Frank
(for a theoretical description, see Jackson, Classical Electrodynamics)



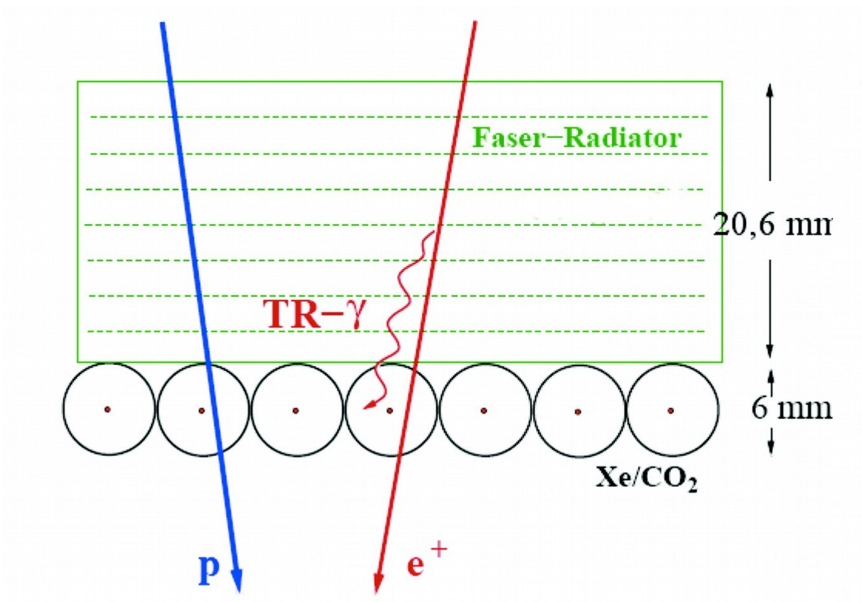
Formation of transition radiation occurs
in a small region, at the boundary,
Formation length: D ≈ $\gamma 10^{-6}$cm

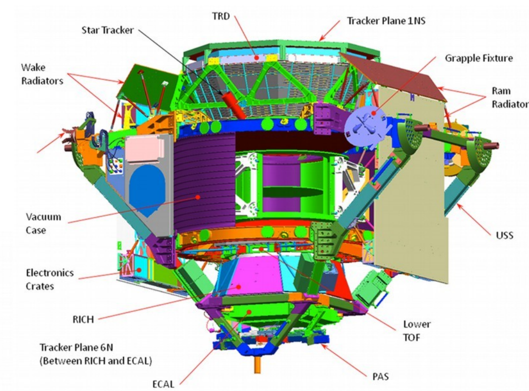
ion is proportional to the

Applications for TRD

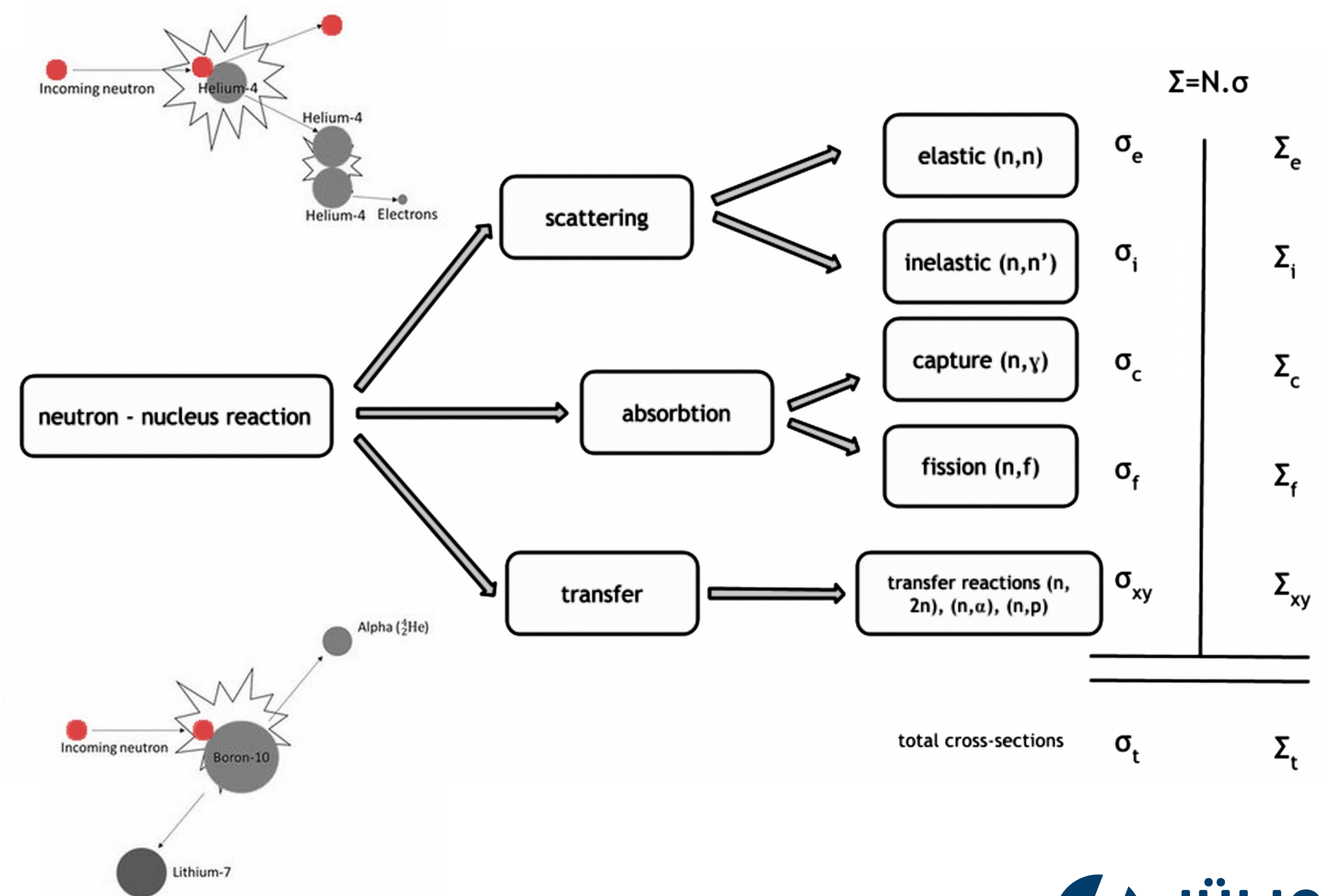
The application of transition radiation detectors is mainly for the identification of electrons;
For a given momentum p, their γ factor is much larger than for hadrons (factor 273 for the lightest charged hadron $\pi^{\pm}$)

For a γ value of 10^3 (e with p=0.5 GeV, $\pi^{\pm}$ with p $\approx$ 140 GeV) about half of the radiated energy is found in the Röntgen energy range (2 –20 keV γradiation)
These γquanta have to be detected, use absorber material with high Z value (absorption via photoelectric effect, see later, e.g. Xenon gas)

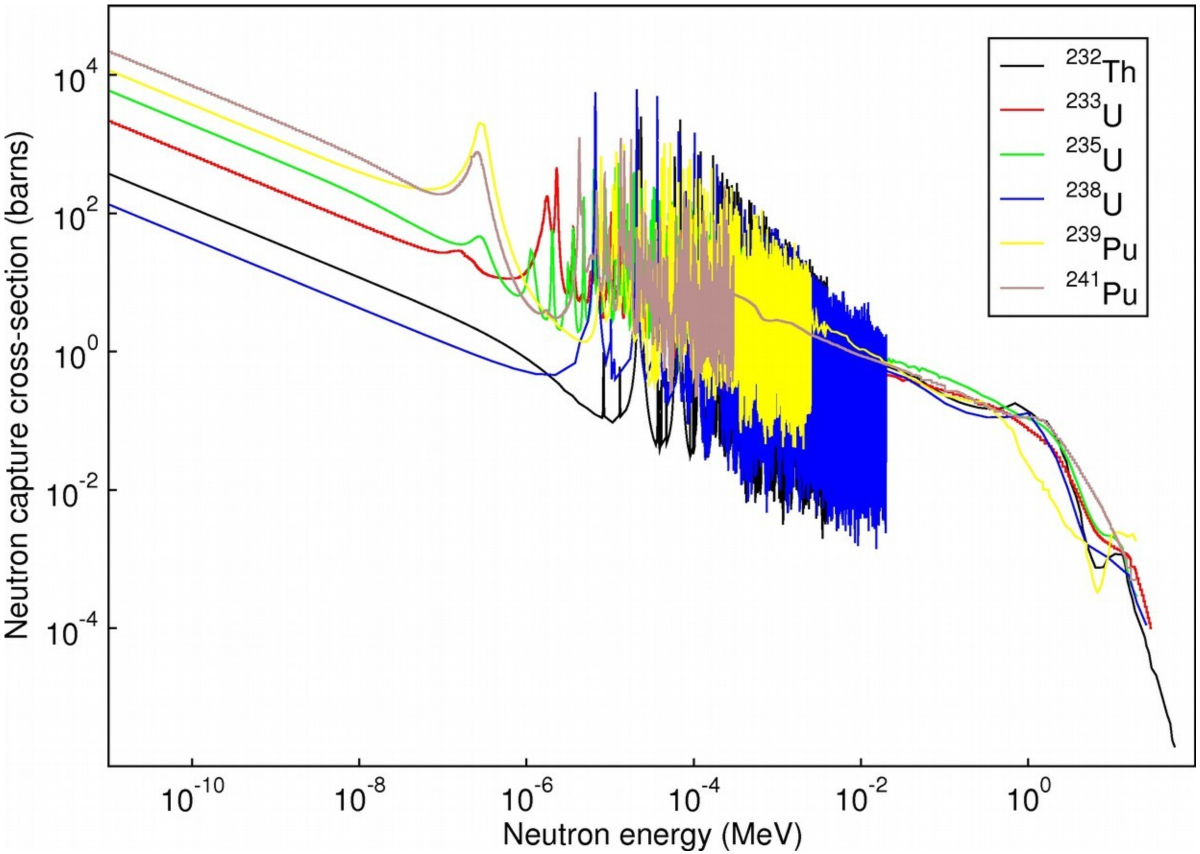


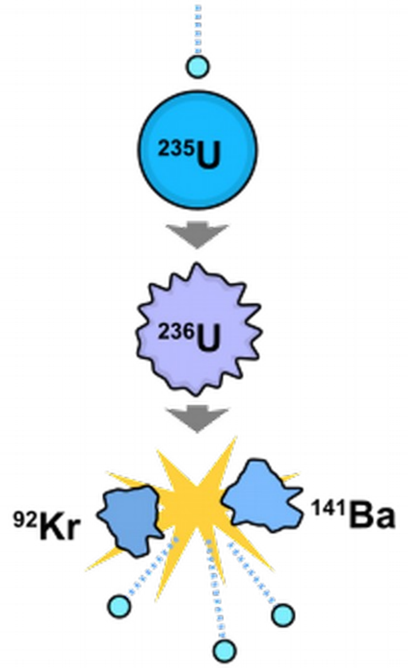


Neutron interaction

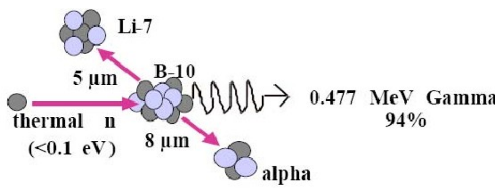


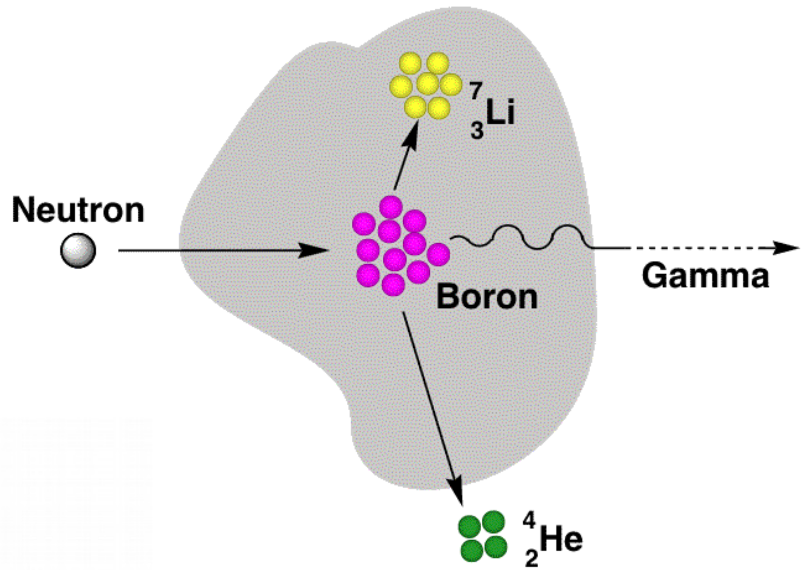
Neutron Capture

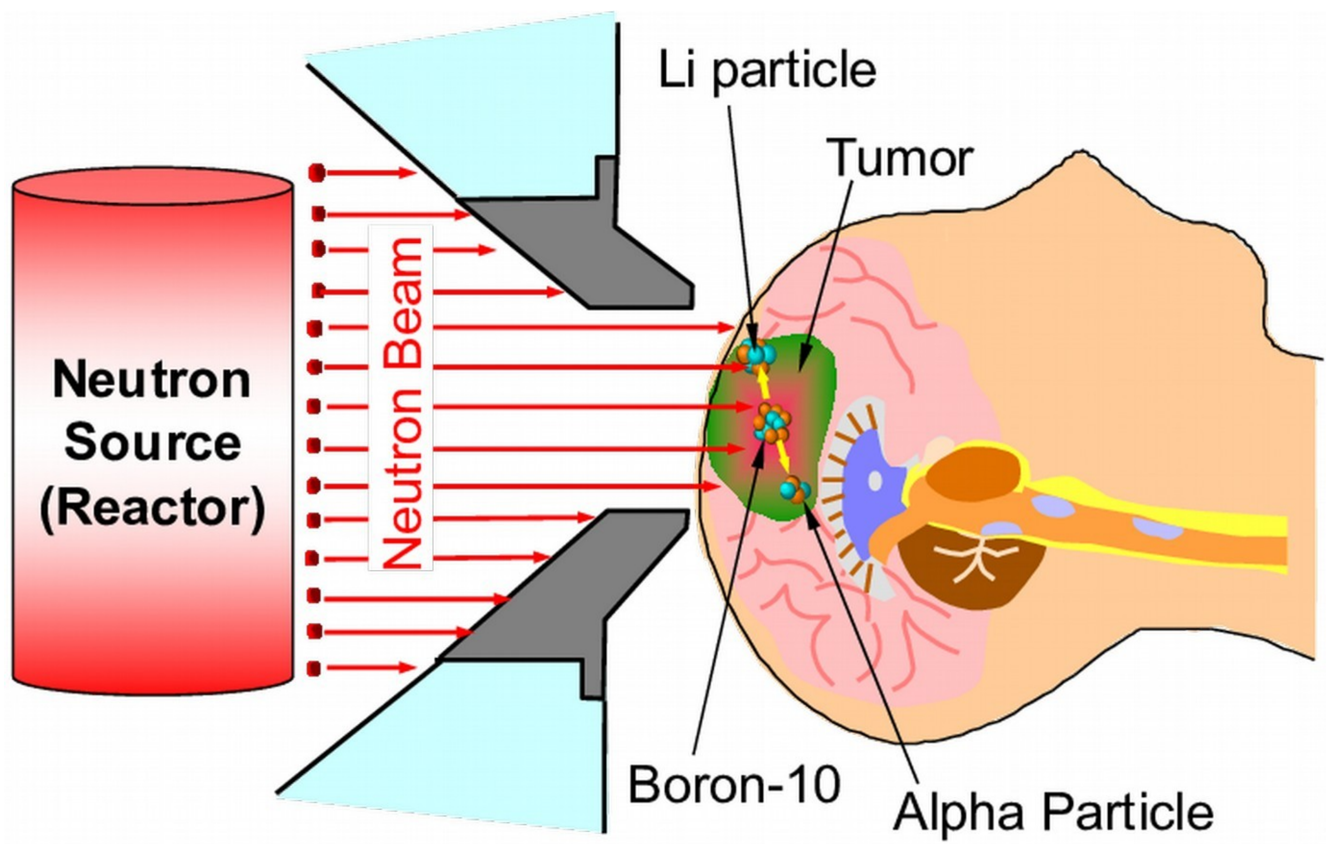




Boron Neutron Capture Therapy







Strong interaction