APPLICATIONS

- **RADIATION INTERACTIONS**
- Detectors
- Accelerators
- Application to Medicine
- Nuclear Astrophysics

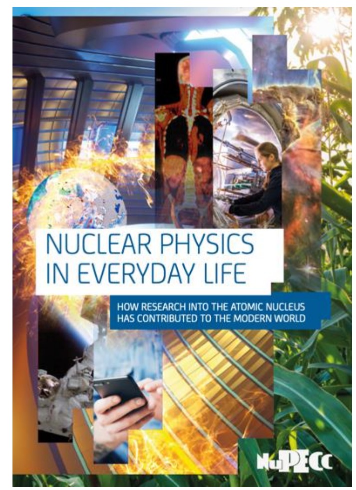
Additional Material at personal web page:
http://www.mi.infn.it/~sleoni

Textbooks

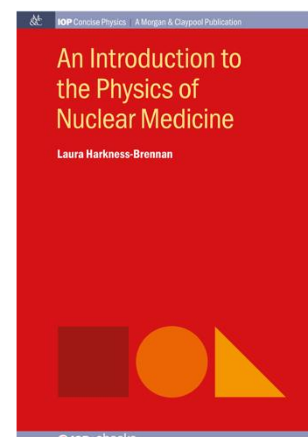
G.F. Knoll
Radiation Detection
and Measurements
Wiley & Sons

W.R. Leo
Techniques for
Nuclear and
Particle Physics Experiments
Springer-Verlag

Nuclear Physics in Everyday Life:
http://www.nupecc.org/pub/np_life_web.pdf



Textbook on application to medicine:
An introduction to physics of nuclear medicine
Laura Harkness-Brennan, IOP



Radiation Interaction

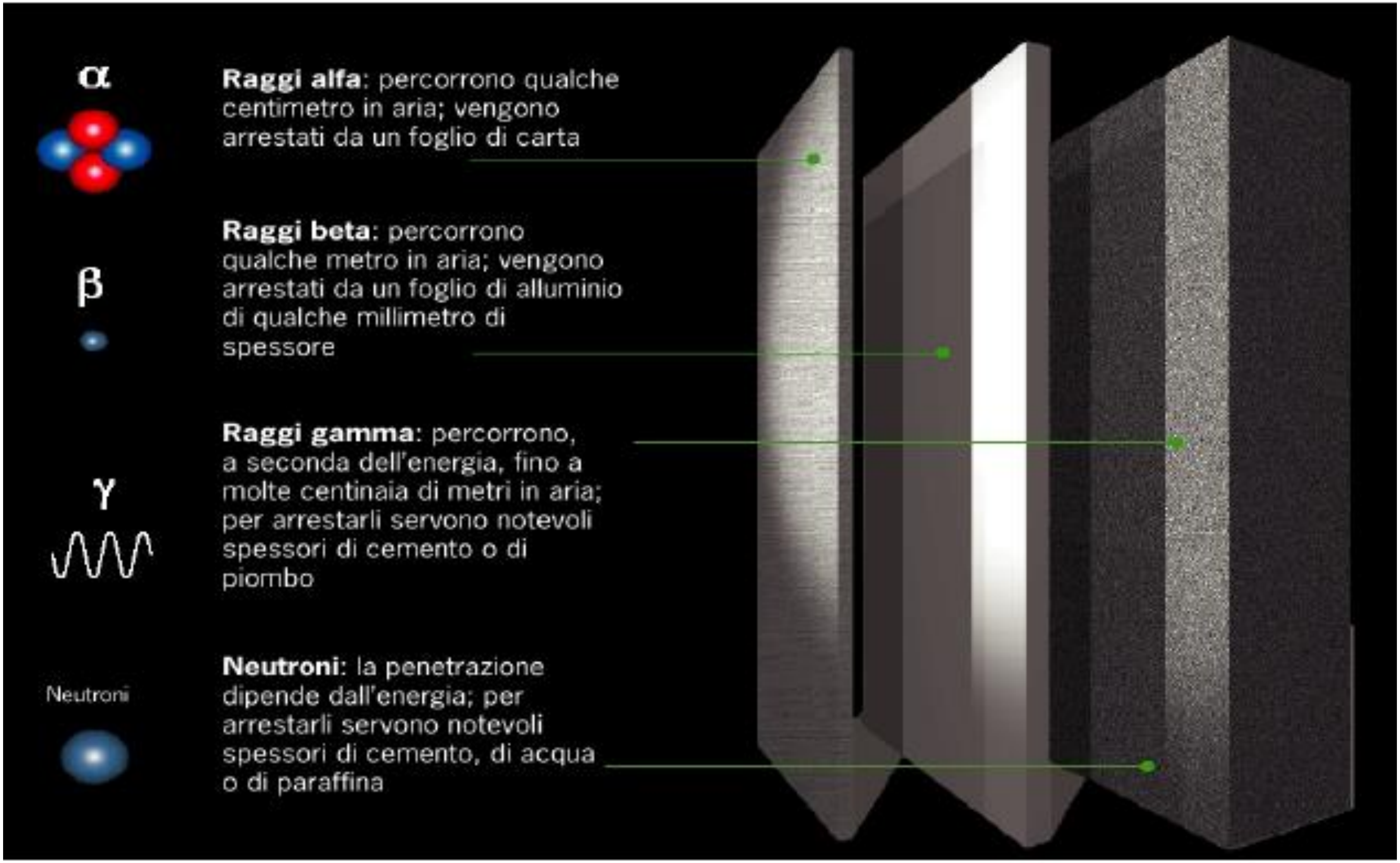
1. charged particles
2. γ-rays
3. neutrons

Charged particle Radiations	**Uncharged Radiations**
heavy charged particles (typical distance $\sim 10^{-5}$m)	neutrons (typical distance $\sim 10^{-1}$m)
Fast electrons (typical distance $\sim 10^{-3}$m)	X- and γ-rays (typical distance $\sim 10^{-1}$m)

Continuous interaction
*via **Coulomb force***
with electrons in the medium

- ***NO** Coulomb Interaction*
- *"**catastrophic**" interaction which alters the particle properties in a **single hit** [often it involves the **nucleus**]*
- ***Full/partial transfer** of energy to atomic electrons or nuclei*

Importance for Radioprotection



Charged Particles

Dominant type of interaction:
inelastic collisions with electrons ⇒ { Atomic excitation, ionization, fluorescence, phosphorescence }

Collisions with nuclei :

$$\frac{\sigma_{nucl}}{\sigma_{atom}} \sim \frac{\pi R_{nucl}^2}{\pi a_Z^2} \sim \frac{A^{2/3} \times 10^{-26} cm^2}{10^{-16} cm^2} \approx A^{2/3} \times 10^{-10} \approx 10^{-7} - 10^{-8}$$

Most interactions of charged particles with material components occur with atomic electrons.

$R_{nucl} = 1.2\,A^{1/3}$ fm $= 1.2\,A^{1/3}\ 10^{-13}$ cm

$a_Z = 1$ A $= 10^{-8}$ cm

A REMINDER

From ***elastic collisions*** *between*
incoming particle m_1, $v_{i,1}$ and electron at rest

$$\begin{cases} \frac{1}{2}m_1 v_{i,1}^2 = \frac{1}{2}m_1 v_{f,1}^2 + \frac{1}{2}m_e v_{f,e}^2 & \Rightarrow m_1(v_{i,1} - v_{f,1})(v_{i,1} + v_{f,1}) = m_e v_{f,e}^2 \\ m_1 v_{i,1} = m_1 v_{f,1} + m_e v_{f,e} & \Rightarrow m_1(v_{i,1} - v_{f,1}) = m_e v_{f,e} \end{cases}$$

$$v_{f,1} = \left(\frac{m_1 - m_e}{m_1 + m_e}\right) v_{i,1} \qquad v_{f,e} = \left(\frac{2m_1}{m_1 + m_e}\right) v_{i,1} \qquad se\ m_1 >> m_e \qquad v_{f,e} \cong 2v_{i,1}$$

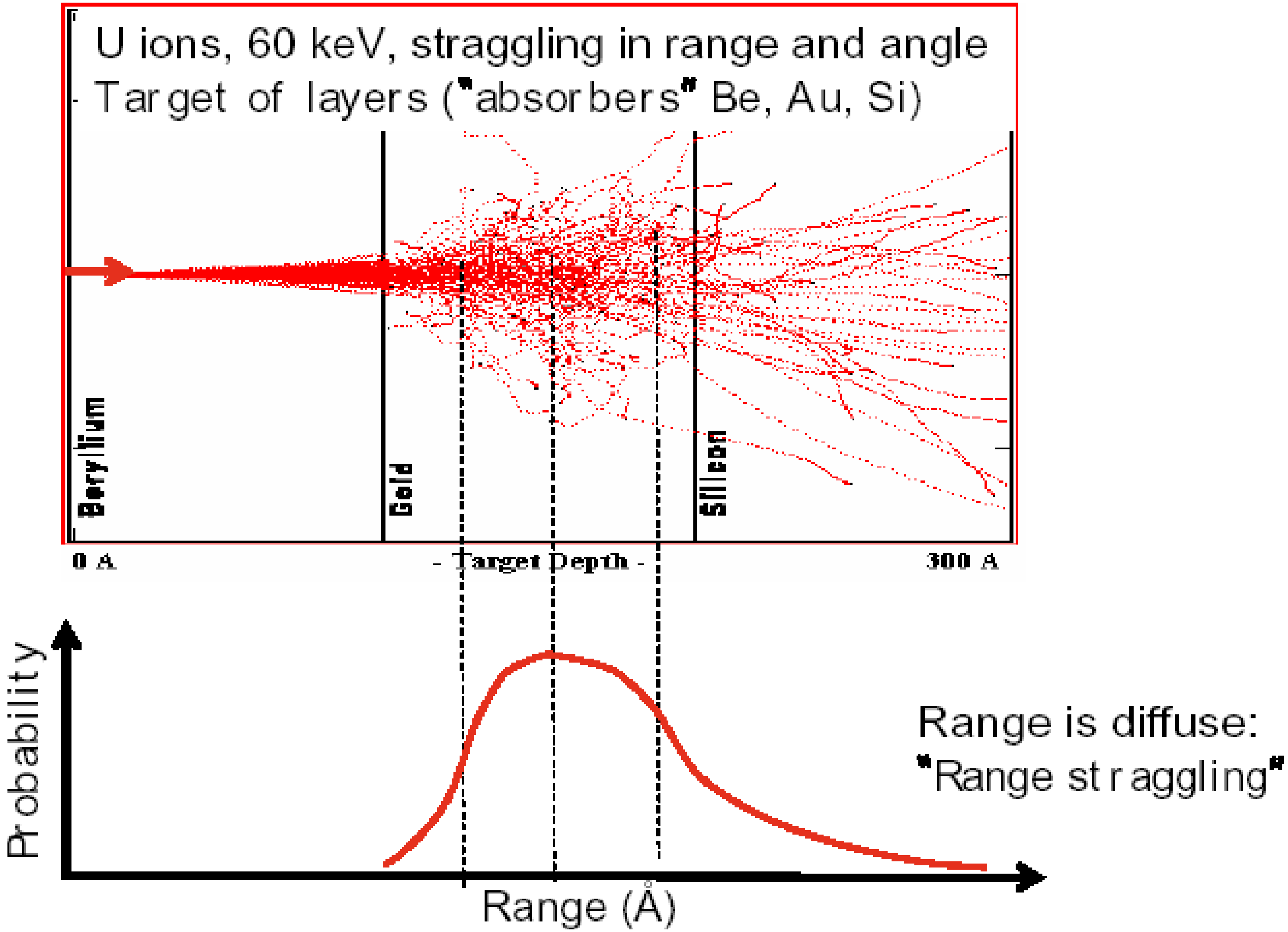
$$E_{cin}(2) = \frac{1}{2}m_e v_{f,e}^2 = 4\frac{1}{2}m_e v_{i,1}^2 = 4\frac{1}{2}\frac{m_e}{m_1}m_1 v_{i,1}^2 = 4\frac{m_e}{m_1}E_{cin}(1)$$

Maximum energy transfer
To atomic electron

Example: *proton transfer 1/500 E_p in a single collision !!!*

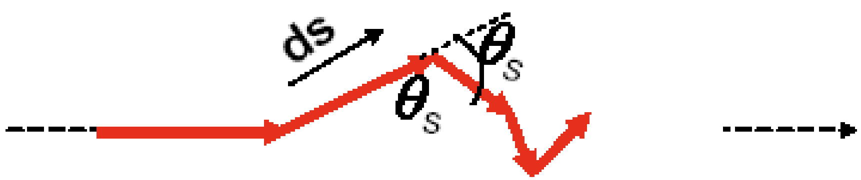
m_p = 1836 m_e~ 2000 m_e

Maximum energy transfered from charged particle to electron is
$4Em_0/m = 1/500$ of the particle energy per nucleon
→ loss of energy by many interactions, ***gradual process***

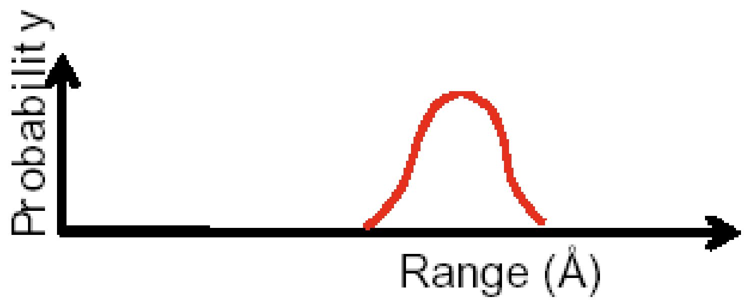


Penetration distance

Range and Stopping Power



Scattering angle θ_s path variable s



Stochastic multiple scattering process produces straggling in range, energy loss, angle

$$R(E) = \int ds \langle \cos \theta_s \rangle = \int_0^E dE' \left[\frac{dE'}{ds}\right]^{-1} \cdot \langle \cos \theta_s \rangle \underset{def}{=} \text{Range}$$

$$\left[\frac{dE}{ds}\right] \underset{def}{=} \text{Stopping power}$$ = Energy loss by the particle in path length dx

$$S(E) = \int ds \geq R(E)$$ Path length of trajectory

PHENOMENOLOGICAL MODEL OF ENERGY LOSS IN MATTER

Bethe et al. (1930-1953): Lindhardt's electron theory describes energy loss (estimated trends and order of magnitude) via ionization of target with incoming ions fully stripped.

ρ = atomic density, Z_T = atomic number of target

$N_e = Z_T \cdot \rho$

IE = ionizing energy

Zp = Z of particle

v = particle velocity

$$-\frac{1}{\rho}\frac{dE}{dx} \approx \frac{4\pi Z_p^2 e^4}{m_e v^2} Z_T \frac{1}{2}\ln\left[\frac{2m_e v^2}{IE}\right]$$

Phenomenological model

Bethe-Bloch Quantum Mechanical Equation

(for heavy particles M >> m_e, $\beta = v/c$)

$$-\frac{1}{\rho}\frac{dE}{dx} \approx 0.1535 \frac{Z_p^2}{\beta^2}\frac{Z_T}{A_T}\left[\ln\left(\frac{2m_e c^2}{IE(1-\beta^2)}\right)^2 - 2\beta^2\right]\frac{MeV}{g/cm^2}$$

Average energy loss

ρ = atomic density

Z_T = atomic number of target

A_T = mass number of target

$$IE = h(v_e) \approx \begin{cases} (12 \cdot Z_T + 7)\, eV & \text{for } Z_T < 13 \\ (9.76 \cdot Z_T + 58.8 \cdot Z_T^{-0.19})\, eV & \text{for } Z_T \geq 13 \end{cases}$$

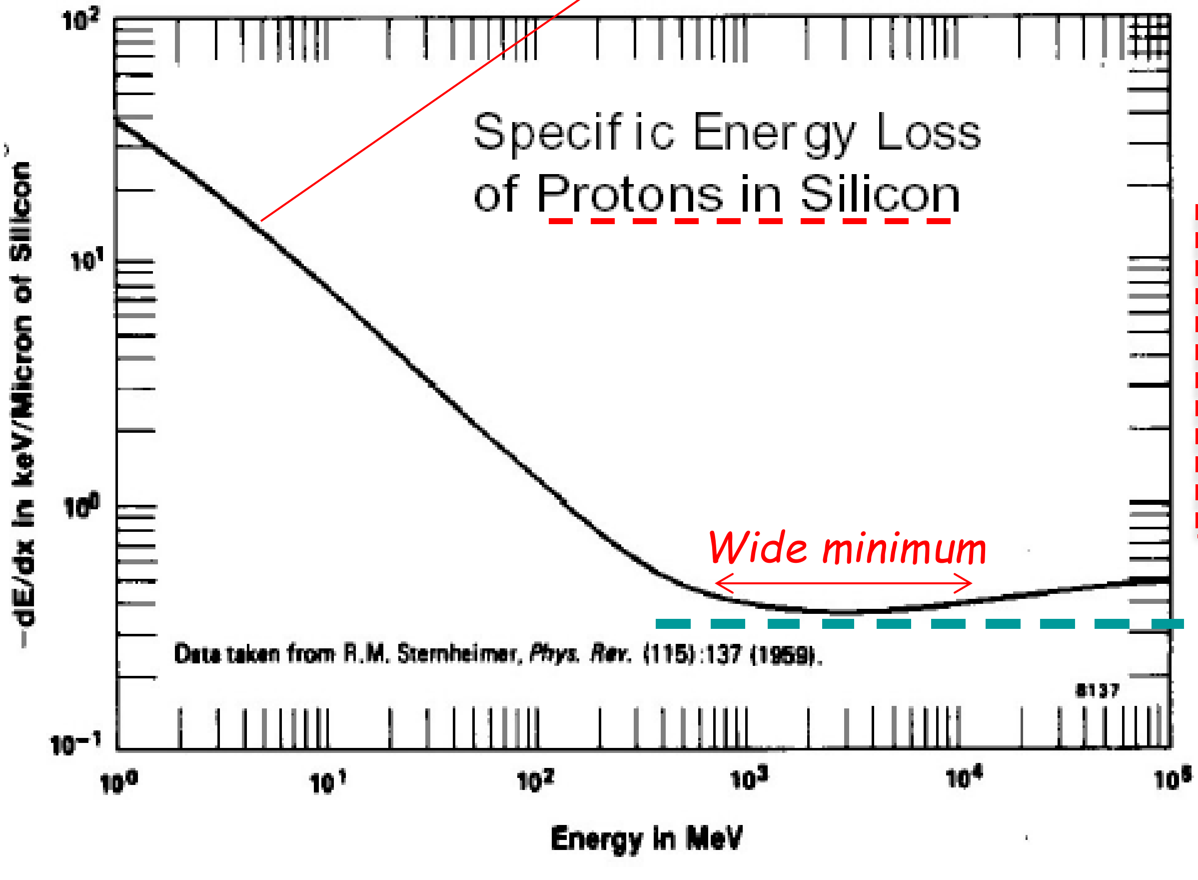
$$-\frac{dE}{dx} \begin{cases} \approx \rho Z_T \rightarrow \text{Large in dense material} \\ \approx Z_p^2 \rightarrow \text{Large for heavy ions} \\ \approx 1/v^2 \rightarrow \text{Large for slow particles} \end{cases}$$

Bethe-Block formula

it is accurate up to the ***minimum in energy loss***

Bethe-Bloch Formula

$$\frac{-1}{\rho}\frac{dE}{dx} \approx 0.1535 \frac{Z_p^2 Z_T}{A_T}\left[\frac{2}{\beta^2}\ln\left(\frac{2m_e c^2}{IE}\right) - \frac{2}{\beta^2}\ln\left(1-\beta^2\right) - 2\beta^2\right]\frac{MeV}{g/cm^2}$$



At high (relativistic energies, the β terms become dominant.

Additional corrections:

In addition, radiation losses (bremsstrahlung) and ρ-dependent plasma effects become important.

→dE/dx(E) has minimum ***for v~c; β~1***

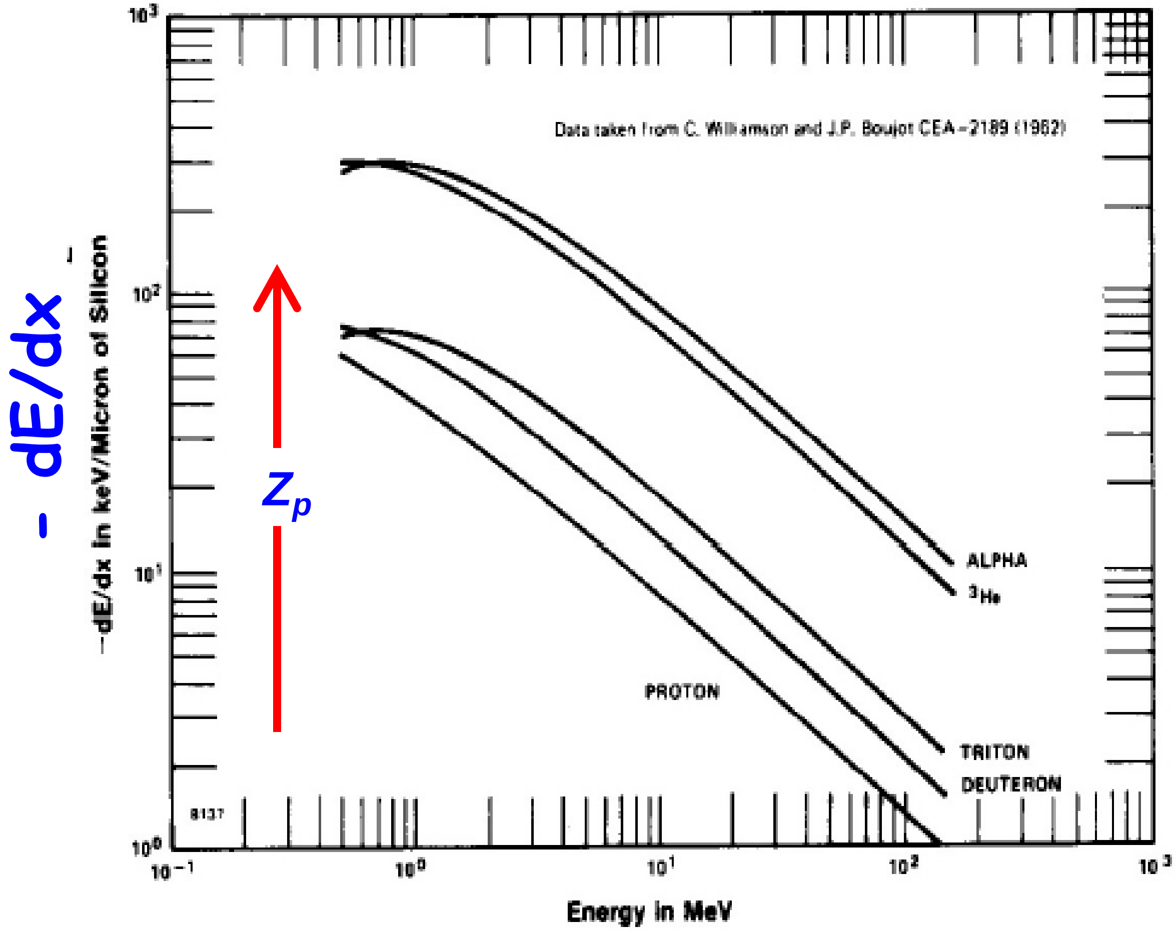
→"minimum-ionizing particles (mip)"

examples: $e^{\pm}$, $\mu^{\pm}$

$$m_d = \frac{m_0}{\sqrt{1-\left(\frac{v}{c}\right)^2}} \approx m_0\left(1+\frac{v^2}{2c^2}\right)$$

Stopping Power in Silicon

Important for applications in radiation detection



Atomic density = $5 \cdot 0.10^{22}$ atoms/cm^3

Mass density

$\rho = 2.35 g/cm^3$

$1 \mu m \triangleq 0.235 mg/cm^2$ Si

$\Delta E/ip = 3.62$ eV/ip

Heavier ions have higher stopping power (dE/dx)

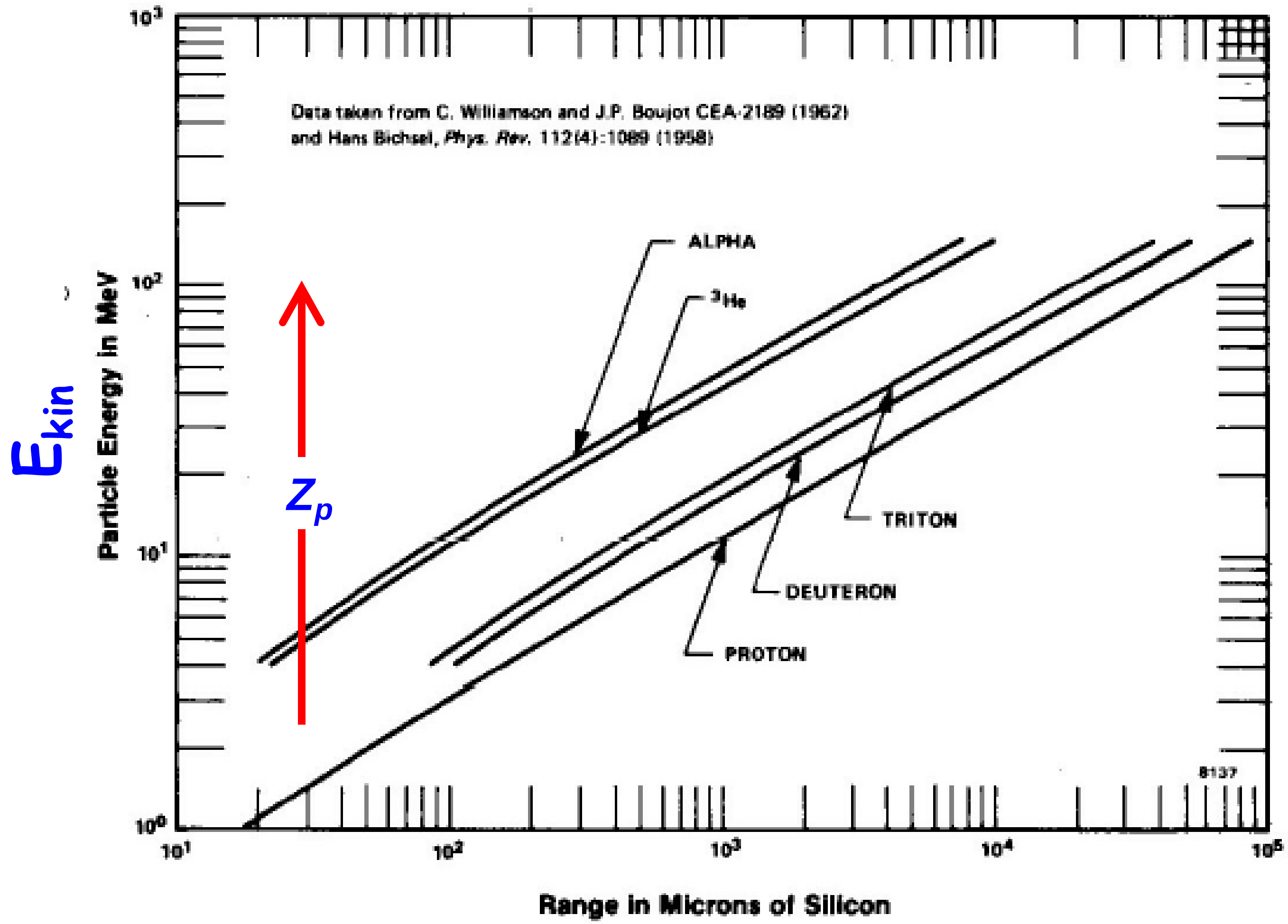
Range in Silicon

Important for applications in radiation detection

Mass density ρ = 2.35g/cm^3

1μm $\triangleq$ 0.235mg/cm^2 Si

ΔE/ip = 3.62 eV/ip

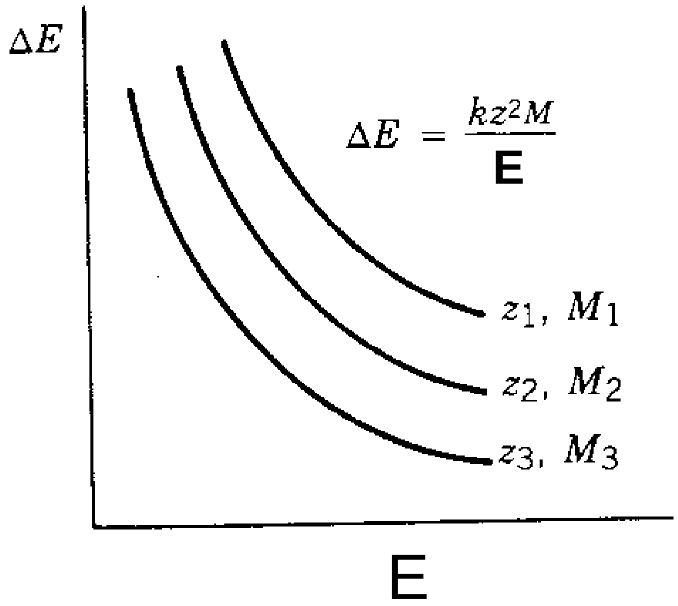


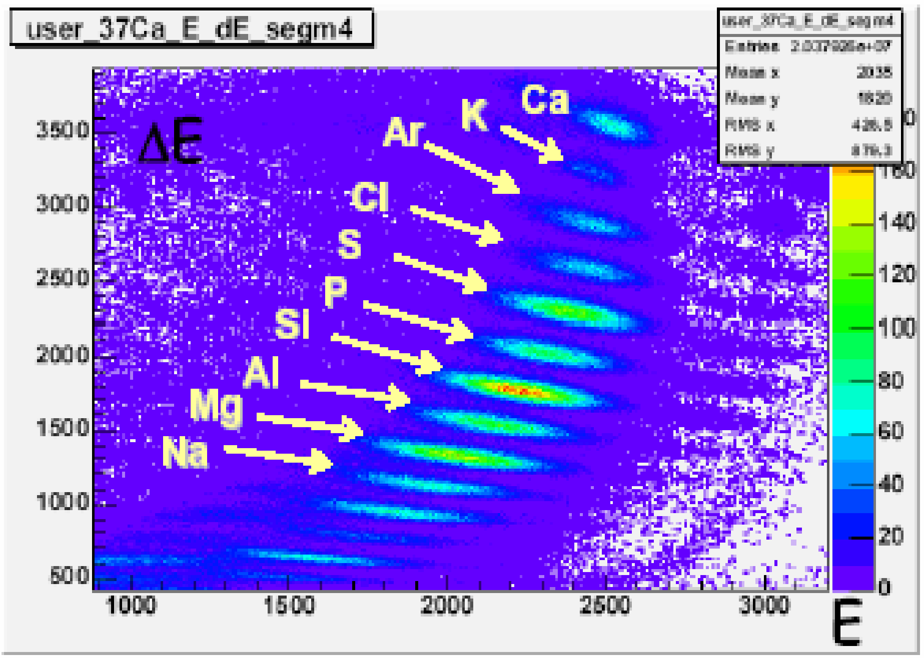
To reach a certain depth, heavier ions must have a higher energy, since they have a higher dE/dx.

[ex. Active area of detector…]

APPLICATION: PARTICLE IDENTIFICATION

$$\frac{dE}{dx} \times E \propto \frac{mZ^2}{E} \times E = mZ^2$$

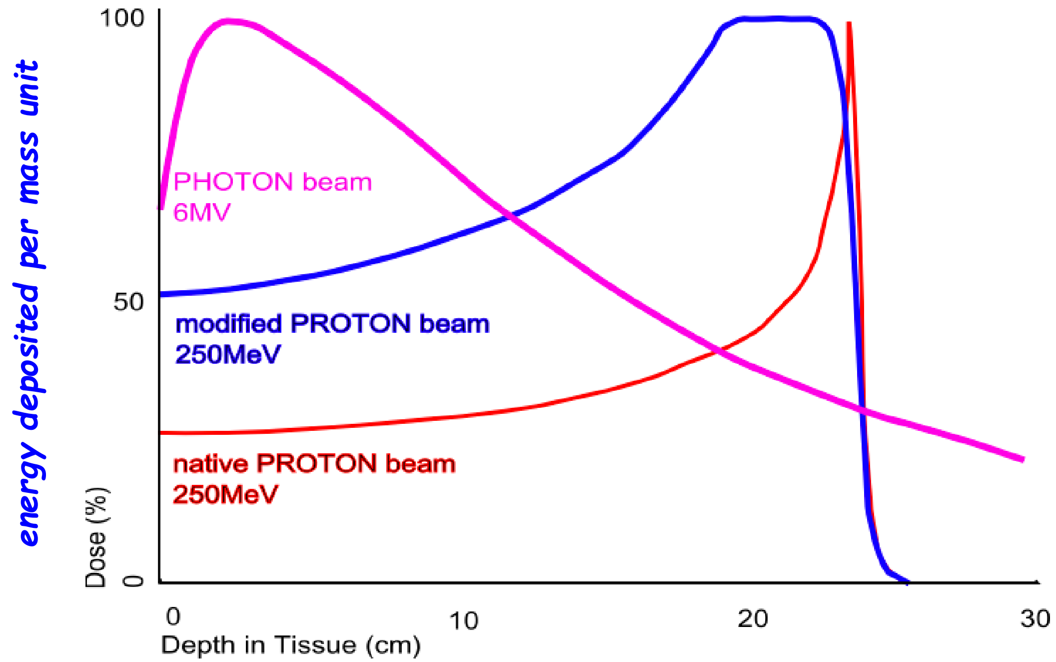




Very useful method to separate ions up to more than A = 30

THE BRAGG PEAK

Application to **medicine**



Absorbed Dose

D = dE/dm

dE = enery deposit
dE = mass

Absorbed dose (also known as **total ionizing dose**, TID) :
energy deposited in a medium by a ionizing radiation per unit mass

Unit of measurements:
Joules/Kilogram = 1 gray (Gy) in SI or rad in GGS

N.B. *The absorbed DOSE depends on: Incident particle and Absorbing material*
Example: *an X-rays can deposit up to 4 times more energy in a bone than in air and none at all in vacuum!*

CNAO Centro Nazionale di Adroterapia Oncologica

Pavia, Italy

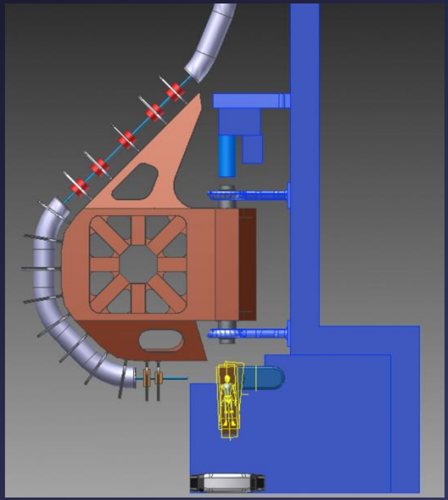
INFN Istituto Nazionale di Fisica Nucleare

Synchrotron Accelerator

25 m diameter, 80 m circumference

250 MeV protons, 4800 MeV Carbon

The Gantry
(beam line extraction and heavy magnet) can rotate 360° around the patient

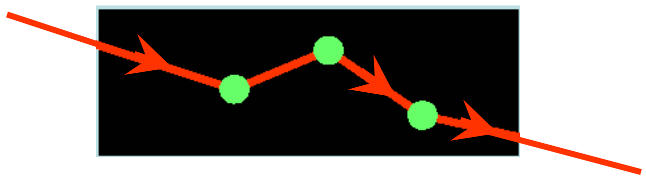


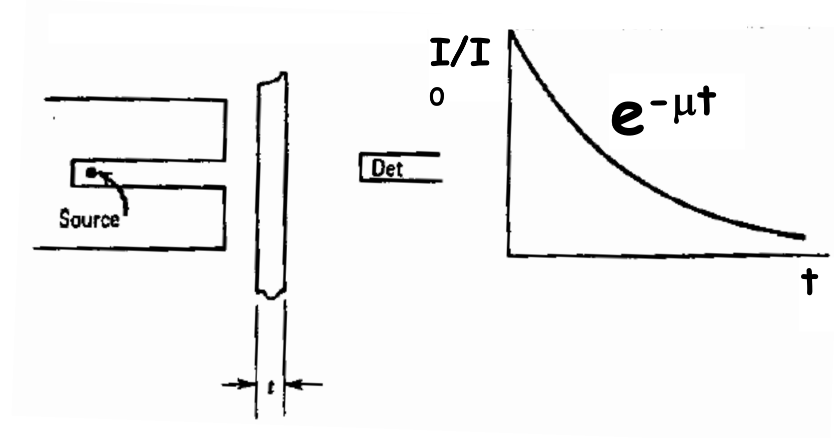
Whole-body proton therapy with the gantry

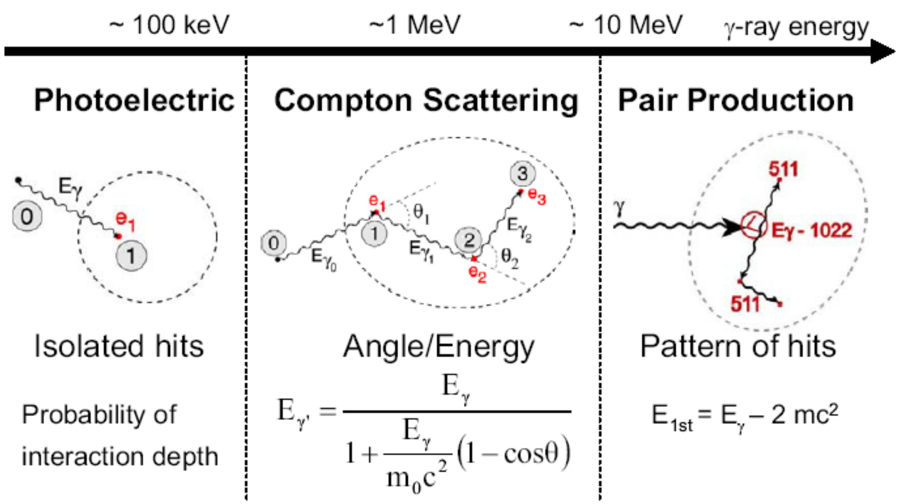
γ-ray interaction

$$I = I_0\, e^{-\mu x}$$

ionization occurs
in limited regions of the absorber







Probability of interaction depth

$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1 - \cos\theta)}$$

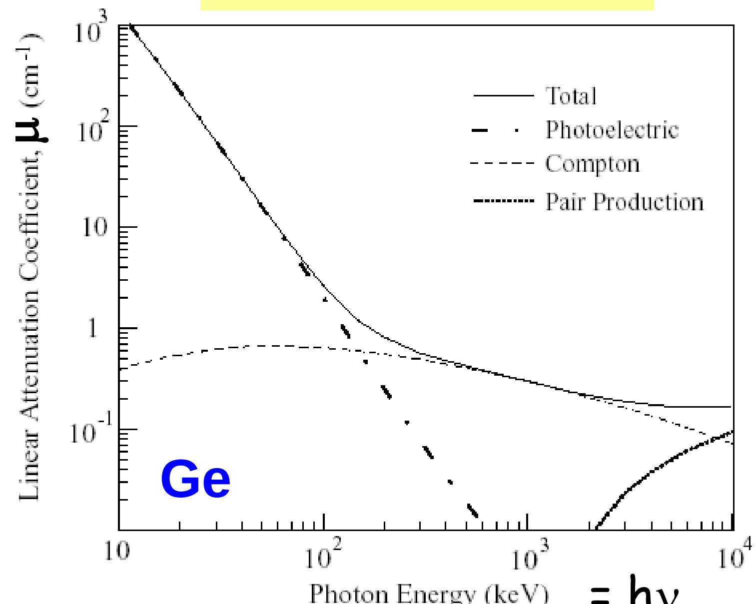
$$E_{1st} = E_\gamma - 2\,mc^2$$

$$\sigma_{ph} \approx \frac{Z^n}{E_\gamma^{3.5}} \qquad \sigma_C \approx Z\frac{\ln E_\gamma}{E_\gamma} \qquad \sigma_{pp} \approx Z^2 \ln E_\gamma$$

$$n = 4 - 5$$

Linear attenuation coefficient
(probability per unit path)

$$\mu = \sigma_{ph} + \sigma_C + \sigma_{pp}$$



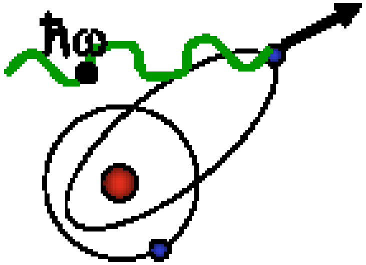
= hν

1. PHOTO-ELECTRIC ABSORPTION

interpreted by Albert Einstein in 1905

Nobel Prize in Physics 1921
A. Einstein for fotoelectric effect

Detection principles are based on:
- Photo-electric absorption
- Compton scattering
- Pair production
- γ-induced reactions



photon is completely absorbed by e^-, which is kicked out of atom

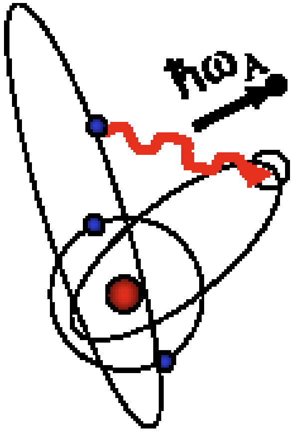
$$E_{kin} = \hbar\varpi - E_n; \quad E_n = binding\ energy$$

$$E_n = Rhc \cdot \frac{(Z-\sigma)^2}{n^2}\ Moseley's\ Law$$

$$Rhc = 13.6\,eV\ \ Rydberg\ constant$$

screening constants

$$\sigma_K \approx 3,\ \sigma_L \approx 5,\ different\ subshells$$

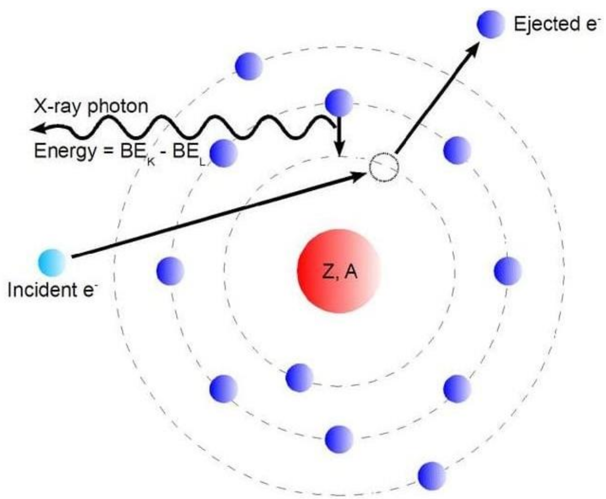


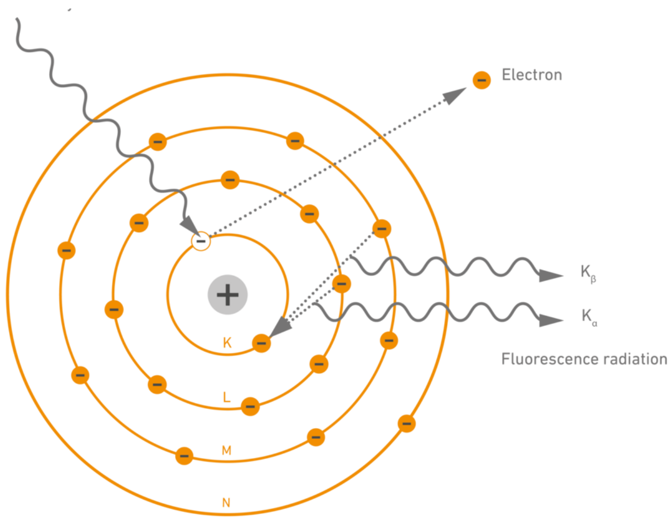
Electronic vacancies are filled by low-energy "Auger" transitions of electrons from higher orbits

(process in competition with X-rays emission)

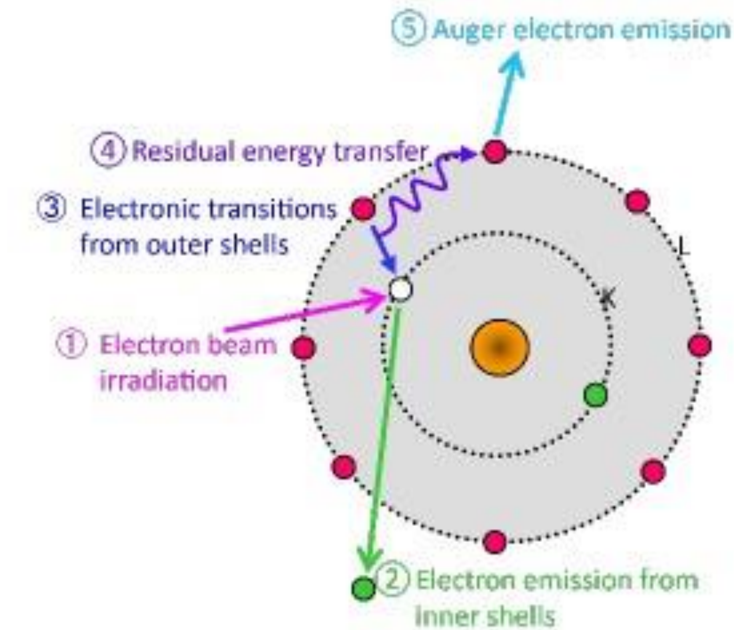
A REMINDER (from atomic physics)

X-rays emission





Auger-electrons



Auger electron kinetic energy:

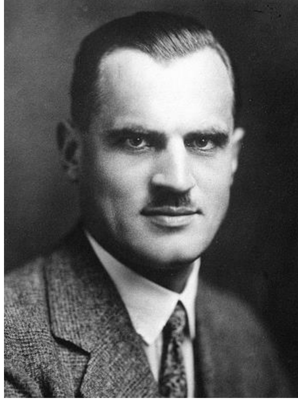
$$E_A = E_K - E_{L1} - E_{L2,3} - \varphi$$

work function of material (minimum energy to extract e- from material)

2. PHOTON SCATTERING (COMPTON EFFECT)

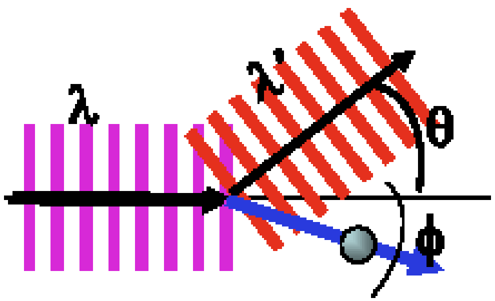
discovered in 1923 by Arthur Holly Compton
while researching the scattering
of X-rays by light elements

Nobel Prize in Physics 1927
A.H. Compton
for photon scattering



$$Relativistic\ E^2 = (pc)^2 + (m_0c^2)^2 \quad photons: m_0 = m_\gamma = 0$$

$$\rightarrow E_\gamma = \hbar\omega_\gamma = p_\gamma c$$



$$\lambda' - \lambda = \lambda_C \cdot (1 - \cos\theta)$$

$$"Compton\ wave\ length\ \lambda_C"$$

$$\lambda_C = \frac{2\pi}{m_e c} = 2.426\,pm$$

$$Momentum\ balance:$$

$$\vec{p}_e = \vec{p}_\gamma - \vec{p}'_\gamma \rightarrow |\vec{p}_e c|^2 = |(\vec{p}_\gamma - \vec{p}'_\gamma)c|^2$$

$$p_e^2c^2 = E_\gamma^2 + E_{\gamma'}^2 - 2E_\gamma E_{\gamma'} \cdot \cos\theta$$

$$Energy\ balance:$$

$$E_\gamma + m_e c^2 = E_{\gamma'} + \sqrt{(p_e c)^2 + (m_e c^2)^2}$$

$$E_{\gamma'} = \frac{E_\gamma}{1 + (E_\gamma / m_e c^2)(1 - \cos\theta)}$$

$$m_e c^2 = 0.511 MeV$$

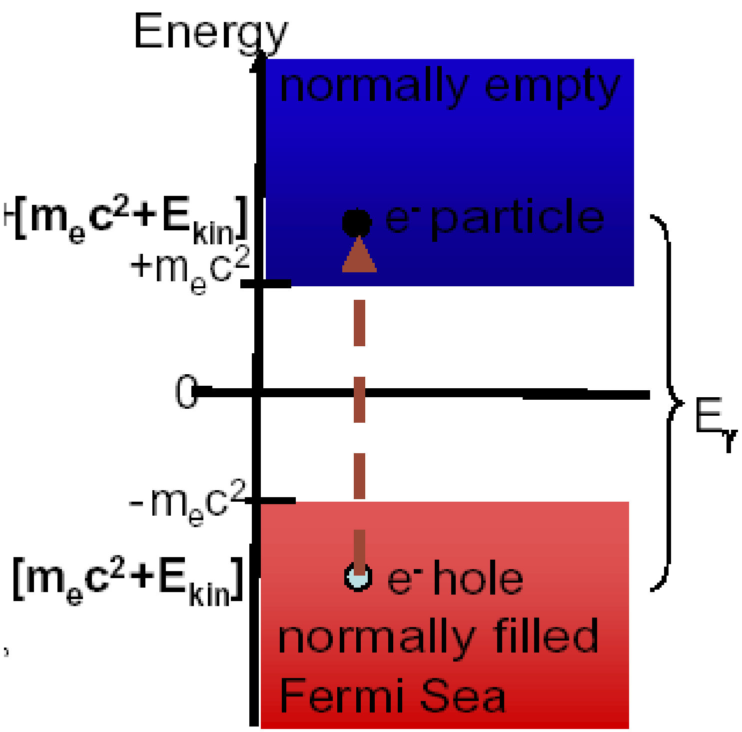
*Important source of **background** in radiation detection*

3. PAIR PRODUCTION

First observed in 1933 by Patrick Blackett
in counter-controlled cloud chamber

Nobel Prize in Physics 1948
cosmic rays investigation
and controlled-cloud
(performed with G. Occhialini!!!)

Dipping into the Fermi Sea: Pair Production



Dirac theory of electrons and holes:

World of normal particles has positive energies, $E \geq +mc^2 > 0$

Fermi Sea is normally filled with particles of negative energy, $E \leq -mc^2 < 0$

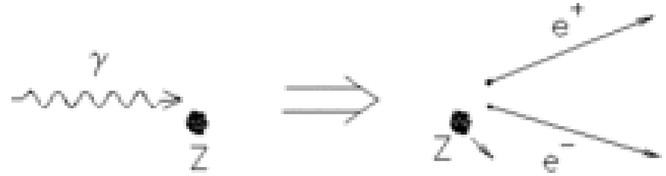
Electromagnetic interactions can lift a particle from the Fermi Sea across the energy gap **$\Delta E = 2\,mc^2$** into the normal world → particle-antiparticle pair

Holes in Fermi Sea: Antiparticles

Minimum energy needed for pair production (for electron/positron)

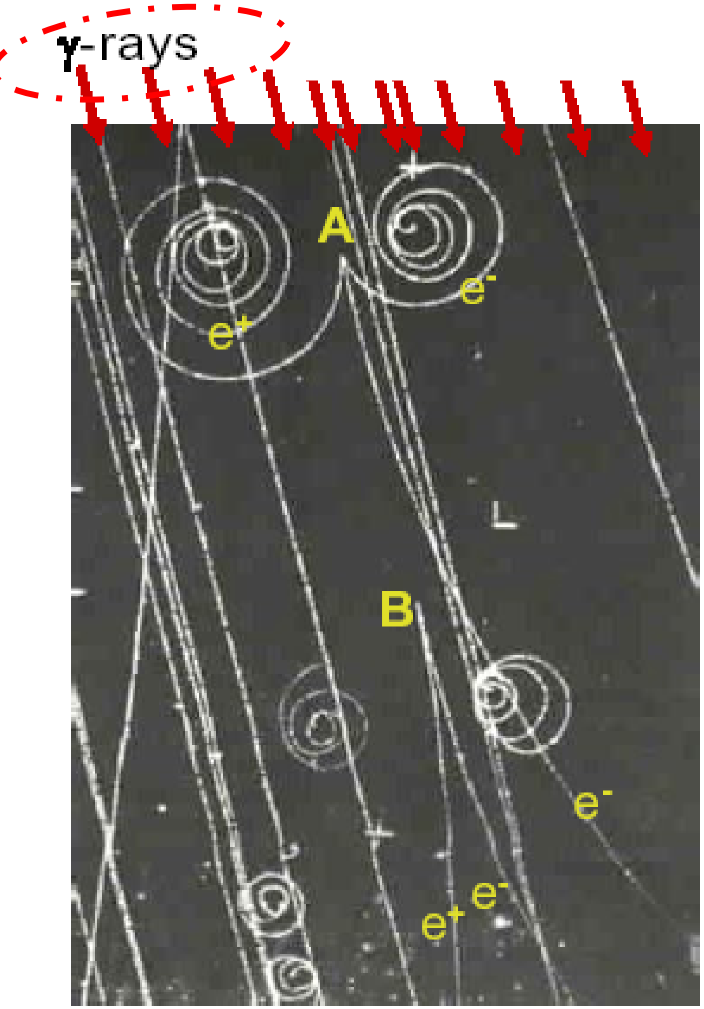
$$E_\gamma > E_{Threshold} = 2m_ec^2 = 1.022MeV$$

$(Z +)\ \gamma \rightarrow e^- + e^+$



Pair Creation by High-Energy γ rays

First observation in Bubble Chambers



Magnetic field outcoming

$\{e^+, e^-, e^-\}$ triplet and one doublet in H bubble chamber

Magnetic field provides momentum/charge analysis

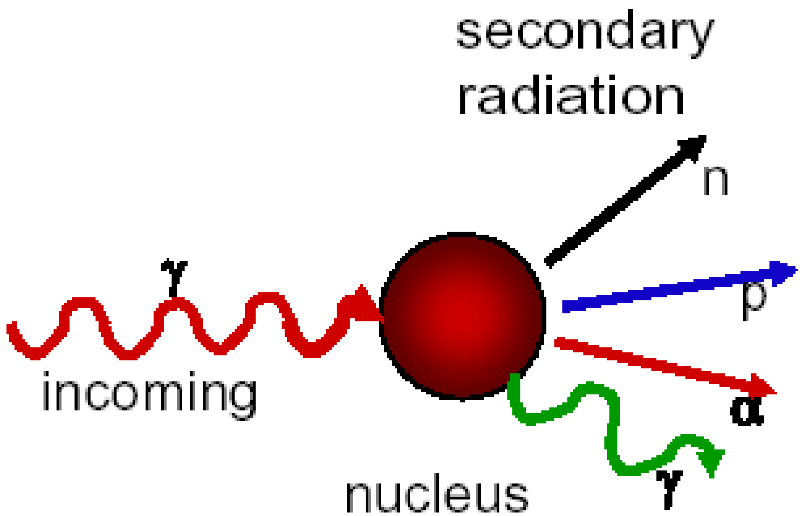
Event A) **γ**-ray (photon) hits atomic electron and produces $\{e^-, e^+\}$ pair

Event B) one photon converts into a $\{e^-, e^+\}$ pair

In each case, the photon leaves no trace in the bubble chamber, before a first interaction with a charged particle (electron or nucleus).

NOT only Interactions with atomic electrons ...

γ- Induced Nuclear Reactions



Real photons or "virtual" elm field quanta of high energies can induce reactions in a nucleus:

(γ, γ'), (γ, n), (γ, p), (γ, α), (γ, f)

Nucleus can emit directly a high-energy secondary particle or, usually sequentially, several low-energy particles or γ-rays.

γ-induced nuclear reactions are most important for high energies, $E_\gamma \gtrsim (5 - 8)$MeV

Can heat nucleus with (one) γ-ray to boiling point, nucleus thermalizes, then "evaporates" particles and γ-rays.

Interaction of Neutrons With Matter

- Neutrons interactions depends on **energies**: from > 100 MeV to < 1 eV

- Neutrons are **uncharged particles**:
  ⇒ **No** interaction with atomic electrons of material
  ⇒ interaction with the nuclei of these atoms

- The **nuclear force**, leading to these interactions, is very short ranged
  ⇒ neutrons have to pass close to a nucleus to be able to interact
  ≈ 10^{-13} cm (nucleus radius)

- Because of small size of the nucleus in relation to the atom, neutrons have low probability of interaction
  ⇒ **long travelling distances in matter**

A REMINDER

While bound neutrons in stable nuclei are stable, FREE neutrons are unstable; they undergo beta decay with a lifetime of just under 15 minutes

$$n \rightarrow p + e^- + \bar{\nu}$$

$\tau_n = 885.7 \pm 0.8$ s ≈ *14.76 min*

Long lifetimes ⇒ before decaying possibility to interact

⇒ n physics …

- Free neutrons are produced in nuclear **fission** and **fusion**
- Dedicated neutron sources like research reactors and spallation sources produce free neutrons for the use in irradiation neutron scattering exp.

N.B. Vita media del protone: $\tau_p > 1.6 \cdot 10^{33}$ anni
età dell'universo: $(13.72 \pm 0{,}12) \times 10^9$ anni.

beta decay $p \rightarrow n + e^+ + \nu$ *can only occur with bound protons*

m_p = 938.27208816(29) MeV/c2
m_n = 939.565378(21) MeV/c2
m_p < m_n

A REMINDER: The neutron lifetime puzzle

From 2016 Istitut Laue-Langevin (ILL, Grenoble) Annual Report

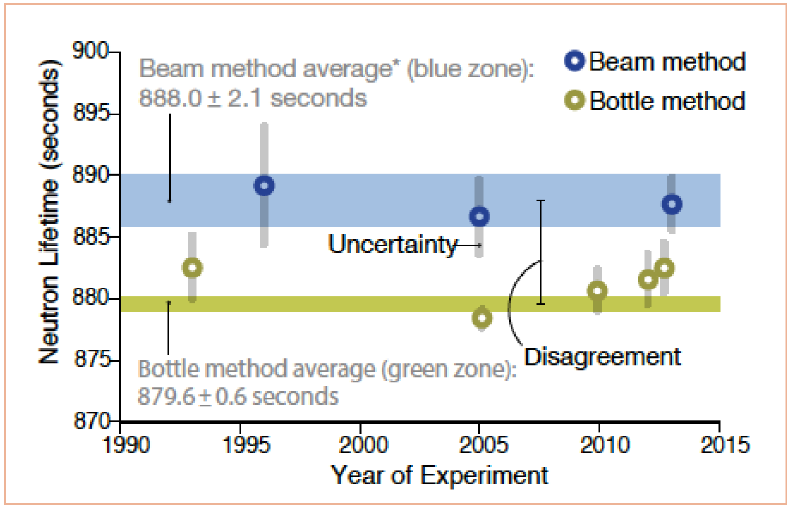


Figure 1

The history of recent neutron lifetime measurements. The green band represents the one standard deviation uncertainty for the average of all "Bottle" experiments. The blue band illustrates the same for all "Beam" experiments.

A discrepancy of more than 8 seconds (1%) !!!!

A. Serebrov et al., Phys. Lett. B 605 (2005) 72
A.T. Yue et al., Phys. Rev. Lett. 111 (2013) 222501
Z. Berezhiani and L. Bento, Phys. Rev. Lett. 96 (2006) 081801
G.L. Greene and P. Geltenbort, Sci. Am. 314 (2016) 36

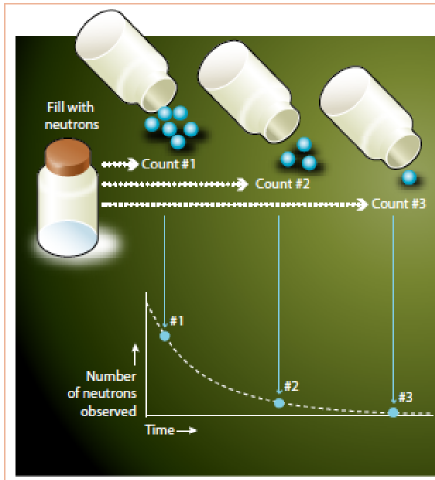


Figure 2

The Bottle Method: One way to measure how long neutrons live is to fill a container with neutrons and empty it after various time intervals under the same conditions to see how many remain. These tests fill in points along a curve that represents neutron decay over time. From this curve, scientists use a simple formula to calculate the average neutron lifetime. Because neutrons occasionally escape through the walls of the bottle, scientists vary the size of the bottle as well as the energy of the neutrons – both of which affect how many particles will escape from the bottle – to extrapolate to a hypothetical bottle that contains netrons perfectly with no losses.

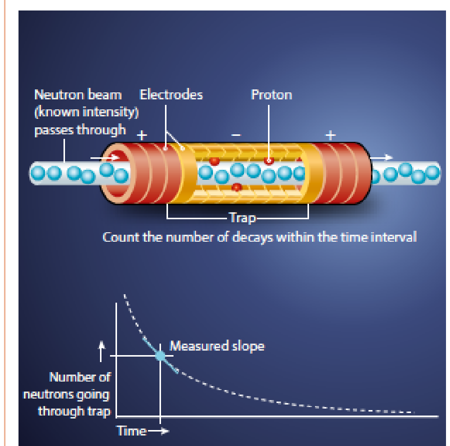


Figure 3

The Beam Method: In contrast to the bottle method, the beam technique looks not for neutrons but for one of their decay products, protons. Scientists direct a stream of neutrons through an electromagnetic 'trap' made of a magnetic field and ring-shaped high-voltage electrodes. The neutral neutrons pass right through, but if one decays inside the trap, the resulting positively charged protons will get stuck. The researchers know how many neutrons were in the beam, and they know how long they spent passing through the trap, so by counting the protons in the trap they can measure the number of neutrons that decayed in that span of time. This measurement is the decay rate, which is the slope of the decay curve at a given point in time and which allows the scientists to calculate the average neutron lifetime.

THE SCIENCES

Neutron Death Mystery Has Physicists Stymied

Conflicting results in measurements of how long neutrons live has physicists rethinking their experiments, because solving the riddle may point the way to exotic new physics

A possible source of dark matter ?

By Clara Moskowitz on May 13, 2014

https://www.scientificamerican.com/article/neutron-lifetime-mystery-new-physics/

Nuclear Interactions of neutron

No electric charge → no direct atomic ionization → only collisions and reactions with nuclei → 10^{-6} x weaker absorption than charged particles

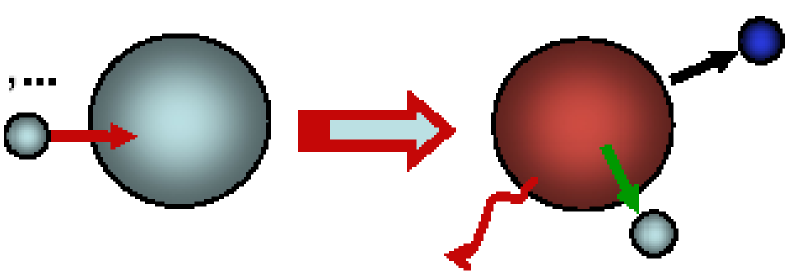
Processes depend on available n energy E_n:

$E_n \sim 1/40$ eV		$(= k_B T)$ Slow diffusion, capture by nuclei
E_n <	10 MeV	Elastic scattering, capture, nucl. excitation
E_n >	10 MeV	Elastic+inel. scattering, various nuclear reactions, secondary charged reaction products

Characteristic secondary nuclear radiation/products:

*Always **heavy charged particles** (NOT electrons as in the case of γ interaction)*

1. γ-rays (n, γ)
2. charged particles (n,p), (n, α),...
3. neutrons (n,n'), (n,2n'),...
4. fission fragments (n,f)



5. Spallation Reactions: high energy neutrons (> 150 MeV) may strike a nucleus producing a <u>shower</u> of secondary particles (very harmful …)

Therminology (often used)

1) High Energy neutrons: $E_n > 100$ *MeV*

2) Fast Neutrons: *100 keV* $< E_n <$ *10 MeV*

3) Epithermal Neutrons: *0.1 eV* $< E_n <$ *100 keV*

4) Thermal/Slow Neutron: $E_n = 1/40$ *eV*

5) Cold/Ultracold Neutrons: $E_n <$ *meV … μeV*

Cross Section versus Neutron Energy

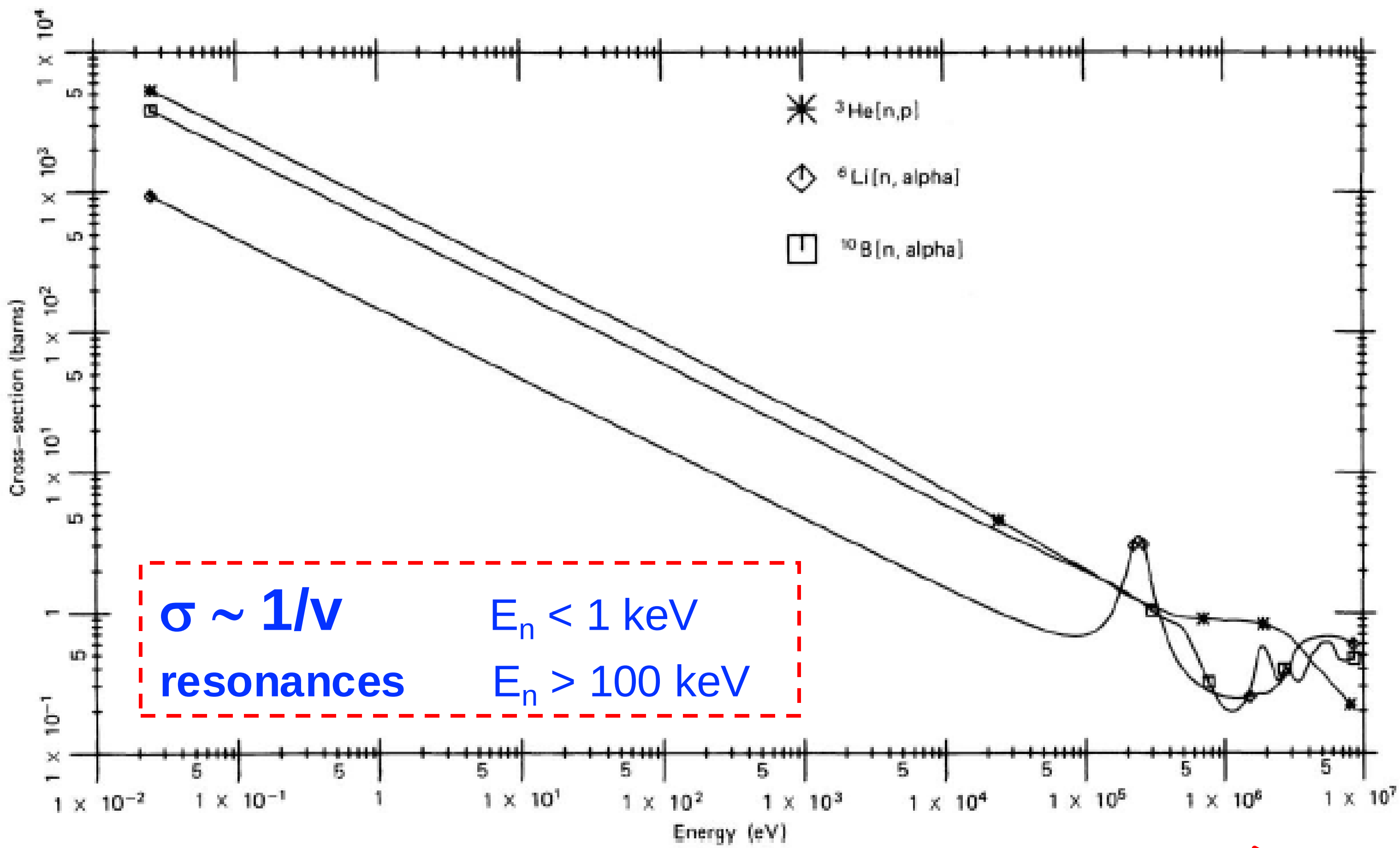


Figure 14.1 Cross section versus neutron energy for some reactions of interest in neutron detection.

Principle of neutron detection

- **Conversion** of incident neutron into secondary charged particles
- **Direct detection** of charged particle

Relative probabilities of different interaction change rapidly with E_n

Cross section are sizable only at very low energy (slow and thermal n)

slow neutrons (E$_n$ < 0.5 eV):

- elastic scattering (NOT favorite for detection of scattered nucleus:
  $\Rightarrow$ little energy given to the nucleus to be detected)
- neutron-induced reactions creating secondary radiation with sufficient energy
  for example radiative capture (n,γ) or (n,α), (n,p), (n, fission)

fast neutrons:

- scattering probability becomes greater: large energy transfer in one collision
  neutron loses energy and is moderated/slowed to lower energy

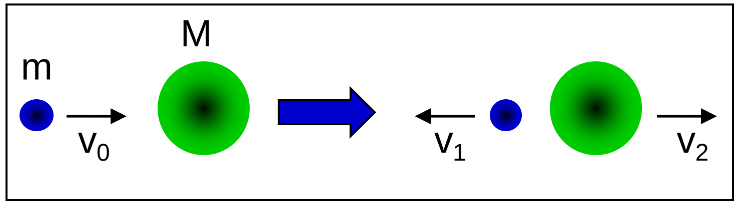
Best moderator is hydrogen

[it can get all n-energy in one collision !]

Energy Spectrum of neutrons

Slowing down of neutrons by **elastic nuclear collisions:**

$$n(E_n) + {}^{A}K \rightarrow n(E'_n) + {}^{A}K$$



Scattering angles:
$\theta_{min} = 0°$
$\theta_{max} = 180°$

from ***elastic scattering*** *reaction kinematics*

$$\left(\frac{A-1}{A+1}\right)^2 E_n \leq E'_n \leq E_n$$

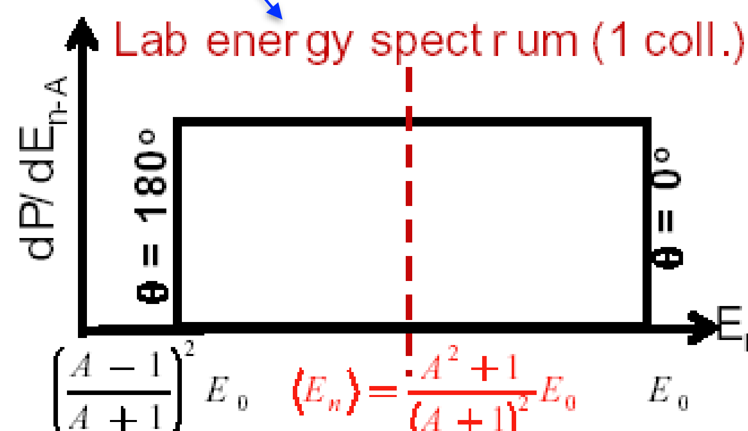
assuming no excitation, no capture, no fission

average ***neutron energy variation*** *after one collision*

$$\left\langle \frac{\Delta E_n}{E_n} \right\rangle = \frac{2A}{(A+1)^2}$$

$$E_1 = E_0 \cdot \left[1 - \frac{2 \cdot m \cdot M}{(m+M)^2} \cdot (1 - \cos\theta_{cm})\right]$$

$$\frac{E'}{E} = \frac{A^2 + 1 + 2A\cos\theta}{(A+1)^2}$$



Example

$$\left(\frac{A-1}{A+1}\right)^2 E_n \leq E'_n \leq E_n$$

$A = 1 \qquad 0 \leq E'_n \leq E_n$ *elastic scattering on* ***proton***

$A = 238 \qquad 0{,}992\,E_n \leq E'_n \leq E_n$ *elastic scattering on* ***uranium***

Average energy loss of the neutrons per collision:

$$\left\langle \frac{\Delta E_n}{E_n} \right\rangle = 1 - \left\langle \frac{E'_n}{E_n} \right\rangle = \frac{1}{2}\left(1 - \left(\frac{A-1}{A+1}\right)^2\right) \Rightarrow \left\langle \frac{\Delta E_n}{E_n} \right\rangle = \frac{2A}{(A+1)^2}$$

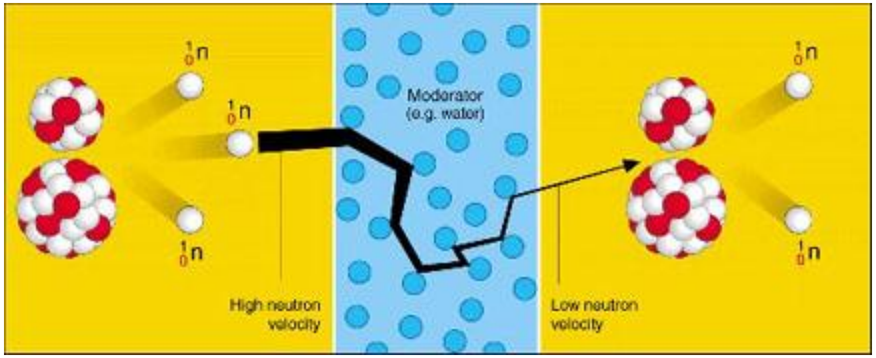
= 50% for A=1

After **1 collision** the neutron energy is **uniform** between $E_{min} = (A-1)^2/(A+1)^2 \times E_0$ and $E_{max} = E_0$

BUT: each neutron scatters **many times**

$\Rightarrow$ we need to calculate ***repetedly*** the energy loss

Moderator	**Average collision number** for a slowing down from 1.75 MeV to 0.025 eV
Hydrogen	18
Deuterium	25
Beryllium	86
Carbon	114



principle of ***neutron energy moderation (with water)*** *for efficient use of fission reactions in reactors.*

REMINDER: *$\sigma(n,\gamma)$ on ^{235}U = 586 b for E_n = 0.025 eV*