Detectors in Nuclear Physics (42 hours)

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Material for the course can be found at the web page **http://www.mi.infn.it/~sleoni**

After an introduction on the interaction mechanisms of charge particles, γ-rays and neutrons with matter, the general properties of radiation detectors are presented. Modern and future detection systems based on different kind of materials are discussed in connection with specific experiments at the frontiers of the nuclear physics research. In the last part of the course techniques for production, acceleration and studies of unstable (exotic) beams are presented.

The course is organized as follows:

1 – Radiation interactions:
a) charged particles;
b) γ-rays;
c) neutrons.

2 – General properties of radiation detectors:
a) gas detectors;
b) scintillator detectors;
c) semiconductor detectors;
d) neutron detectors;
[e) momentum measurement]

3- Modern detector systems:
a) large volume composite Ge detectors;
b) Ge arrays: the European project EUROBALL;
c) Si arrays;
d) scintillators arrays;
e) electron conversion spectrometers ;
f) neutron arrays ;
g) heavy ions detectors ;
h) magnetic spectrometers.

4- Future developments in γ-detection:
a) segmented Ge detectors: pulse shape analysis and tacking techniques;
b) the ultimate array for γ-spectroscopy: the European project AGATA.

5- Production and acceleration of radioactive beams:
a) fragmentation;
b) isotopic separation on line;
c) overview of present and future facilities in Europe.

Complemetary material:

Lecture Notes on MyAriel: γ-spectroscopy LAB (Prof. Franco Camera)
Lecture Notes on MyAriel: Introductory Nuclear Physics – A (Prof. Silvia Leoni)

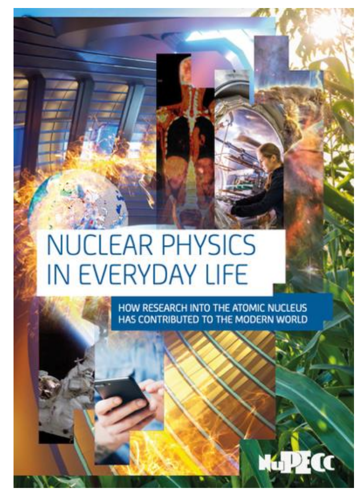
Additional Material at personal web page:
http://www.mi.infn.it/~sleoni

Textbooks

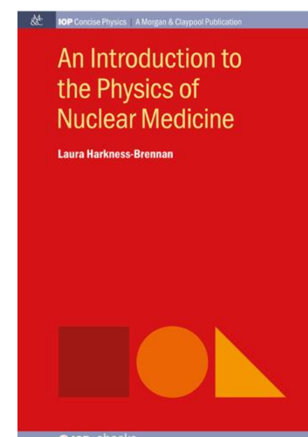
G.F. Knoll
Radiation Detection
and Measurements
Wiley & Sons

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



Application to Medicine (~ 2 Lectures)

Giuseppe Battistoni (INFN, Milano), Giuseppe.Battistoni@mi.infn.it
Applicazioni della fisica delle interazioni radiazione materia: radioterapia e adroterapia

Andrea Mairani (Heildelberg e CNAO) – fino a 2019, Andrea.Mariani@mi.infn.it

- **Monte Carlo methods:**
  1) Introduction
  2) Simulation techniques
  3) FLUKA
- **Ion interaction with matter and its MC modeling:**
  1) Electromagnetic interaction
  2) Multiple scattering
  3) Nuclear interaction
- **Simulation of real experimental situations:**
  1) nTOF
  2) ICARUS (neutrino – Argon interaction)
- **Medical Applications**
  1) Radiotherapy
  2) Ion beam therapy
  3) PET/CT simulations

Additional seminars:

- Applications to Environmental and Cultural Heritage studies (~ 1 Lectures)
- Physics with Neutrons (~ 1 Lectures)

Radiation Interaction

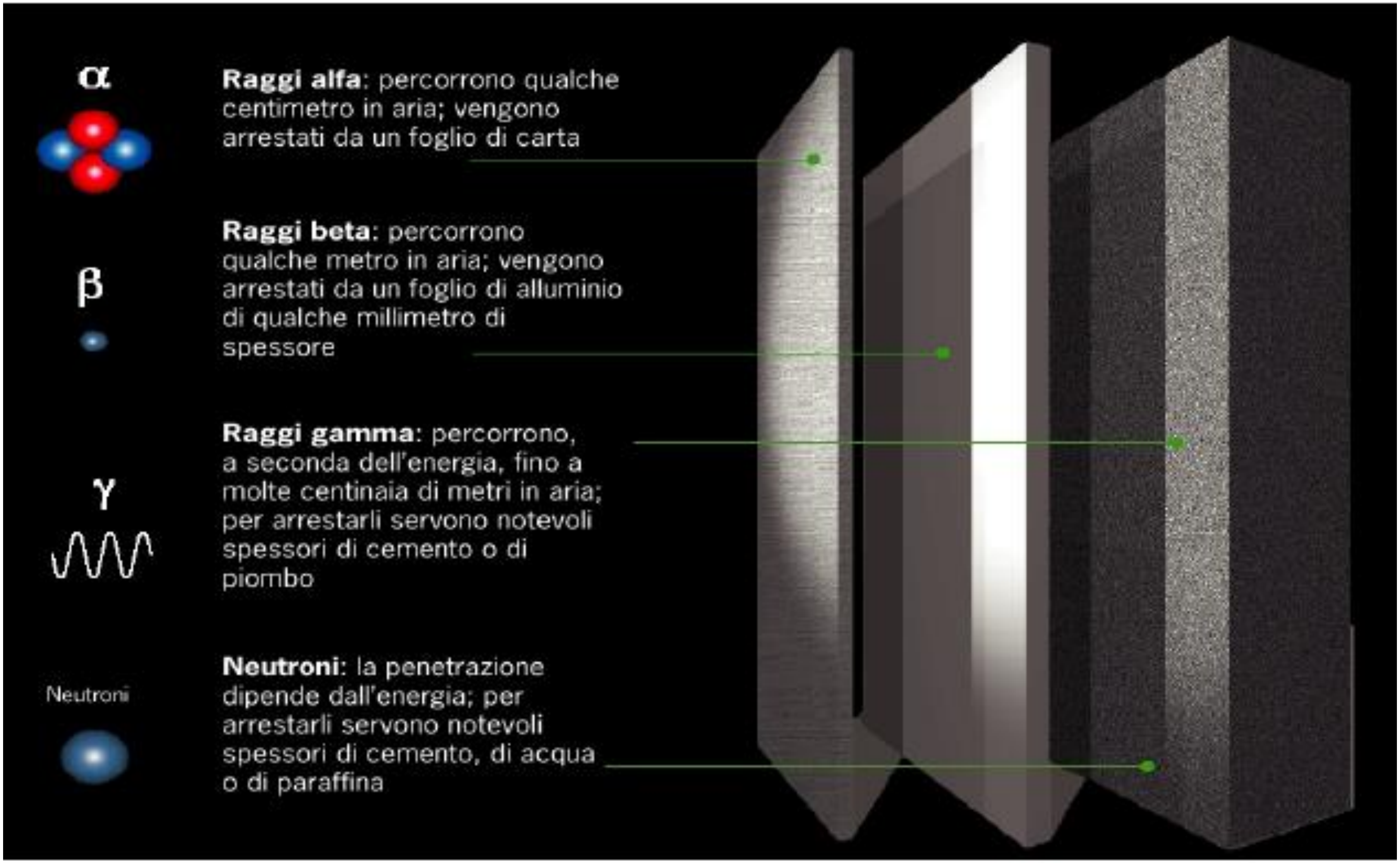
1. charged particles
2. γ-rays
3. neutrons

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 $\Rightarrow$ $\left\{\begin{array}{l}\text{Atomic excitation} \\ \text{ionization} \\ \text{fluorescence} \\ \text{phosphorescence}\end{array}\right.$

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.

$R_{nucl} = 1.2\, A^{1/3}\ fm \quad = 1.2\, A^{1/3}\ 10^{-13}\ cm$
$a_Z \quad = 1\, A = 10^{-8}\ cm$

From **elastic collisions** between

incoming particle m_1, $v_{i,1}$ and electron at rest

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

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

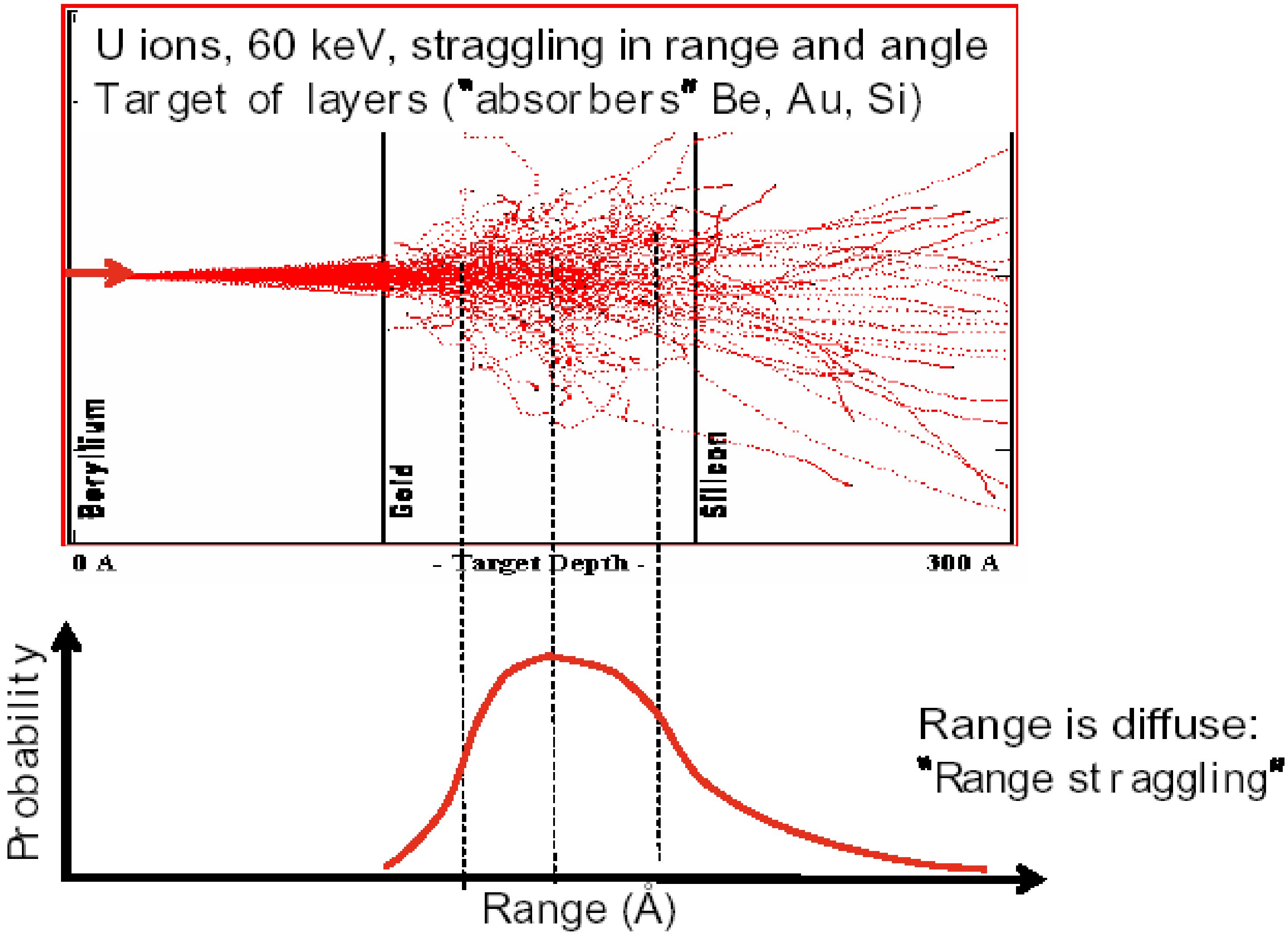
$$E_{cin}(2) = \frac{1}{2}m_e v_{f,e}^2 = 4\frac{1}{2}m_e v_{i,1}^2 = 4\frac{1}{2}\frac{m_e}{m_1}m_1 v_{i,1}^2 = 4\frac{m_e}{m_1}E_{cin}(1)$$

Maximum energy transfer
To atomic electron

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

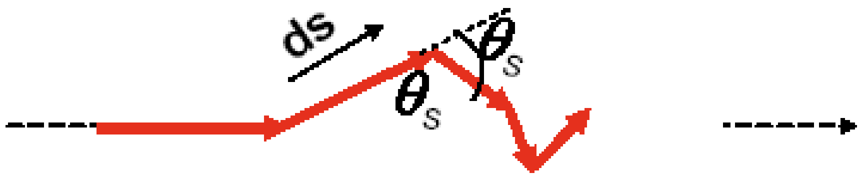
$m_p = 1836\ m_e \sim 2000\ m_e$

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***



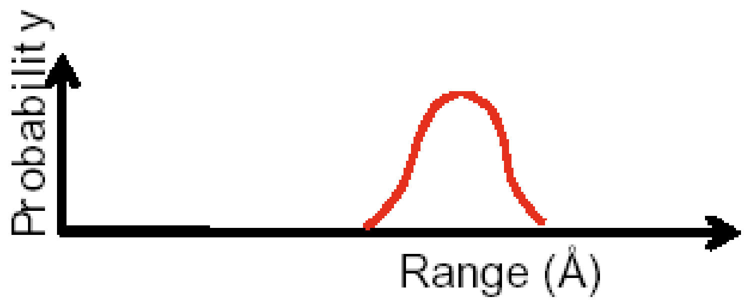
Penetration distance

Range and Stopping Power



Scattering angle θ_s path variable s

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

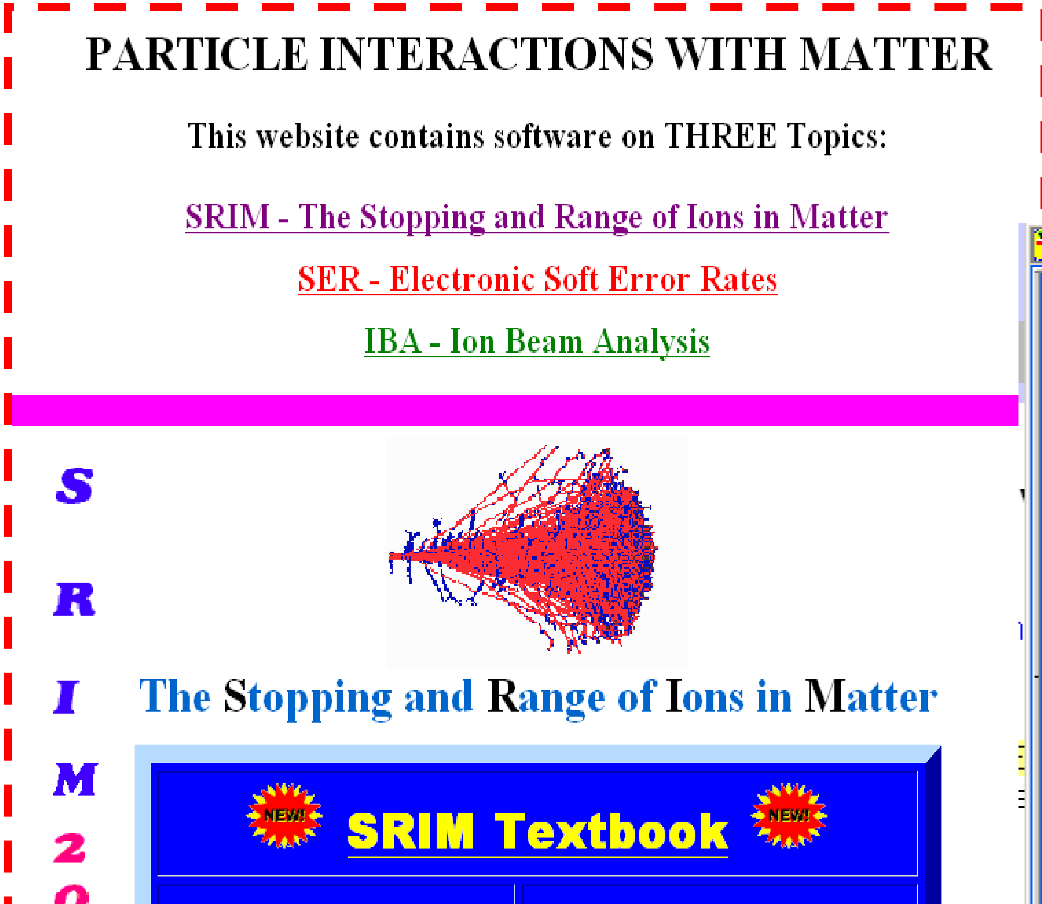


$$R(E) = \int ds \langle \cos\theta_s \rangle = \int_0^E dE' \left[\frac{dE'}{ds}\right]^{-1} \cdot \langle \cos\theta_s \rangle \underset{def}{=} \text{Range}$$

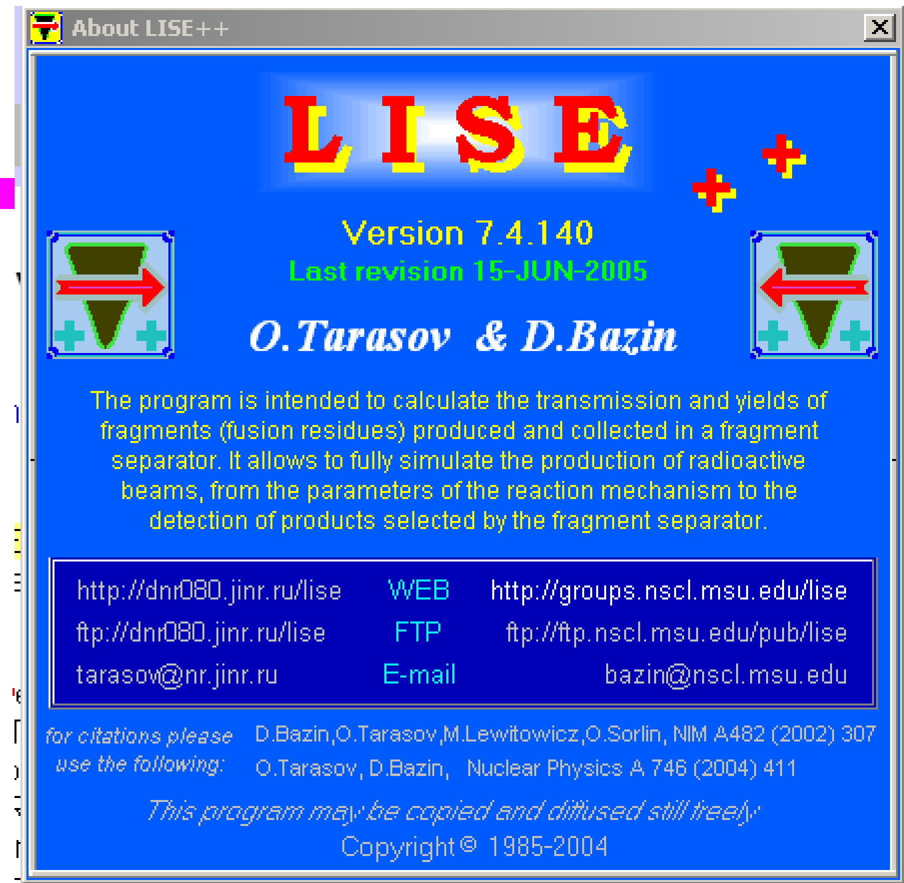
$$\left[\frac{dE}{ds}\right] \underset{def}{=} \text{Stopping power}$$ = *Energy loss by the particle in path length dx*

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

Stopping Power and Range tables

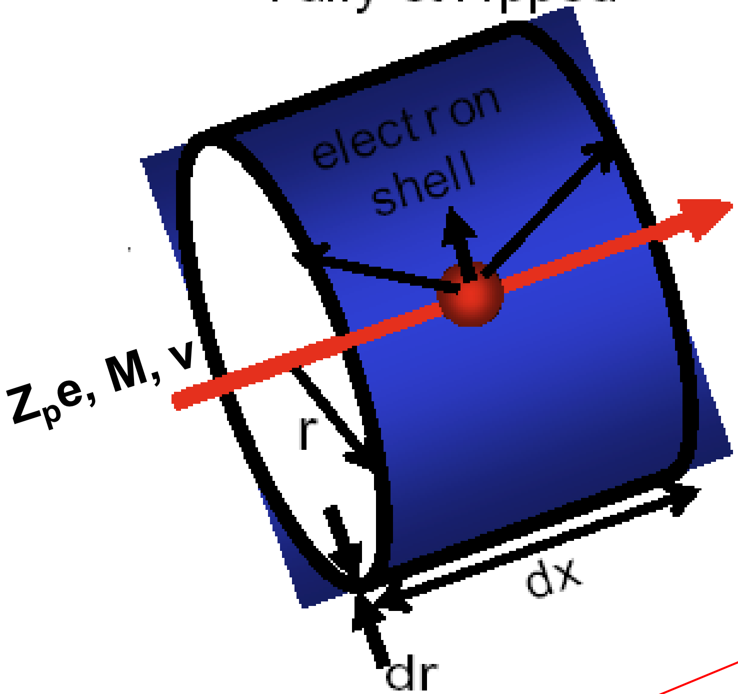


SRIM & TRIM
Ziegler et al.



Phenomenological Model Of Energy Loss in Matter

Bethe et al. (1930-1953), Lindhardt's electron theory
Describes energy loss through ionization, incoming ions are fully stripped



Estimate of trends/Order of magnitude

E=particle kinetic energy, $e^- \approx$ at rest

Z_pe = particle charge

$$\Delta p_e = F_{Coul} \cdot \Delta t_{coll} \approx \left(\frac{e^2 Z_p}{r^2}\right) \cdot \left(\frac{2r}{v}\right)$$

$$-dE(r,x) \sim \left[2\pi r\, dr\, dx\, N_e\right] \cdot \left[\frac{(\Delta p_e)^2}{2m_e}\right]$$

$$-\frac{dE(r,x)}{dr\, dx} \sim \left[\frac{4\pi e^4 Z_p^2}{m_e v^2} N_e\right] \cdot \frac{1}{r}$$

number of interacting electrons

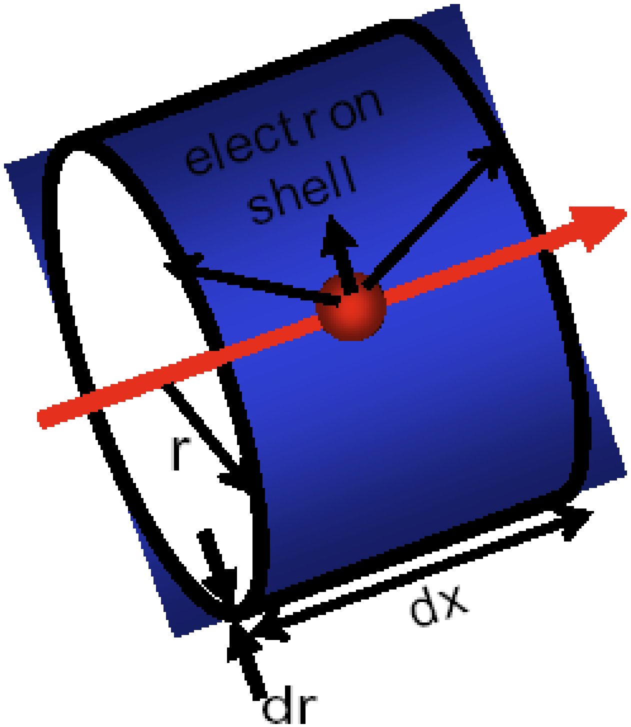
\# electrons per unit volume

Phenomenological Model Of Energy Loss in Matter

Integrate over radial coordinate:

$$\frac{dE(x)}{dx} = \int_{r_{min}}^{r_{max}} dr\, \frac{dE(r,x)}{dr\,dx}$$

$$-\frac{dE(x)}{dx} \sim \left[\frac{4\pi e^4 Z_p^2}{m_e v^2} N_e\right] \cdot \ln\left(\frac{r_{max}}{r_{min}}\right)$$



r_{min} corresponds to maximum kinetic energy T_{max} gained by e$^-$

It corresponds to head-on-collision:

$$v = \frac{2M}{m+M} v_0 \xrightarrow{M>>M} v = 2v_0 \longrightarrow T_{max} = \frac{1}{2} m (2v)^2 = 2mv^2$$

$$T_{max} = \frac{(\Delta p_{max})^2}{2m_e} = \frac{2Z_p^2 e^4}{m_e v^2 r_{min}^2} = 2m_e v^2$$

$$r_{min}^2 = \frac{Z_p^2 e^4}{m_e^2 v^4}$$

r_{max} corresponds to minimum kinetic energy T_{min} gained by e$^-$

$$T_{min} = IE = ionization\ \ en. \begin{cases} (12 \cdot Z_T + 7)\, eV & for\ Z_T < 13 \\ (9.76 \cdot Z_T + 58.8 \cdot Z_T^{-0.19})\, eV & for\ Z_T \geq 13 \end{cases} \sim 10\ Z\ \text{eV}$$

$$T_{min} = IE = \frac{2Z_p^2 e^4}{m_e v^2 r_{max}^2}$$

$$r_{max}^2 = \frac{2Z_p^2 e^4}{(IE) m_e v^2}$$

Estimate of Radial Limits:

$$-\frac{dE(x)}{dx} \sim \left[\frac{4\pi e^4 Z_p^2}{m_e v^2} N_e\right] \cdot \ln\left(\frac{r_{max}}{r_{min}}\right) \approx \frac{4\pi Z_p^2 e^4}{m_e v^2} N_e \frac{1}{2} \ln\left[\frac{2m_e v^2}{IE}\right]$$

Insert: ρ = atomic density, Z_T = atomic number of target

$N_e = Z_T \cdot \rho$

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

Phenomenological model

Bethe-Bloch Quantum Mechanical Equation

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

Average energy loss

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

ρ = atomic density

Z_T = atomic number of target

A_T = mass number of target

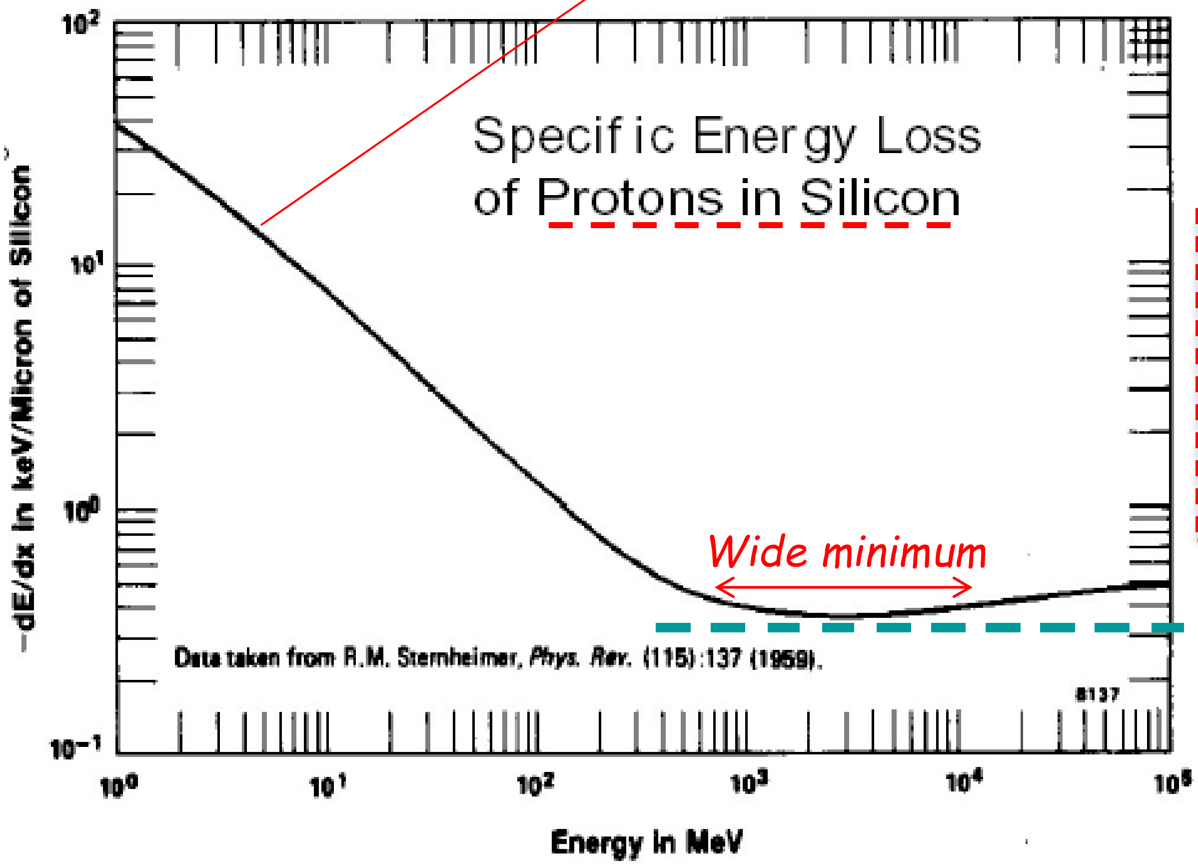
$$IE = h(\nu_e) \approx \begin{cases} (12 \cdot Z_T + 7)\,eV & \text{for } Z_T < 13 \\ (9.76 \cdot Z_T + 58.8 \cdot Z_T^{-0.19})\,eV & \text{for } Z_T \geq 13 \end{cases}$$

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

Minimum Ionizing Particles

Bethe-Bloch Formula

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



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: $e^\pm$, $\mu^\pm$

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

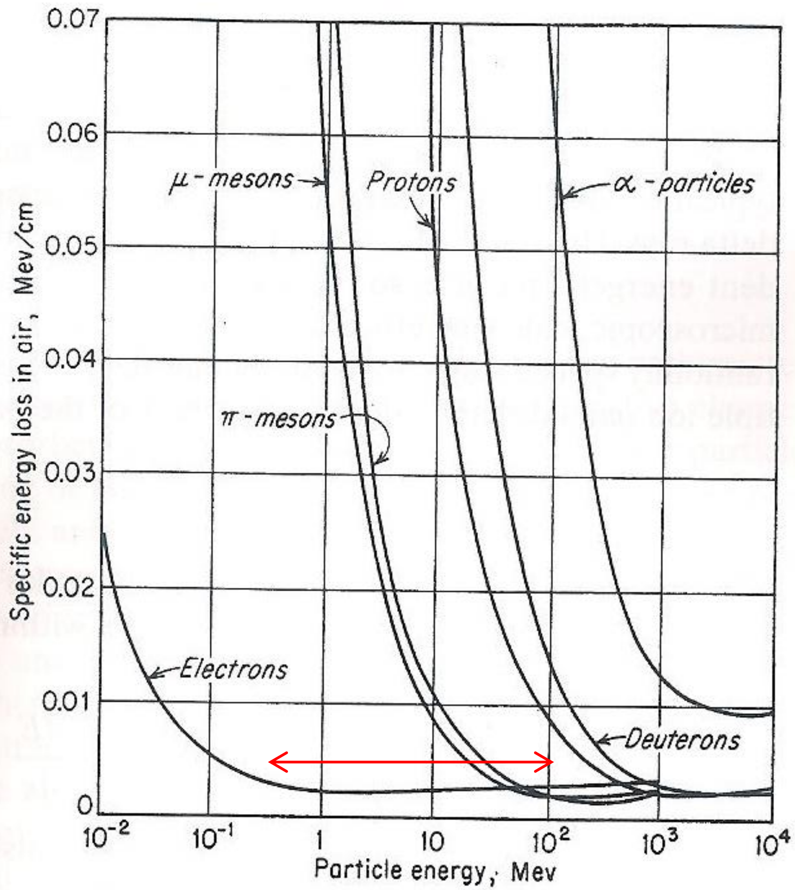


Figure 2.1 Variation of the specific energy loss in air versus energy of the charged particles shown. (From Beiser.[2])

Near Constant
Broad Minimum

for $v \rightarrow c$

At the minimum:
very ***similar behaviour***
for different light particles
at E > 100 MeV

"minimum ionizing particles"

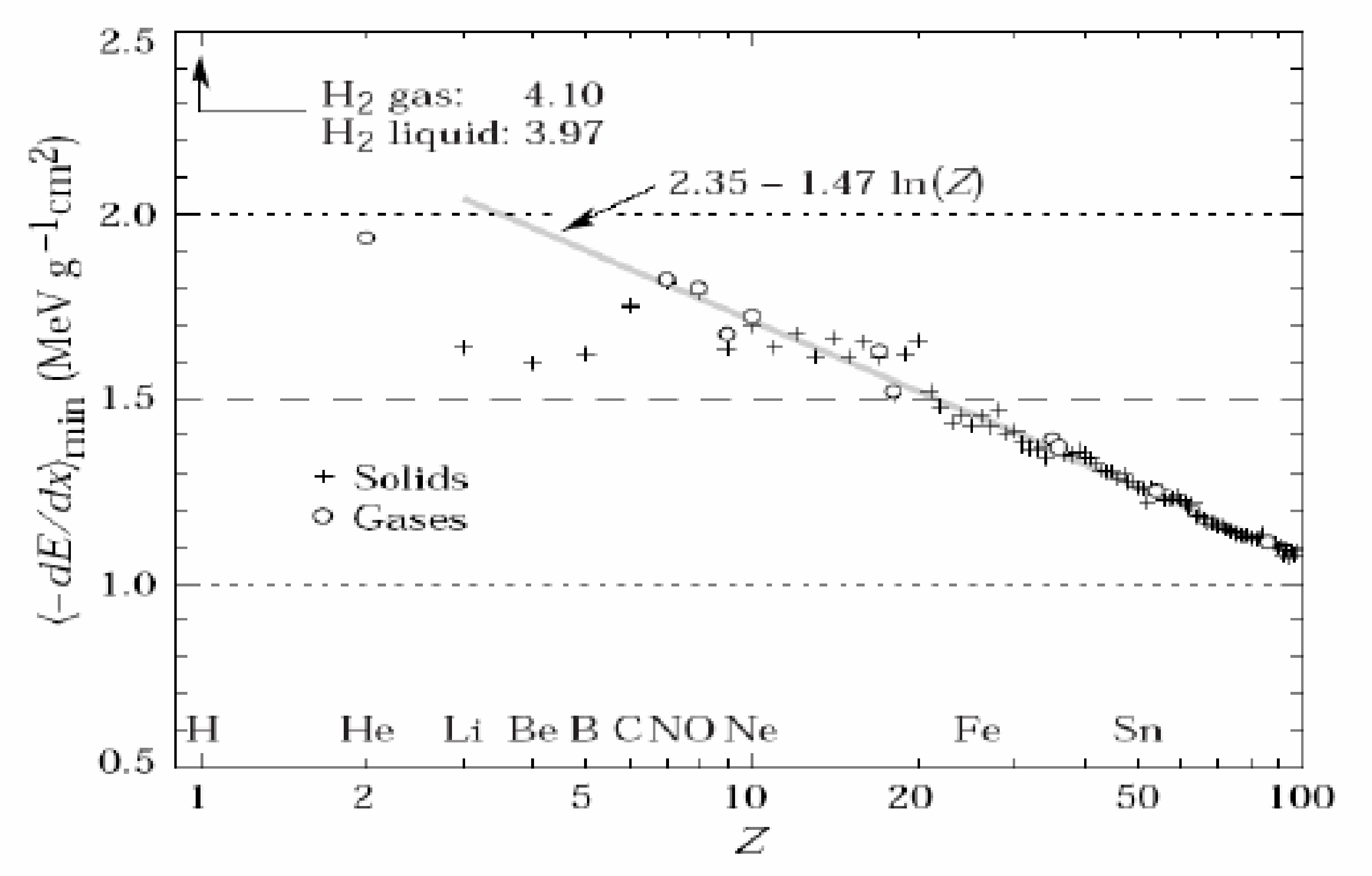
Electrons are at the minimum of ionization at E > 1 MeV !!!

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

$E=mc^2 = m_0c^2 + E_{kin}$

very different *dE/dx behaviour*
for different particles at $E < E_{min:}$
Technique used for particle identification

$(dE/dx)_{min}$ versus Z

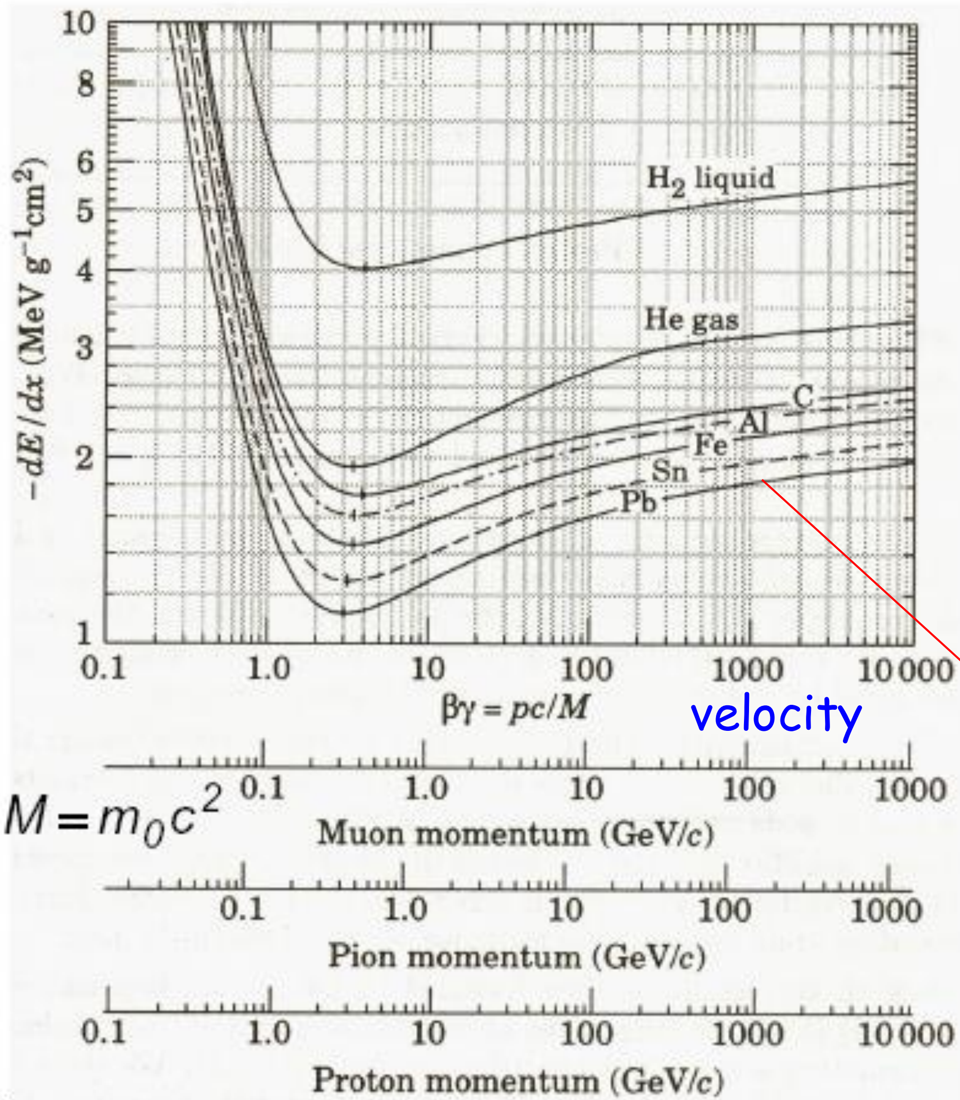


<u>***The straight line is fitted for Z > 6***</u>***.***

A simple functional dependence on Z is not to be expected, since ⟨–dE/dx⟩ also depends on other variables.

Stopping Power of Relativistic Particles

Review of Particle Properties, Phys. Rev. D50, 1173 (1994)



$$M = m_0 c^2$$

$$E^2 = (pc)^2 + \left(m_0 c^2\right)^2$$

$$m_0 = \text{particle rest mass}$$

$$v = \text{particle velocity}$$

$$c = 2.9979 \cdot 10^8\, ms^{-1}$$

$$\beta = v/c$$

$$\gamma = \left(\sqrt{1-\beta^2}\right)^{-1}$$

$$pc = (\gamma m_0) vc = \gamma\beta m_0 c^2$$

Relativistic rise:
part of the energy is also
Subtracted by light
(Cerenkov radiation)

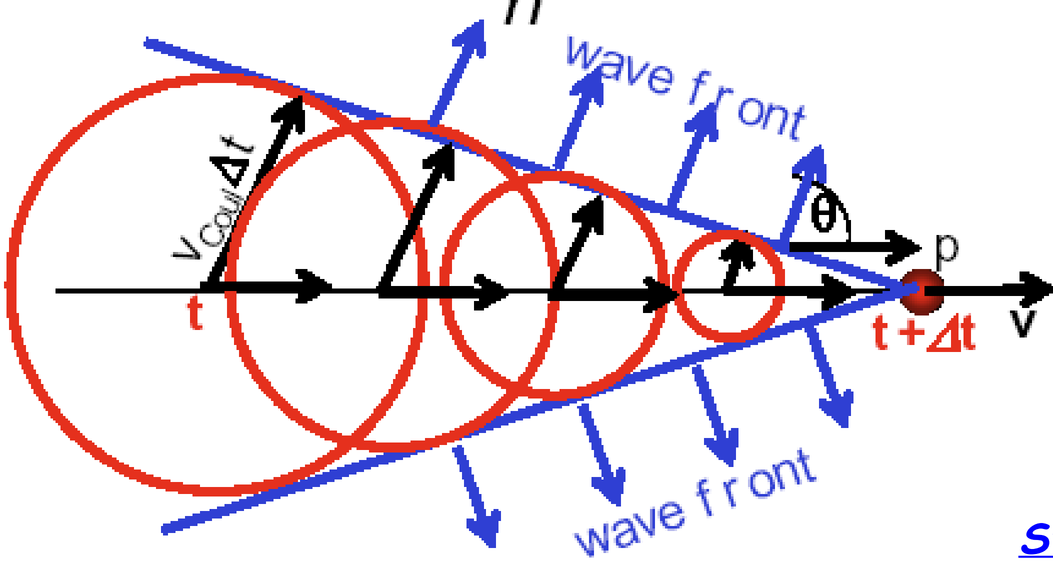
Note: here ρdE/dx → dE/dx

N.B. Bethe-Block is accurate for pions in the range 6 MeV-6 GeV

Čerenkov Effect

Similar to supersonic boom in acoustic medium. Occurs for particle velocity

$$v > c_{medium} = \frac{c_{vacuum}}{n} \qquad n = \textit{index of refraction}$$



Atoms become electrically polarized by Coulomb field (field velocity v_{Coul}=c/n) of fast particle, atoms radiate coherently

$$\cos\theta = \frac{c}{nv} = \frac{1}{\beta n} \quad \textit{Emission of Č light}$$

Strong correlation $\theta \rightarrow \beta$:
Cerenkov effect is used to identify particles (Cerenkov counters: photomultipliers)

$$\textit{Light spectrum}: \frac{dN(\nu)}{d\nu} = \frac{4\pi^2}{hc^2}(eZ_p)^2\left[1 - \frac{1}{(\beta n)^2}\right]$$

Corrections to Bethe-Bloch formula

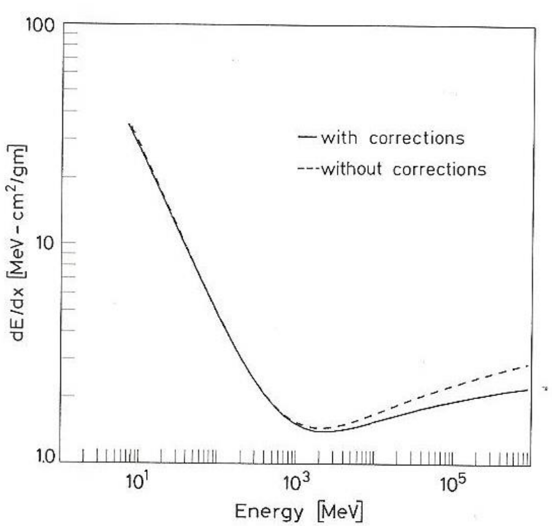
Average energy loss

Corrections

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

Density correction
(importat for high energy):

- Atoms are polarized by electric field of the particle
- Far electrons are shielded→ less contribution to dE/dx

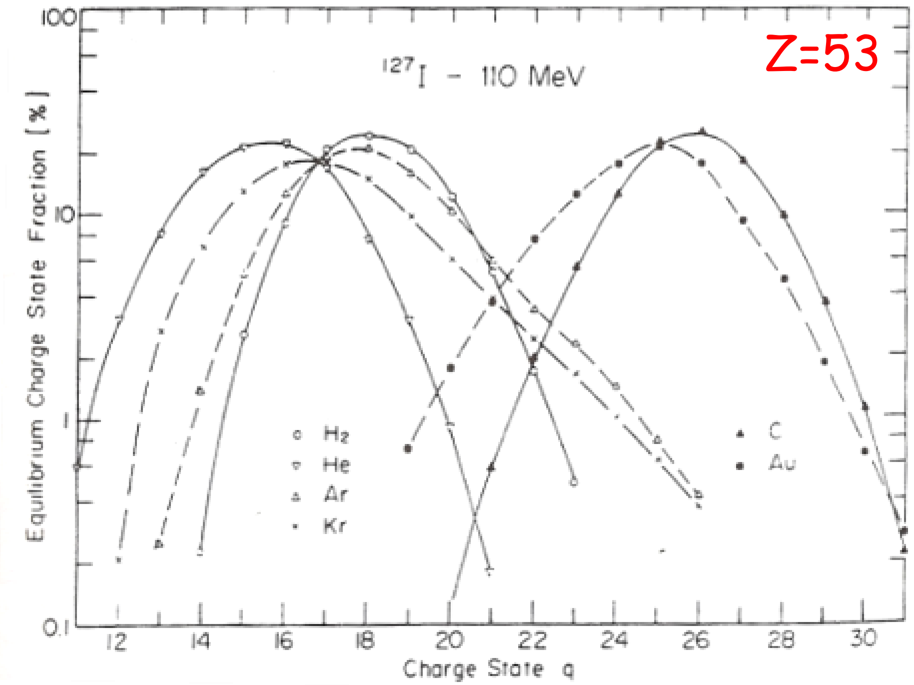


Shell correction
(important for low energy):

- Velocity of incident particle comparable to orbital velocity of bound electrons
- electrons are **NOT** stationary with respect to incoming particle

→ Picking up of electrons to the charged particle
→ Reduced charge

Equilibrium charge state distribution for 110 MeV ^{127}I ions stripped in various materials



<u>Average charge</u> *depends on Energy E, and for solid absorbers is*

$$\frac{\bar{q}}{Z} = 0.708(x - 0.058)^{1/2} - 0.042$$

for $0.05 < x < 0.5$

$x = 3.858\, Z^{-0.45} (E/A)^{1/2}$

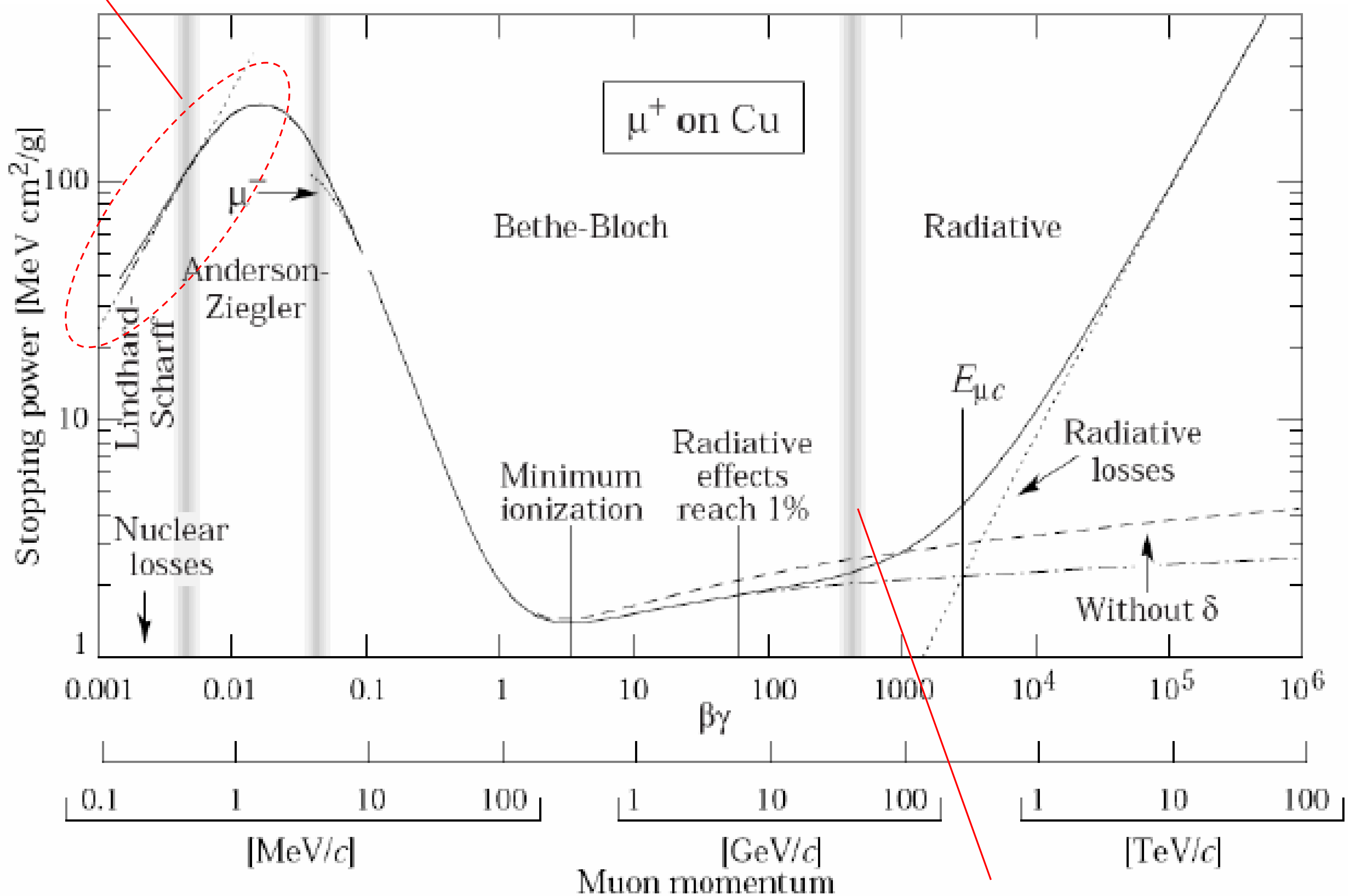
average charge decreases with decreasing energy (see Ziegler et al.) → dE/dx decreases

R.O. Sayer, Revue de Physique Appliquee, 1977, 12 (10), 1543.

K. Shima, T. Ishihara, T. Mikumo, Nuc. Inst. Meth. 200, (1982) 605.

dE/dx on large scale

Capture of low energy electrons decreases the particle charge [the ion may become neutral]



Nuclear physics
$\beta\gamma < 1$

Boundaries between different approximations

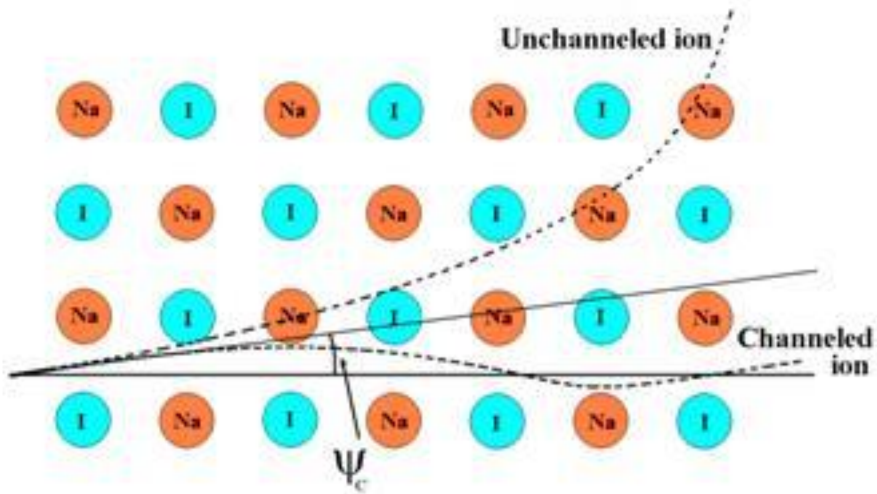
Exception to Bethe-Block formula: Channeling Effects

importat for material with spatially symmetric atomic structure:

Series of correlated scattering guiding the particle down an open channel of the lattice

→ ***Less electrons encounterd*** *as compared to* ***amorphous material*** *(assumed by Bethe-Block)*

→ *Importance of* ***crystal orientation***



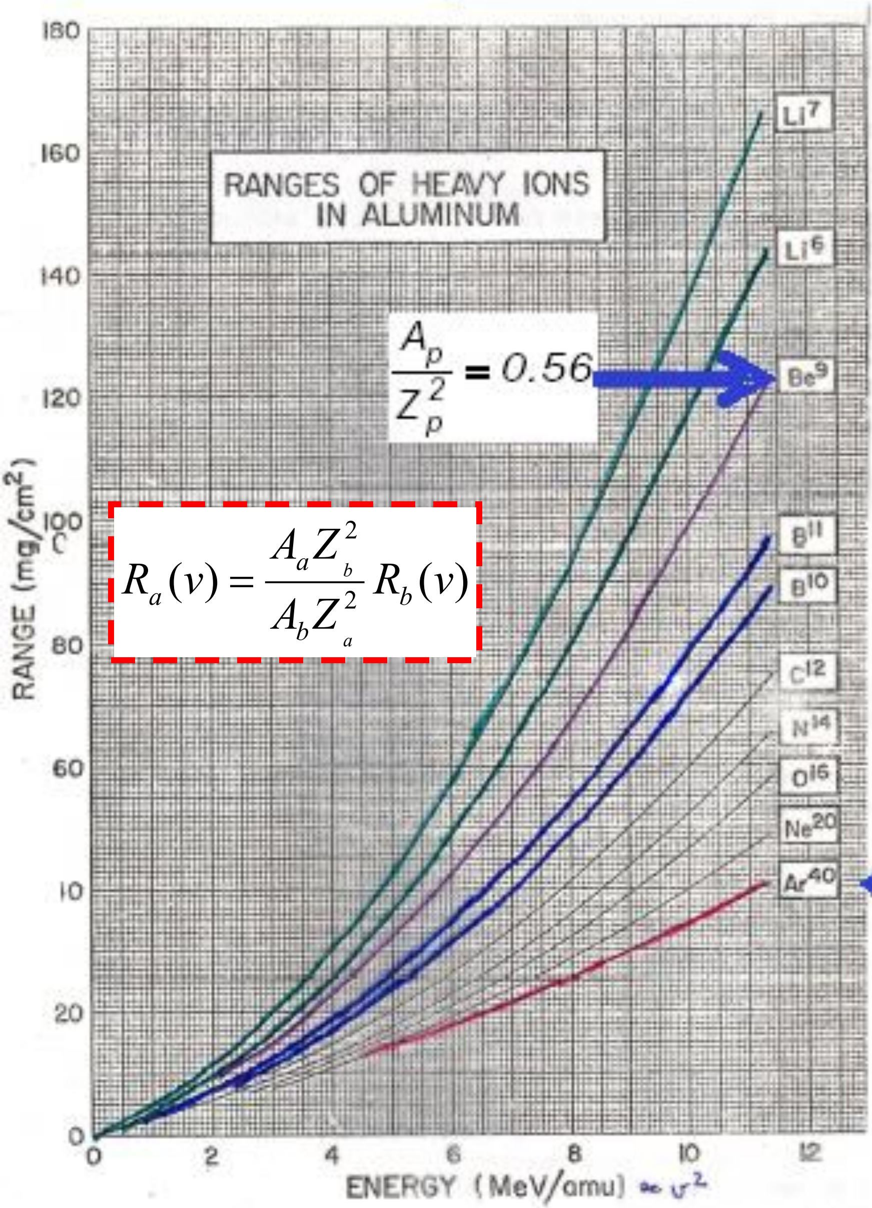
Critical angle for channeling is small (≈ 1° for $\beta \approx 0.1$)

$$\phi_c \simeq \frac{\sqrt{z Z a_0 A d}}{1670\,\beta\sqrt{\gamma}}$$

a_0 = Bohr radius
d = interatomic spacing

For $\phi > \phi_c$ channeling does NOT occurn → the material can be treated as amourphous

Stopping Power Isotopic Scaling Laws



$$\frac{A_p}{Z_p^2} = 0.56$$

$$\boxed{R_a(v) = \frac{A_a Z_b^2}{A_b Z_a^2} R_b(v)}$$

$$\frac{dE}{dx} = \frac{d\left(m_p v^2/2\right)}{dx} = Z_p^2 \times f(v)$$

$$\frac{dv}{dx} = \left(\frac{Z_p^2}{A_p}\right) \cdot g(v) \rightarrow$$

unique function for particle with velocity v

$$R(v) \approx \int dv \left(\frac{dv}{dx}\right)^{-1} \approx \left(\frac{A_p}{Z_p^2}\right) \cdot h(v)$$

Describes well the difference of R for different isotopes of a given element, but:

$$\frac{A_p}{Z_p^2} = 0.12$$

R(Be)/R(Ar)=2.97 expt 4.67 theo

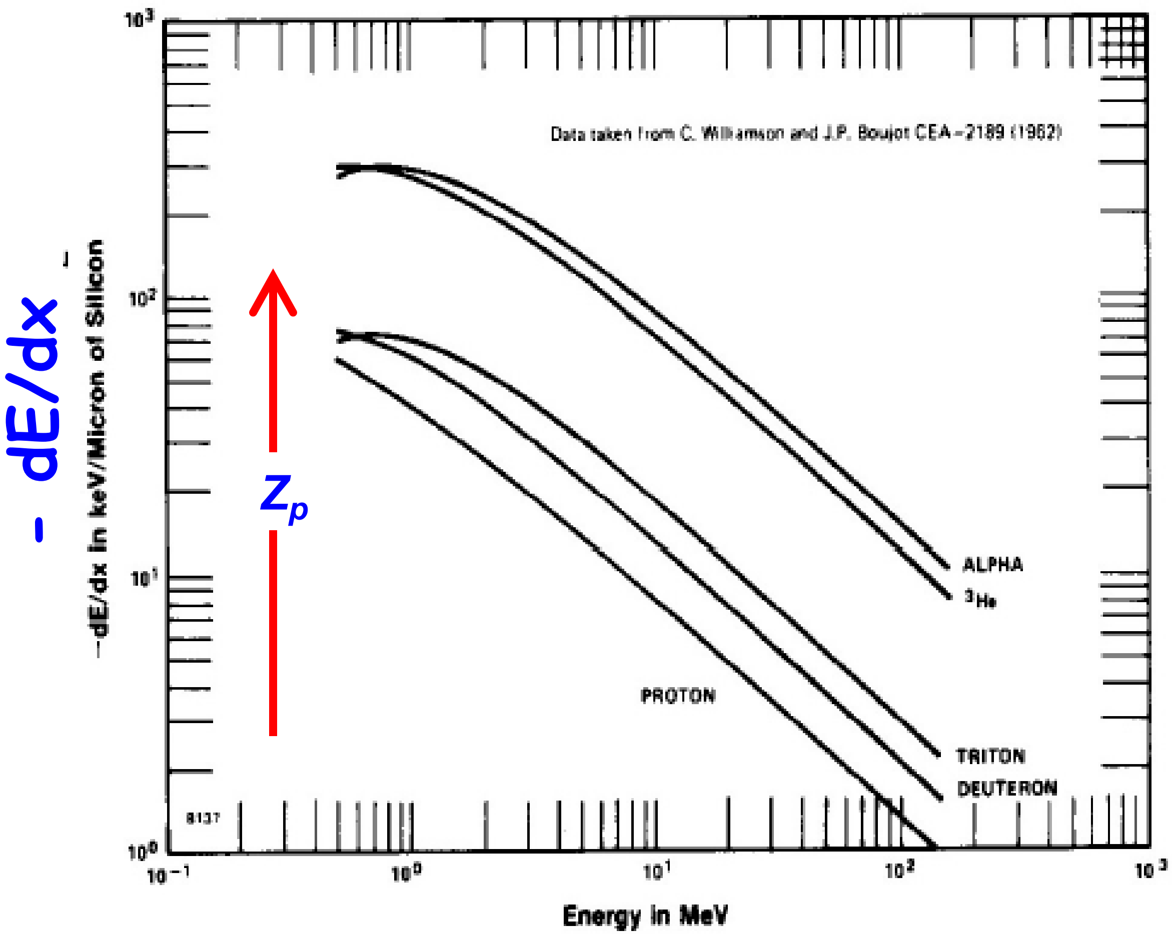
$Z_{eff} \neq Z_p$ effective charge

the particle charge changes at the end of the path due to electrons pick up

Examples for Nuclear Physics

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)

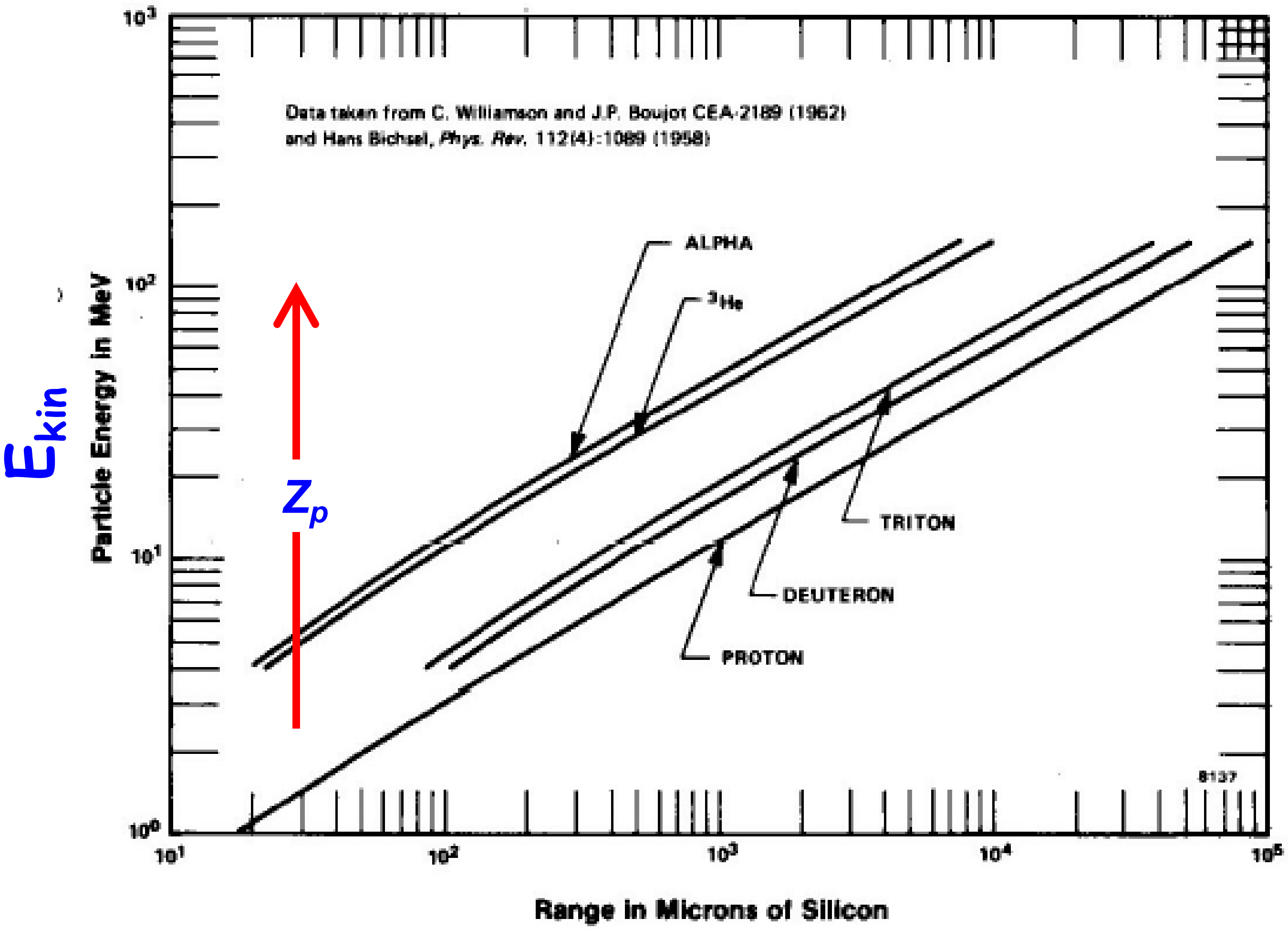
Range in Silicon

Important for applications in radiation detection

Mass density ρ = 2.35g/cm^3

1μm $\triangleq$ 0.235mg/cm^2 Si

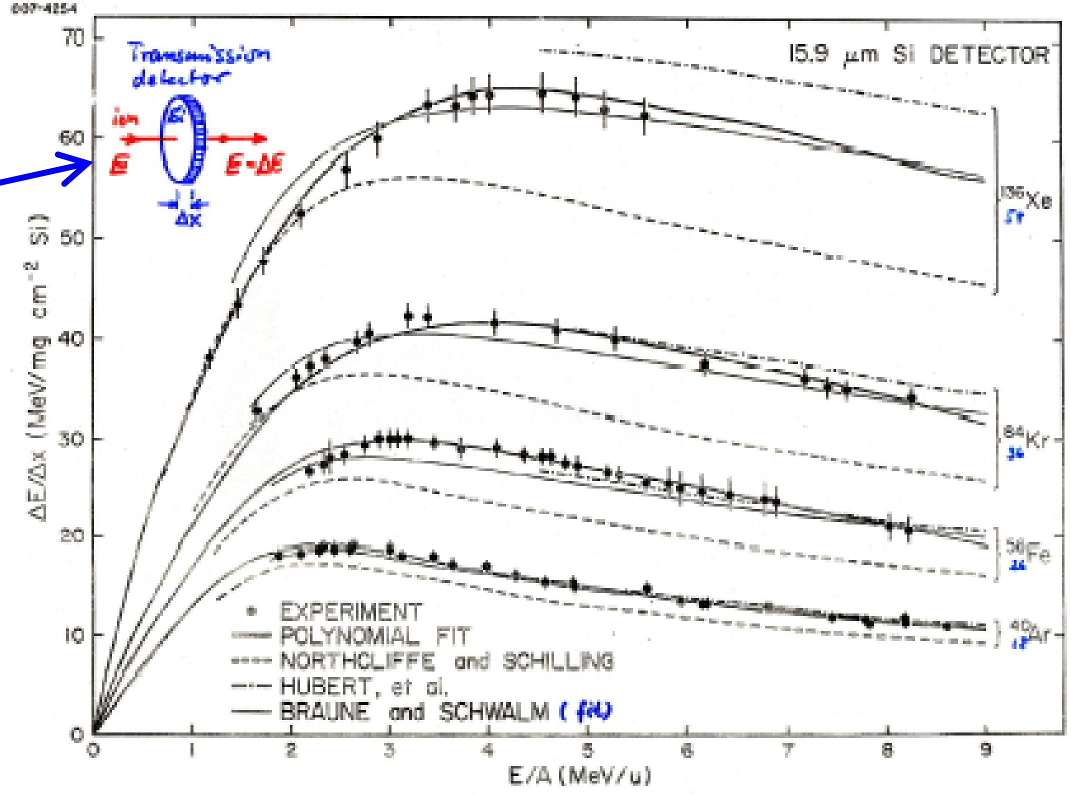
ΔE/ip = 3.62 eV/ip



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

[ex. Active area of detector…]

Theory and Practice for Very Heavy Ions



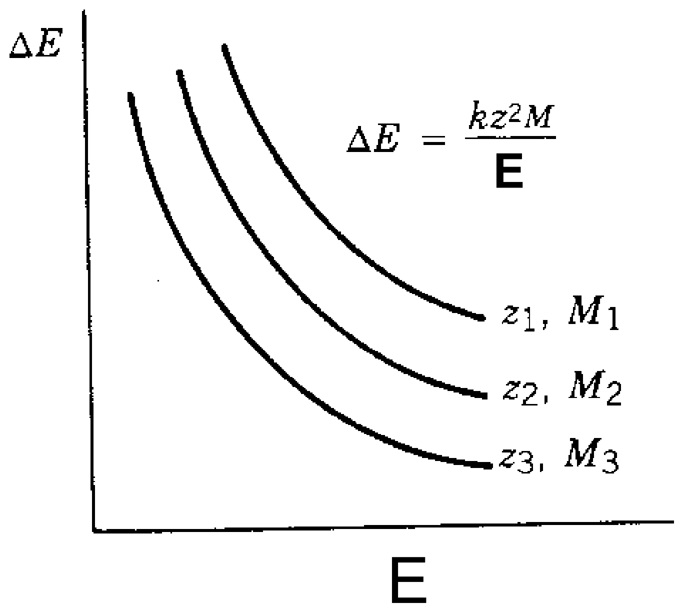
Energy lost by various ions in a 15.9 μm Si transmission detector vs. ion energy per nucleon (mass number A). Curves represent different theories.

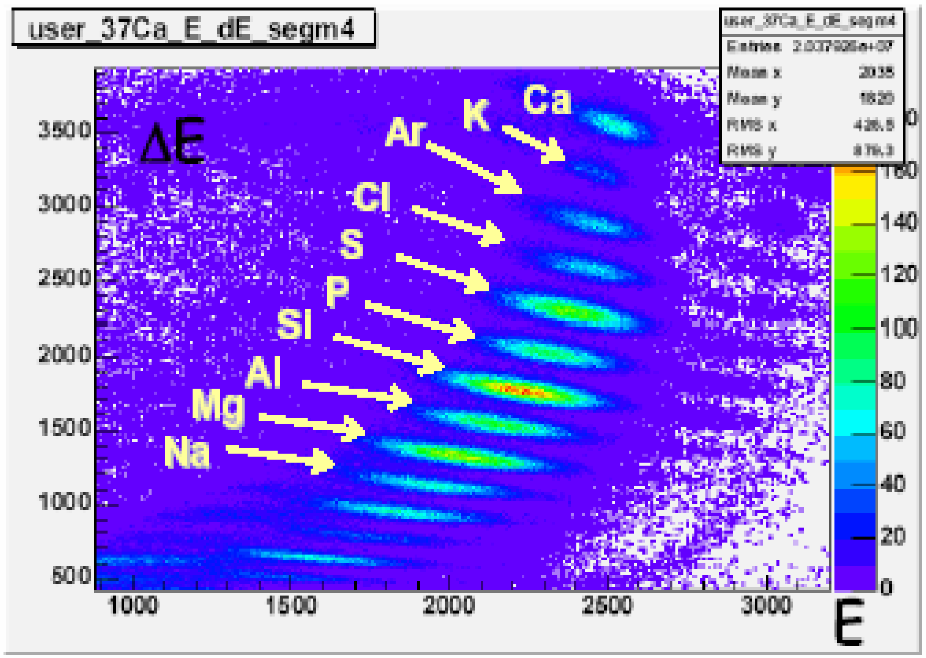
Theoretical energy loss in material of finite thickness is obtained from integration of the Bethe-Bloch formula or equivalent.

Actual data may differ: Calibration required

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

Application: Particle identification





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

Bethe-Bloch Quantum Mechanical Equation

for FAST electrons

FAST electrons can loose energy by
- Ionization/collisions
- Radiation (bremsstrahung)

*Trajectories are **complex**:*
mass is small and equal to orbital electrons

$$S = -\frac{dE}{dx} = -\left(\frac{dE}{dx}\right)_{coll} - \left(\frac{dE}{dx}\right)_{rad} \qquad Ratio = \frac{\left(\frac{dE}{dx}\right)_{rad}}{\left(\frac{dE}{dx}\right)_{Coll}} = \frac{EZ}{700}$$

with E in MeV

$$-\left(\frac{dE}{dx}\right)_{coll} \approx \frac{2\pi e^4}{m_e v_e^2}\rho Z_T \left[\ln\left(\frac{2m_e v^2 E}{2(IE)^2\left(1-\beta^2\right)}\right) - (\ln 2)\left(2\sqrt{1-\beta^2}-1+\beta^2\right) + \left(1-\beta^2\right) + \frac{1}{8}\left(1-\sqrt{1-\beta^2}\right)^2\right]$$

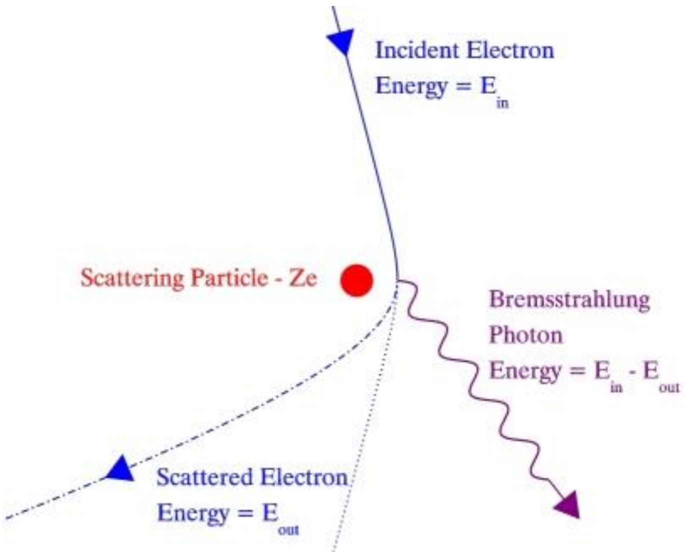
Similar to heavy-ions

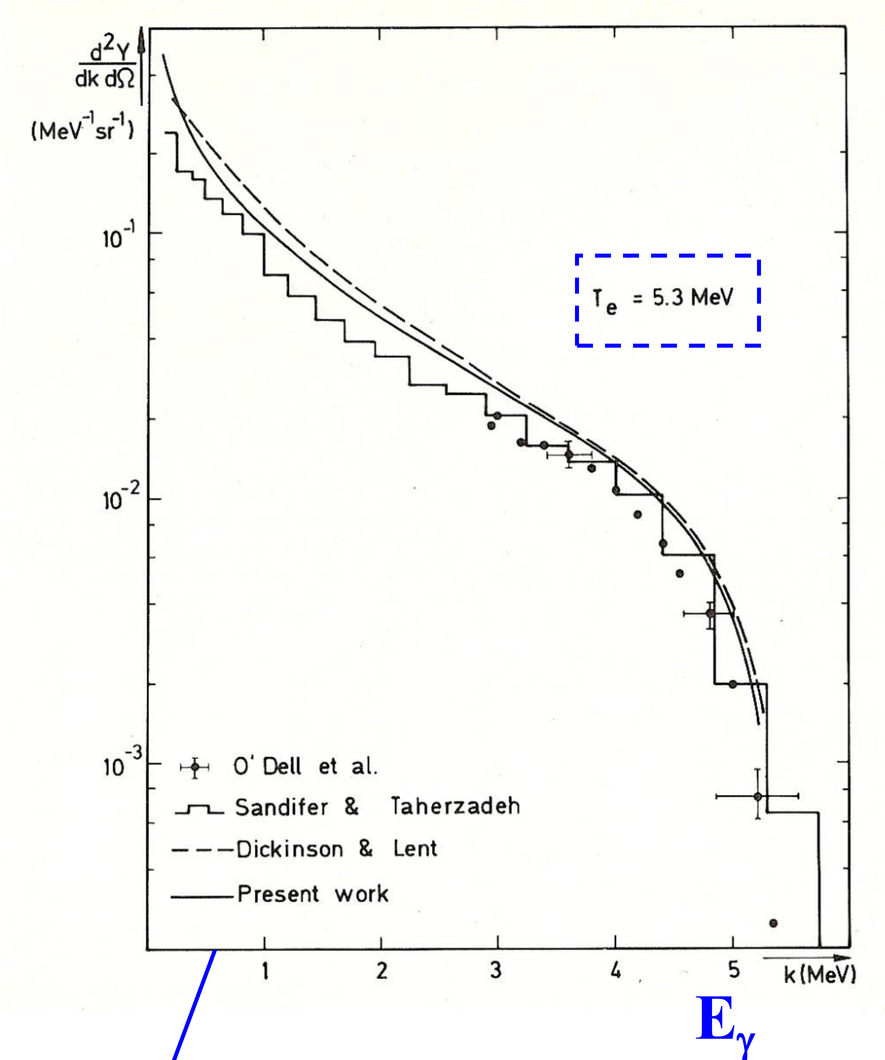
relativistic terms

$$-\left(\frac{dE}{dx}\right)_{r} \approx \frac{\rho E Z(Z+1)e^4}{137 m_e^2 c^4}\left(4\ln\frac{2E}{m_e c^2} - \frac{4}{3}\right)$$

$$\approx E\rho Z^2 \rightarrow$$ *large for energetic electrons in <u>heavy materials</u>*

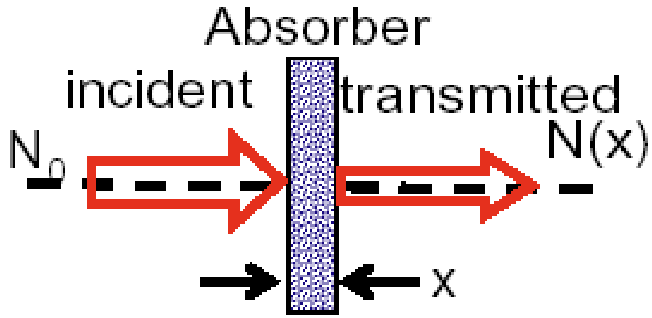
In nuclear physics





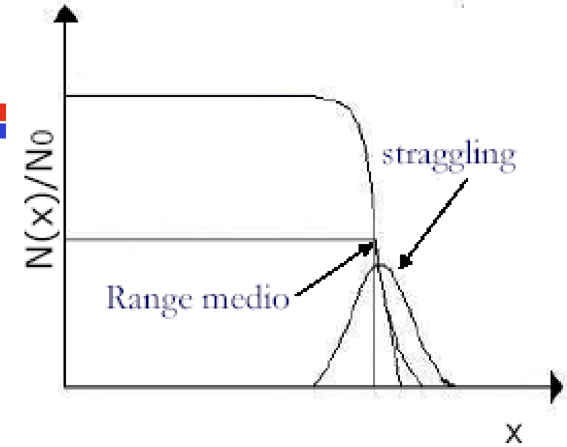
For typical electron energy, ***<u>bremsstrahlung photon energy</u>*** *is quite* ***<u>small</u>***
$\Rightarrow$ it is reabsorbed close to its point of origin

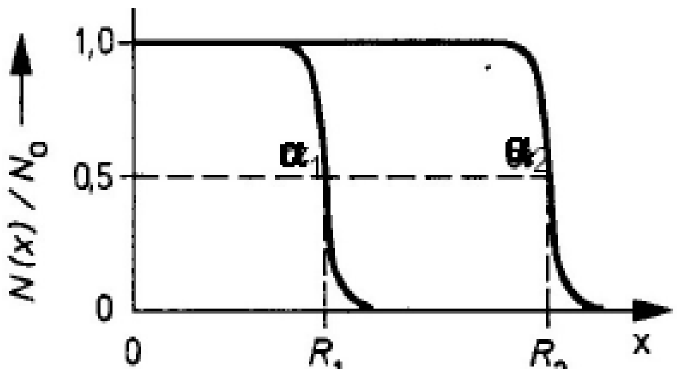
Transmission Functions



Transmission

$T(x) = N(x)/N_0$

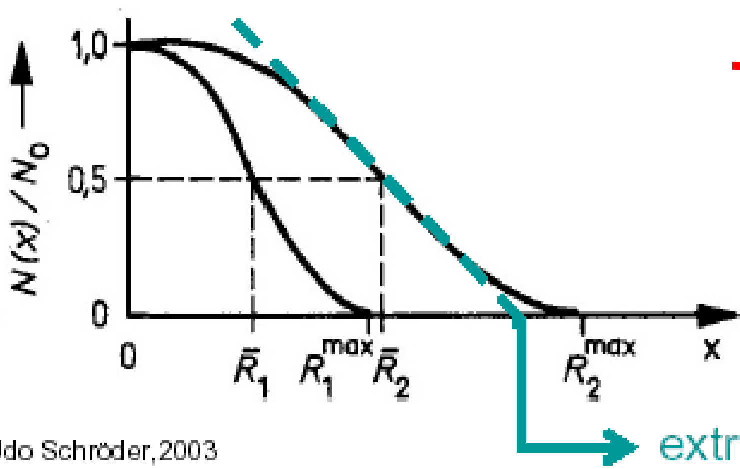




→ Heavy particles (α, p,..HI) have a well defined range, R(E).

→ *it corresponds to thickness x where $N(x) = N_0/2$*

Multiple scattering at small angles only, because of $M \gg m_e$



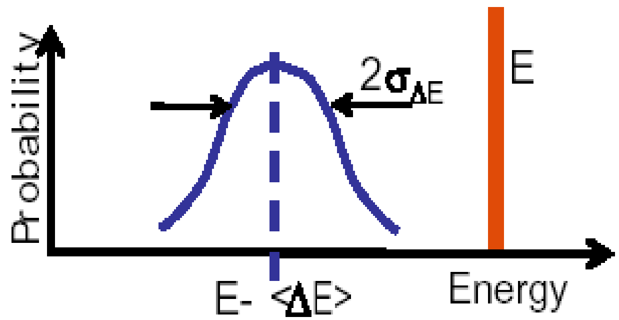
→ Light particles (electrons) and photons are scattered off original path by large angles

Range is not well defined

Energy Loss Distributions *After absorber*

Absorber of thickness x; (ρ, Z_T, A_T), many statistical scattering events

→ Central Limit Theorem: Gaussian distribution in energy loss ΔE



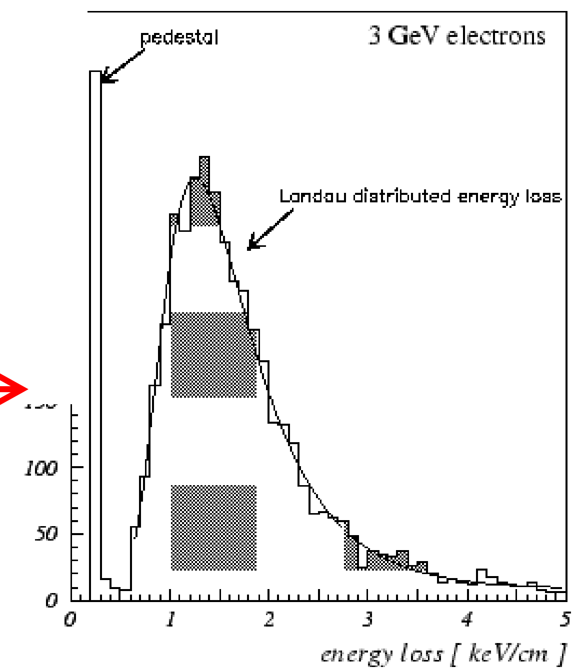
$$\Gamma_{FWHM} = 2.35 \cdot \sigma$$

The distribution is Gaussian only if Δx is large enough

$$P(\Delta E) \propto \exp\left\{ -\frac{\left(\Delta E - \langle \Delta E \rangle\right)^2}{2\sigma_{\Delta E}} \right\}$$

$$\sigma_{\Delta E} = 4\pi N_A r_e^2 m_e^2 c^4 \rho \frac{Z_T}{A_T} x = 0.1569\, \rho \frac{Z_T}{A_T} x \; MeV^2$$

Thin absorber: Asymmetric tail towards higher ΔE



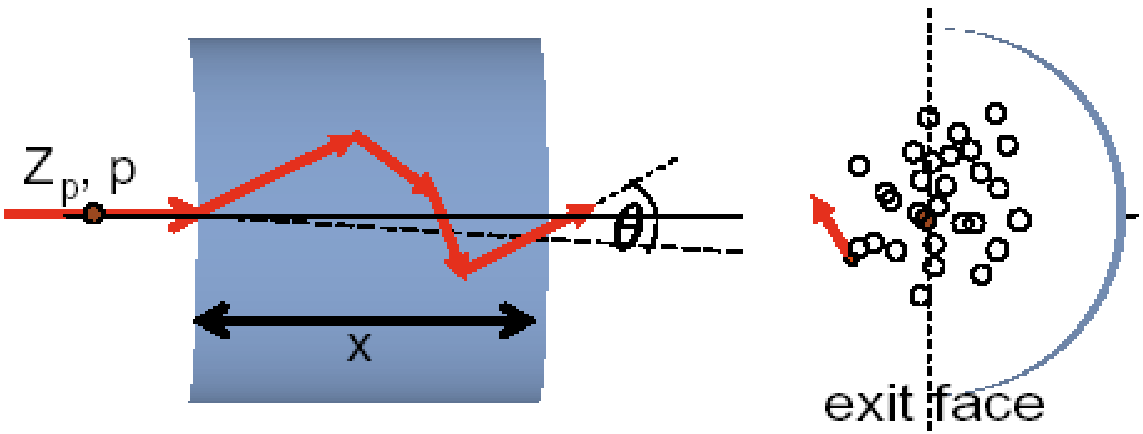
*Landau has shown that the **asymmetric tail** is due to **great energy losses** in **close collisions***

Important in Nuclear Rections with Thick Targets

Angular Straggling *After absorber*

Theory by Moliere, see W.T. Scott, Rev. Mod. Phys. 35, 231 (1963)

HI : M. Wong et al., Med. Phys. 17, 163 (1990)



Non-trivial geometry !

$$\frac{d\sigma_{MS}(\theta)}{d\Omega} = \frac{1}{2\pi\theta_0^2} exp\left\{-\frac{\theta^2}{2\theta_0^2}\right\}$$ *cross section*

Assume multiple Coulomb scattering

$$\theta_0 \approx \frac{13.6 MeV}{\beta pc} Z_p \sqrt{\frac{x}{L}}\left[1 + 0.038\, ln\left(\frac{x}{L}\right)\right]$$

Gaussian angular distribution

$$L \approx \frac{716.4\, A_T}{Z_T\,(Z_T+1)\, ln\left(287/\sqrt{Z_T}\right)} \frac{g}{cm^2}$$ *radiation length*

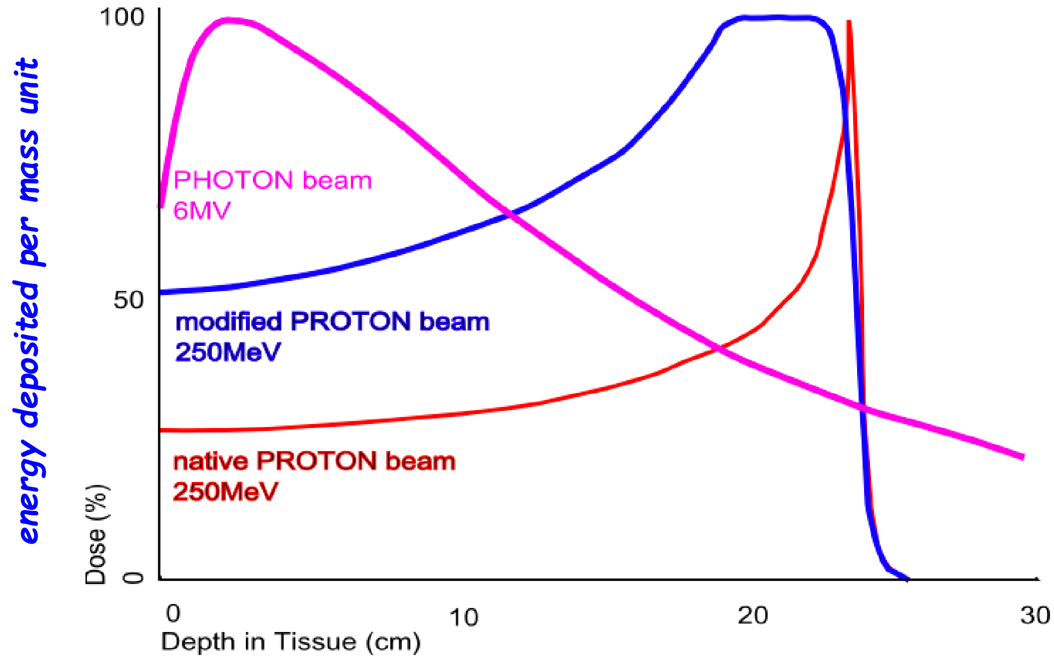
- *mean distance over which a high-energy e^- reduces to 1/e of its energy by bremsstrahlung*
- *7/9 of the mean free path for pair production by a high-energy photon*
- *appropriate scale length for high-energy electromagnetic cascades*

Important in Nuclear Rections with Thick Targets

Importance in application of Monte Carlo Simulation programs !!!

(… See Lectures on hadron therapy)

The Bragg Peak



Absorbed Dose

D = dE/dm

dE = enery deposit
dE = mass

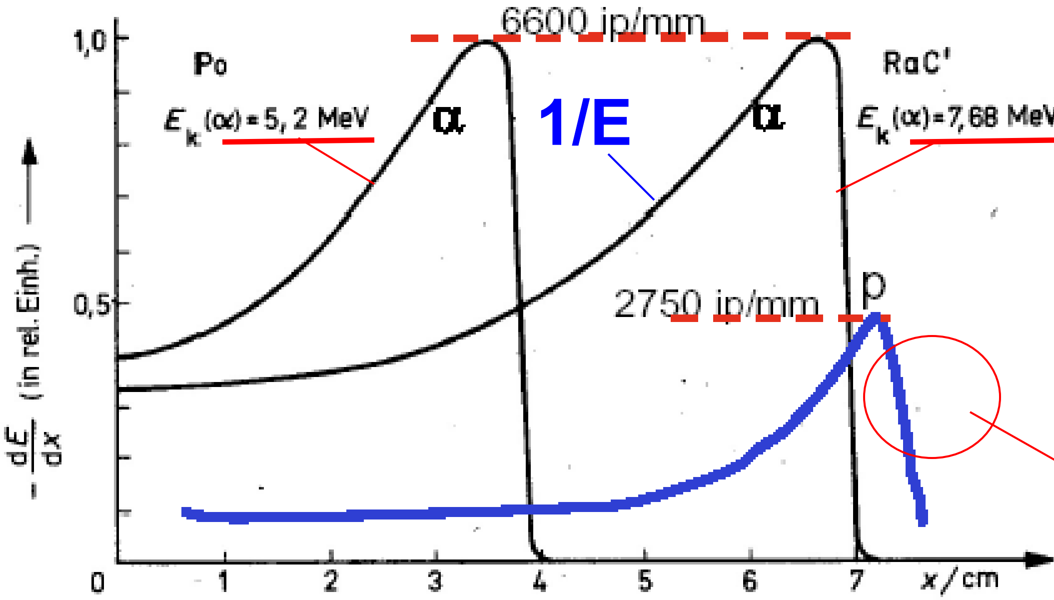
Absorbed dose (also known as **total ionizing dose**, TID) :
<u>*energy deposited in a medium by a ionizing radiation per unit mass*</u>

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

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

Range and Specific Ionization

E-loss in Air: 1atm, 15°C



Stopping power dE/dx (specific energy loss) depends on energy E and therefore on x

Bragg Curve

Highest E loss close to end of path → Bragg maximum

Charge is reduced due to electrons pick up

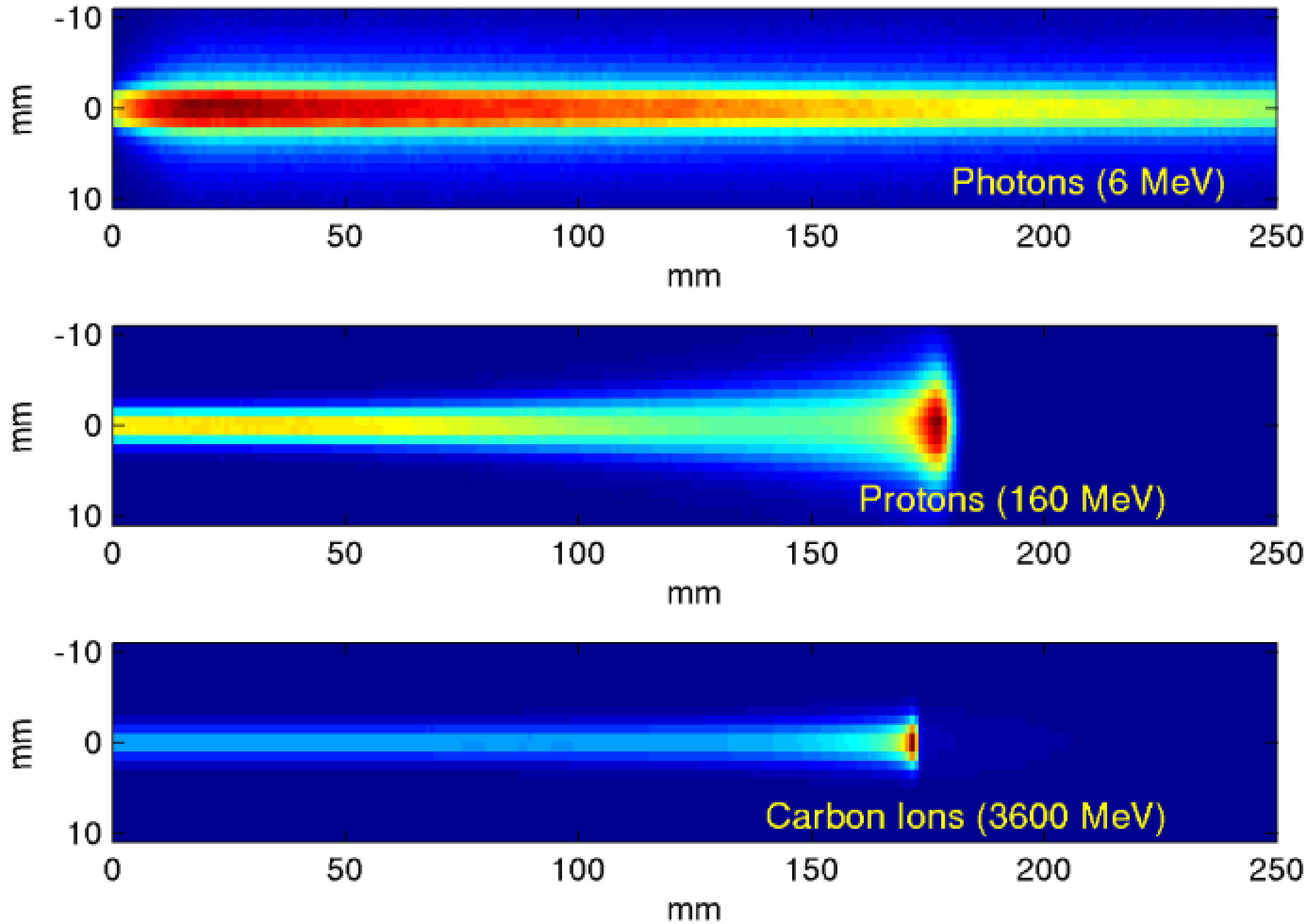
$$\frac{dE}{dx} \triangleq \frac{\#\left(e^- - ion\ pairs\right)}{unit\ \ length}$$

α *particles :*

$$\frac{dE}{dx} \leq \frac{7 \cdot 10^3\ pairs}{mm}$$

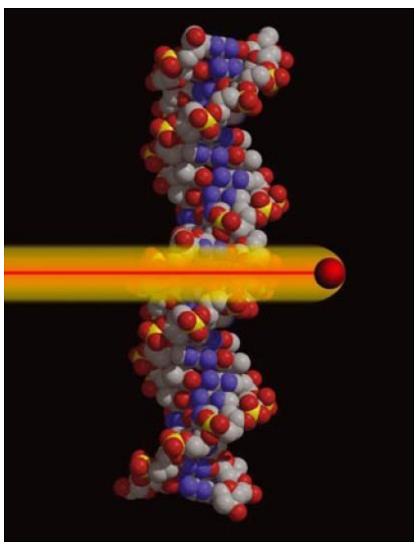
Main E-loss mechanism: ionization, production of ***δ* electrons**, electron-ion pairs

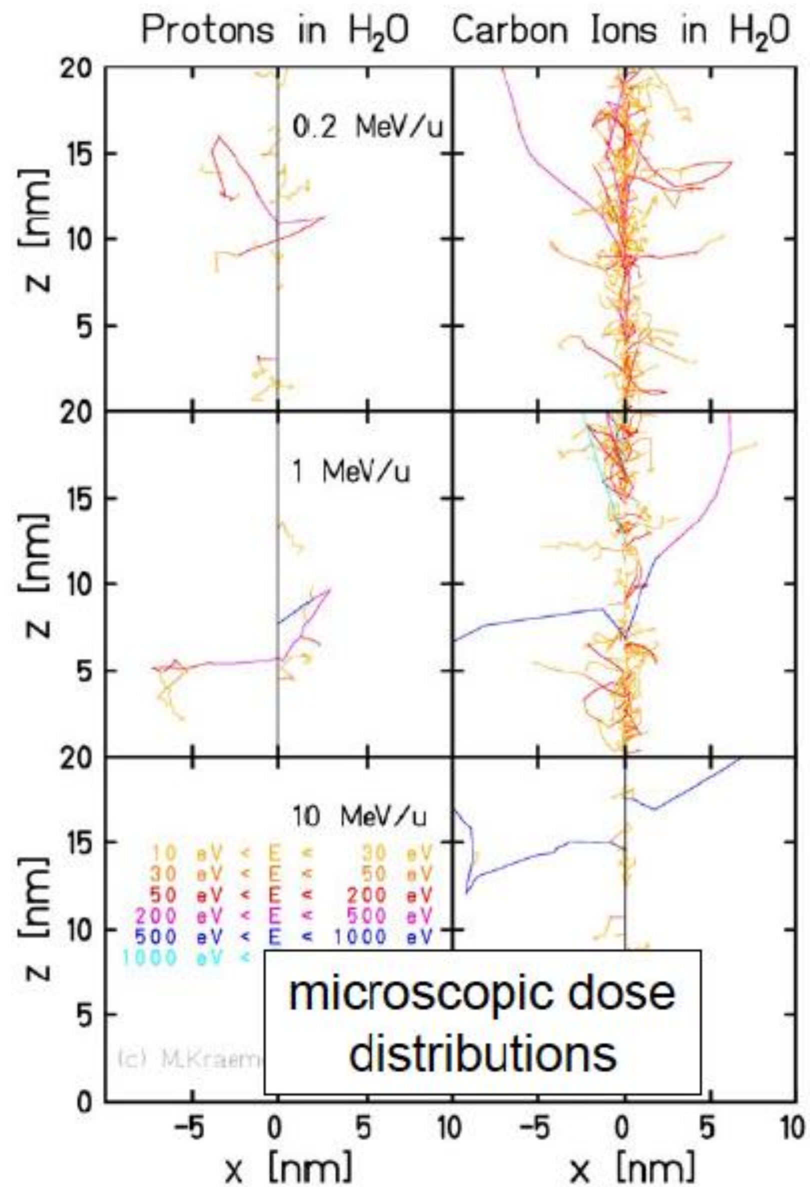
Radiation Effects



Physics and Biology of Radiation Therapy

Basic effect of radiation on cells:
Energy loss in matter leads to defects in the DNA – double strand breaks of the DNA kills the cell.
Tumor cells have less repair capabilities than normal cells.

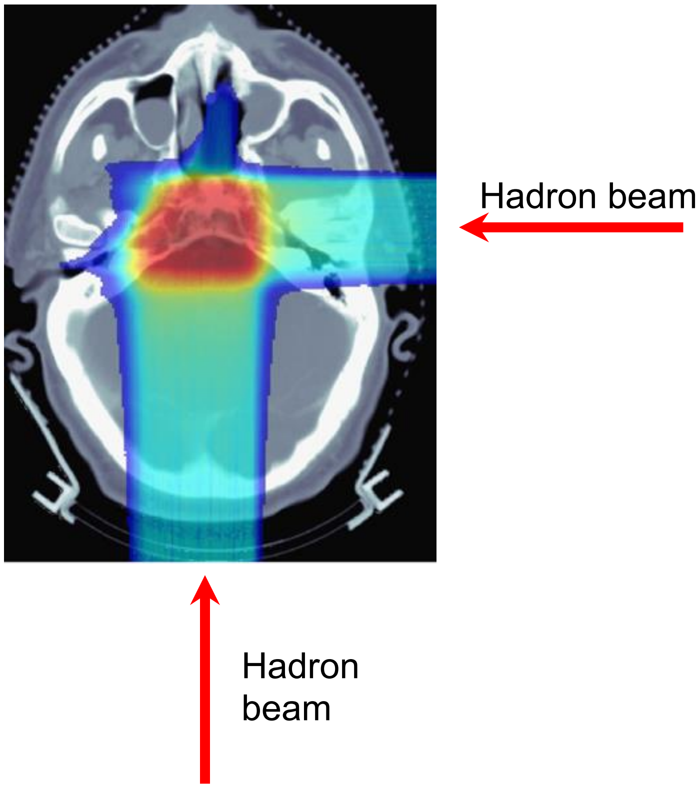




Accurate Simulation Calculations of Radiation interaction and Dose Distribution are needed

(also verified experimentally)

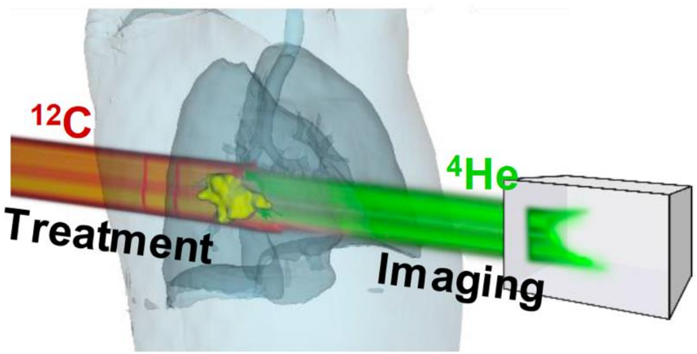
Calculated dose distribution (Monte Carlo Simulation)



Treatment on moving organs coming soon ..
(lung cancer, …)

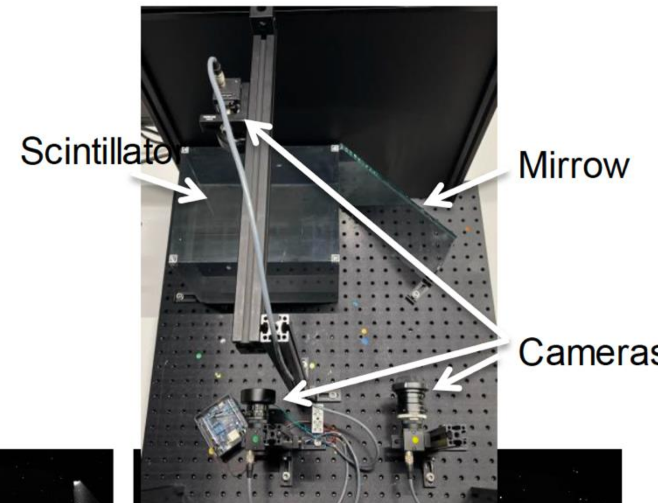
Some highlights
… Imaging with mixed C- and He beams

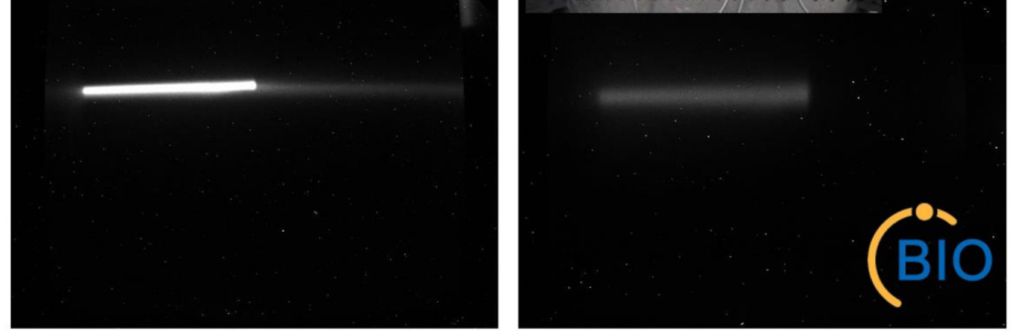
C- and He ions simultaneously accelerated



May 2025 – First images with a scintillator-camera system (UCL)

Carbon beam stopped with rangeshifter

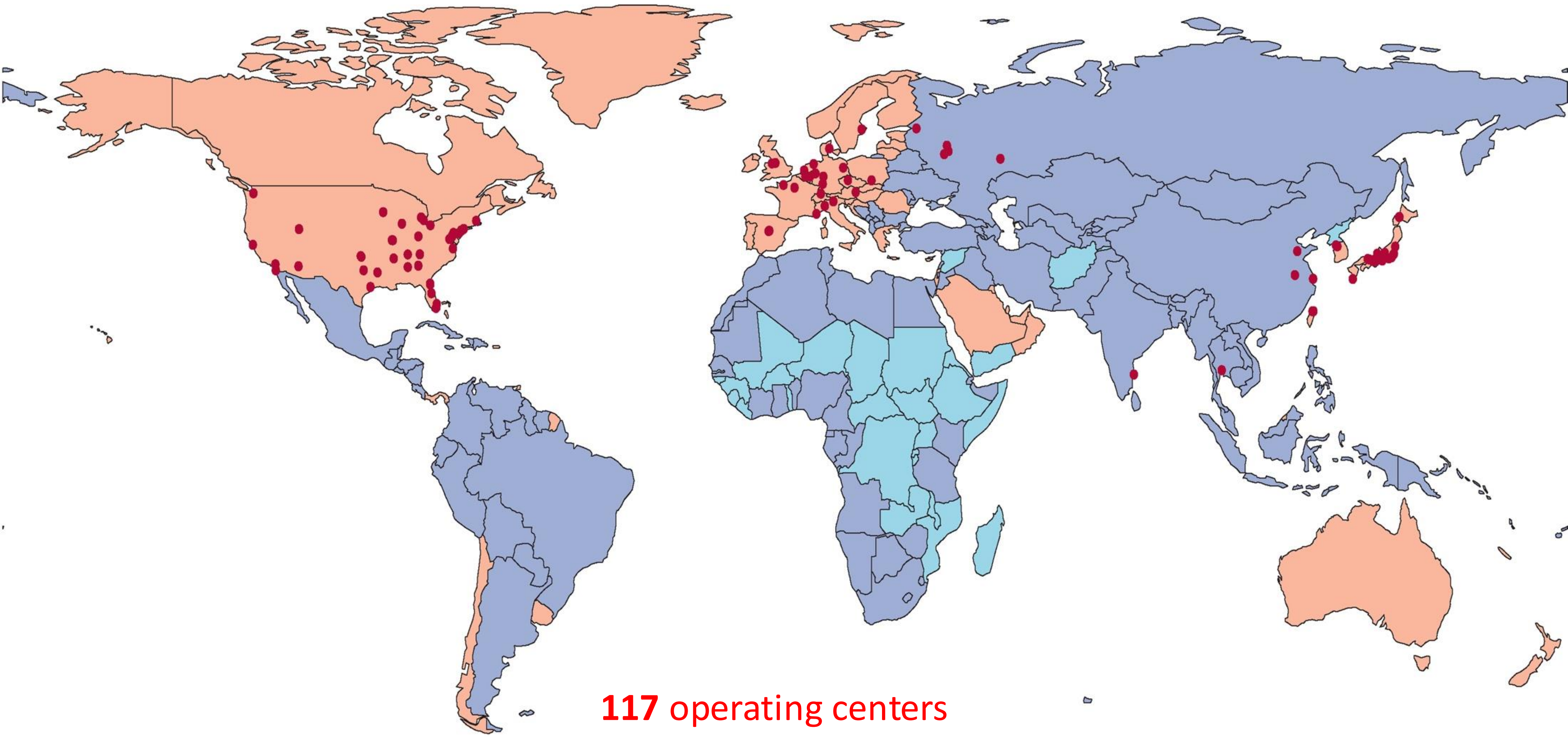




European Research Council

Experiment will continue at GSI till 2029 and then could be implemented at CNAO or MedAustron(ERC Christian Graeff)

Centers for hadron therapy worldwide



117 operating centers
(12 using carbon beams)

38 under construction
(6 using carbon beams)

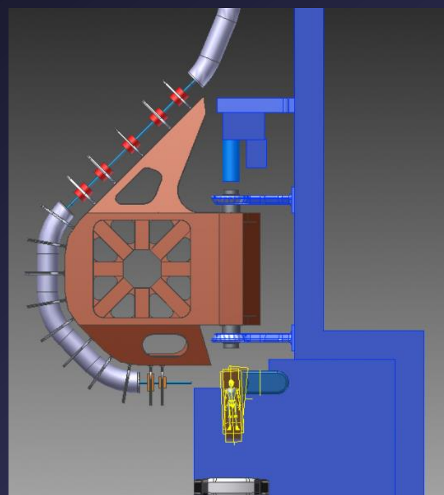
CNAO
Centro Nazionale di Adroterapia Oncologica

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

Pavia, Italy - possibility for visits of Schools

CNAO
Centro Nazionale di Adroterapia Oncologica

PATOLOGIE TRATTABILI | ACCESSO ALLA TERAPIA

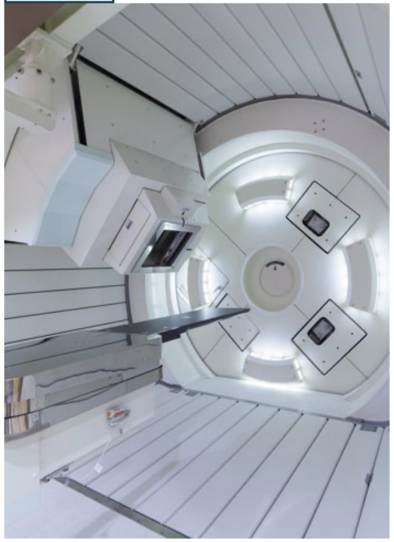
ADROTERAPIA | PERCORSO TERAPEUTICO | AREA PAZIENTI | RICERCA | AREA MEDICI | DONA

UN IMPIANTO CON TESTATA ROTANTE POTRÀ COLPIRE IL TUMORE DA PIÙ DIREZIONI

CNAO CRESCE: UNA NUOVA AREA PER LA PROTONTERAPIA

Homepage › Notizie ed eventi › CNAO cresce: una nuova area per la protonterapia

10
MAR/20



Un accordo con la multinazionale giapponese Hitachi firmato a dicembre 2019 segna una tappa importante nella storia della Fondazione CNAO: entro la fine del 2020 inizieranno, infatti, i lavori di installazione di un **moderno impianto per protoni con tecnologia di ultima generazione** che sarà ospitato in un nuovo edificio contiguo e integrato con quello già esistente. La consegna dell'impianto è prevista all'inizio del 2023.

La nuova area, che sarà adiacente e collegata all'attuale sede del CNAO, si svilupperà su due piani per un totale di circa 6000 metri quadri, comprenderà **un acceleratore di protoni**, una nuova sala trattamento con testata rotante (gantry) per colpire il tumore da molteplici direzioni e spazi legati all'accoglienza dei pazienti e alla loro preparazione alle terapie.
La nuova macchina renderà possibile l'utilizzo, durante il trattamento, della tecnica **"Intensity Modulated Proton Therapy", IMPT**, che consentirà di ridurre ulteriormente l'esposizione alle radiazioni dei tessuti sani, con la conseguente diminuzione degli effetti collaterali. Inoltre, le immagini radiologiche di altissima qualità permetteranno il controllo costante della posizione del 'bersaglio tumorale' durante l'erogazione di ciascun trattamento.

Grazie a questo progetto di espansione, **CNAO diventerà l'unico centro di adroterapia al mondo** a disporre sia di un sincrotrone per ioni multipli (protoni e ioni carbonio) che di un sincrotrone con gantry dedicato ai protoni.

Scopri come funziona il sincrotrone https://fondazionecnao.it/adroterapia/sincrotrone

Innaugurato da Presidente Mattarella 3 Ottobre 2025

https://fondazionecnao.it/news/cnao-cresce-una-nuova-area-per-la-protonterapia

Heidelberg Ion-Beam Therapy Center (HIT)