Interaction of Charged Particles with Matter

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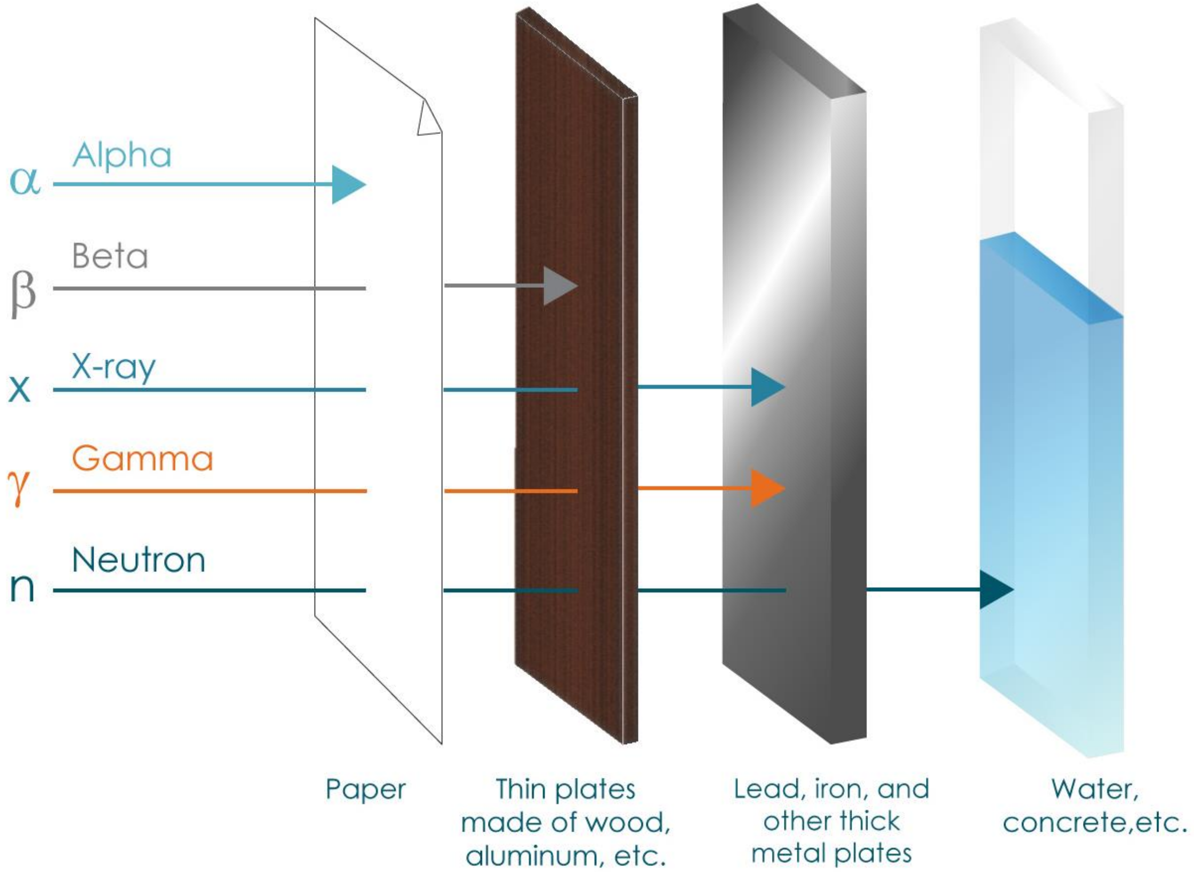
Introduction

- Particulate or wave
- Charged or neutral

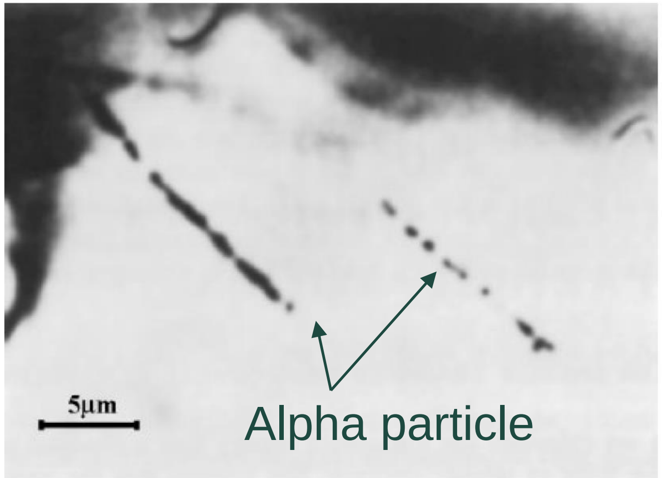
❖ Energy loss in air
  - ~0.25 keV/mm for β
  - ~100 keV/mm for α

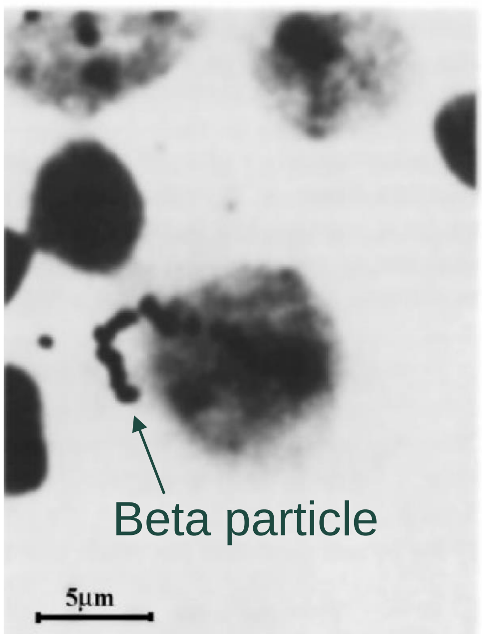


Introduction

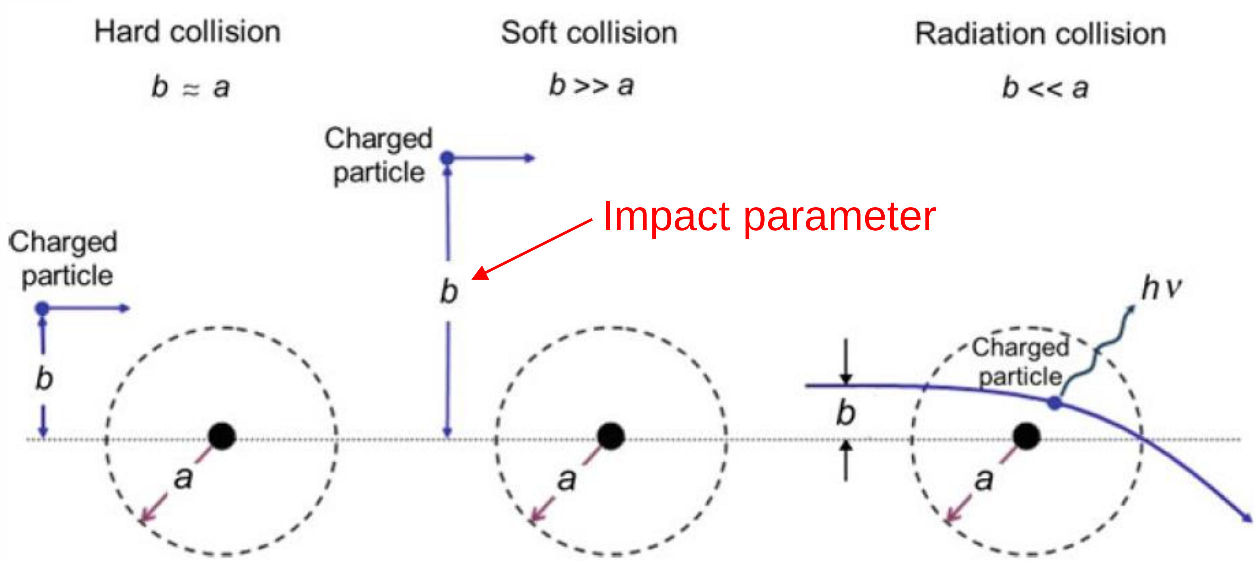
- Radiation emitted by radioactive nuclides, both inside and outside our bodies, interacts with our tissues.
- Photons (EM waves) are far more abundant than matter in our universe; for every nucleon there are about 10^9 photons.
- Cosmic rays and the subatomic debris they create during interactions in the atmosphere also impinge on us (e.g. ~10^9 neutrinos/$cm^2 \cdot s$).
- For radiation to produce biological damage, it must first interact with the tissue and ionize cellular atoms, which, in turn, alter molecular bonds and change the chemistry of the cells. Likewise, for radiation to produce damage in structural and electrical materials, it must cause interactions that disrupt crystalline and molecular bonds.
- Such radiation must be capable of creating electron-ion pairs and is termed ionizing radiation (directly ionizing or indirectly ionizing).
- We will study how the ionizing radiations interact with matter. Particular emphasis is given to how the radiations are attenuated as they pass through a medium, and to quantify the rate at which they interact and transfer energy to the medium.

General aspects of charged particles interaction with matter





- A charged particle is surrounded by its Coulomb electric field that interacts with orbital electrons and the nucleus of all atoms it encounters, as it penetrates into matter.
- Charged particle interactions with orbital electrons of the absorber result in collision loss (collisional stopping power), interactions with nuclei of the absorber result in radiation loss (radiation stopping power).



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General aspects of stopping power

- Linear stopping power ($-dE/dx$): the rate of energy loss per unit of path length (typically expressed in MeV cm^{-1}) by a charged particle in an absorbing medium. It is also referred to as the linear energy transfer (LET) of the particle (usually expressed as keV µm^{-1} in water).
- Mass stopping power ($-dE/\rho dx$): linear stopping power divided by the mass density of the absorber (typically expressed in MeV·cm^2/g).

$$S_{\mathrm{tot}} = S_{\mathrm{rad}} + S_{\mathrm{col}}.$$

- Radiation stopping power (also called nuclear stopping power): Only light charged particles (electrons and positrons) experience appreciable energy loss through these interactions that are usually referred to as bremsstrahlung interactions. For heavy charged particles (protons, α-particles, etc.) the radiation (bremsstrahlung) loss is negligible in comparison with the collision loss.
- Collision stopping power (also called ionization or electronic stopping power): Both heavy and light charged particles experience these interactions that result in energy transfer from the charged particle to orbital electrons through impact excitation and ionization of absorber atoms.

Energy-loss mechanism of heavy charged particles

- A heavy charged particle traversing matter loses energy primarily through the ionization and excitation of atoms. (Except at low velocities, a heavy charged particle loses a negligible amount of energy in nuclear collisions.)
- The moving charged particle exerts electromagnetic forces on atomic electrons and imparts energy to them.
- The energy transferred may be sufficient to knock an electron out of an atom and thus ionize it, or it may leave the atom in an excited, non-ionized state.
- A heavy charged particle can transfer only a small fraction of its energy in a single electronic collision. Its deflection in the collision is negligible. Thus, a heavy charged particle travels an almost straight path through matter, losing energy almost continuously in small amounts through collisions with atomic electrons, leaving ionized and excited atoms in its wake.
- Occasionally, however, as observed in Rutherford's experiments with alpha-particle scattering from a gold foil, a heavy charged particle will undergo a substantial deflection due to elastic scattering from an atomic nucleus.

Maximum energy transfer in a single collision

- Energy and momentum conservation

$$\tfrac{1}{2}MV^2 = \tfrac{1}{2}MV_1^2 + \tfrac{1}{2}mv_1^2 \qquad MV = MV_1 + mv_1.$$

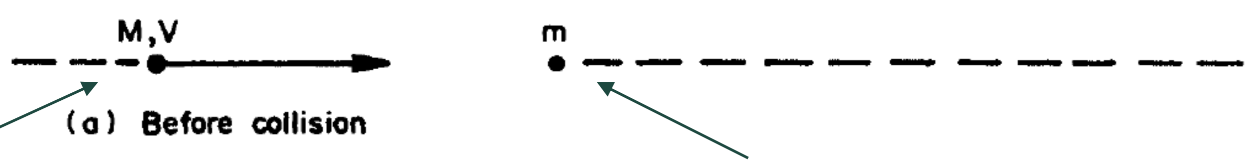
- The maximum energy transfer

$$Q_{\max} = \frac{1}{2}MV^2 - \frac{1}{2}MV_1^2 = \frac{4mME}{(M+m)^2}$$

- The exact relativistic expression

$$Q_{\max} = \frac{2\gamma^2 mV^2}{1 + 2\gamma m/M + m^2/M^2}$$

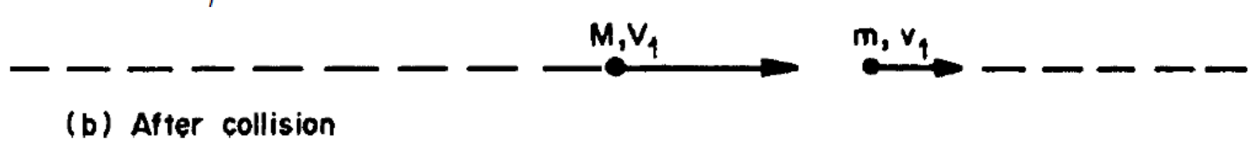
$$\xrightarrow{\gamma m/M \ll 1} \quad Q_{\max} = 2\gamma^2 mV^2 = 2\gamma^2 mc^2\beta^2$$



Heavy charged particle with speed V

$E = MV^2/2$

Free electron initially at rest



Maximum energy transfer in a single collision

Example

Calculate the maximum energy that a 10-MeV proton can lose in a single electronic collision.

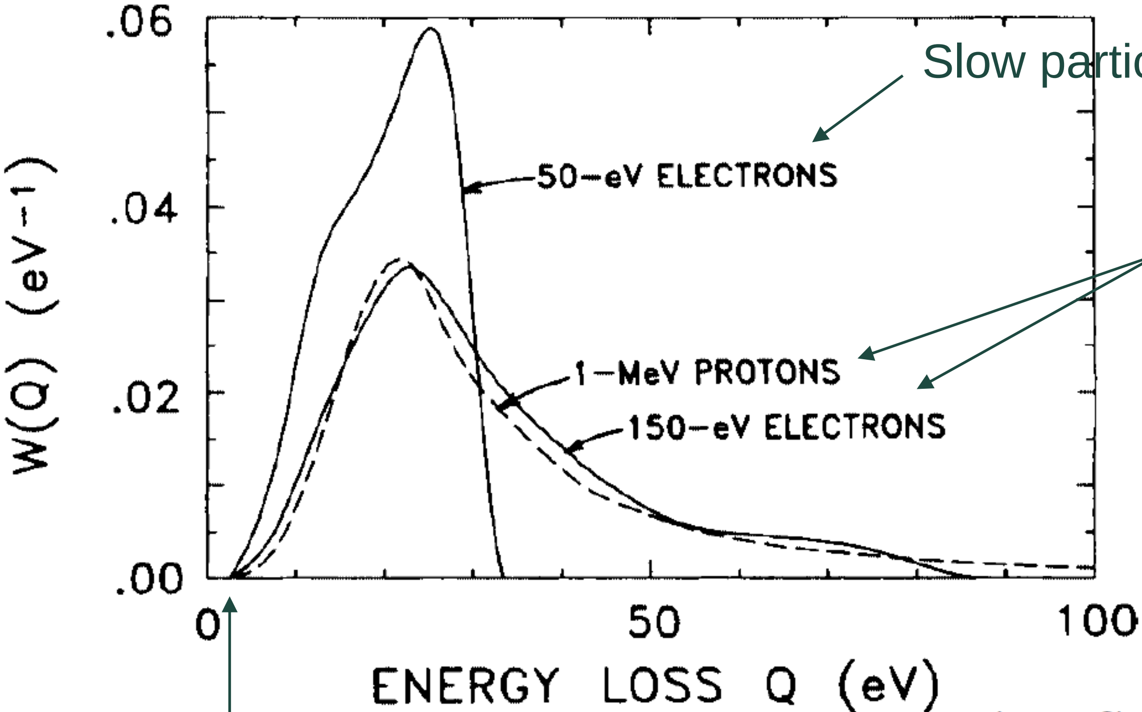
Solution

For a proton of this energy the nonrelativistic formula (5.4) is accurate. Neglecting m compared with M, we have $Q_{max} = 4mE/M = 4 \times 1 \times 10/1836 = 2.18 \times 10^{-2}$ MeV = 21.8 keV, which is only 0.22% of the proton's energy.

Proton Kinetic Energy E (MeV)	Q_{max} (MeV)	Maximum Percentage Energy Transfer $100Q_{max}/E$
0.1	0.00022	0.22
1	0.0022	0.22
10	0.0219	0.22
100	0.229	0.23
10^3	3.33	0.33
10^4	136.	1.4
10^5	1.06×10^4	10.6
10^6	5.38×10^5	53.8
10^7	9.21×10^6	92.1

Single-collision energy loss spectra

- The ordinate gives the probability density W(Q) per eV, such that W(Q)dQ is the probability that a given collision will result in an energy loss between Q and Q + dQ, with Q expressed in eV.



Slow particle: long interaction time

Fast particles: energy-loss spectrum is similar in the energy range of 10 ~ 70 eV

Minimum threshold energy

Fig. 5.3 Single-collision energy-loss spectra for 50-eV and 150-eV electrons and 1-MeV protons in liquid water. (Courtesy Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc., for the Department of Energy.)

Stopping power

- For a given type of charged particle at a given energy, the stopping power is given by the product of (1) the linear attenuation coefficient (μ, the probability of electronic collision per unit distance of travel) and (2) the average energy loss per collision (Q_{avg}).

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \mu Q_{\text{avg}} = \mu \int_{Q_{\min}}^{Q_{\max}} QW(Q)\,\mathrm{d}Q.$$

Example

The macroscopic cross section for a 1-MeV proton in water is 410 μm^{-1}, and the average energy lost in an electronic collision is 72 eV. What is the stopping power in MeV cm^{-1} and in J m^{-1}?

Solution

With $\mu = 410\ \mu\text{m}^{-1}$ and $Q_{\text{avg}} = 72$ eV, Eq. (5.10) gives

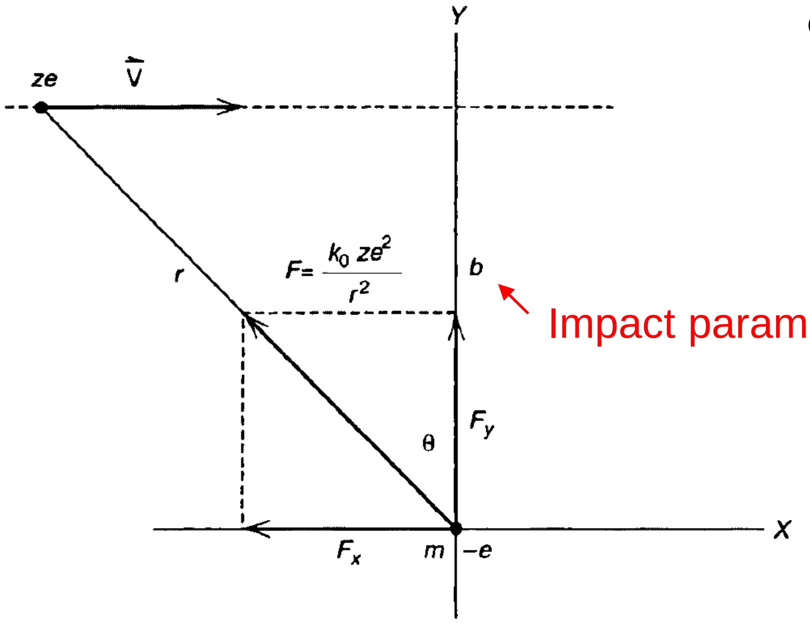
$$\lambda = \frac{1}{\mu} = 2.4\ \text{nm}$$

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \mu Q_{\text{avg}} = 410 \times 72 = 2.95 \times 10^4\ \text{eV}\ \mu\text{m}^{-1}.$$

Since 1 eV = 10^{-6} MeV and 1 μm = 10^{-4} cm, we obtain $-\mathrm{d}E/\mathrm{d}x = 295\ \text{MeV cm}^{-1}$. Converting units further, we have $-\mathrm{d}E/\mathrm{d}x = 295\ \text{MeV cm}^{-1} \times 1.60 \times 10^{-13}\ \text{J MeV}^{-1} \times 100\ \text{cm m}^{-1} = 4.72 \times 10^{-9}\ \text{J m}^{-1}$.

Semiclassical calculation of stopping power

- In 1913, Bohr derived an explicit formula giving the stopping power for heavy charged particles. He calculated the energy loss of a heavy particle in a collision with an electron at a given distance of passing and then averaged over all possible distances and energy losses.



- The total momentum imparted to the electron in the collision is

$$p = \int_{-\infty}^{\infty} F_y \, \mathrm{d}t = \int_{-\infty}^{\infty} F \cos\theta \, \mathrm{d}t = k_0 z e^2 \int_{-\infty}^{\infty} \frac{\cos\theta}{r^2} \, \mathrm{d}t.$$

$$\int_{-\infty}^{\infty} \frac{\cos\theta}{r^2} \, \mathrm{d}t = 2 \int_0^{\infty} \frac{b}{r^3} \, \mathrm{d}t = 2b \int_0^{\infty} \frac{\mathrm{d}t}{(b^2 + V^2 t^2)^{3/2}}$$

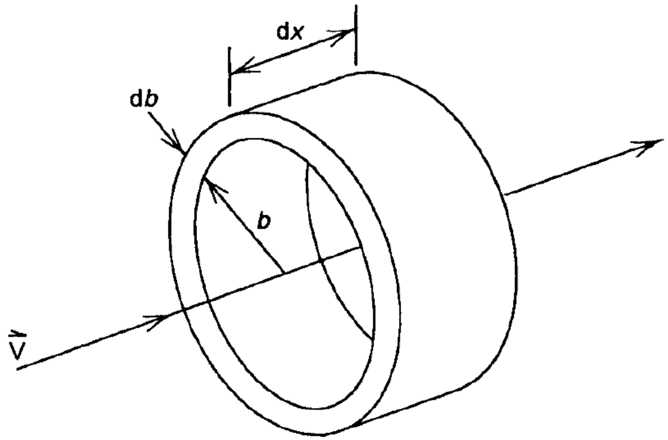
$$= 2b \left[\frac{t}{b^2 (b^2 + V^2 t^2)^{1/2}} \right]_0^{\infty} = \frac{2}{Vb}.$$

- The momentum transferred to the electron in the collision: $p = \dfrac{2 k_0 z e^2}{Vb}.$

Semiclassical calculation of stopping power

- The energy transferred to the electron in the collision:

$$Q = \frac{p^2}{2m} = \frac{2k_0^2 z^2 e^4}{mV^2 b^2}.$$



- In traversing a distance $\mathrm{d}x$ in a medium having a uniform density of n electrons per unit volume, the heavy particle encounters $2\pi nb\ \mathrm{d}b\ \mathrm{d}x$ electrons at impact parameters between b and $b + \mathrm{d}b$.
- The energy lost to these electrons per unit distance traveled is therefore $2\pi nQb\mathrm{d}b$.

- The total linear rate of energy loss is found by integration over all possible energy loses:

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = 2\pi n \int_{Q_{\min}}^{Q_{\max}} Qb\,\mathrm{d}b = \frac{4\pi k_0^2 z^2 e^4 n}{mV^2} \int_{b_{\min}}^{b_{\max}} \frac{\mathrm{d}b}{b} = \frac{4\pi k_0^2 z^2 e^4 n}{mV^2} \ln \underbrace{\frac{b_{\max}}{b_{\min}}}_{?}.$$

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Semiclassical calculation of stopping power

- Maximum possible energy transfer ($Q_{\max}$) ~ the energy transfer by head-on collision ($2mV^2$).
- Minimum possible energy transfer ($Q_{\min}$) ~ the mean excitation energy of the medium (I).
- For a given atom, its mean excitation energy is always larger than the ionization energy of the atom, since I accounts for all possible atomic ionizations as well as atomic excitations, while the atomic ionization energy pertains to the energy required to remove the least bound atomic electron (i.e., valence electron in the outer shell).

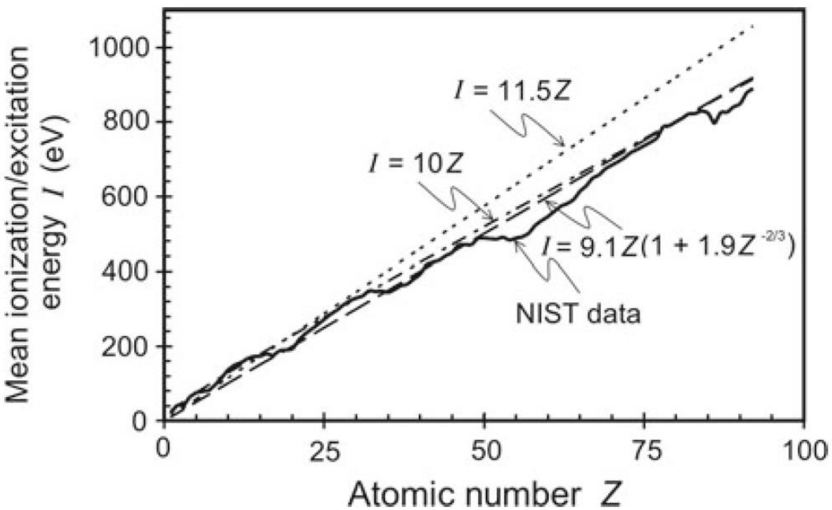


Table 6.3 Mean ionization/excitation energy I for various absorbing materials (from the ICRU Report 37)

Element	H	C	Al	Cu	Ag	W	Pb	Ra	U	Cf
Z	1	6	13	29	47	74	82	88	92	98
I (eV)	19.2	78	167	322	470	727	823	826	890	966

Table 6.4 Mean ionization/excitation energy I for various compounds of interest in medical physics (from the ICRU Report 37)

Compound	I (eV)	Compound	I (eV)
Air (dry)	85.7	Lithium fluoride	94
Water (liquid)	75	Photographic emulsion	331
Water (vapor)	71.6	Sodium iodide	452
Muscle (skeletal)	75.3	Polystyrene	68.7
Bone (compact)	91.9	A-150 plastic	65.1

Semiclassical formula for stopping power

- In the logarithm

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = 2\pi n \int_{Q_{\min}}^{Q_{\max}} Qb\,\mathrm{d}b = \frac{4\pi k_0^2 z^2 e^4 n}{mV^2} \int_{b_{\min}}^{b_{\max}} \frac{\mathrm{d}b}{b} = \frac{4\pi k_0^2 z^2 e^4 n}{mV^2} \ln \frac{b_{\max}}{b_{\min}}.$$

$$\frac{b_{\max}}{b_{\min}} = \left(\frac{Q_{\max}}{Q_{\min}}\right)^{1/2} = \left(\frac{2mV^2}{I}\right)^{1/2}$$

- The final form of semiclassical stopping power:

$$S^{\mathrm{Bohr}} = -\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{2\pi k_0^2 z^2 e^4 n}{mV^2} \ln \frac{2mV^2}{I}$$

No. of electrons per unit volume

$$n = Z\frac{\text{No. of atoms}}{\text{volume}} = Z\frac{N_A}{A}\rho$$

- Mass stopping power:

$$S_\rho^{\mathrm{Bohr}} = -\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{2\pi k_0^2 z^2 e^4}{mV^2}\frac{ZN_A}{A} \ln \frac{2mV^2}{I}$$

Bethe formula for stopping power

- Using relativistic quantum mechanics, Bethe derived the following expression for the stopping power of a uniform medium for a heavy charged particle:

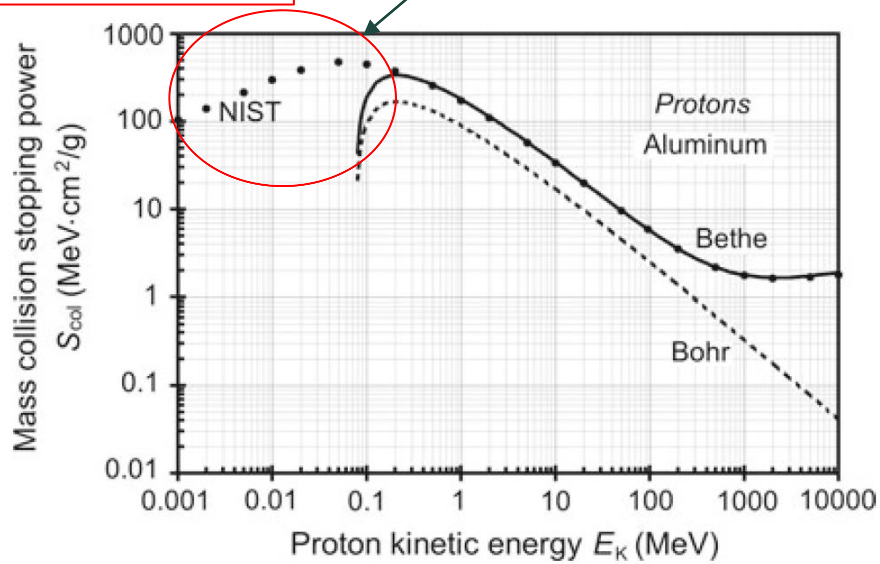
$$S^{\text{Bethe}} = -\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{4\pi k_0^2 z^2 e^4 n}{mc^2\beta^2}\left[\ln\frac{2mc^2\beta^2}{I(1-\beta^2)} - \beta^2\right]$$

- Mass stopping power

$$S_\rho^{\text{Bethe}} = -\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{4\pi k_0^2 z^2 e^4}{mc^2\beta^2}\frac{ZN_A}{A}\left[\ln\frac{2mc^2\beta^2}{I(1-\beta^2)} - \beta^2\right]$$

Not valid at low energy

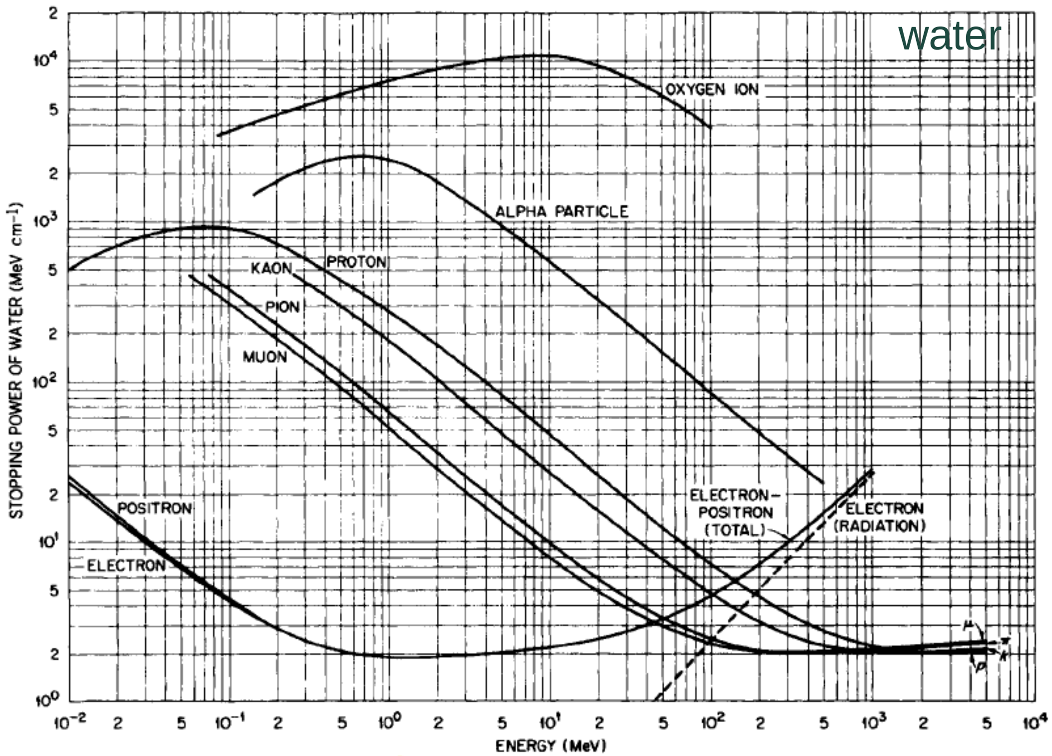
$k_0 = 8.99 \times 10^9\ \mathrm{N\,m^2\,C^{-2}}$ (Appendix C),
z = atomic number of the heavy particle,
e = magnitude of the electron charge,
n = number of electrons per unit volume in the medium,
m = electron rest mass,
c = speed of light in vacuum,
$\beta = V/c$ = speed of the particle relative to c,
I = mean excitation energy of the medium.



Energy-loss mechanism of electrons or positrons

- We treat electron and positron energy-loss processes together, referring to both simply as "electrons" or "beta particles." Their stopping powers and ranges are virtually the same, except at low energies.
- Like heavy charged particles, beta particles can excite and ionize atoms. In addition, they can also radiate energy by bremsstrahlung. The radiative contribution to the stopping power becomes important only at high energies.

$$\left(-\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{\pm}_{\mathrm{tot}} = \left(-\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{\pm}_{\mathrm{col}} + \left(-\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{\pm}_{\mathrm{rad}}$$



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Collisional stopping power

- The collisional stopping power for beta particles is different from that of heavy charged particles because of two physical factors:
  1) A beta particle can lose a large fraction of its energy in a single collision with an atomic electron, which has equal mass.
  2) A β^- particle is identical to the atomic electron with which it collides and a β^+ is the electron's antiparticle.
- The collisional stopping-power formulas for electrons and positrons

$$\left(-\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{\pm}_{\mathrm{col}} = \frac{4\pi k_0^2 e^4 n}{mc^2\beta^2}\left[\ln\frac{mc^2\tau\sqrt{\tau+2}}{\sqrt{2}I} + F^{\pm}(\beta)\right],$$

$$\tau = \frac{T}{mc^2}$$

where

$$F^{-}(\beta) = \frac{1-\beta^2}{2}\left[1+\frac{\tau^2}{8}-(2\tau+1)\ln 2\right]$$

For electrons

$$F^{+}(\beta) = \ln 2 - \frac{\beta^2}{24}\left[23+\frac{14}{\tau+2}+\frac{10}{(\tau+2)^2}+\frac{4}{(\tau+2)^3}\right]$$

For positrons

Radiative stopping power

- Bremsstrahlung occurs when a beta particle is deflected in the electric field of a nucleus and, to a lesser extent, in the field of an atomic electron. At high beta-particle energies, the radiation is emitted mostly in the forward direction, that is, in the direction of travel of the beta particle.

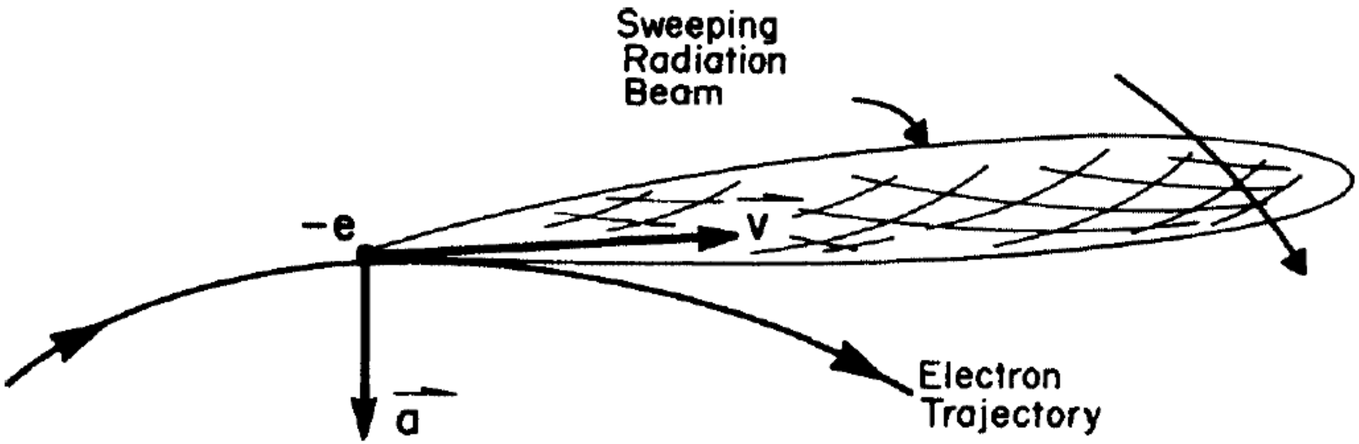

Fig. 6.3 Synchrotron radiation. At high energies, photons are emitted by electrons (charge $-e$) in circular orbits in the direction (crosshatched area) of their instantaneous velocity **v**. The direction of the electrons' acceleration **a** is also shown.

Accelerated charged particle: emission of radiation

- An accelerated or decelerated charged particle emits some of its kinetic energy in the form of photons referred to as bremsstrahlung radiation.
- The intensity of the emitted radiation is defined as the energy flow per unit area A per unit time t and is given by the Poynting vector S

$$S = |\mathbf{S}| = \frac{\mathcal{E}\mathcal{B}}{\mu_0} = \varepsilon_0 c \mathcal{E}^2 = \frac{1}{16\pi^2\varepsilon_0} \frac{q^2 a^2}{c^3} \frac{\sin^2\theta}{r^2}. \tag{4.17}$$

The following characteristics of the emitted radiation intensity are notable:

1. Emitted radiation intensity $S(r,\theta)$ is linearly proportional to: q^2, square of particle's charge; a^2, square of particle's acceleration; and $\sin^2\theta$.
2. Emitted radiation intensity $S(r,\theta)$ is inversely proportional to r^2, reflecting an inverse square law behavior.
3. Emitted radiation intensity $S(r,\theta)$ exhibits a maximum at right angles to the direction of motion where $\theta = \frac{1}{2}\pi$. No radiation is emitted in the forward direction $(\theta = 0)$ or in the backward direction $(\theta = \pi)$.

q is the charge of the charged particle, identical in both reference frames.
$\mathbf{r}$ is the radius vector connecting the origin of Σ with the point-of-interest P.
θ is the angle between $\boldsymbol{v}$ and $\mathbf{r}$ in the reference frame Σ.

Radiation power emitted by accelerated charged particle

- The power P (energy per unit time) emitted by the accelerated charged particle in the form of bremsstrahlung radiation is obtained by

$$P = \frac{\mathrm{d}E}{\mathrm{d}t} = \int S(r,\theta)\,\mathrm{d}A = \int S(r,\theta) r^2\,\mathrm{d}\Omega = 2\pi \int_0^\pi S(r,\theta) r^2 \sin\theta\,\mathrm{d}\theta$$

$$= -\frac{2\pi}{16\pi^2\varepsilon_0}\frac{q^2a^2}{c^3}\int_0^\pi \sin^2\theta\,\mathrm{d}(\cos\theta)$$

$$= -\frac{q^2a^2}{8\pi\varepsilon_0 c^3}\int_0^\pi (1-\cos^2\theta)\,\mathrm{d}(\cos\theta) = \frac{1}{6\pi\varepsilon_0}\frac{q^2a^2}{c^3}.$$

$$a \propto \frac{zZe^2}{m}$$

Larmor formula

- Cross section for emission of bremsstrahlung (Hans Bethe and Walter Heitler)

$$\sigma_{\text{rad}} \propto \alpha r_e^2 Z^2 \left(\text{cm}^2/\text{nucleus}\right), \qquad (6.5)$$

where

α is the fine structure constant $\left[e^2/(4\pi\varepsilon_0\hbar c) = 1/137\right]$.
r_e is the classical electron radius $\left[e^2/\left(4\pi\varepsilon_0 m_e c^2\right) = 2.818\ \text{fm}\right]$.
Z is the atomic number of the absorber target.

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Total mass stopping power for electrons

Table 6.1 Electron Collisonal, Radiative, and Total Mass Stopping Powers; Radiation Yield; and Range in Water

Kinetic Energy	β^2	$-\frac{1}{\rho}\left(\frac{dE}{dx}\right)^{-}_{col}$ (MeV cm^2 g^{-1})	$-\frac{1}{\rho}\left(\frac{dE}{dx}\right)^{-}_{rad}$ (MeV cm^2 g^{-1})	$-\frac{1}{\rho}\left(\frac{dE}{dx}\right)^{-}_{tot}$ (MeV cm^2 g^{-1})	Radiation Yield	Range (g cm^{-2})
10 eV	0.00004	4.0	—	4.0	—	4×10^{-8}
30	0.00012	44.	—	44.	—	2×10^{-7}
50	0.00020	170.	—	170.	—	3×10^{-7}
75	0.00029	272.	—	272.	—	4×10^{-7}
100	0.00039	314.	—	314.		5×10^{-7}
200	0.00078	298.	—	298.	—	8×10^{-7}
500 eV	0.00195	194.	—	194.	—	2×10^{-6}
1 keV	0.00390	126.	—	126.	—	5×10^{-6}
2	0.00778	77.5	—	77.5	—	2×10^{-5}
5	0.0193	42.6	—	42.6	—	8×10^{-5}
10	0.0380	23.2	—	23.2	0.0001	0.0002
25	0.0911	11.4	—	11.4	0.0002	0.0012
50	0.170	6.75	—	6.75	0.0004	0.0042
75	0.239	5.08	—	5.08	0.0006	0.0086
100	0.301	4.20	—	4.20	0.0007	0.0140
200	0.483	2.84	0.006	2.85	0.0012	0.0440
500	0.745	2.06	0.010	2.07	0.0026	0.174
700 keV	0.822	1.94	0.013	1.95	0.0036	0.275
1 MeV	0.886	1.87	0.017	1.89	0.0049	0.430
4	0.987	1.91	0.065	1.98	0.0168	2.00
7	0.991	1.93	0.084	2.02	0.0208	2.50
10	0.998	2.00	0.183	2.18	0.0416	4.88
100	0.999+	2.20	2.40	4.60	0.317	32.5
1000 MeV	0.999+	2.40	26.3	28.7	0.774	101.

$$\left(-\frac{dE}{dx}\right)^{\pm}_{tot} = \left(-\frac{dE}{dx}\right)^{\pm}_{col} + \left(-\frac{dE}{dx}\right)^{\pm}_{rad}$$

- Approximate formula

$$\frac{(-dE/dx)^{-}_{rad}}{(-dE/dx)^{-}_{col}} \cong \frac{ZE}{800}.$$

E: total energy in MeV

- Radiation yield (radiation loss divided by total loss)

$$Y \cong \frac{6 \times 10^{-4} ZT}{1 + 6 \times 10^{-4} ZT}.$$

T: incident kinetic energy in MeV

Stopping power of water for various charged particles

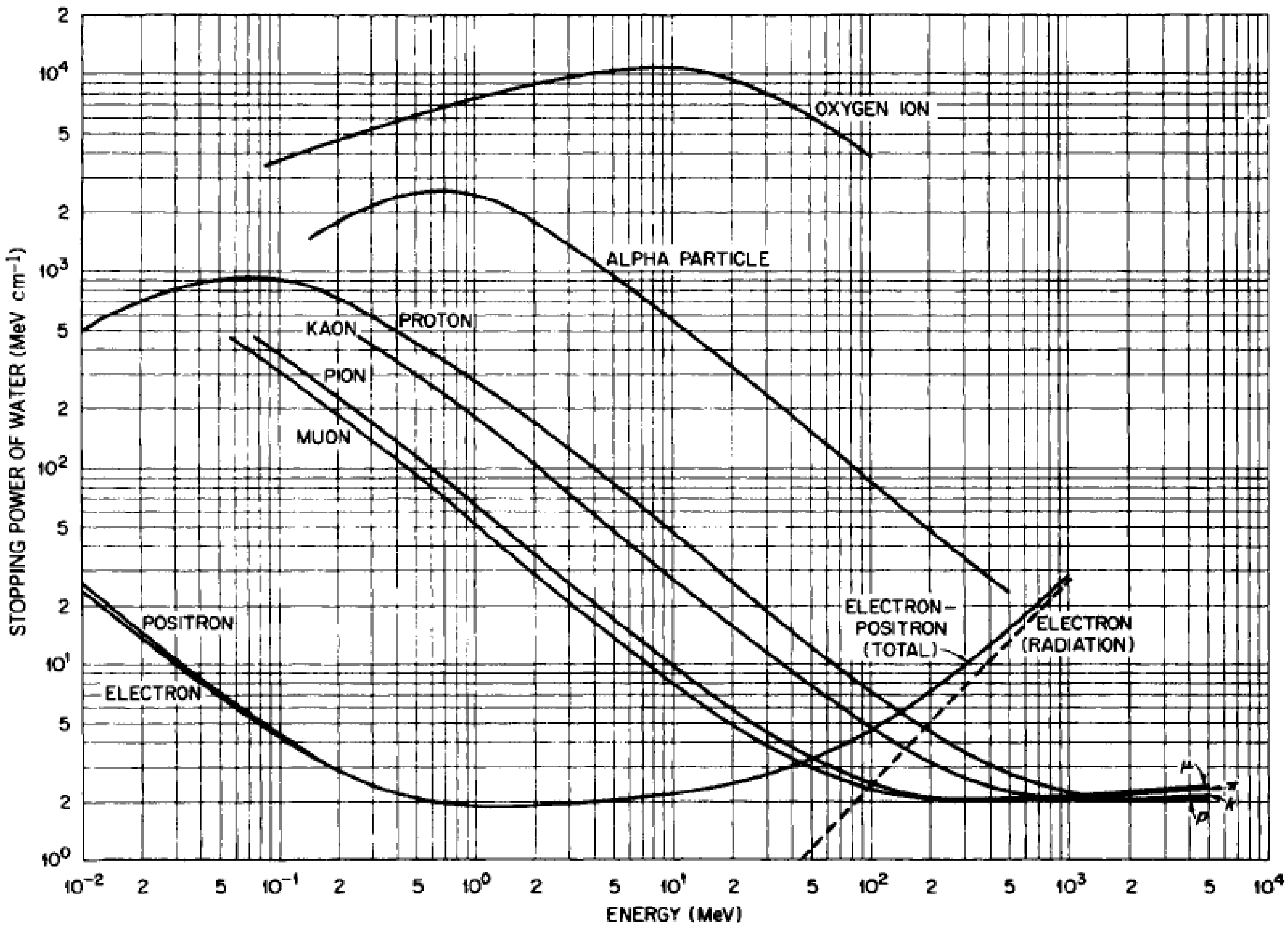
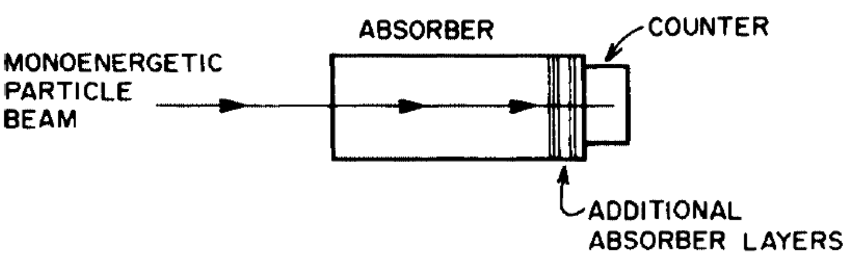


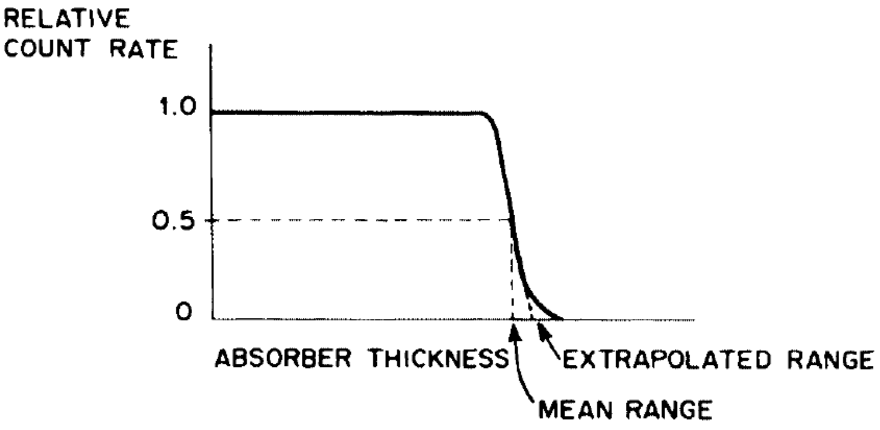
Fig. 5.6 Stopping power of water in MeV cm^{-1} for various heavy charged particles and beta particles. The muon, pion, and kaon are elementary particles with rest masses equal, respectively, to about 207, 270, and 967 electron rest masses. (Courtesy Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc., for the Department of Energy.)

Range

- The range of a charged particle is the distance it travels before coming to rest. The reciprocal of the stopping power gives the distance traveled per unit energy loss. Therefore, the range $R(T)$ of a particle of kinetic energy T is the integral of this quantity down to zero energy:

$$R(T) = \int_T^0 \frac{dx}{dE} dE = \int_0^T \left(-\frac{dE}{dx}\right)^{-1} dE = \int_0^T \frac{dE}{S(E)}$$



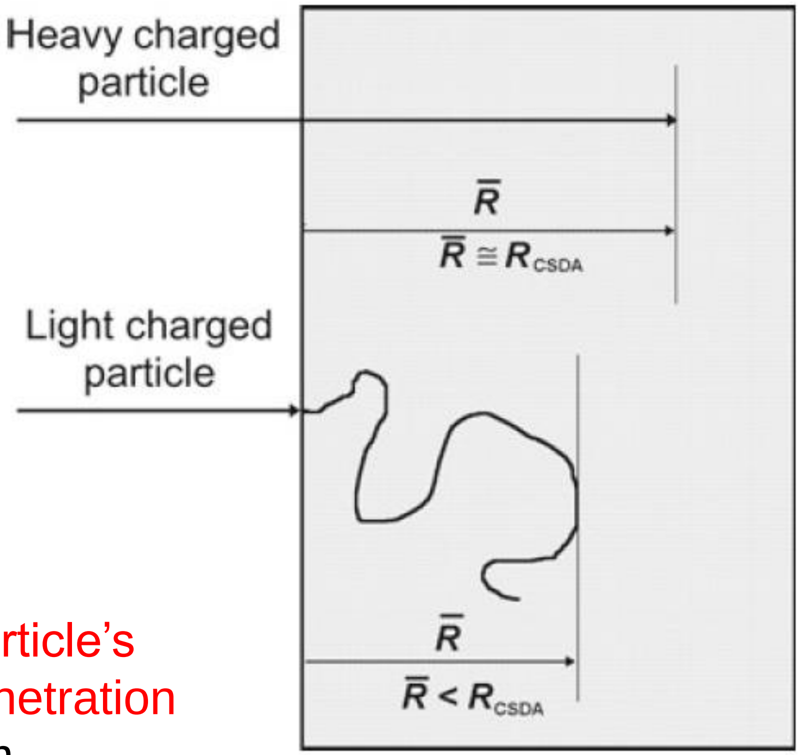


Range

- Most of the collision and radiation interactions individually transfer only minute fractions of the incident particle's kinetic energy, and it is convenient to think of the particle that is moving through an absorber as losing its kinetic energy gradually and continuously in a process often referred to as the "continuous slowing down approximation" (CSDA).

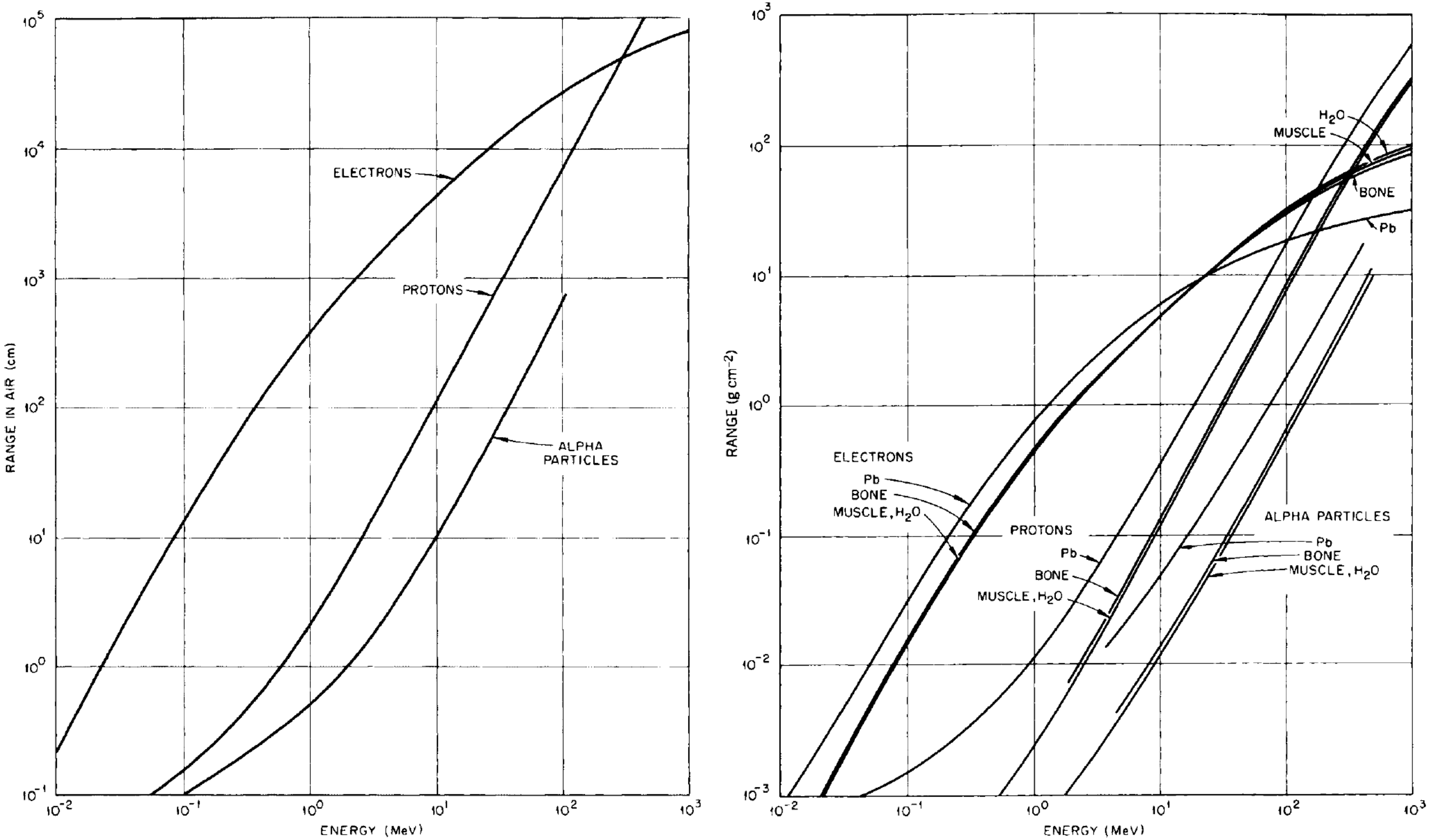
$$R_{CSDA} = \int_0^{(E_K)_0} \frac{dE}{S_{tot}(E)},$$

R_{CSDA} is the CSDA range (mean path length) of the charged particle in the absorber (typically in $cm^2 \cdot g^{-1}$).
$(E_K)_0$ is the initial kinetic energy of the charged particle.
$S_{tot}(E)$ is the total mass stopping power of the charged particle as a function of the kinetic energy E_K.



- The CSDA range is a calculated quantity that represents the mean path length along the particle's trajectory and not necessarily the depth of penetration in a defined direction in the absorbing medium.

Range: air vs. water



Specific ionization

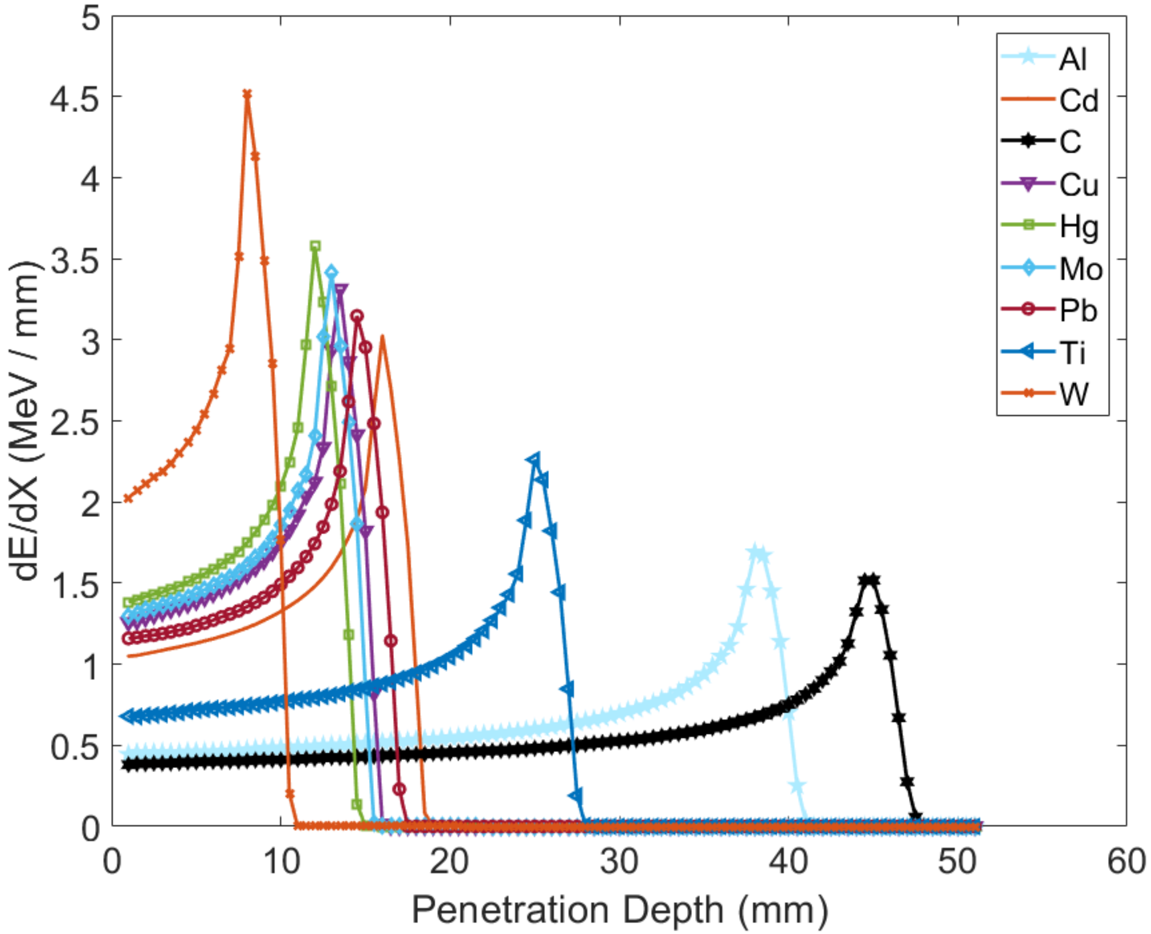
- The average number of ion pairs that a particle produces per unit distance traveled is called the specific ionization. This quantity, which expresses the density of ionizations along a track, is often considered in studying the response of materials to radiation and in interpreting some biological effects.
- The specific ionization of a particle at a given energy is equal to the stopping power divided by the average energy required to produce an ion pair at that particle energy.

$$\text{Specific ionization} = \frac{1}{W}\frac{dE}{dx}$$

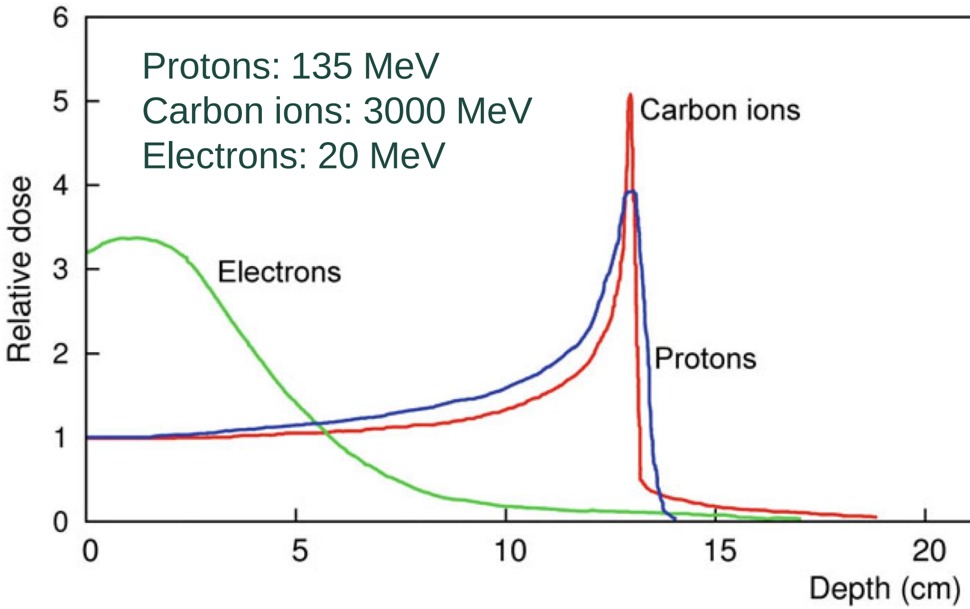
$$W: \frac{\text{required energy}}{\text{one ion pair}} \qquad \frac{dE}{dx}: \frac{\text{energy loss}}{\text{unit length}}$$

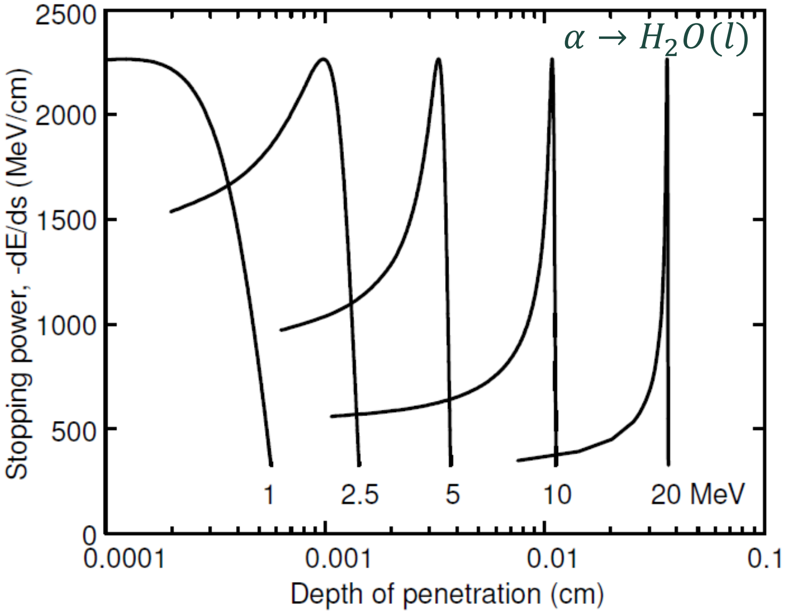
Bragg curve and Bragg peak (1903)

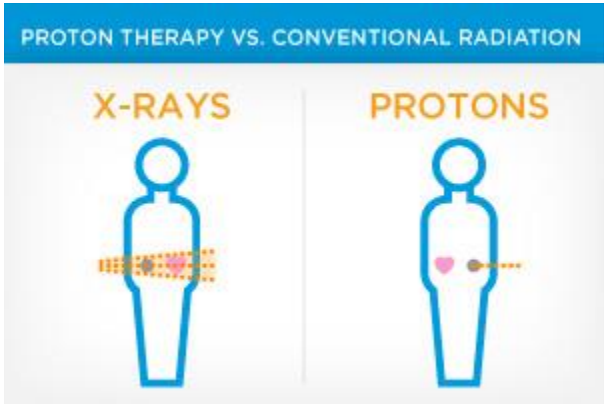
- Stopping of 100-MeV proton in various materials



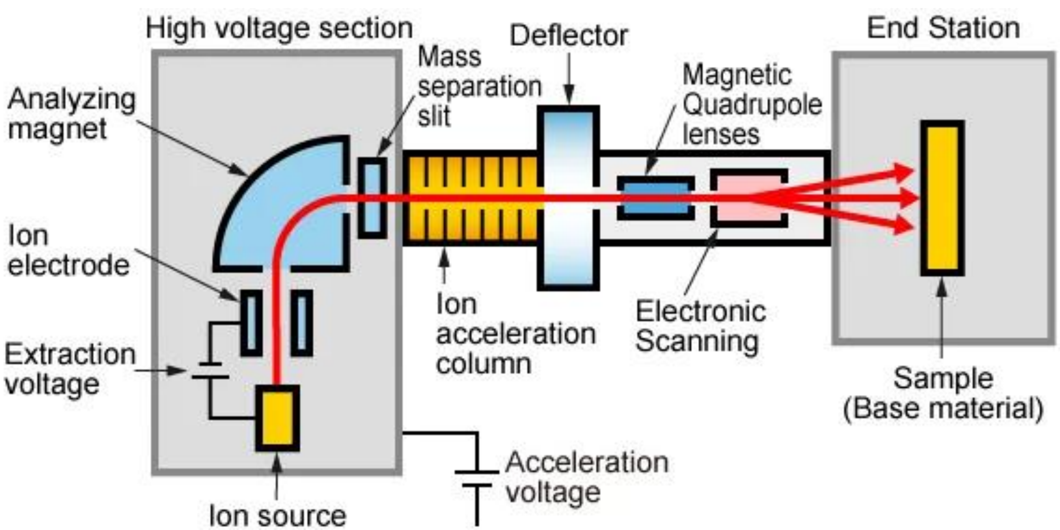
Application: cancer therapy

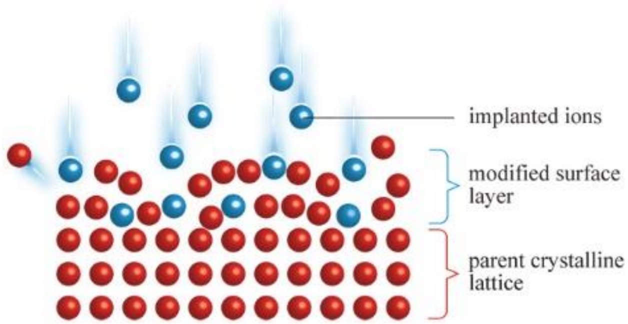


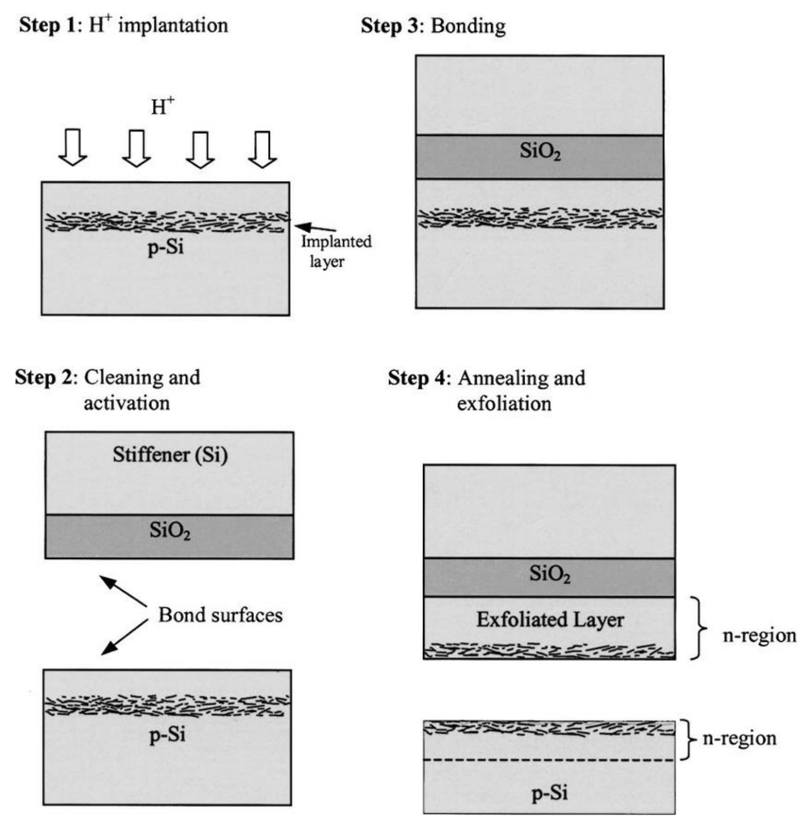




Application: semiconductor doping (ion implantation)







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Homework

- J. Turner, Atoms, Radiation, and Radiation Protection, Wiley (2007), chapter 5

  Problems: 22, 26
- J. Turner, Atoms, Radiation, and Radiation Protection, Wiley (2007), chapter 6

  Problems: 14