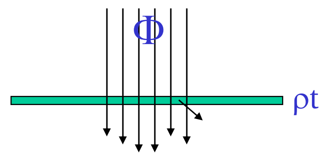
CHAGED-PARTICLE INTERATIONS IN MATTER

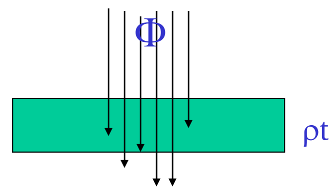
Attix: Chapter 8 (part 3)

Calculation of Absorbed Dose - review -

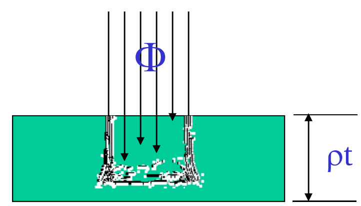
❖Thin foils



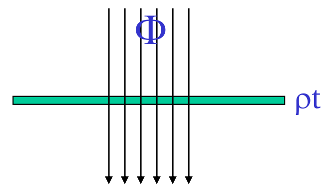
❖Thicker foils 1



❖Thicker foils 2



Calculation of absorbed dose
- thin foils -



SIMPLEST CASE

a. collision stopping power remains practically constant.
b. scattering is negligible.
c. kinetic energy carried out of the foil by δ-rays is negligible

$$E = \Phi \left(\frac{dT}{\rho dx}\right)_c \rho t$$

Pathlenght through the foil

Calculation of absorbed dose
- simplest case -

Pathlenght through the foil

$$D = \frac{\Phi (dt/\rho dx)_c \, \rho t}{\rho t} = \Phi \left(\frac{dT}{\rho dx}\right)_c \quad \text{(MeV/g)}$$

$$= 1.602 \times 10^{-10} \, \Phi \left(\frac{dT}{\rho dx}\right)_c \text{ Gy} \qquad (8.27)$$

Foil thickness

Considering δ-ray Energy Losses

- What if some kinetic energy is carried out of the foil by δ-rays ?
- One can estimate the dose by replacing the mass collision stopping power by the corresponding restricted stopping power, $(dT/\rho dx)_\Delta$.
- Choosing Δ to be the energy of those δ-rays having $<t> = \rho t$
- Discarding all the energy given to δ-rays having projected ranges greater than the foil thickness.

$$\mathbf{D} = 1.602 \times 10^{-10}\, \mathbf{\Phi} \left(\frac{dT}{\rho dx}\right)_{c\Delta} \text{Gy}$$

Estimating Path Lengthening Due to Scattering in the Foil

- Is it necessary correction for path lengthening for heavy particle in thin foil?
- A correction to Eq. (8.27) for path lengthening is not necessary for heavy particles since ~ straight path through the foil in the direction of the entering particles.

Estimating Path Lengthening Due to Scattering in the Foil (for electrons)

❖ And what for electrons?

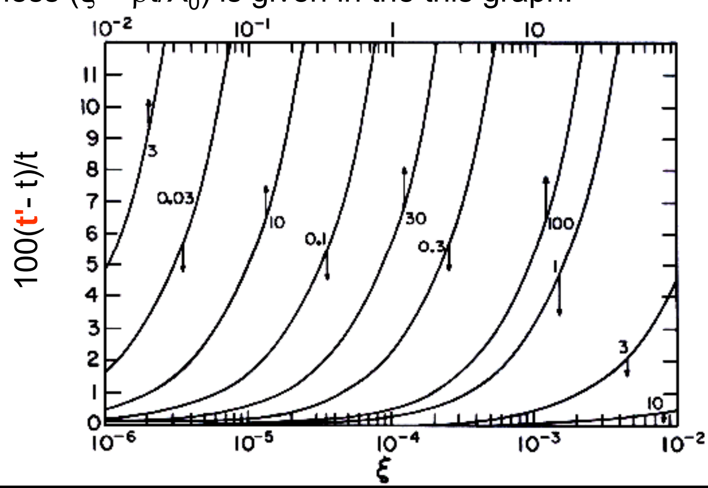
❖ For electrons, however, significant path lengthening results from multiple scattering and a correction to Eq. (8.27) may be indicated.

$$D = \frac{\Phi(dt/\rho dx)_c}{\rho t} \times \rho\, t'$$

❖ How *t*' can be obtained?

Estimating Path Lengthening Due to Scattering in the Foil (for electrons)

❖ The mean percentage path increase of electrons traversing a foil as a function of the normalized foil thickness ($\xi = \rho t/X_0$) is given in the this graph:



Estimating Path Lengthening Due to Scattering in the Foil (for electrons)

TABLE 8.6. Radiation Lengths for Selected Elements[a]

Element	Z	X_o (g/cm^2)
H	1	63.04
He	2	94.39
C	6	43.35
Al	13	24.46
Cu	29	13.04
Sn	50	8.919
Pb	82	6.496
U	92	6.124

[a] After Seltzer and Berger (1985).

Average Dose in Thicker Foils

- Can we use stopping power to calculate average dose in thicker foils?
- We use of charged-particle CSDA range tables instead of stopping-power tables
- Delta-ray effects should be considered?
- Delta-ray effects may be neglected since the foil thickness is now large compared to most δ-ray ranges
- And what about straight tracks consideration?
- Assumption requiring straight tracks through the foil will not be satisfied for this case, especially for electrons.

Average Dose in Thicker Foils
- heavy particles -

- What is the energy spent in the foil by heavy particles?
  - $\Delta T = T_0 - T_{ex}$ (MeV)
  - Where T_{ex} is the residual kinetic energy obtained using the table for the CSDA, considering a pathlenght equal to the foil thickness

Average Dose in Thicker Foils
- heavy particles (cnt) -

- What is the average absorbed dose in the foil by the heavy particles?
  - $D_{av} = \Phi \, \Delta T / \rho t$ (MeV/g)
    $= 1.602 \; 10^{-10} \, \Phi \, \Delta T / \rho t$ Gy

Average Dose in Thicker Foils
- electrons -

- How do we can calculate the energy spent in the foil by electrons?
  - In the same manner but the first step is to estimate the true mean pathlength for the electrons, which is done by the ξ method
  - Using electron range tables such as those in Appendix E, one enters at the incident kinetic energy T_0 and obtains the corresponding CSDA range. From this the true mean pathlength of the electrons is subtracted to obtain the residual range of the exiting electron…

Average Dose in Thicker Foils
- electrons (cnt)-

- How do we consider the energy escape by bremsstrahlung?

- To estimate the production of x-rays (which we will assume all escape), the "radiation yield" column in the Berger-Seltzer tables in Appendix E is employed.
- The energy fraction spent in collision interactions is 1 -$Y(T)$.
- The energy spent in collision interactions in the foil is

$$\Delta T_c = (T_0 - T_{ex})_c = T_0\,[1- Y(T_0)] - T_{ex}\,[1 - Y(T_{ex})]$$

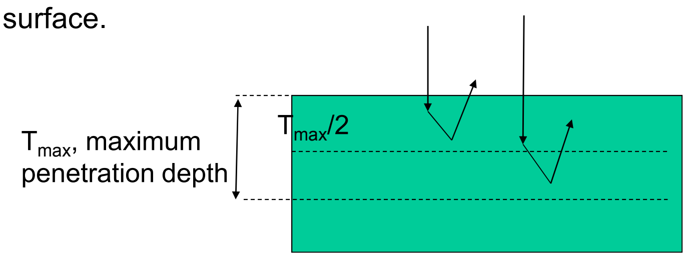
Average Dose in Thicker Foils - Example

- Consider Φ = 10^{10} cm^{-2} 10 MeV electrons ⊥ incident on 1mm Pb ($1.13gcm^{-2}$)

- From Tab 8.6 ➔ radiation length X_0 = 6.496
- Normalized thickness ξ = $\rho t/X_0$ = 0.174
- From Fig 8.11 p increases = 8.5%
- The mean pathlength = 1.13 x 1.085 = 1.23 gcm^{-2}
- From App E at T_0=10 ➔ R_{CSDA} = 6.133 gcm^{-2}
- Residual range of exiting elec = 4.9 gcm^{-2}
- Residual kinetic energy T_{ex} = 7.29 MeV
- The radiation yield Y_0, Y_{ex} = 0.3162, 0.2607
- $\Delta T_c = T_0(1-Y_0) - T_{ex}(1-Y_{ex})$ = 1.449 MeV
- $D_{av} = 1.602\times10^{-10}\Phi\Delta T_c/\rho t$ = 2.05 Gy

Average Dose in Thicker Foils - electrons backscattering -

- Heavy particles are seldom scattered through large angles.
- For electrons, backscattering due to nuclear elastic interactions can be an important cause of dose reduction, especially for high Z, low T_0, and thick target layers.
- In this connection, a thickness of $t_{max}/2$ will be provides an infinitely thick foil with respect to the backscattering.
- Particles penetrating beyond that depth obviously cannot return to the surface.



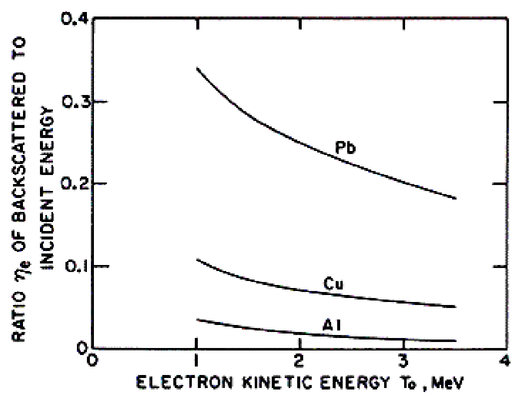
Average Dose in Thicker Foils
- electrons backscattering -

- On average, backscattering can be assumed to occur in the *midplane* of such foil ($t_{max}/4$).
- The energy spent in the foil by an electron reflected from the *midplane* is the same as if it passed straight through without backscattering.
- The energy distribution vs. depth in the foil is thus shifted toward the entry surface.
- Backscattering correction requires a knowledge of what fraction of the incident energy fluence is redirected into the reverse hemisphere.

Average Dose in Thicker Foils
- electrons backscattering (cnt) -

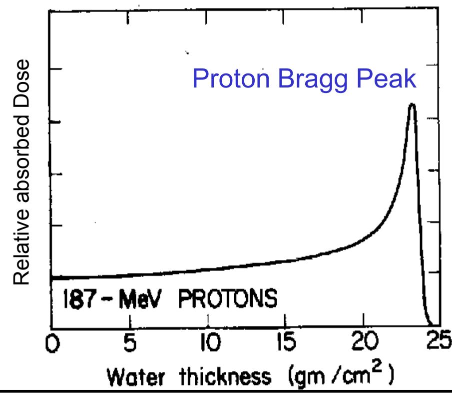
- For electrons perpendicularly incident on infinitely thick layers ($t > t_{max}/2$), this fraction may be called the *electron energy backscattering coefficient,* η_e

(its measurement is best accomplished by calorimetry).



Dose vs. Depth for Charged-Particle Beams

- The variation of absorbed dose vs. depth in a medium shows quite different characteristics from Fig. 8.9
- The shape of this function depends on particle type and energy, the medium being penetrated, and the geometry of the beam.

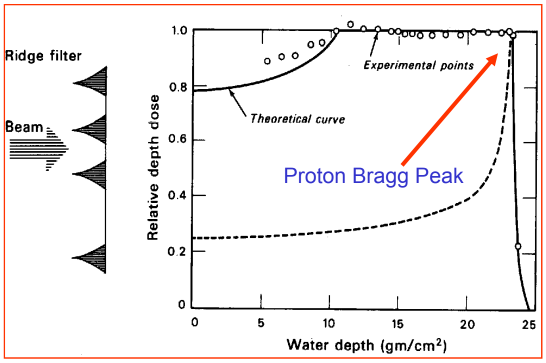


Dose vs. Depth for Charged-Particle Beams
- The Bragg Curve for heavy particles -

- Heavy charged particles (protons and heavier) show a dose-vs.-depth distribution in the shape of the classical *Bragg curve.*
- This is a consequence of the T^2 dependence of the range at low energy (and $ß^{-2}$ dependence of the stopping power).
- This means that if a particle spends the first half of its initial kinetic energy along a pathlength *x,* the remaining half of the energy will be spent in distance = *x/3,* thus crowding the spatial rate of energy expenditure toward the end of the track.
- The dose decreases from its maximum as the particles run out of energy and stop.

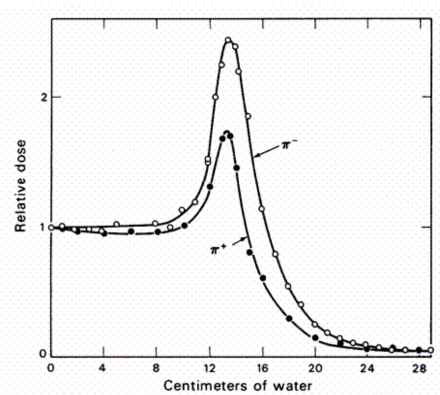
Dose vs. Depth for Charged-Particle Beams
- The Bragg Curve for protons -

- ❖ The highly localized dose maximum suggests the possible usefulness for delivery therapeutic doses of ionizing radiation to tumors at some depth in the body while minimizing dose to overlying normal tissues.
- ❖ The Bragg peak of heavy particles is *too* localized, and needs to be "smeared out" in depth if tumors even 1 cm in diameter are to be uniformly dosed.
- ❖ Oscillating wedges can be used to produce a distribution of incident energies, resulting in a roughly square-topped Bragg peak but at the expense of increasing the "plateau" dose level relative to the Bragg peak dose.

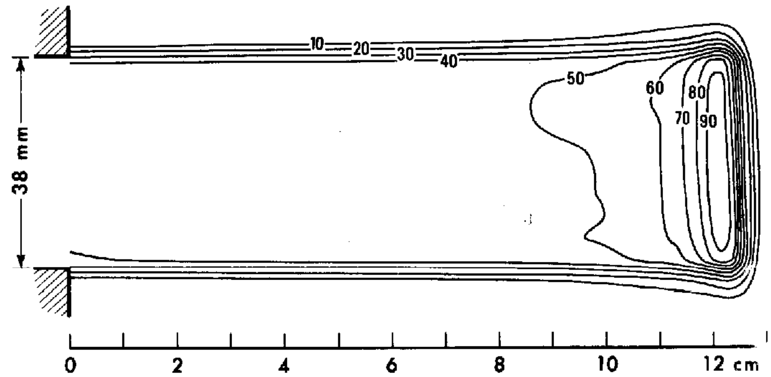


Dose vs. Depth for Charged-Particle Beams
- The Bragg Curve for pions -

- ❖ Negative pions are captured by atoms of tissue when they stop, causing the atomic nuclei to emit neutrons, γ-rays, and heavy charged particles. These heavy charged particles, being of relatively short range, enhance the dose in the vicinity of the Bragg peak.
- ❖ This Figure shows the resulting enhanced Bragg curve, in comparison with the corresponding curve for positive pions that are not captured.

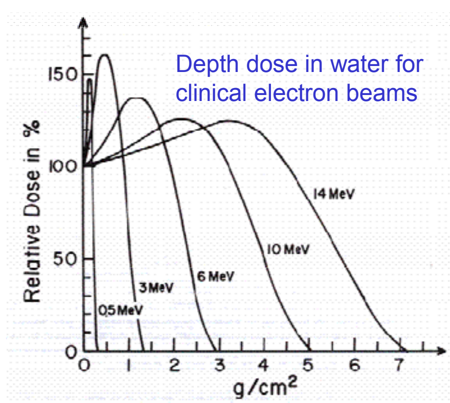


Dose vs. Depth for Charged-Particle Beams - Helium Ion Beam -



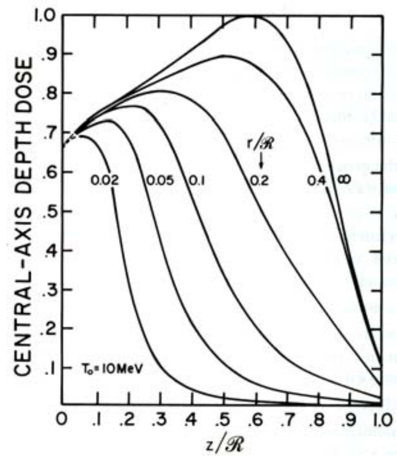
Dose vs. Depth for Charged-Particle Beams - for electrons -

- The small mass of electrons makes them scatter easily.
- As a result, they do not give rise to a Bragg peak near the end of their projected range as heavy particles do.
- Instead, a diffuse maximum is reached at roughly half of the maximum penetration depth.



Dose vs. Depth for Charged-Particle Beams
- for electrons -

- ❖ An electron beam is defined as broad if its radius upon entry is at least equal to its CSDA range.
- ❖ This Figure shows the (strong) effect of decreasing the radius below that value for a I0-MeV beam.



Calculation of Absorbed Dose at Depth

- ❖ At any point P at depth x in a medium w where the charged-particle fluence spectrum is known, the absorbed dose can be calculated as

$$D_w = 1.602 \times 10^{-10} \int_0^{T_{max}} \Phi_x(T) \left(\frac{dT}{\rho dx} \right)_{c,w} dT$$

differential charged-particle fluence spectrum, excluding δ-rays

- ❖ The exclusion of δ-rays is based on the assumption that CPE exists at P for the δ-rays. The use of the mass collision stopping power, rather than a restricted stopping power, is consistent with this assumption.

Calculation of Absorbed Dose at Depth - heavy particles -

- The problem of determining Φ_x at the point of interest is, of course, nontrivial, generally requiring radiation-transport calculations for a good solution.
- However, an estimate can be obtained rather easily from range tables for heavy charged particle since scattering and energy straggling are small.
- First one determine the range $\Re$ for T_0
- From this the depth x is subtracted to obtain the remaining range $\Re_r$ at depth *x.*
- Then the table is reentered at range $\Re_r$ to determine the remaining kinetic energy T_r.
- The particle fluence Φ_x at depth x in this simple case is taken to be the same as the Φ_0 incident on the surface and all the particles are assumed to have energy T_r (MeV).
- The dose (Gy) is given by

Evaluated at T_r

$$D_w = 1.602 \times 10^{-10} \Phi_x(T) \left(\frac{dT}{\rho dx} \right)_{c,w}$$

Calculation of Absorbed Dose at Depth - for electrons -

- For the case of a broad beam of monoenergetic electrons of energy T_0 > 1 MeV incident on a semi-infinite homogeneous low-Z medium, one can roughly estimate the most probable energy of the electrons at depth.
- Since the range is proportional to the kinetic energy for megavolt electrons, the modal energy decreases from T_0 to 0 approximately linearly with depth as x goes from 0 to the range $\Re$.
- However, the electron fluence at depth is *not* easily estimated, mainly because of multiple scattering.
- Thus dose calculations on the basis of electron fluence generally require radiation transport calculations.
- Chapter 10 ➔ The problem of measuring dose in a medium by inserting a small sensor or probe at the point of interest ➔ cavity theory.
- Chapter 13 ➔ in-phantom dosimetry, including practical application of cavity theory.
- The usefulness of the above method for estimating the electron modal energy vs. depth will become apparent there, as it provides an effective energy at which stopping-power ratios (used in cavity theory) can be evaluated.