Radiation-matter interaction

1. General details for charged particles
2. Heavy charged particles
3. Electrons and positrons
4. Photons
5. Neutrons
6. Simulating particle transport in matter

1. General details for charged particles

- **problem:**
  - -assume a particle that collides with an atomic electron
  - -the particle moves rapidly with respect to the electron
  - -the energy transferred is large compared to the binding energy
    - ✳ the electron is free and at rest

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kinetic energy conservation: $\frac{1}{2}MV_{\mathrm{i}}^2 = \frac{1}{2}mv_{\mathrm{f}}^2 + \frac{1}{2}MV_{\mathrm{f}}^2$

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$$V_\mathrm{f} = \frac{M-m}{M+m}V_\mathrm{i}$$

$$Q_\mathrm{max} = \frac{1}{2}MV_\mathrm{i}^2 - \frac{1}{2}MV_\mathrm{f}^2 = \frac{4mM}{(M+m)^2}K_i$$

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relativistic expression

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

$$\gamma = (1 - \beta^2)^{-1/2}; \quad \beta = V_{\mathrm{i}}/c$$

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1. General details for charged particles

-electrons may loss a large fraction of energy in a collision:

tortuous paths in matter

-heavy charged particles loss small fractions of energy:

straight paths in matter

energy

⁎the electron is free and at rest

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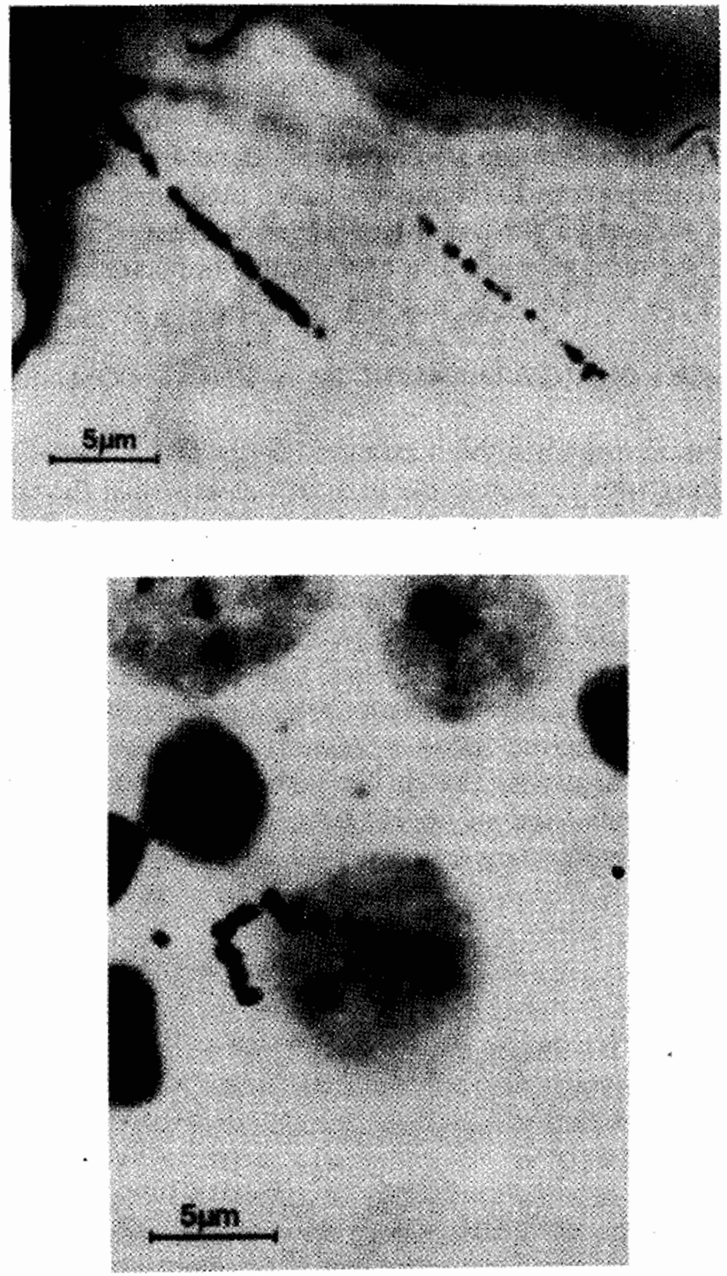

FIGURE 5.1. (Top) Alpha-particle autoradiograph of rat bone after inhalation of ^{241}Am. Biological preparation by R. Masse and N. Parmentier. (Bottom) Beta-particle autoradiograph of isolated rat-brain nucleus. The ^{14}C-thymidine incorporated in the nucleolus is located at the track origin of the electron emitted by the tracer element. Biological preparation by M. Wintzerith and P. Mandel. (Courtesy R. Rechenmann and E. Wittendorp-Rechenmann, Laboratoire de Biophysique des Rayonnements et de Methodologie INSERM U.220, Strasbourg, France.)

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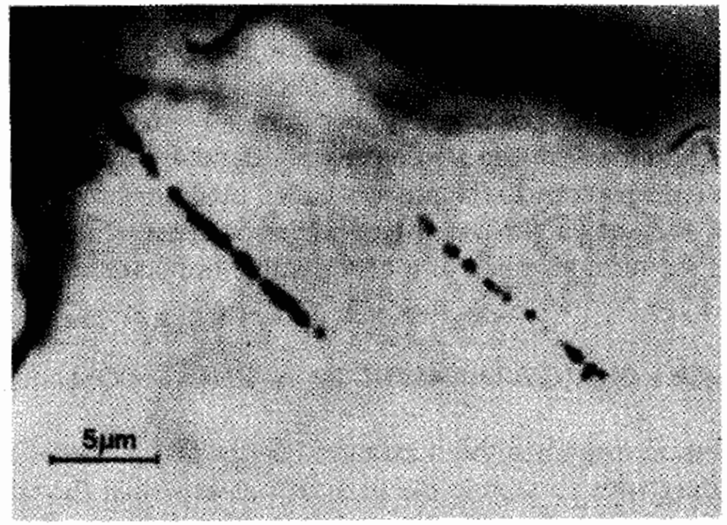
Maximum Possible Energy Transfer, Q_{max}, in Proton Collision with Electron

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



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Maximum Possible Energy Transfer, Q_{max}, in Proton Collision with Electron

maximum fractional energy loss small

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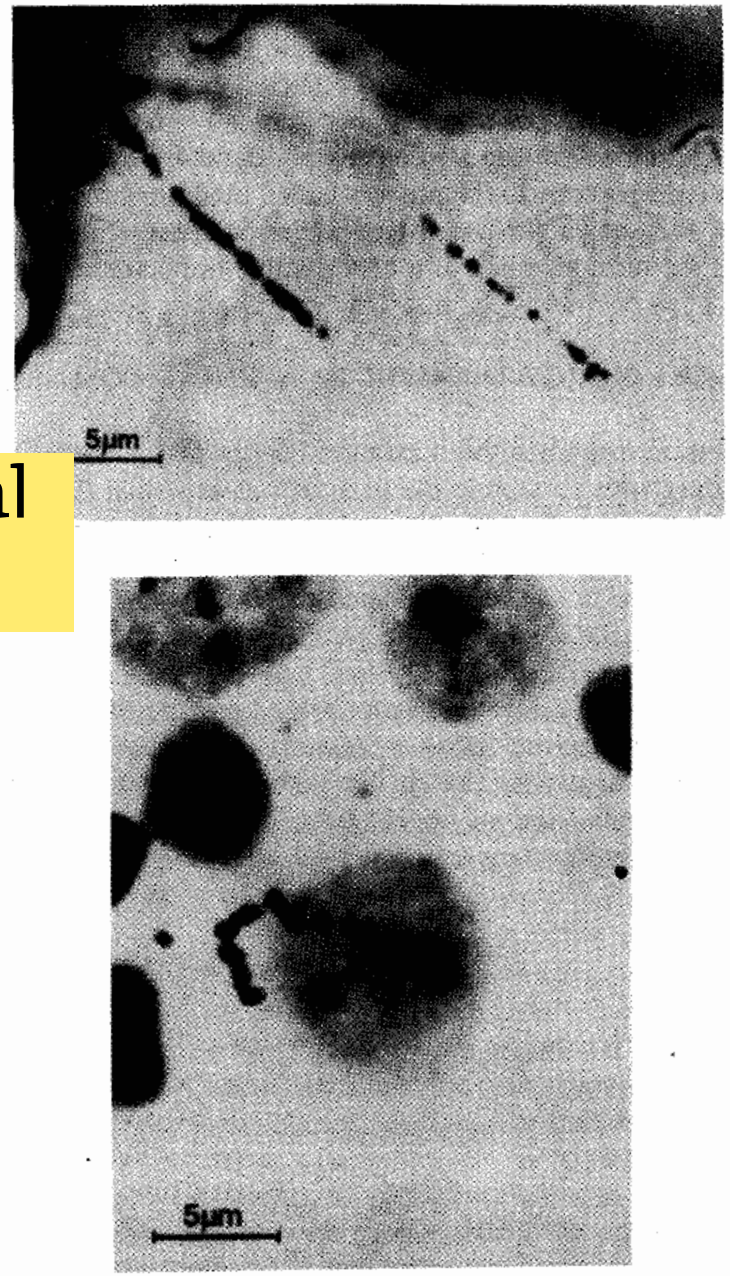

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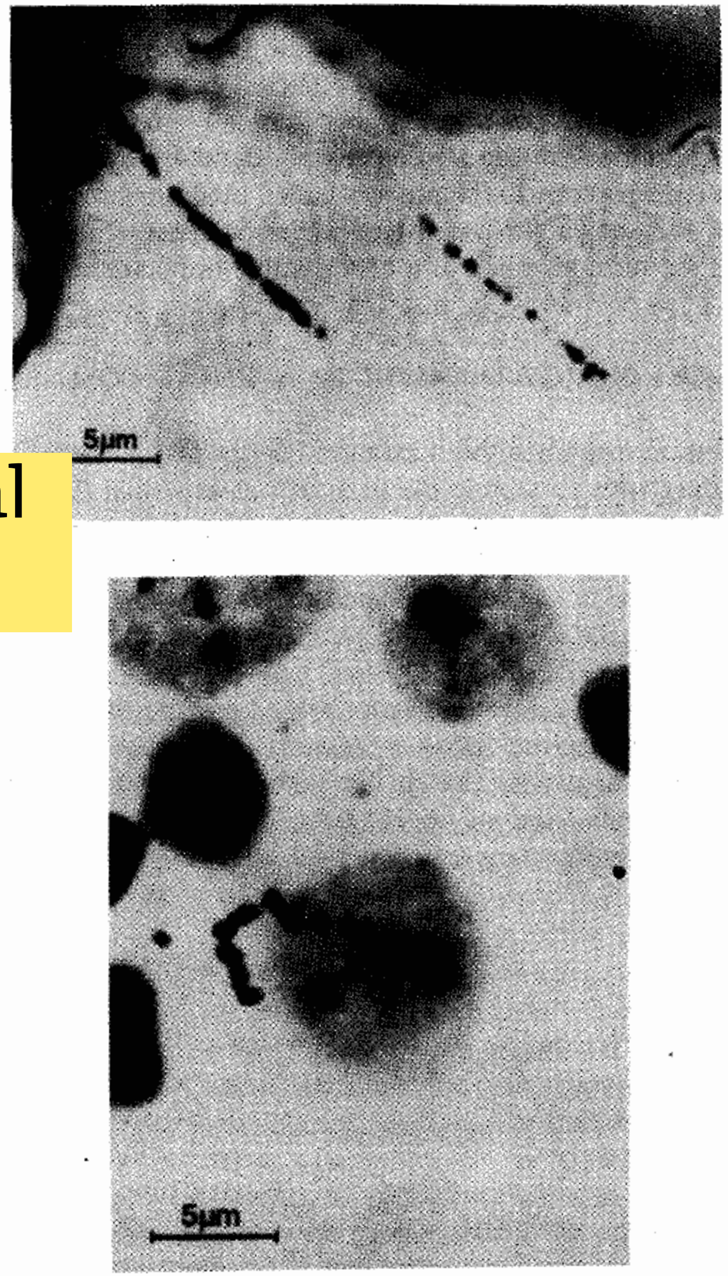

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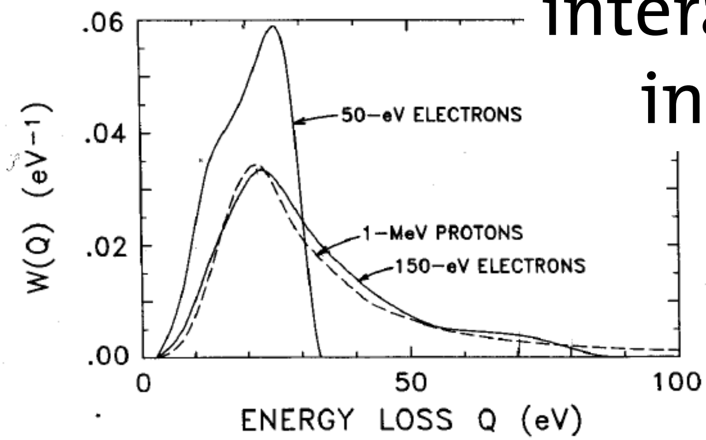
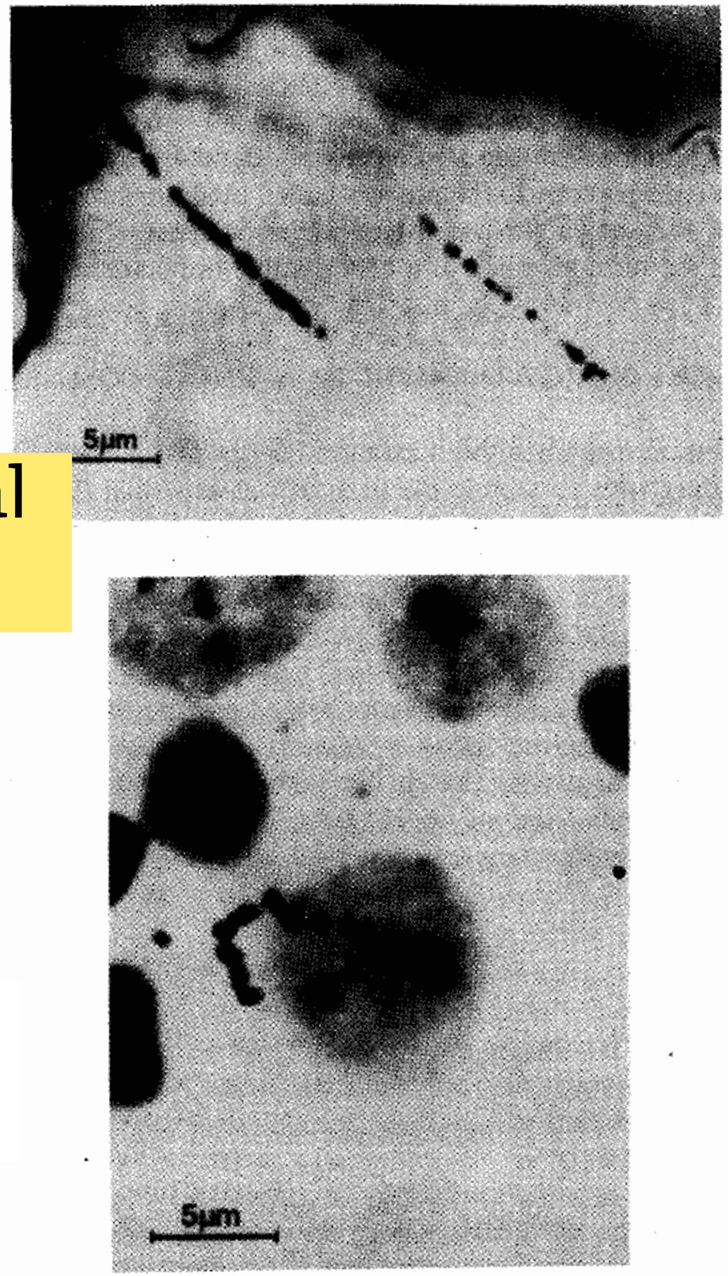


interactions are inelastic !!

FIGURE 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.)



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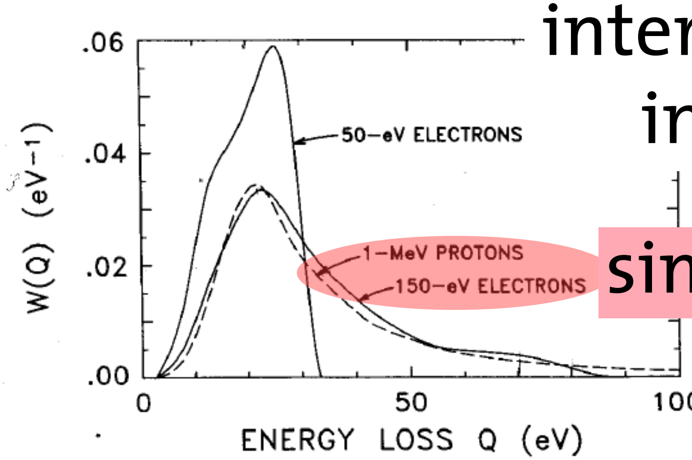

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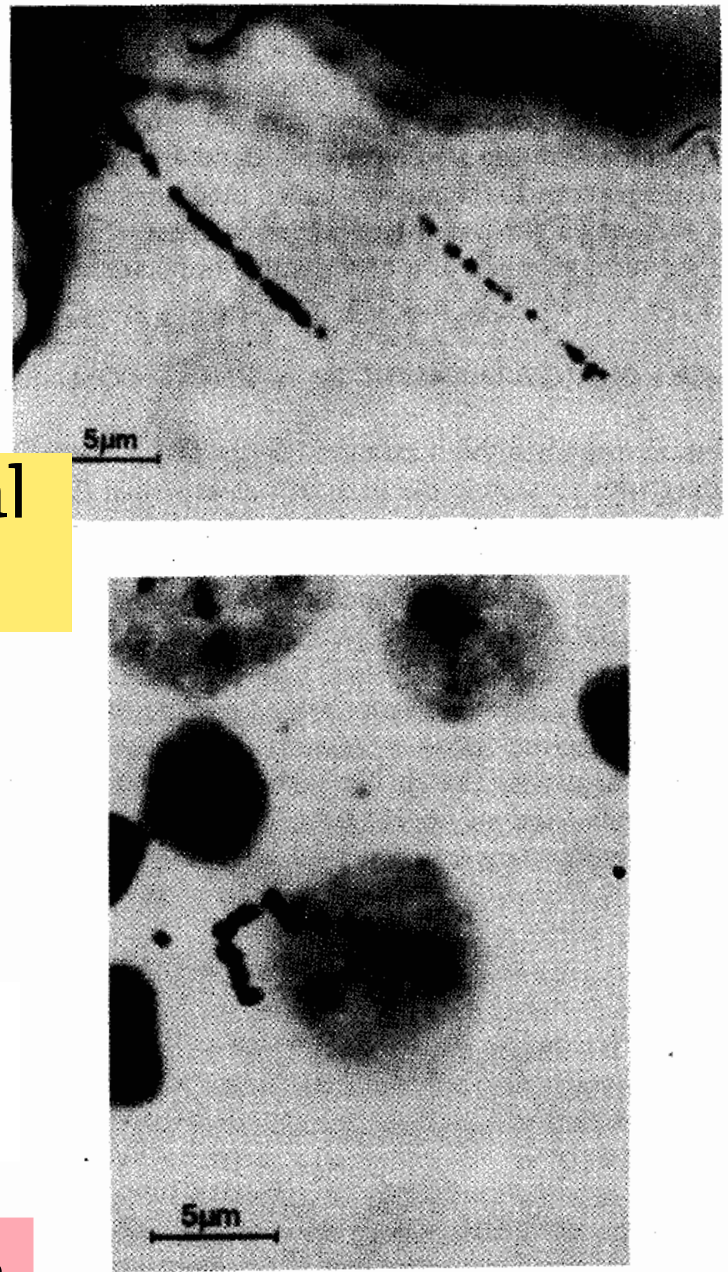

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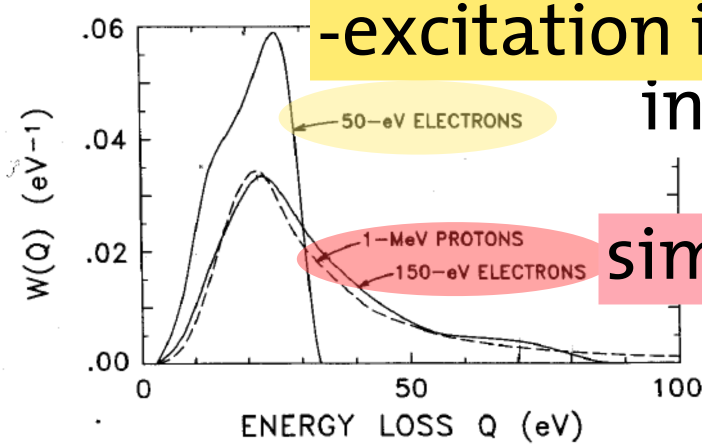

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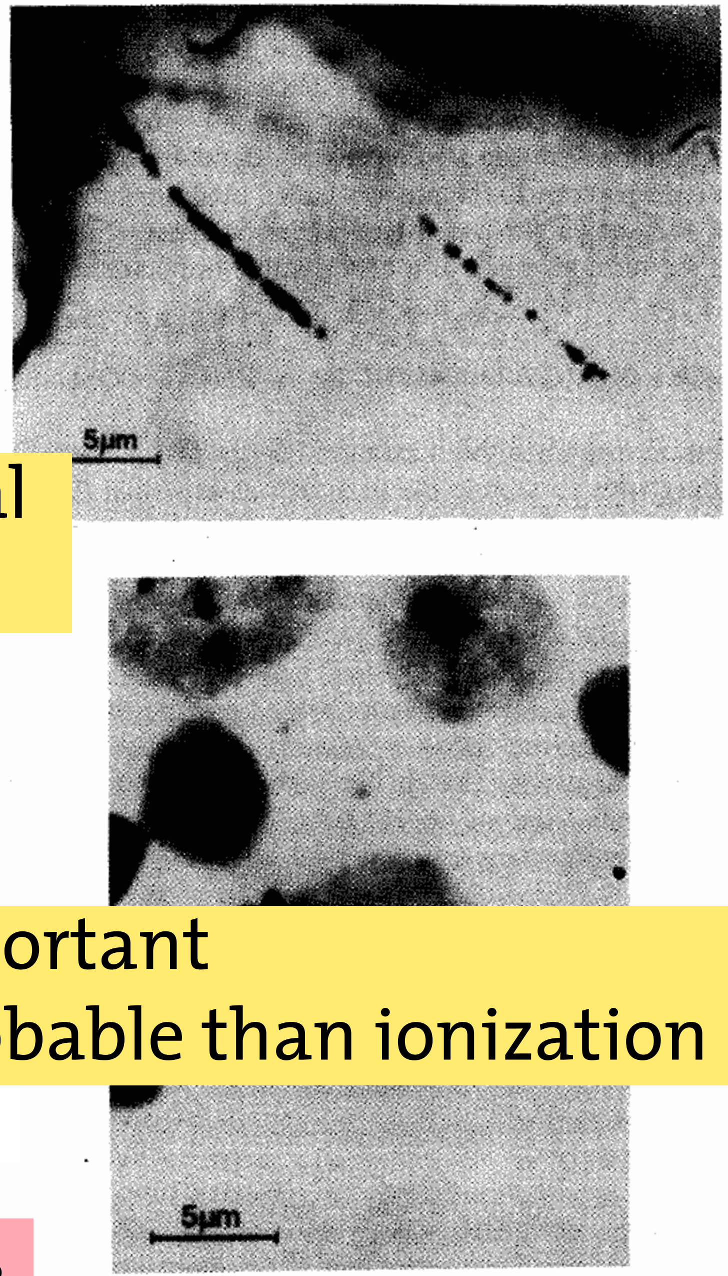

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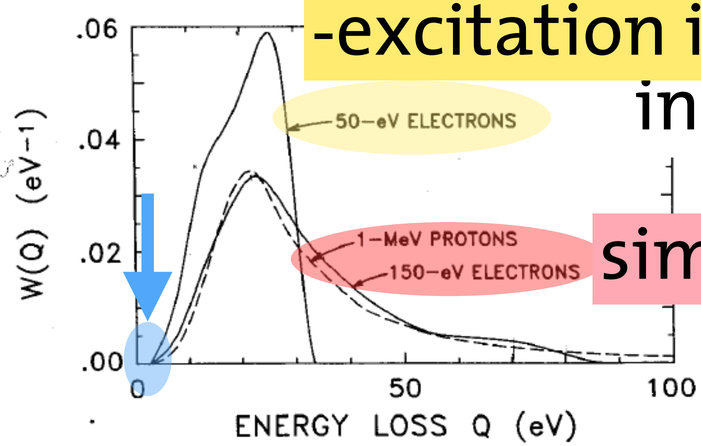

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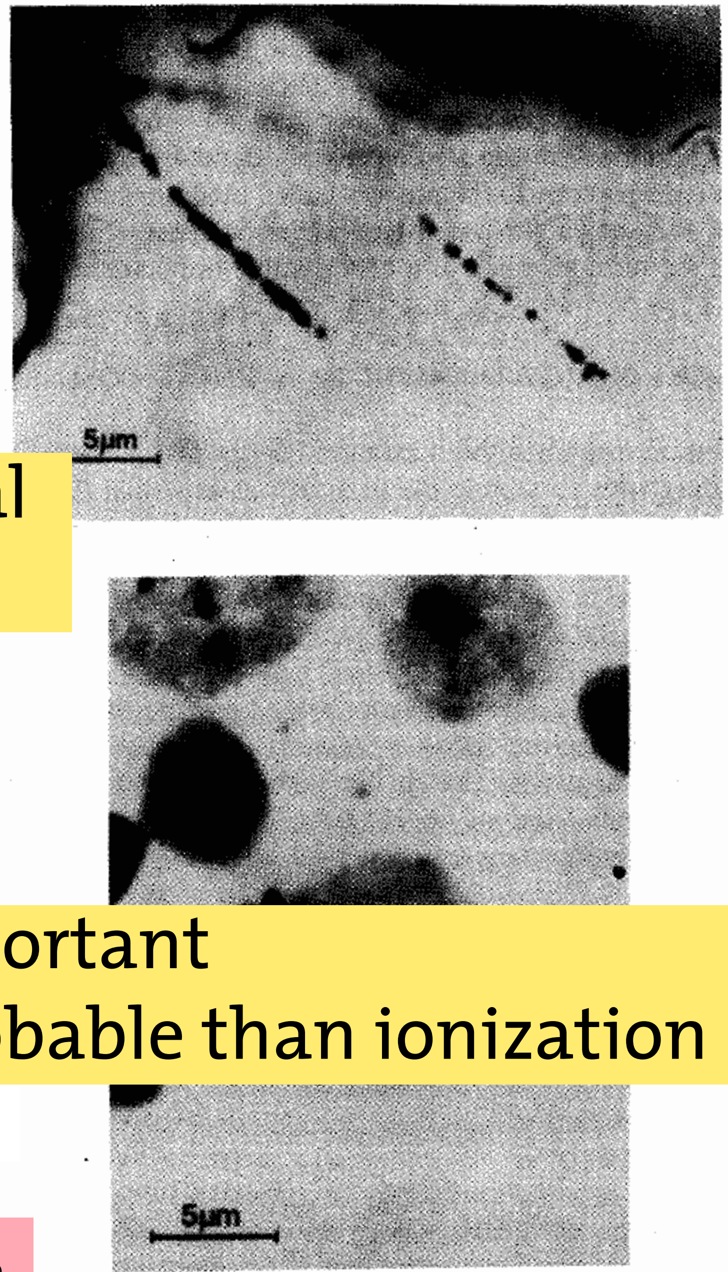

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• **Bethe's formula:**

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

$k_o = 8.99 \times 10^9$ N m^2 C^{-2}, (the Boltzman constant)
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.

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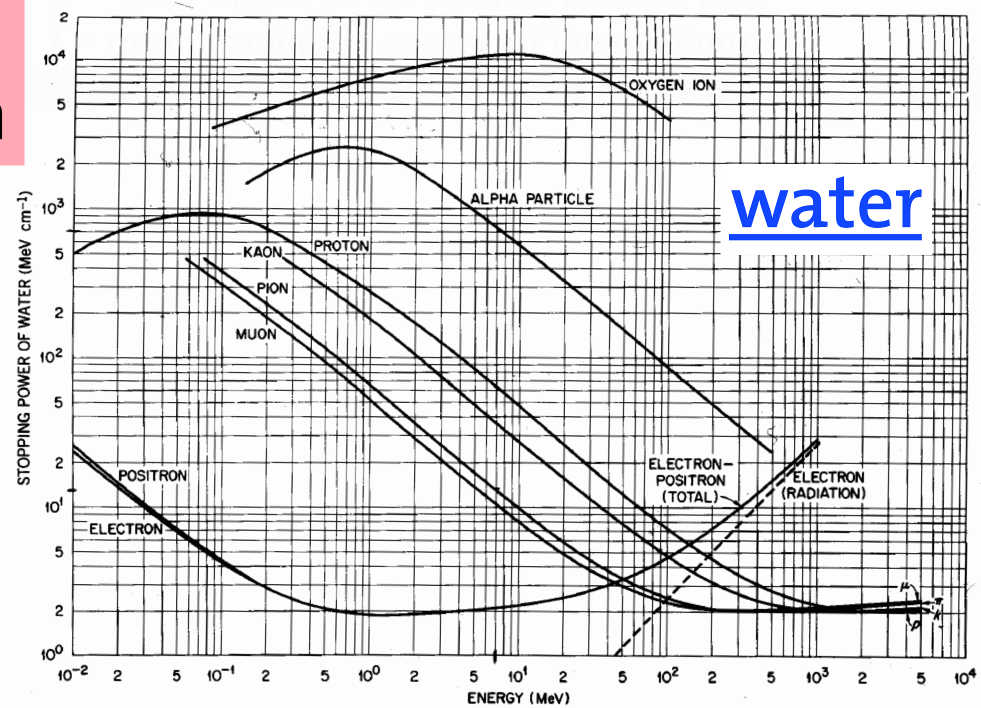

FIGURE 5.6. Stopping power of water in MeV cm^{-1} for various heavy charged particles and beta particles. The muon, pion, and kaon are elementary particles with rest masses equal, respectively, to about 207, 270, and 967 electron rest masses. (Courtesy Oak Ridge National Laboratory, operated by Martin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

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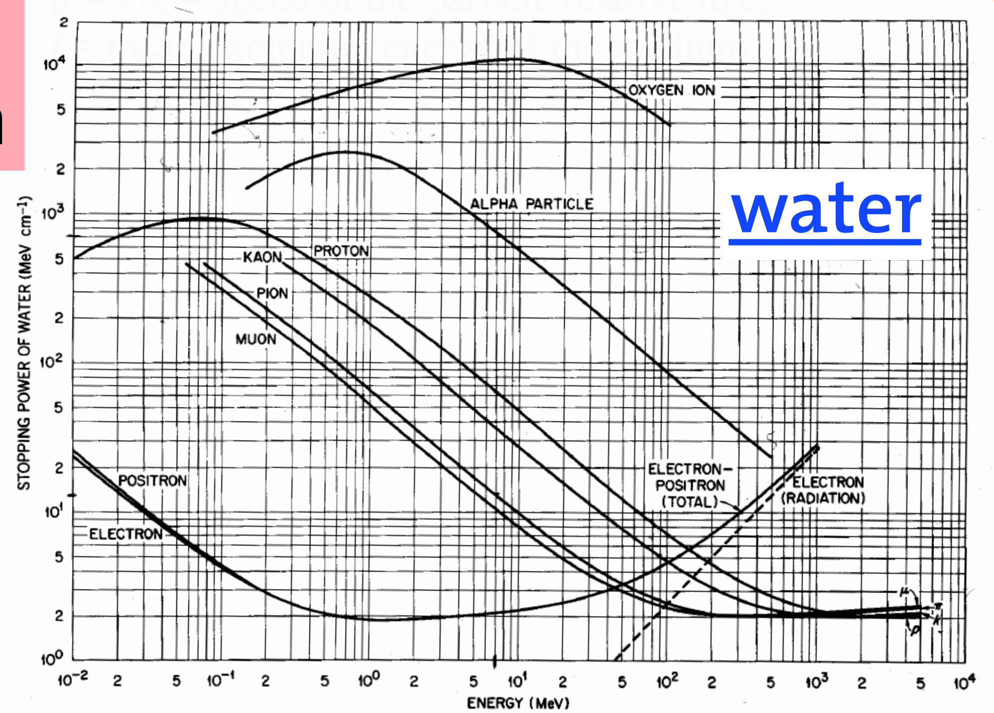
electronic density and mean excitation energy of the medium

• <u>mass stopping power</u> $-\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x}$

-similar for materials with similar atomic composition



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- **range**
  - distance traveled by the particle before coming to rest

$$R(K) = \int_0^K \mathrm{d}E \left(-\frac{\mathrm{d}E}{\mathrm{d}x} \right)^{-1}$$

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TABLE 5.3. Mass Stopping Power $-dE/\rho dx$ and Range R_p for Protons in Water

Kinetic Energy (MeV)	β^2	$-dE/\rho dx$ (MeV cm^2 g^{-1})	R_p (g cm^{-2})
0.01	.000021	500.	3×10^{-5}
0.04	.000085	860.	6×10^{-5}
0.05	.000107	910.	7×10^{-5}
0.08	.000171	920.	9×10^{-5}
0.10	.000213	910.	1×10^{-4}
0.50	.001065	428.	8×10^{-4}
1.00	.002129	270.	0.002
2.00	.004252	162.	0.007
4.00	.008476	95.4	0.023
6.00	.01267	69.3	0.047
8.00	.01685	55.0	0.079
10.0	.02099	45.9	0.118
12.0	.02511	39.5	0.168
14.0	.02920	34.9	0.217
16.0	.03327	31.3	0.280
18.0	.03731	28.5	0.342
20.0	.04133	26.1	0.418
25.0	.05126	21.8	0.623
30.0	.06104	18.7	0.864
35.0	.07066	16.5	1.14
40.0	.08014	14.9	1.46
45.0	.08948	13.5	1.80
50.0	.09867	12.4	2.18
60.0	.1166	10.8	3.03
70.0	.1341	9.55	4.00
80.0	.1510	8.62	5.08
90.0	.1675	7.88	6.27
100.	.1834	7.28	7.57
150.	.2568	5.44	15.5
200.	.3207	4.49	25.5
300.	.4260	3.52	50.6
400.	.5086	3.02	80.9
500.	.5746	2.74	115.
600.	.6281	2.55	152.
700.	.6721	2.42	192.
800.	.7088	2.33	234.
900.	.7396	2.26	277.
1000.	.7658	2.21	321.
2000.	.8981	2.05	795.
4000.	.9639	2.09	1780.

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  - ranges for two heavy particles with the same initial velocity

$$R_1(\beta) = \frac{z_2^2 M_1}{z_1^2 M_2} R_2(\beta)$$

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0.08	.000171	920.	9×10^{-5}
0.10	.000213	910.	1×10^{-4}
0.50	.001065	428.	8×10^{-4}
1.00	.002129	270.	0.002
2.00	.004252	162.	0.007
4.00	.008476	95.4	0.023
6.00	.01267	69.3	0.047
8.00	.01685	55.0	0.079
10.0	.02099	45.9	0.118
12.0	.02511	39.5	0.168
14.0	.02920	34.9	0.217
16.0	.03327	31.3	0.280
18.0	.03731	28.5	0.342
20.0	.04133	26.1	0.418
25.0	.05126	21.8	0.623
30.0	.06104	18.7	0.864
35.0	.07066	16.5	1.14
40.0	.08014	14.9	1.46
45.0	.08948	13.5	1.80
50.0	.09867	12.4	2.18
60.0	.1166	10.8	3.03
70.0	.1341	9.55	4.00
80.0	.1510	8.62	5.08
90.0	.1675	7.88	6.27
100.	.1834	7.28	7.57
150.	.2568	5.44	15.5
200.	.3207	4.49	25.5
300.	.4260	3.52	50.6
400.	.5086	3.02	80.9
500.	.5746	2.74	115.
600.	.6281	2.55	152.
700.	.6721	2.42	192.
800.	.7088	2.33	234.
900.	.7396	2.26	277.
1000.	.7658	2.21	321.
2000.	.8981	2.05	795.
4000.	.9639	2.09	1780.

2. Heavy charged particles

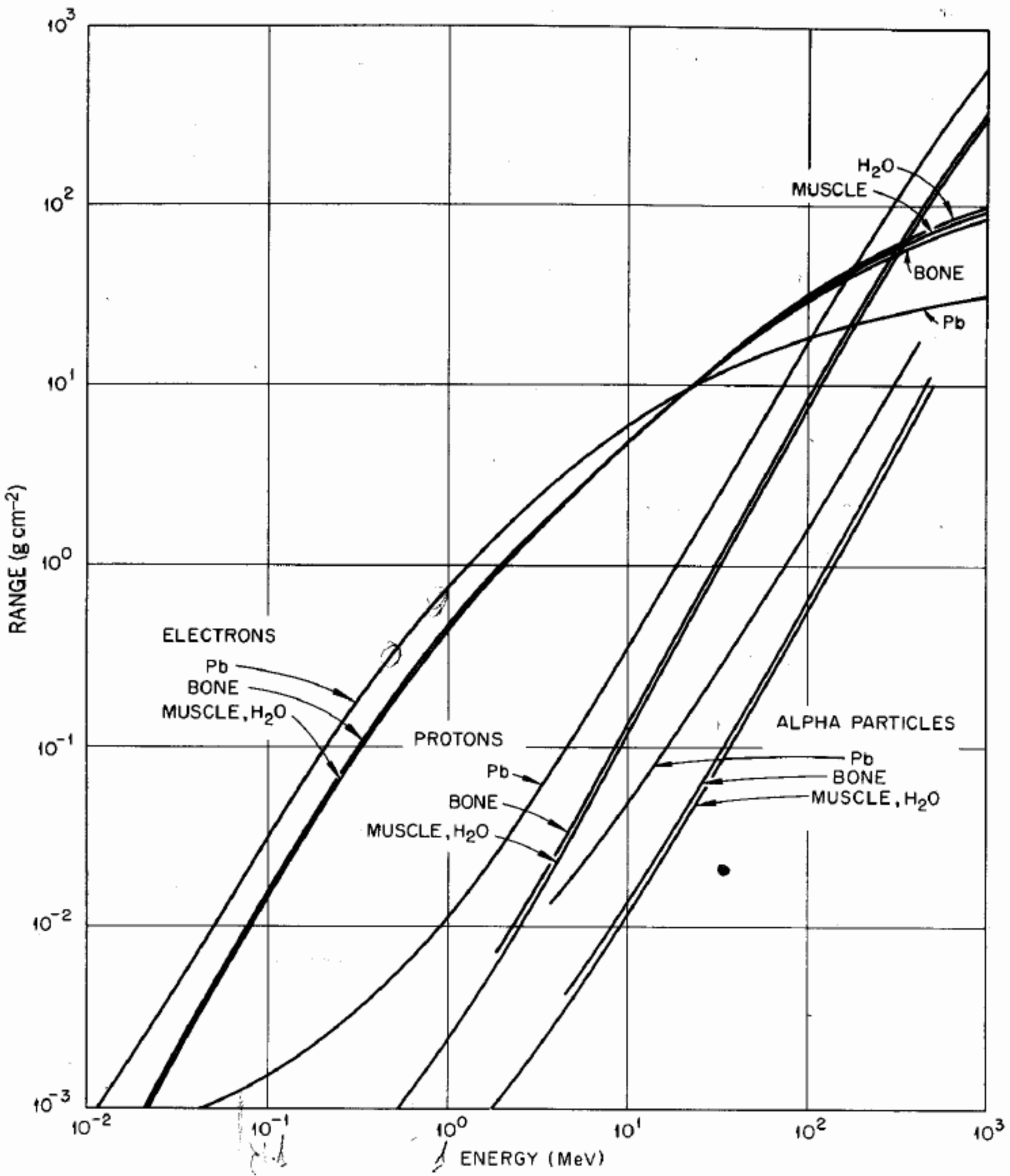

FIGURE 5.7. Ranges of protons, alpha particles, and electrons in water, muscle, bone, and lead, expressed in g cm^{-2}. (Courtesy Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc., for the Department of Energy.)

2. Heavy charged particles

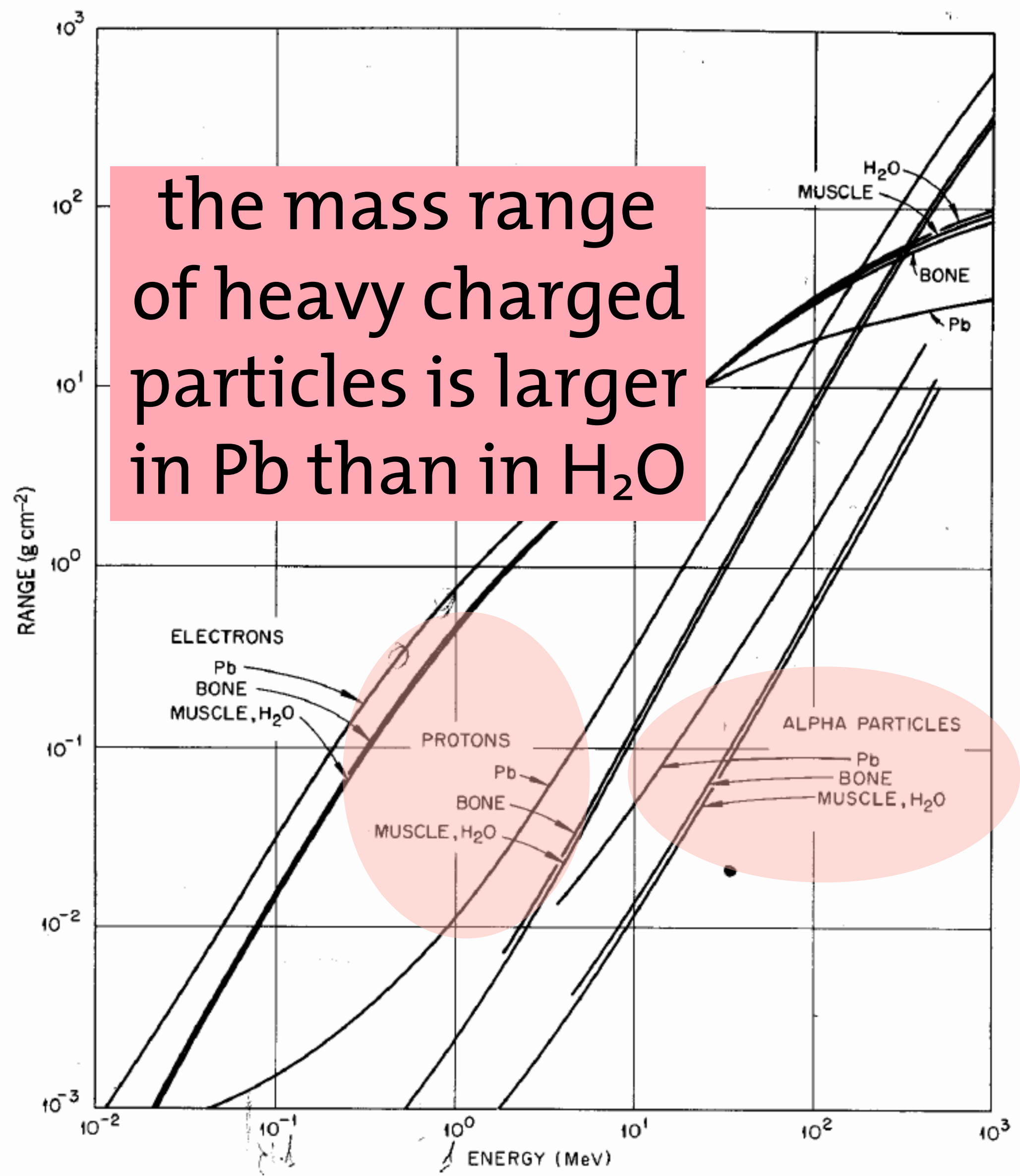

FIGURE 5.7. Ranges of protons, alpha particles, and electrons in water, muscle, bone, and lead, expressed in g cm^{-2}. (Courtesy Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc., for the Department of Energy.)

2. Heavy charged particles

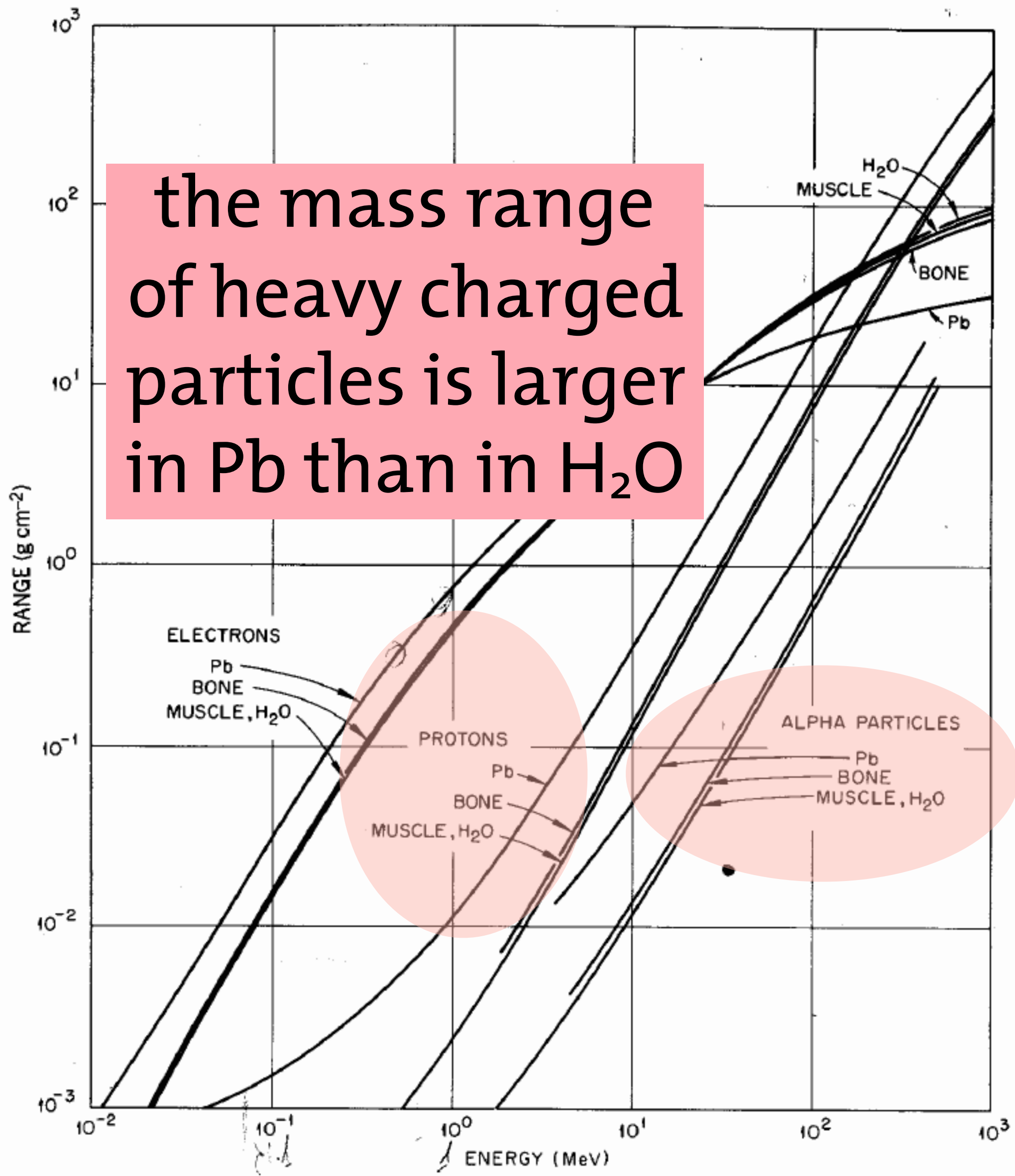

FIGURE 5.7. Ranges of protons, alpha particles, and electrons in water, muscle, bone, and lead, expressed in g cm^{-2}. (Courtesy Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc., for the Department of Energy.)

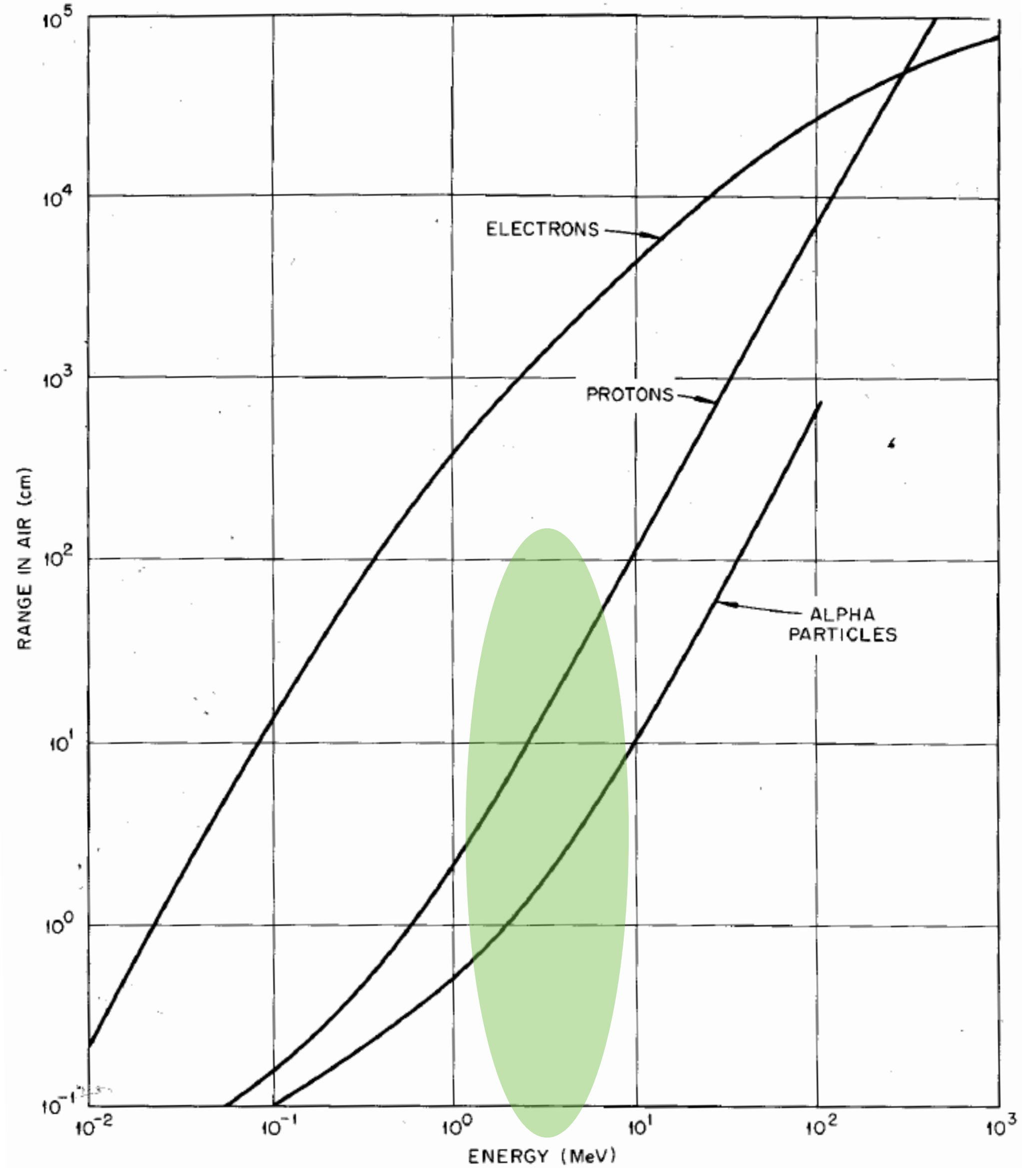

FIGURE 5.8. Ranges in cm of protons, alpha particles, and electrons in air at STP. (Courtesy Oak Ridge National Laboratory, operated by Martin Marietta Energy Systems, Inc., for the Department of Energy.)

3. Electron and positrons

3. Electron and positrons

- electrons and positrons ionize and excite material atoms

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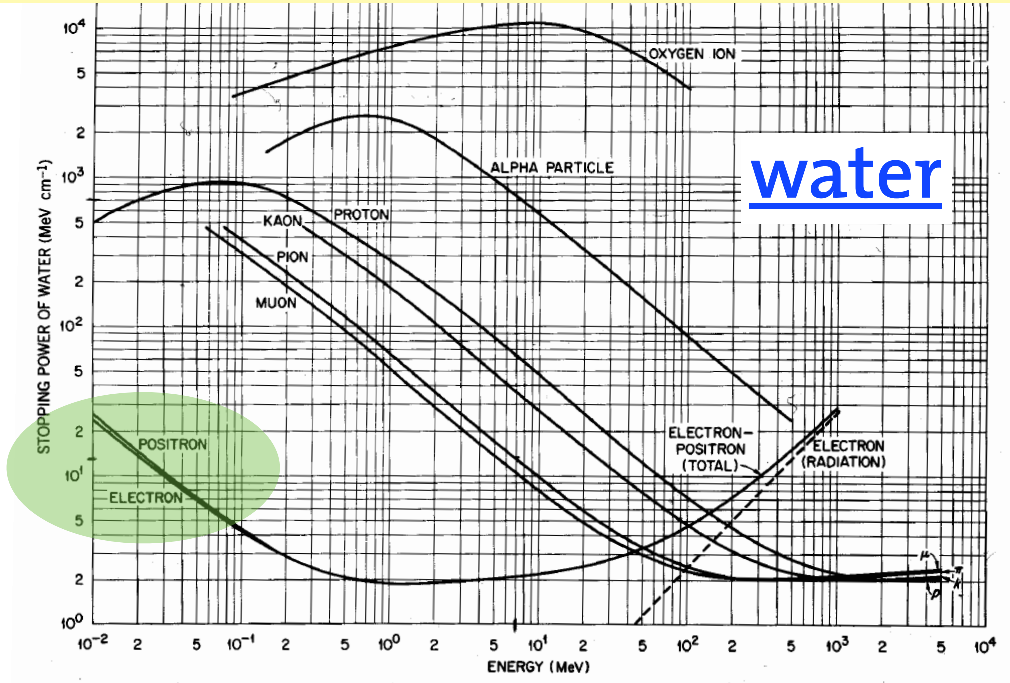

FIGURE 5.6. Stopping power of water in MeV cm^{-1} for various heavy charged particles and beta particles. The muon, pion, and kaon are elementary particles with rest masses equal, respectively, to about 207, 270, and 967 electron rest masses. (Courtesy Oak Ridge National Laboratory, operated by Martin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

3. Electron and positrons

- **stopping power**

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

- electrons and positrons ionize and excite material atoms

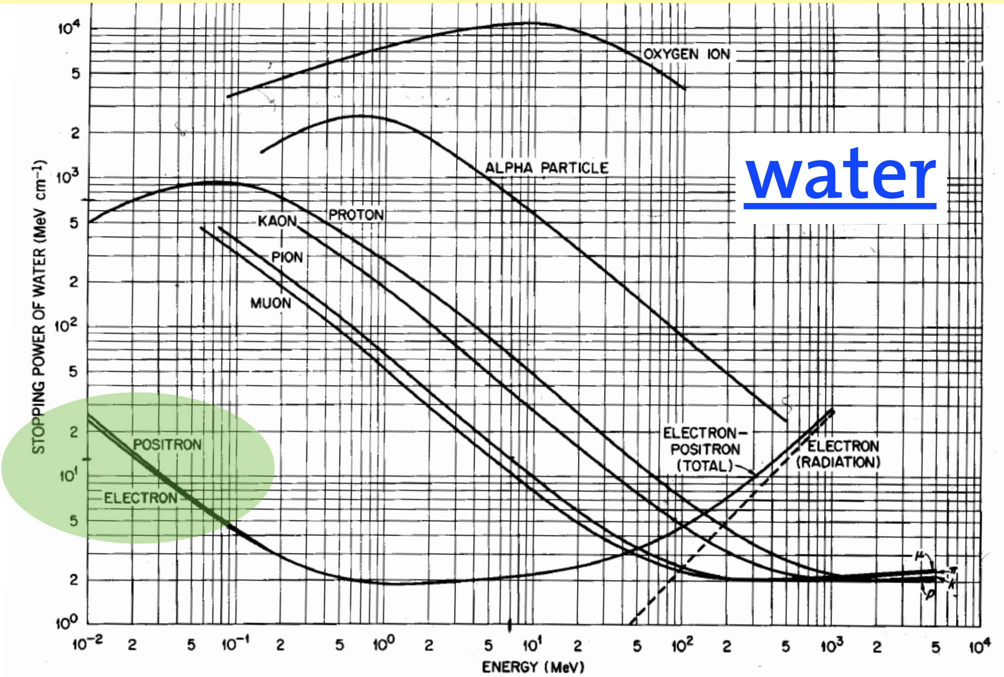

FIGURE 5.6. Stopping power of water in MeV cm^{-1} for various heavy charged particles and beta particles. The muon, pion, and kaon are elementary particles with rest masses equal, respectively, to about 207, 270, and 967 electron rest masses. (Courtesy Oak Ridge National Laboratory, operated by Martin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

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

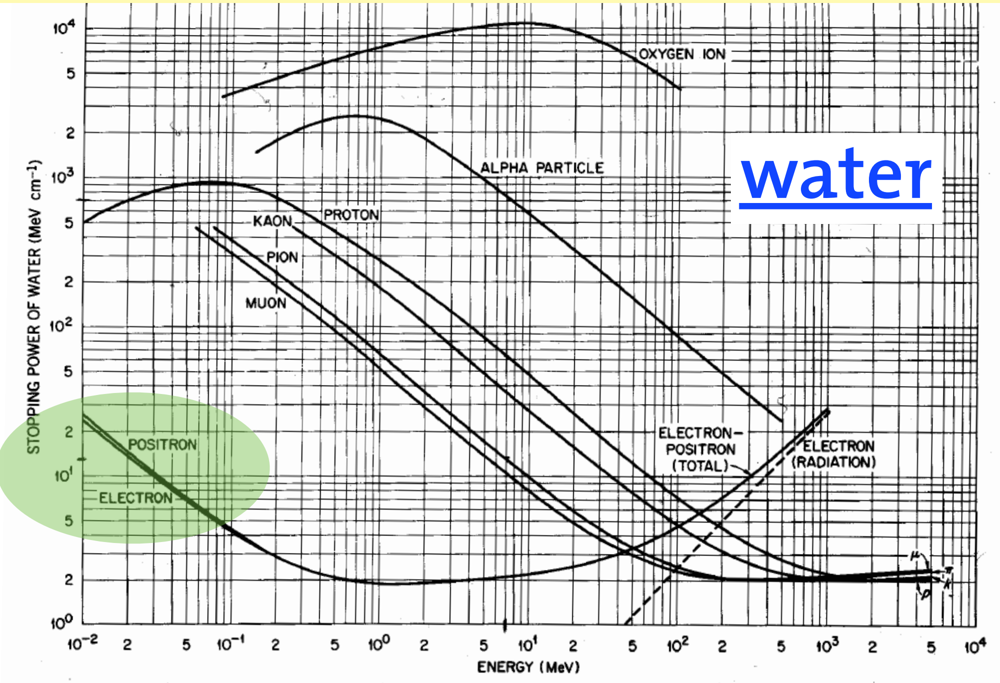

FIGURE 5.6. Stopping power of water in MeV cm^{-1} for various heavy charged particles and beta particles. The muon, pion, and kaon are elementary particles with rest masses equal, respectively, to about 207, 270, and 967 electron rest masses. (Courtesy Oak Ridge National Laboratory, operated by Martin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

• **collisional stopping power**

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

$$F^{-}(\beta) = \frac{1-\beta^2}{2}\left[1+\frac{\tau^2}{8} - (2\tau+1)\ln 2\right], \quad F^{+}(\beta) = \ln 2 - \frac{\beta^2}{24}\left[23+\frac{14}{\tau+2}+\frac{10}{(\tau+2)^2}+\frac{4}{(\tau+2)^3}\right]$$

3. Electron and positrons

- electrons and positrons ionize and excite material atoms

- **stopping power**

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

Kinetic Energy	β^2	$-\frac{1}{\rho}\left(\frac{dE}{dx}\right)^-_{col}$ (MeV cm² g⁻¹)	$-\frac{1}{\rho}\left(\frac{dE}{dx}\right)^-_{rad}$ (MeV cm² g⁻¹)	$-\frac{1}{\rho}\left(\frac{dE}{dx}\right)^-_{tot}$ (MeV cm² g⁻¹)	Radiation Yield
10 eV	0.00004	4.0	—	4.0	—
30	0.00012	44.	—	44.	—
50	0.00020	170.	—	170.	—
75	0.00029	272.	—	272.	—
100	0.00039	314.	—	314.	—
200	0.00078	298.	—	298.	—
500 eV	0.00195	194.	—	194.	—
1 keV	0.00390	126.	—	126.	—
2	0.00778	77.5	—	77.5	—
5	0.0193	42.6	—	42.6	—
10	0.0380	23.2	—	23.2	0.0001
25	0.0911	11.4	—	11.4	0.0002
50	0.170	6.75	—	6.75	0.0004
75	0.239	5.08	—	5.08	0.0006
100	0.301	4.20	—	4.20	0.0007
200	0.483	2.84	0.006	2.85	0.0012
500	0.745	2.06	0.010	2.07	0.0026
700 keV	0.822	1.94	0.013	1.95	0.0036
1 MeV	0.886	1.87	0.017	1.89	0.0049
4	0.987	1.91	0.065	1.98	0.0168
7	0.991	1.93	0.084	2.02	0.0208
10	0.998	2.00	0.183	2.18	0.0416
100	0.999+	2.20	2.40	4.60	0.317
1000 MeV	0.999+	2.40	26.3	28.7	0.774

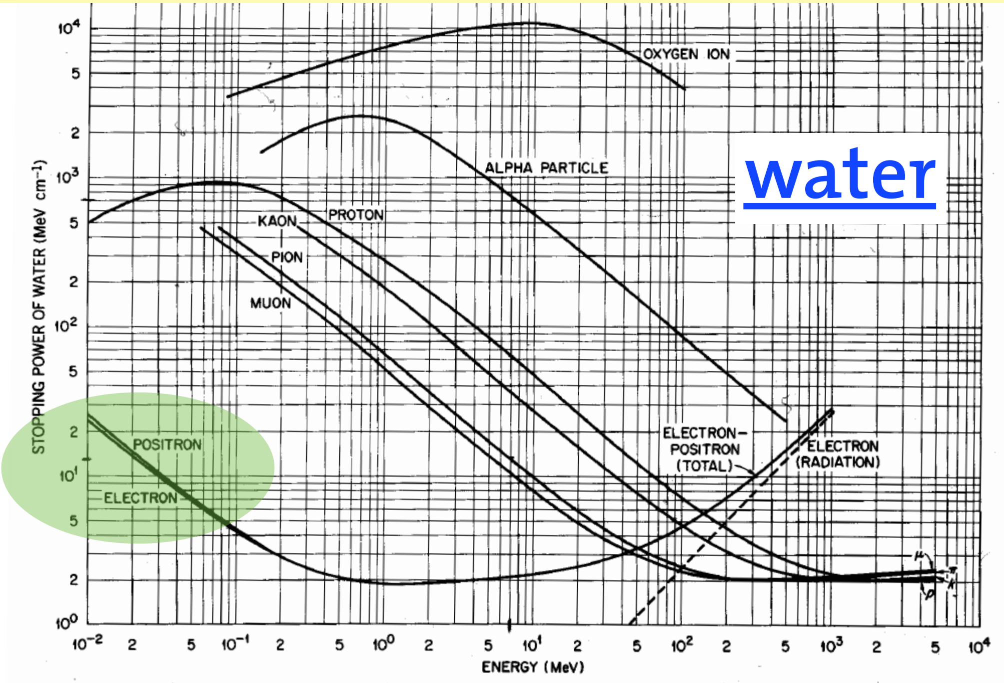

FIGURE 5.6. Stopping power of water in MeV cm^{-1} for various heavy charged particles and beta particles. The muon, pion, and kaon are elementary particles with rest masses equal, respectively, to about 207, 270, and 967 electron rest masses. (Courtesy Oak Ridge National Laboratory, operated by Martin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

- **collisional stopping power**

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

$$F^{-}(\beta) = \frac{1-\beta^2}{2}\left[1+\frac{\tau^2}{8}-(2\tau+1)\ln 2\right], \quad F^{+}(\beta) = \ln 2 - \frac{\beta^2}{24}\left[23+\frac{14}{\tau+2}+\frac{10}{(\tau+2)^2}+\frac{4}{(\tau+2)^3}\right]$$

3. Electron and positrons

- **stopping power**

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

- electrons and positrons ionize and excite material atoms

Kinetic Energy	β^2	$-\frac{1}{\rho}\left(\frac{dE}{dx}\right)^-_{col}$ (MeV cm² g⁻¹)	$-\frac{1}{\rho}\left(\frac{dE}{dx}\right)^-_{rad}$ (MeV cm² g⁻¹)	$-\frac{1}{\rho}\left(\frac{dE}{dx}\right)^-_{tot}$ (MeV cm² g⁻¹)	Radiation Yield
10 eV	0.00004	4.0	—	4.0	—
30	0.00012	44.	—	44.	—
50	0.00020	170.	—	170.	—
75	0.00029	272.	—	272.	—
100	0.00039	314.	—	314.	—
200	0.00078	298.	—	298.	—
500 eV	0.00195	194.	—	194.	—
1 keV	0.00390	126.	—	126.	—
2	0.00778	77.5	—	77.5	—
5	0.0193	42.6	—	42.6	—
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1 MeV	0.886	1.87	0.017	1.89	0.0049
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10	0.998	2.00	0.183	2.18	0.0416
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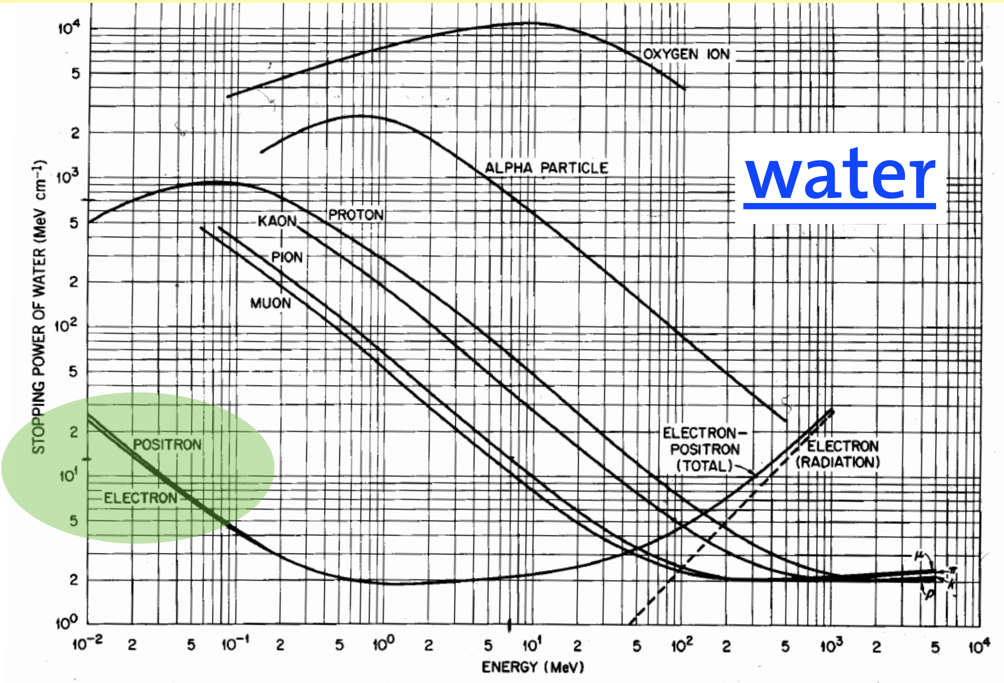

FIGURE 5.6. Stopping power of water in MeV cm⁻¹ for various heavy charged particles and beta particles. The muon, pion, and kaon are elementary particles with rest masses equal, respectively, to about 207, 270, and 967 electron rest masses. (Courtesy Oak Ridge National Laboratory, operated by Martin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

$$\frac{\left(-\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{\pm}_{\mathrm{rad}}}{\left(-\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{\pm}_{\mathrm{col}}} \simeq \frac{ZE}{800}$$

- **collisional stopping power**

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

$$F^-(\beta) = \frac{1-\beta^2}{2}\left[1 + \frac{\tau^2}{8} - (2\tau+1)\ln 2\right], \quad F^+(\beta) = \ln 2 - \frac{\beta^2}{24}\left[23 + \frac{14}{\tau+2} + \frac{10}{(\tau+2)^2} + \frac{4}{(\tau+2)^3}\right]$$

3. Electron and positrons

- electrons and positrons ionize and excite material atoms

• stopping power

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

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
10 eV	0.00004	4.0	—	4.0	—
30	0.00012	44.	—	44.	—
50	0.00020	170.	—	170.	—
75	0.00029	272.	—	272.	—
100	0.00039	314.	—	314.	—
200	0.00078	298.	—	298.	—
500 eV	0.00195	194.	—	194.	—
1 keV	0.00390	126.	—	126.	—
2	0.00778	77.5	—	77.5	—
5	0.0193	42.6	—	42.6	—
10	0.0380	23.2	—	23.2	0.0001
25	0.0911	11.4	—	11.4	0.0002
50	0.170	6.75	—	6.75	0.0004
75	0.239	5.08	—	5.08	0.0006
100	0.301	4.20	—	4.20	0.0007
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1 MeV	0.886	1.87	0.017	1.89	0.0049
4	0.987	1.91	0.065	1.98	0.0168
7	0.991	1.93	0.084	2.02	0.0208
10	0.998	2.00	0.183	2.18	0.0416
100	0.999+	2.20	2.40	4.60	0.317
1000 MeV	0.999+	2.40	26.3	28.7	0.774

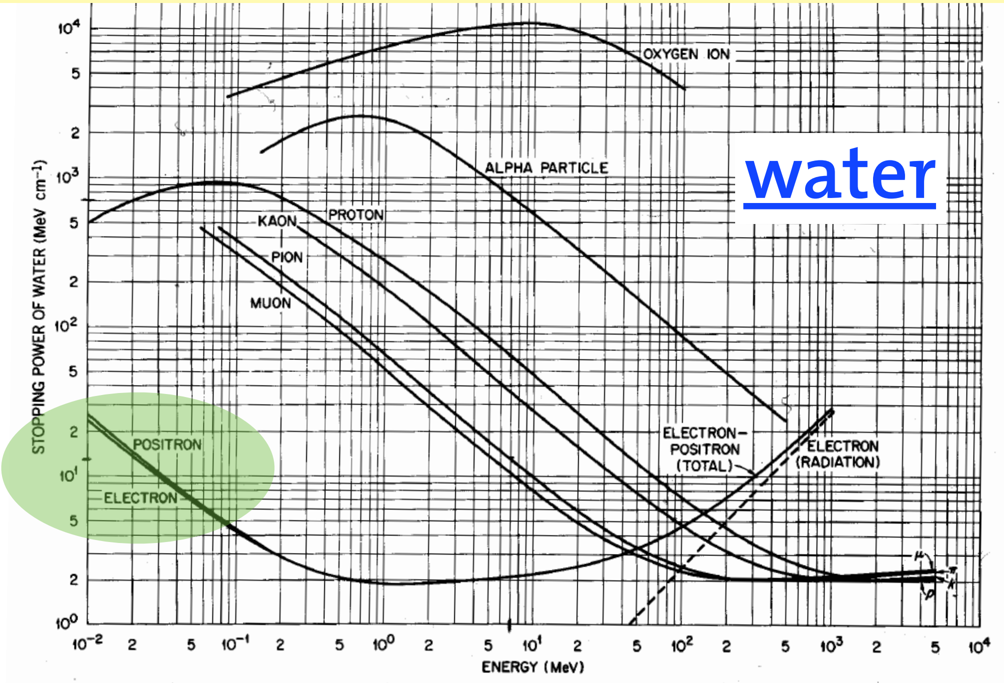


FIGURE 5.6. Stopping power of water in MeV cm^{-1} for various heavy charged particles and beta particles. The muon, pion, and kaon are elementary particles with rest masses equal, respectively, to about 207, 270, and 967 electron rest masses. (Courtesy Oak Ridge National Laboratory, operated by Martin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

$$\frac{\left(-\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{\pm}_{\mathrm{rad}}}{\left(-\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{\pm}_{\mathrm{col}}} \simeq \frac{ZE}{800}$$

radiation yield

$$Y \simeq \frac{6\cdot 10^{-4} Z T}{1 + 6\cdot 10^{-4} Z T}$$

• collisional stopping power

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

$$F^{-}(\beta) = \frac{1-\beta^2}{2}\left[1 + \frac{\tau^2}{8} - (2\tau+1)\ln 2\right], \quad F^{+}(\beta) = \ln 2 - \frac{\beta^2}{24}\left[23 + \frac{14}{\tau+2} + \frac{10}{(\tau+2)^2} + \frac{4}{(\tau+2)^3}\right]$$

3. Electron and positrons

3. Electron and positrons

- **range**
  - distance traveled by the particle before coming to rest

$$R(K) = \int_0^K \mathrm{d}E \left(-\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{-1}$$

3. Electron and positrons

- range
  - distance traveled by the particle before coming to rest

$$R(K) = \int_0^K \mathrm{d}E \left(-\frac{\mathrm{d}E}{\mathrm{d}x} \right)^{-1}$$

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.

3. Electron and positrons

- **range**
  - distance traveled by the particle before coming to rest

$$R(K) = \int_0^K \mathrm{d}E \left(-\frac{\mathrm{d}E}{\mathrm{d}x}\right)^{-1}$$

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.

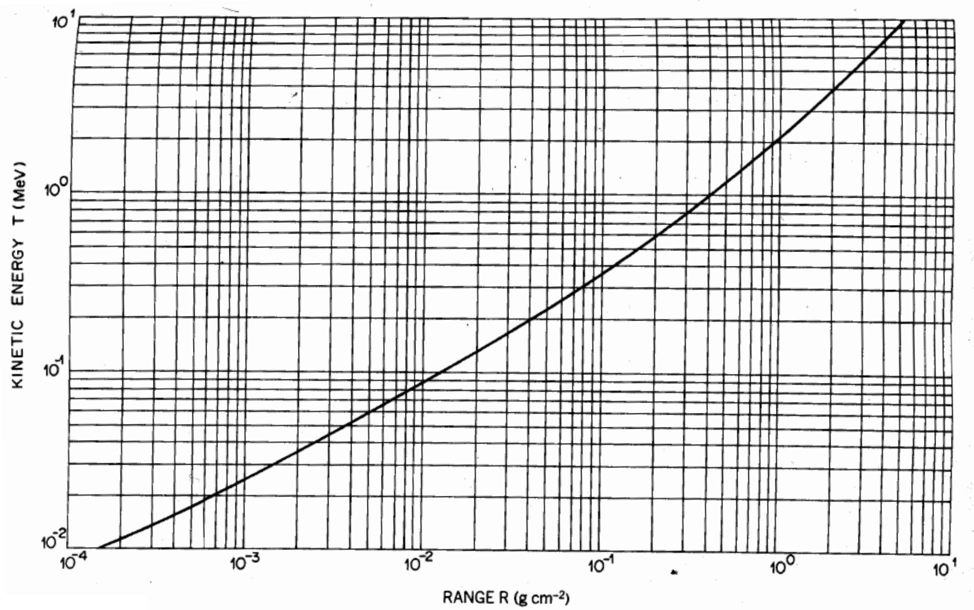


FIGURE 6.4. Beta-particle range–energy curve for materials of low atomic number. [From U.S. Public Health Service, *Radiological Health Handbook*, Publ. No. 2016, Bureau of Radiological Health, Rockville, MD (1970).]

3. Electron and positrons

3. Electron and positrons

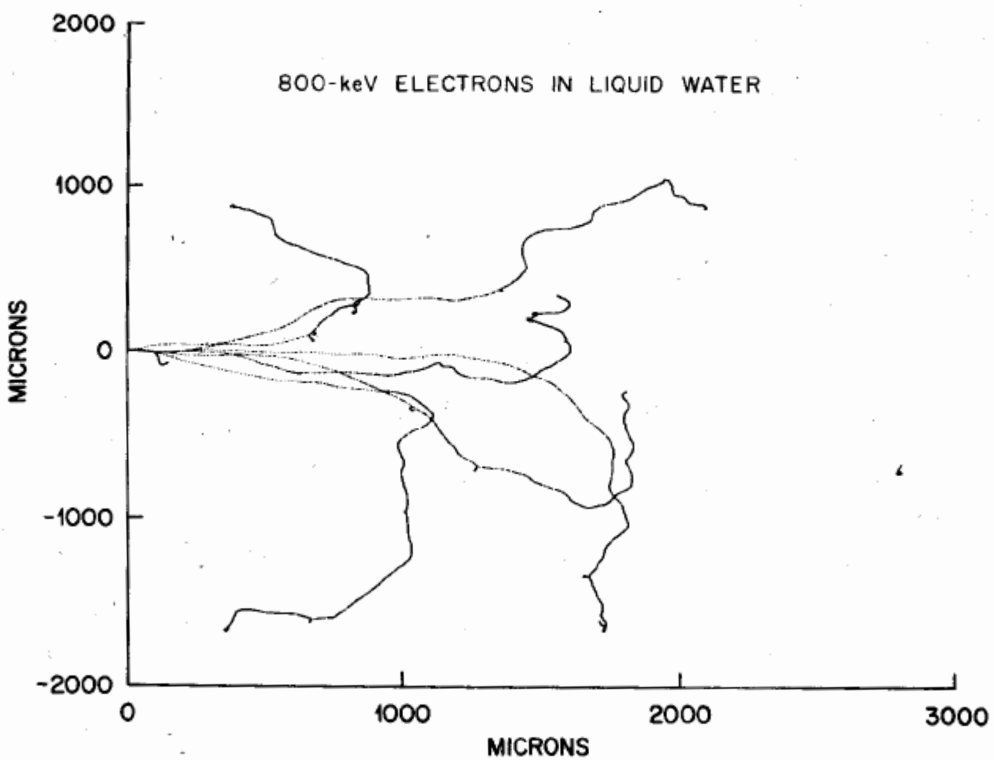


FIGURE 6.7. Calculated tracks (projected into the plane of the figure) of 800-keV electrons in water. Each electron starts moving horizontally toward the right from the point 0 on the vertical axis.

3. Electron and positrons

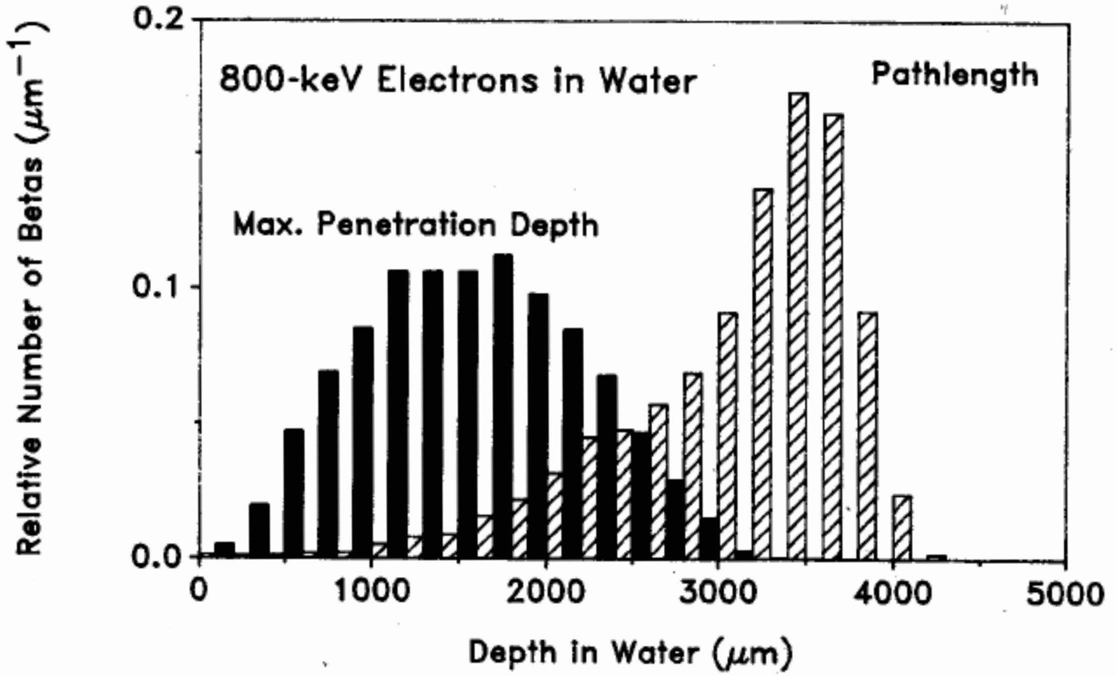


FIGURE 6.8. Distributions in pathlength and in maximum depth of penetration for 800-keV electrons in water.

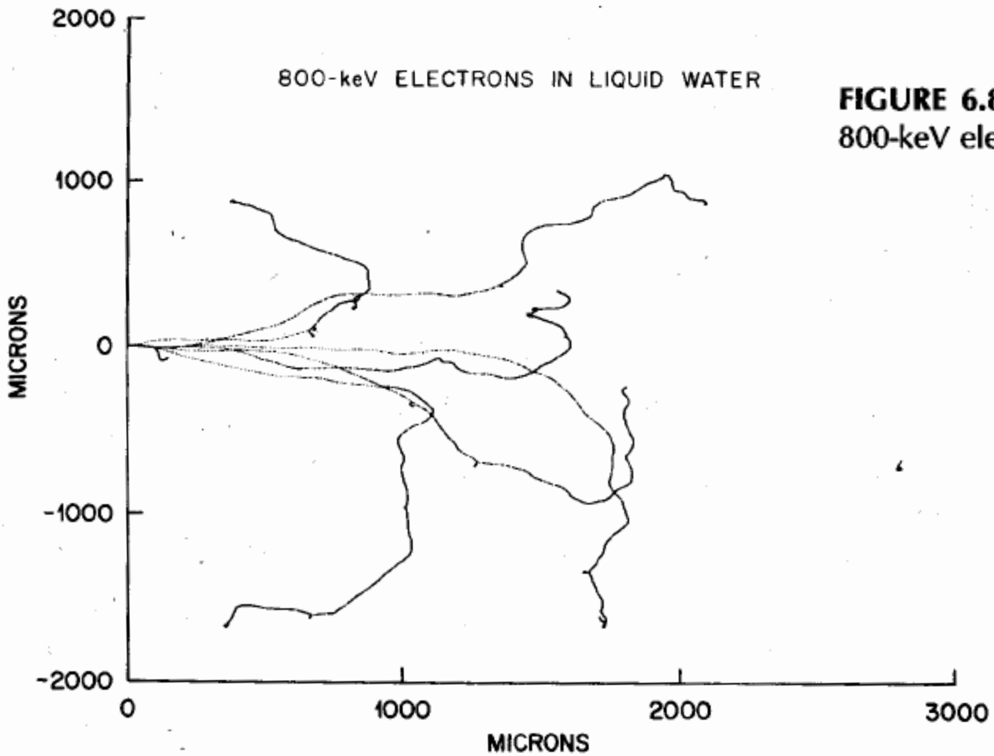
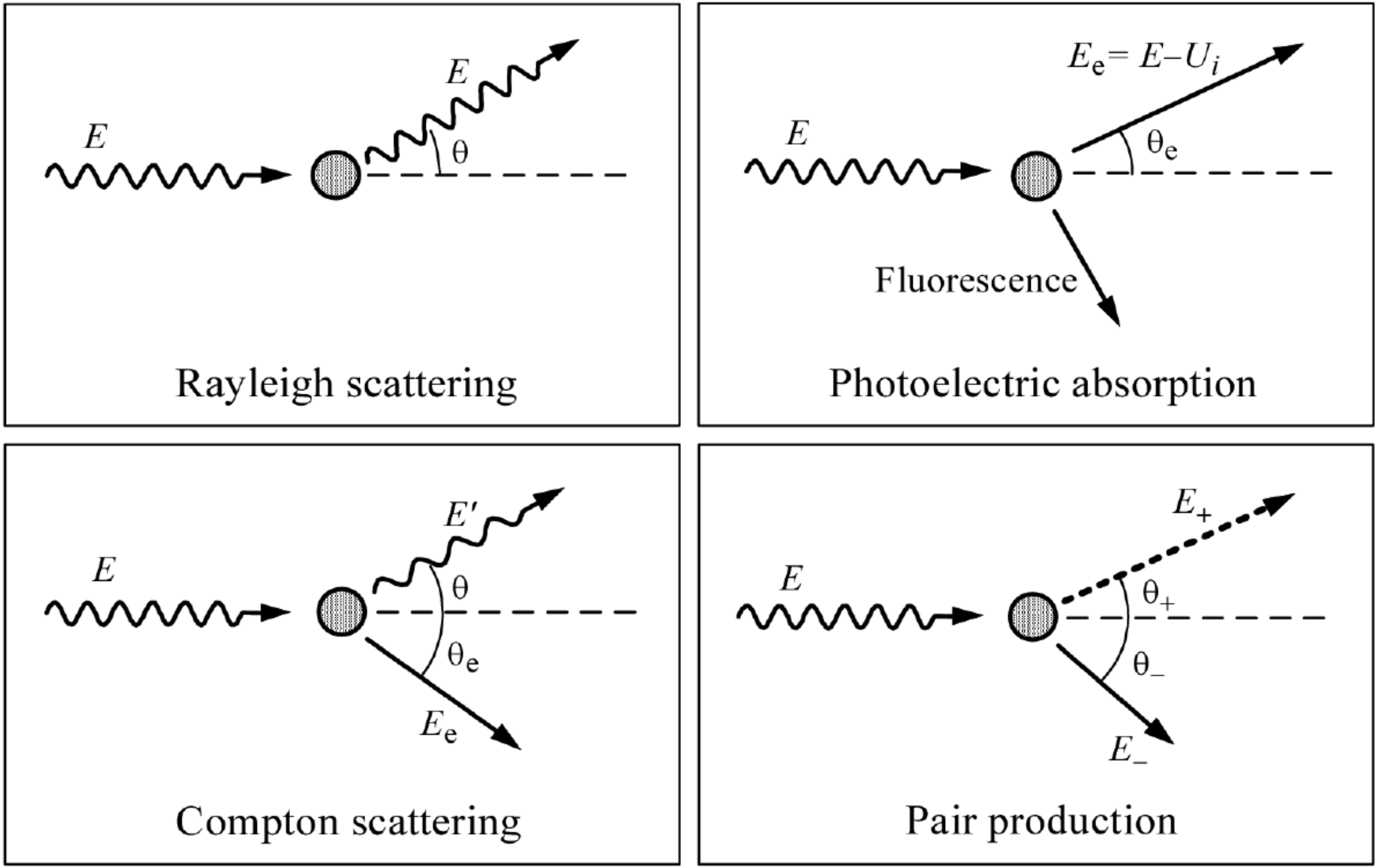


FIGURE 6.7. Calculated tracks (projected into the plane of the figure) of 800-keV electrons in water. Each electron starts moving horizontally toward the right from the point 0 on the vertical axis.

4. Photons

photon interactions

photon interactions



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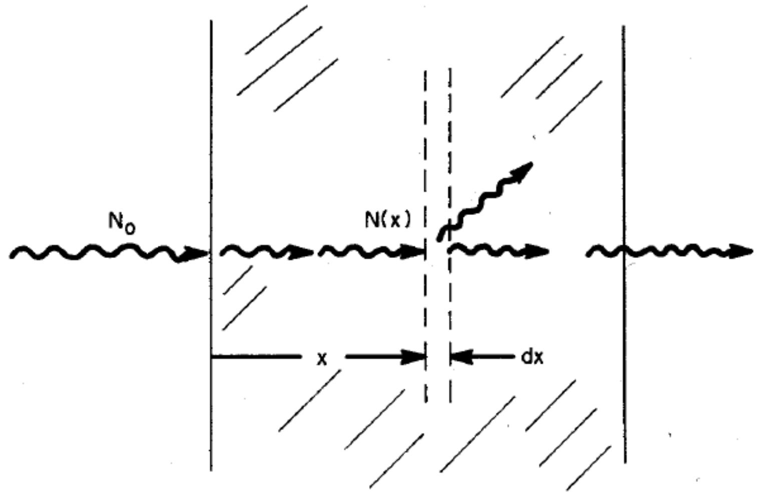

FIGURE 8.6. Pencil beam of N_0 monoenergetic photons incident on slab. The number of photons that reach a depth x without having an interaction is given by $N(x) = N_0 e^{-\mu x}$, where μ is the linear attenuation coefficient.

- <u>linear attenuation coefficient</u>
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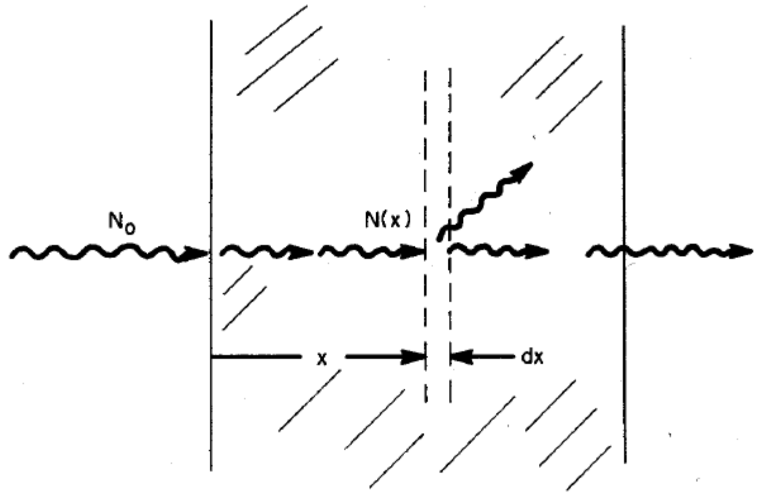
$$\mathrm{d}N(x) = -\mu\, N(x)\, \mathrm{d}x$$
$$\Downarrow$$
$$N(x) = N_0 \, \exp(-\mu x)$$



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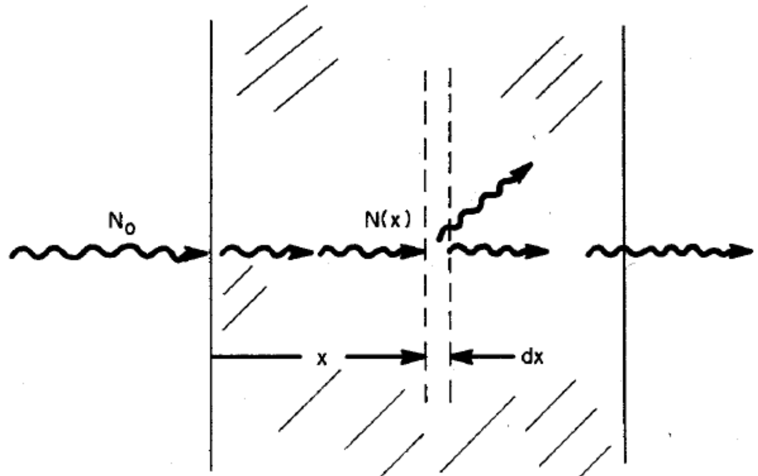

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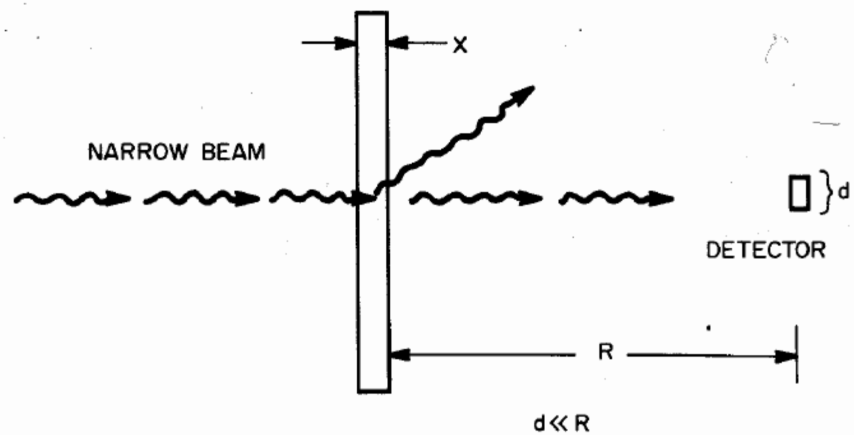

FIGURE 8.7. Illustration of "good" scattering geometry for measuring linear attenuation coefficient μ. Photons from a *narrow* beam that are absorbed or scattered by the absorber do not reach a small detector placed in beam line some distance away.

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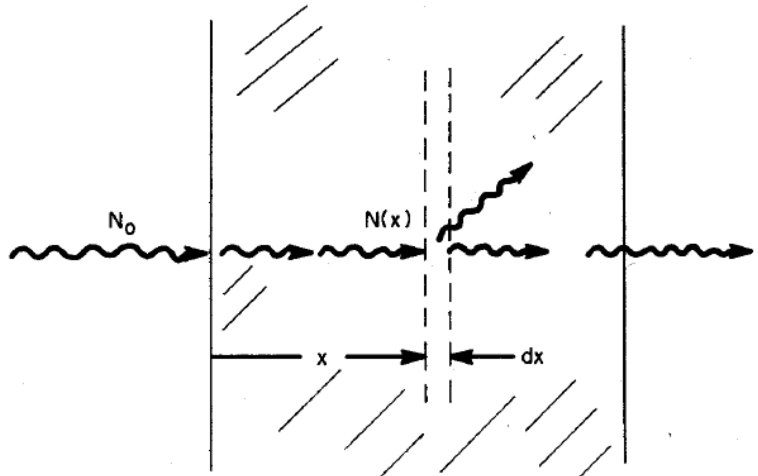

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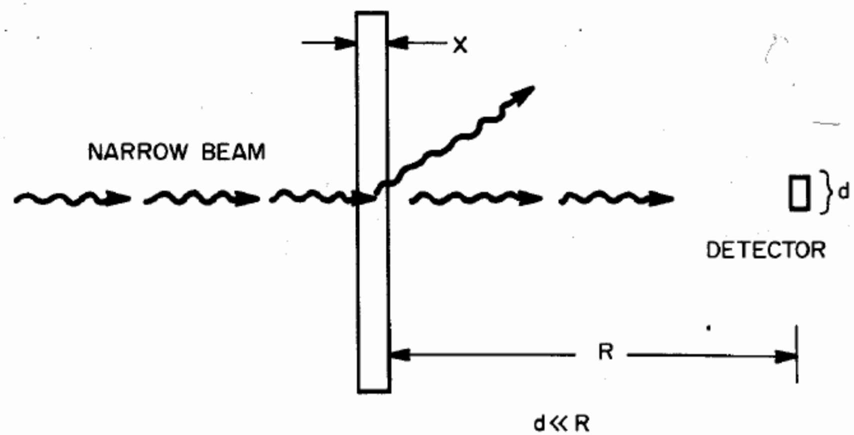
$$\exp(-\mu x) = N(x)/N_0$$

probability that a normally incident photon will traverse a slab of thickness *x* without interacting



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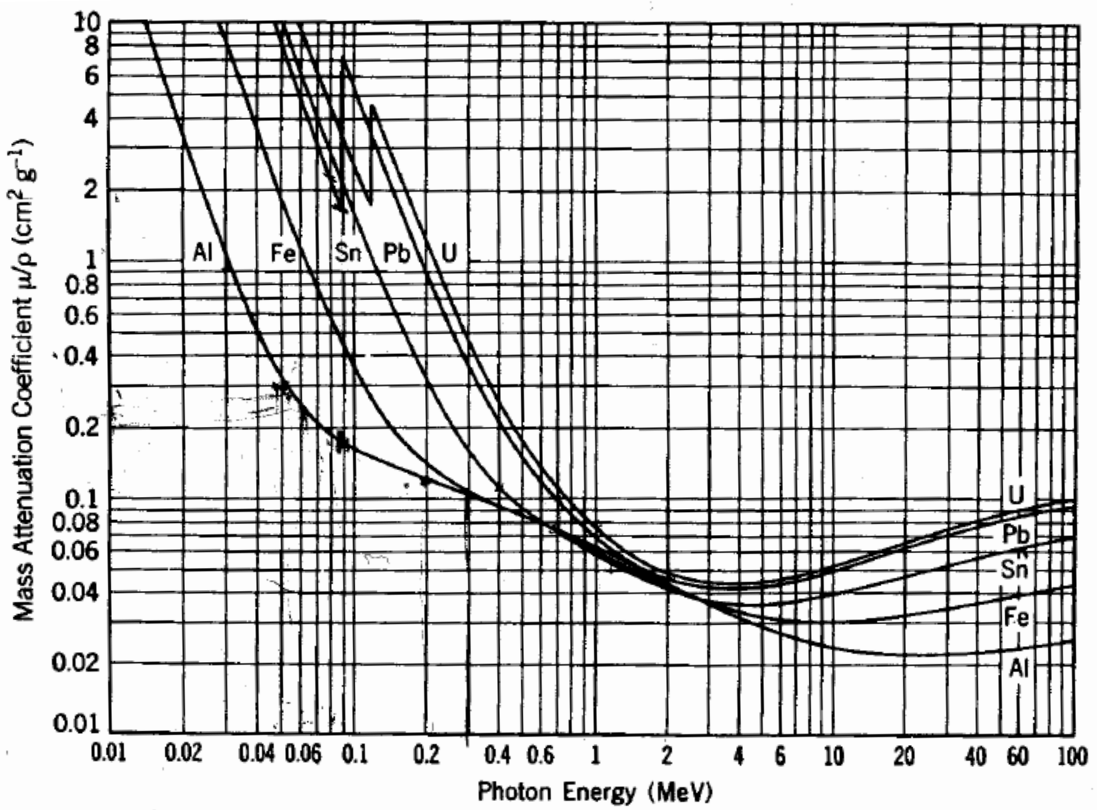

FIGURE 8.8. Mass attenuation coefficients for various elements. [Reprinted with permission from K. Z. Morgan and J. E. Turner, eds., *Principles of Radiation Protection*, Wiley, New York (1967). Copyright 1967 by John Wiley & Sons.]

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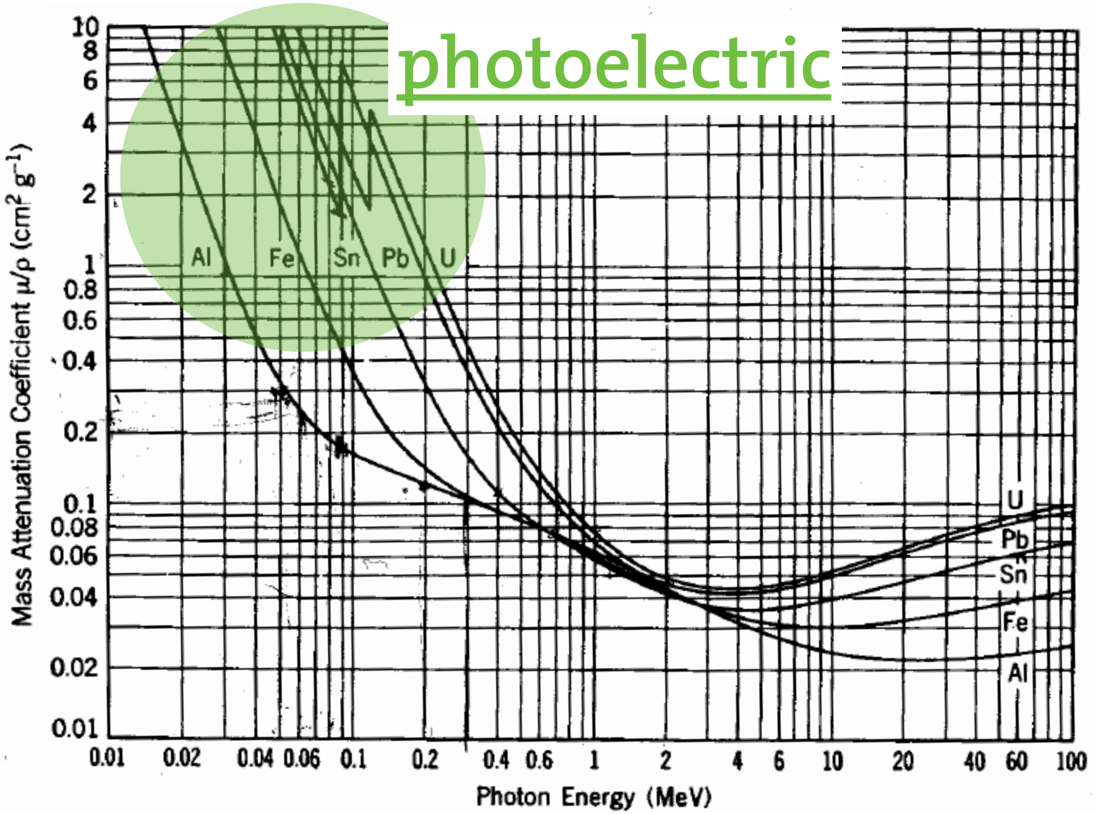

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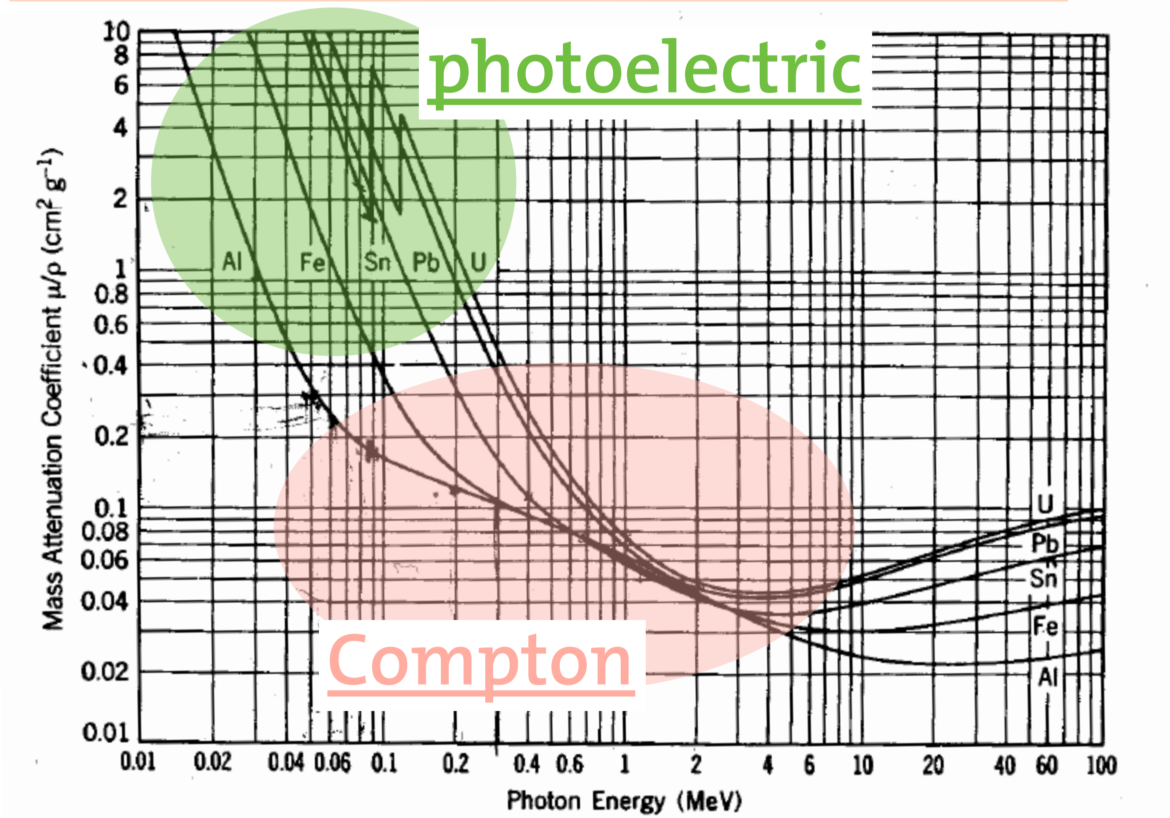

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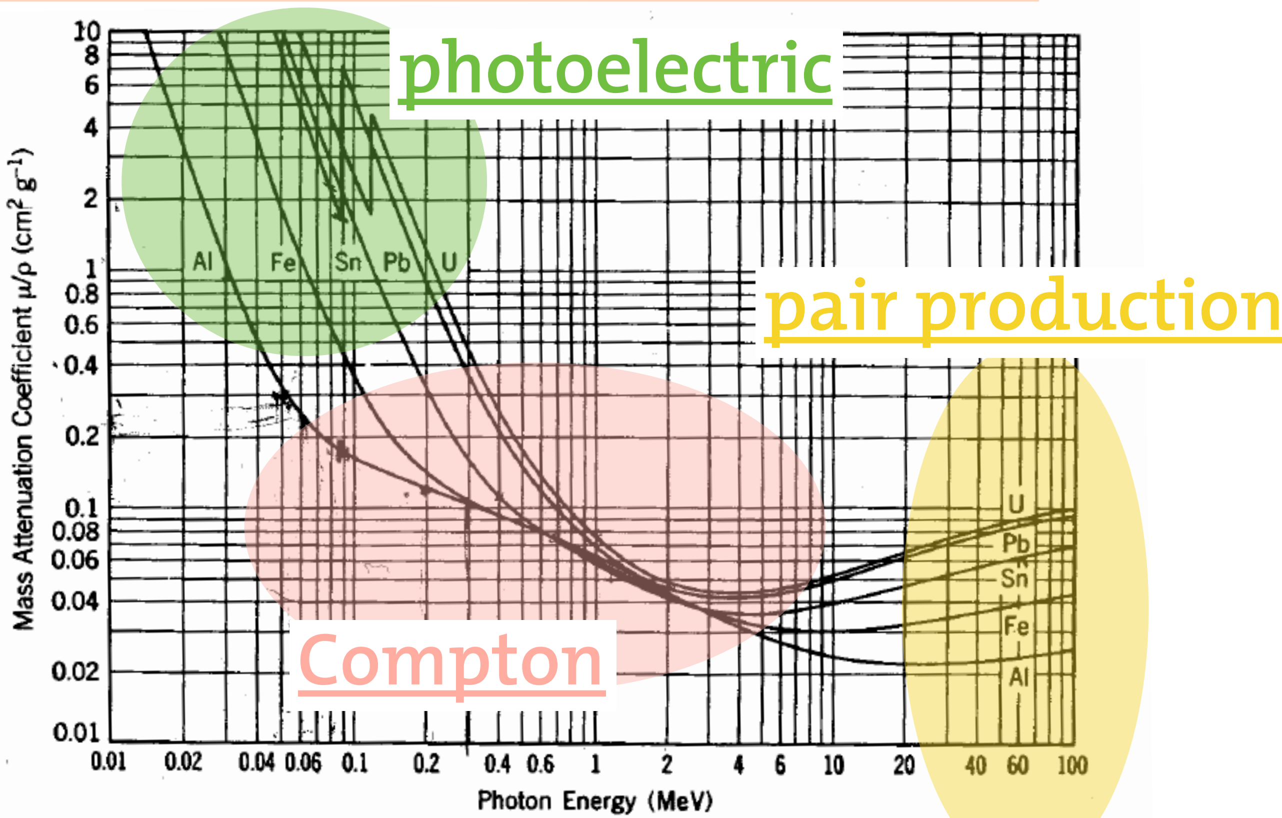

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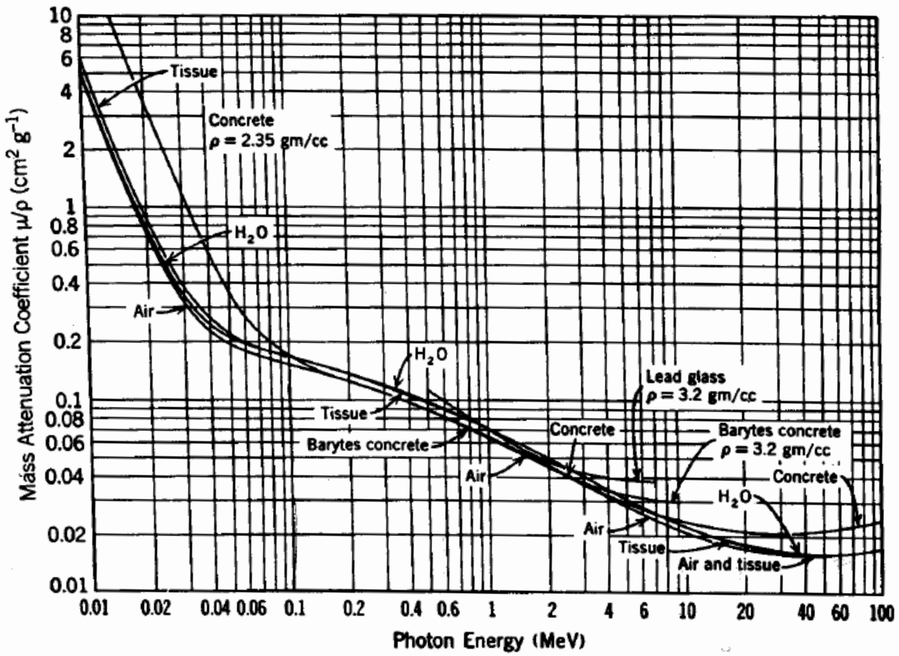
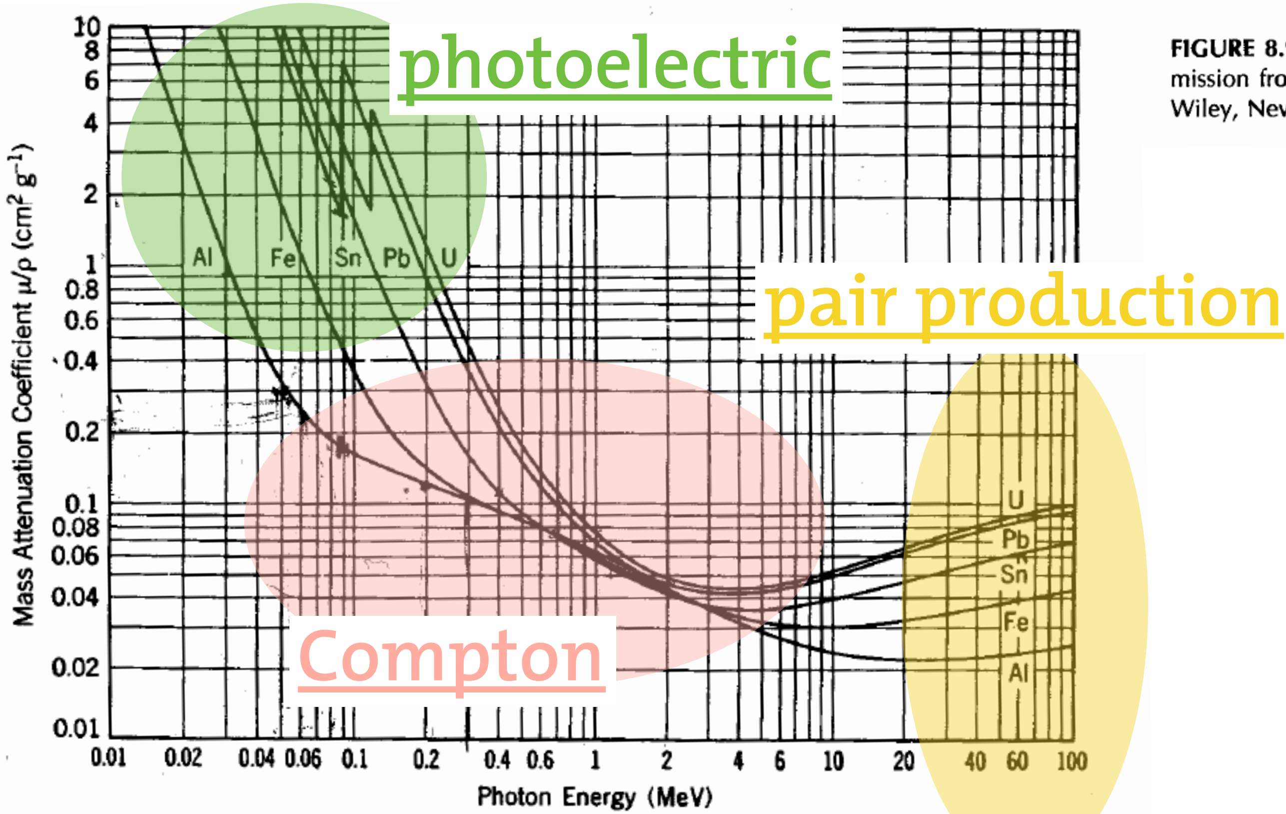


FIGURE 8.9. Mass attenuation coefficients for various materials. [Reprinted with permission from K. Z. Morgan and J. E. Turner, eds., *Principles of Radiation Protection*, Wiley, New York (1967). Copyright 1967 by John Wiley & Sons.]



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- **energy transfer coefficients**
  - not all energy delivered by the incident photons is transferred to electrons (which are those actually depositing the energy in the material)

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x-rays, Auger electrons

$$\frac{\mu_{\mathrm{ph}}^{\mathrm{tr}}}{\rho} = \frac{\mu_{\mathrm{ph}}}{\rho}\left(1 - \frac{\delta}{h\nu}\right)$$

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  - electrons may produce Bremsstrahlung photons

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TABLE 8.3. Mass Attenuation, Mass Energy-Transfer, and Mass Energy-Absorption Coefficients ($cm^2\ g^{-1}$) for Photons in Water and Lead

Photon Energy (MeV)	Water			Lead		
	μ/ρ	μ_{tr}/ρ	μ_{en}/ρ	μ/ρ	μ_{tr}/ρ	μ_{en}/ρ
0.01	5.33	4.95	4.95	131.	126.	126.
0.10	0.171	0.0255	0.0255	5.55	2.16	2.16
1.0	0.0708	0.0311	0.0310	0.0710	0.0389	0.0379
10.0	0.0222	0.0163	0.0157	0.0497	0.0418	0.0325
100.0	0.0173	0.0167	0.0122	0.0931	0.0918	0.0323

Source: Based on P. D. Higgins, F. H. Attix, J. H. Hubbell, S. M. Seltzer, M. J. Berger, and C. H. Sibata, *Mass Energy-Transfer and Mass Energy-Absorption Coefficients, Including In-Flight Positron Annihilation for Photon Energies 1 keV to 100 MeV*, NISTIR 4680, National Institute of Standards and Technology, Gaithersburg, MD (1991).

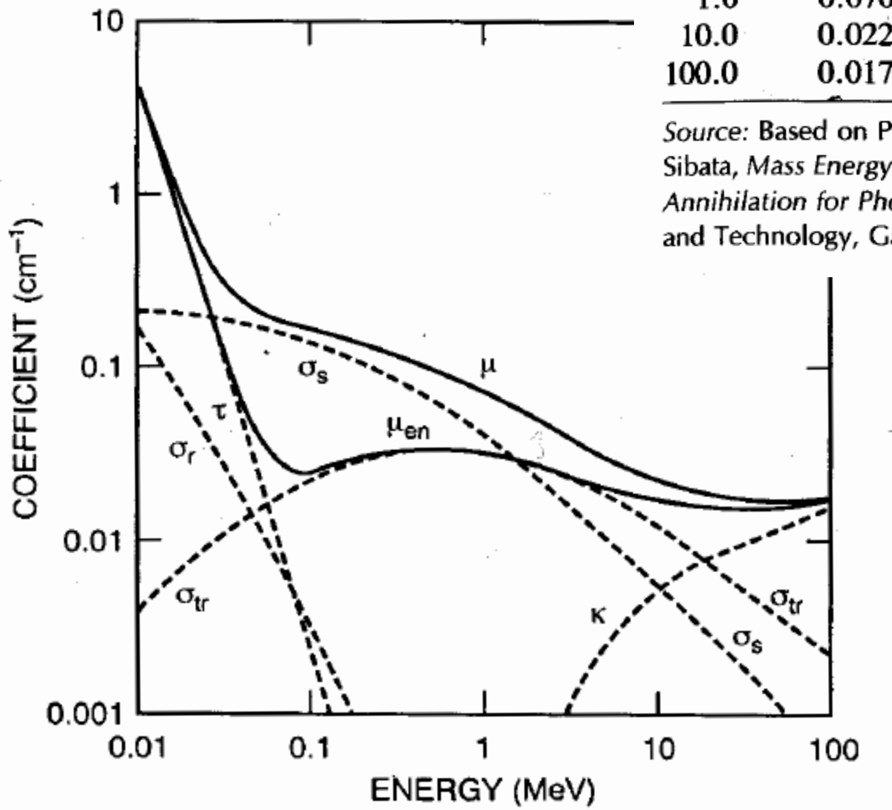

FIGURE 8.13. Linear attenuation and energy-absorption coefficients as functions of energy for photons in water.

5. Neutrons

nuclear reactions:
production and interaction

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- cannot be accelerated !

‣ produced at a high energy and then moderated

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Thermal	~0.025 eV
Epithermal	~1 eV
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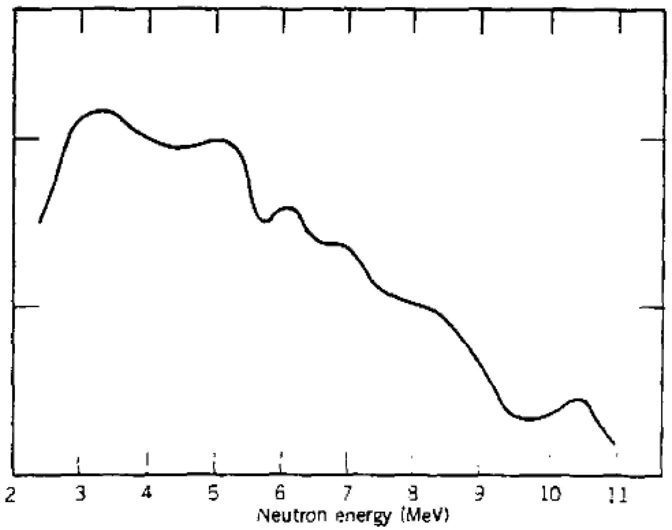

^{226}Ra
^{210}Po
^{239}Pu
^{241}Am

Figure 12.1 Neutron energy spectrum from a Ra-Be source, measured with a proton recoil counter. Several neutron groups are present; they result from reactions induced by α's with differing energies and in which the ^{12}C is left either in the ground state or the 4.43- or 7.6-MeV excited states.

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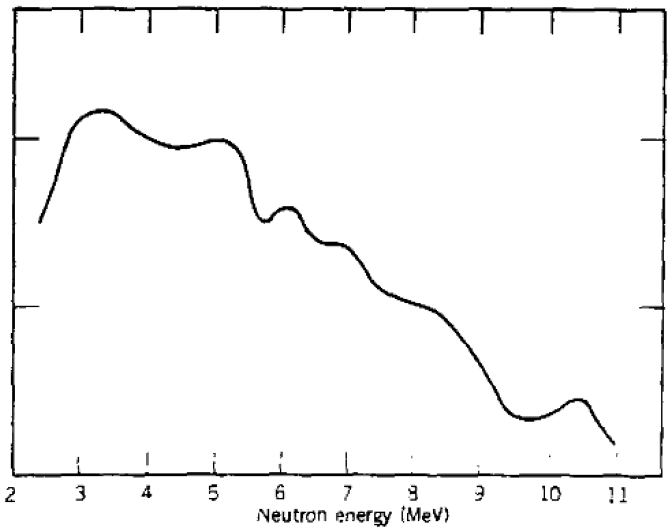

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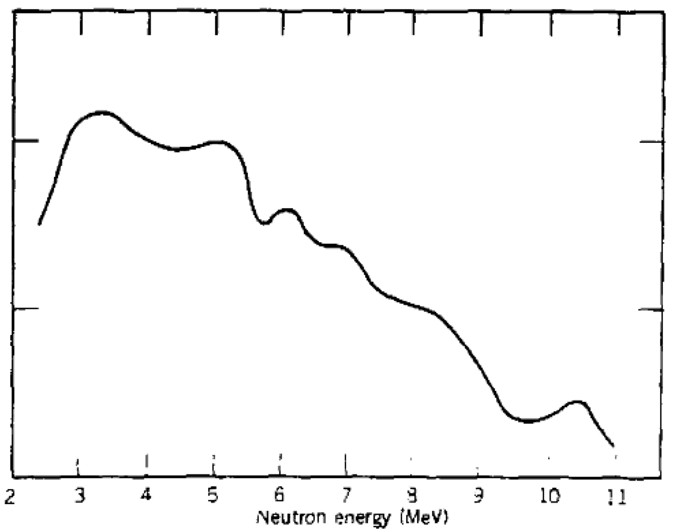

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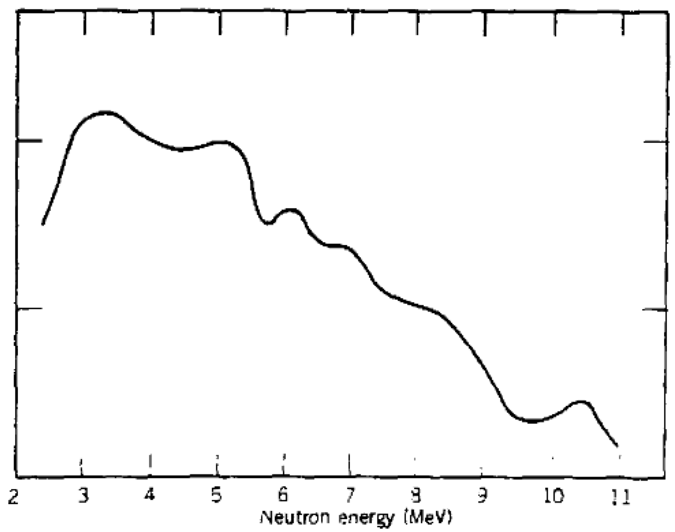

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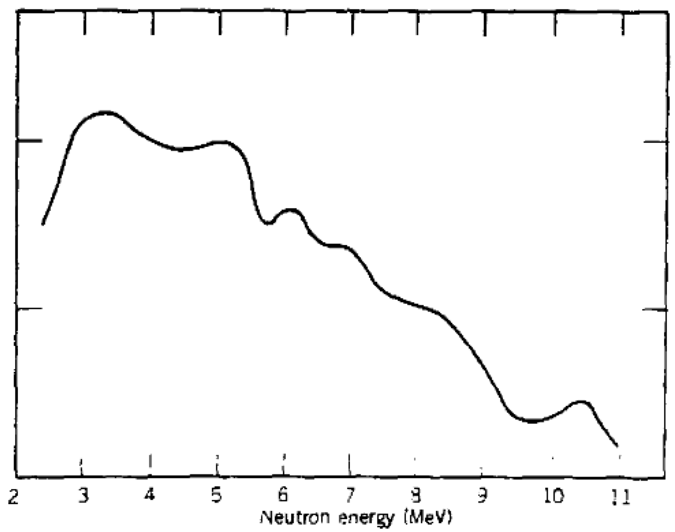

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reaction	Q (MeV)
$^{3}H(d,n)^{4}He$	17.6
$^{2}H(d,n)^{3}He$	3.3
$^{12}C(d,n)^{13}N$	-0.3
$^{3}H(p,n)^{3}He$	-0.8
$^{7}Li(p,n)^{7}Be$	-1.7

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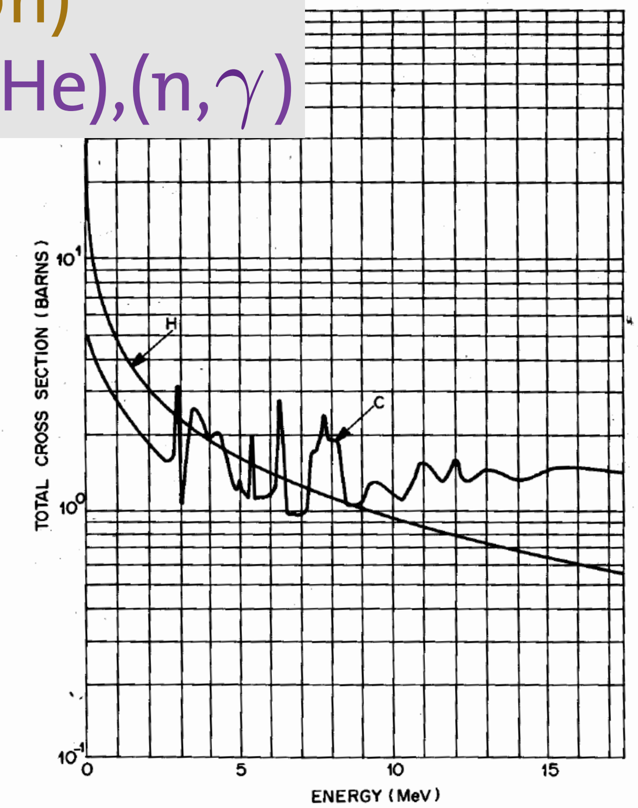

FIGURE 9.2. Total cross sections for neutrons with hydrogen and carbon as functions of energy.

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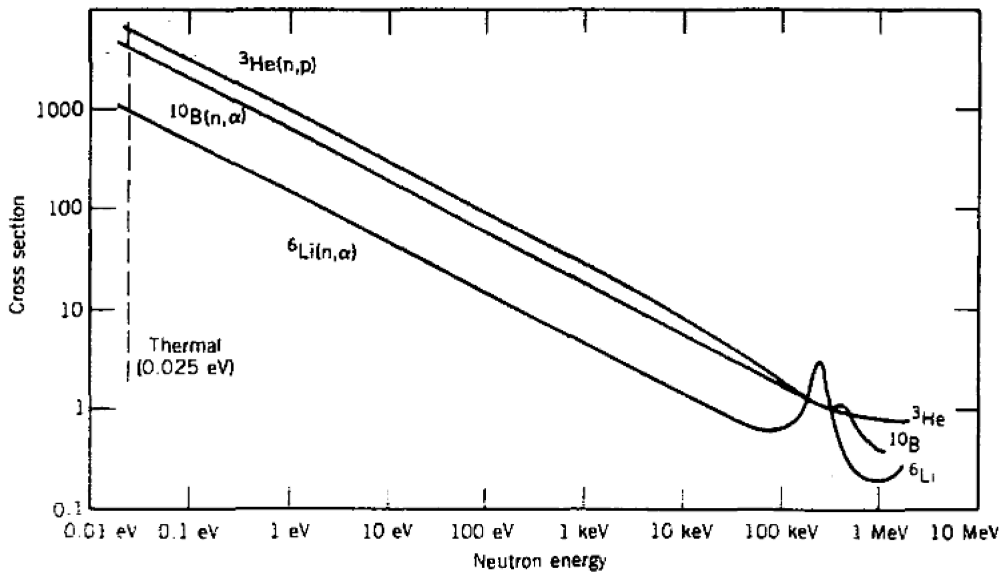
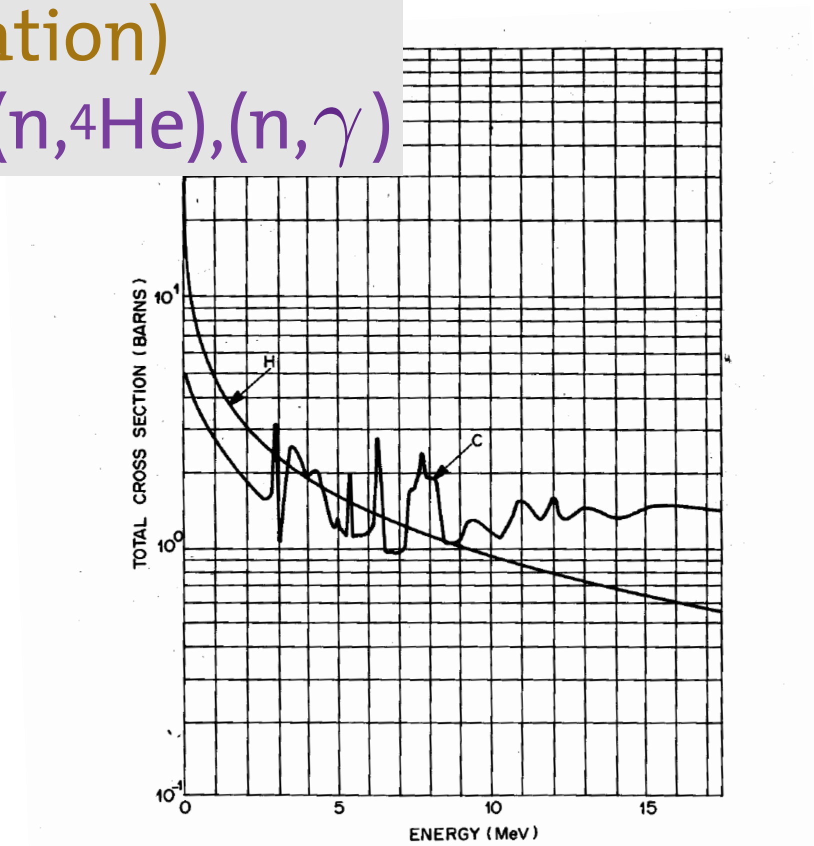


Figure 12.5 Neutron cross sections for ^{3}He(n, p), ^{10}B(n, α), and ^{6}Li(n, α). The cross section shows the $1/v$ behavior for $E < 1$ keV, but begins to show resonances above 100 keV.



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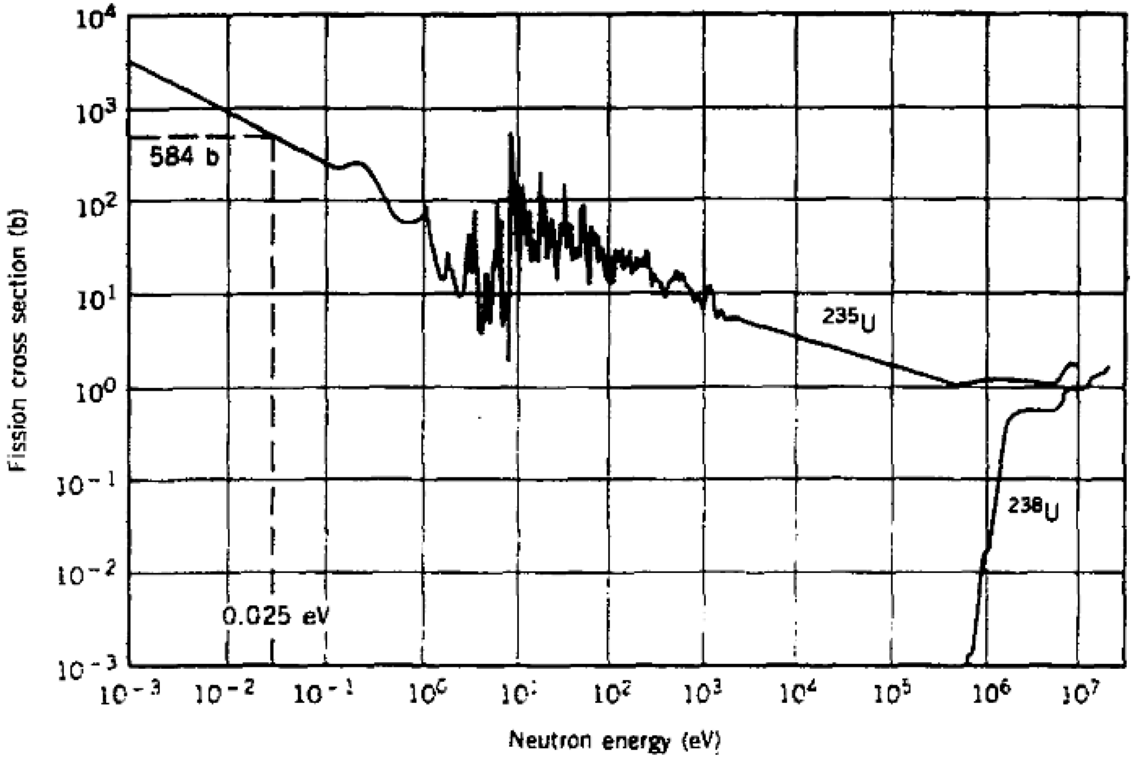
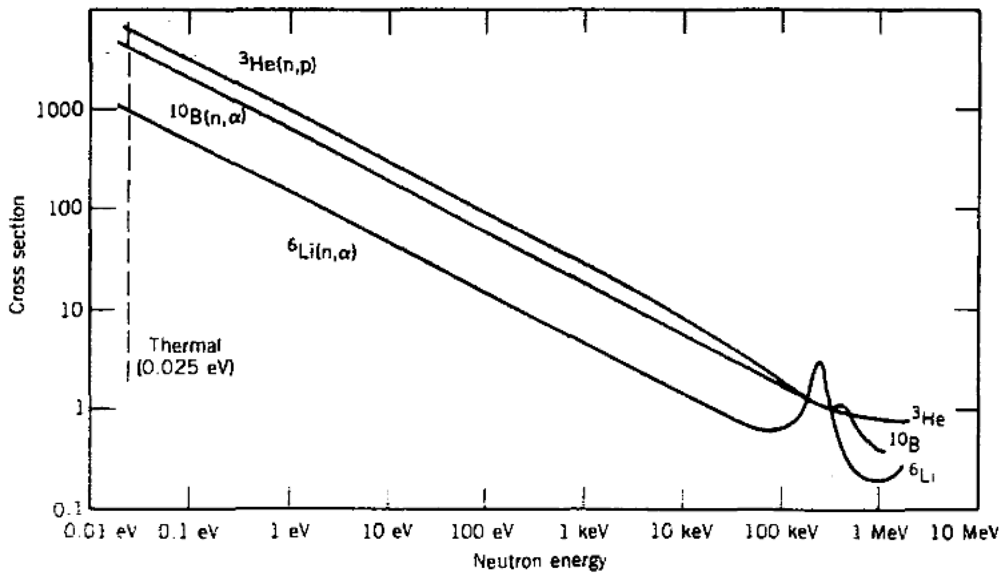


Figure 13.9 Cross sections for neutron-induced fission of ^{235}U and ^{238}U.



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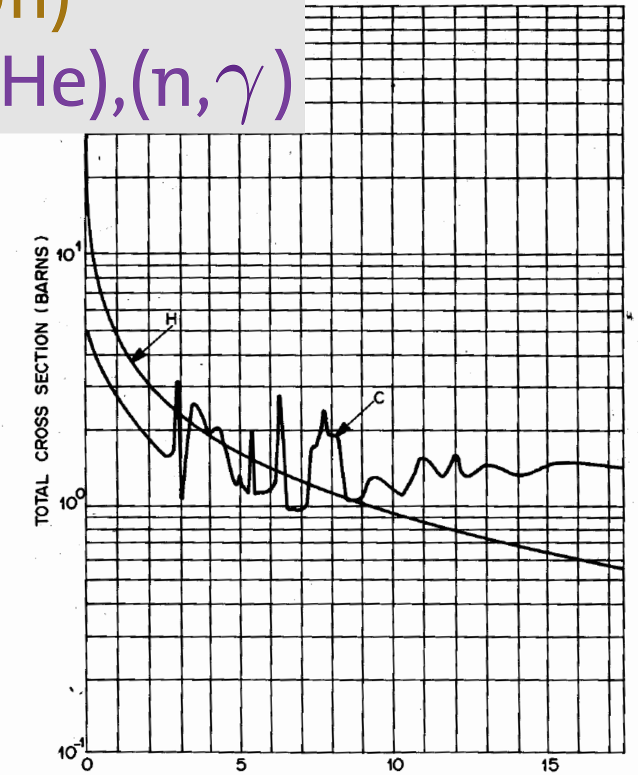

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6. Simulating particle transport in matter

- radiation transport in materials:

  topic of interest in numerous fields

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  topic of interest in numerous fields

  - electronic and positronic surface spectrosopy
  - electronic microscopy
  - microanalysis with electronic probe
  - design and use of radiation detectors
  - dosimetry
  - radiotherapy
  - ...

- **radiation transport in materials:**

  topic of interest in numerous fields

- **high energy particles in materials:**

  suffer many interactions, transfer energy and produce secondary particles

6. Simulating particle transport in matter

- radiation transport in materials:

  topic of interest in numerous fields

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6. Simulating particle transport in matter

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  - difficult in limited geometries
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- **first MC simulation of photon transport:**
  Hayward and Hubbell (1954): 67 histories

6. Simulating particle transport in matter

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- solving the problem:
  - multiple scattering theories
    - the effect of a large number of interaction events is simulated globally
    - approximate theories: possible problems
    - details depend on the particular code

6. Simulating particle transport in matter

Scattering model and probability distributions

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scattering model

$$\frac{\mathrm{d}^2\sigma_\mathrm{A}}{\mathrm{d}W\,\mathrm{d}\Omega}(E;W,\theta) \quad \frac{\mathrm{d}^2\sigma_\mathrm{B}}{\mathrm{d}W\,\mathrm{d}\Omega}(E;W,\theta)$$

$W \equiv$ energy lost after an interaction

$\Omega \equiv$ solid angle in the new direction

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6. Simulating particle transport in matter

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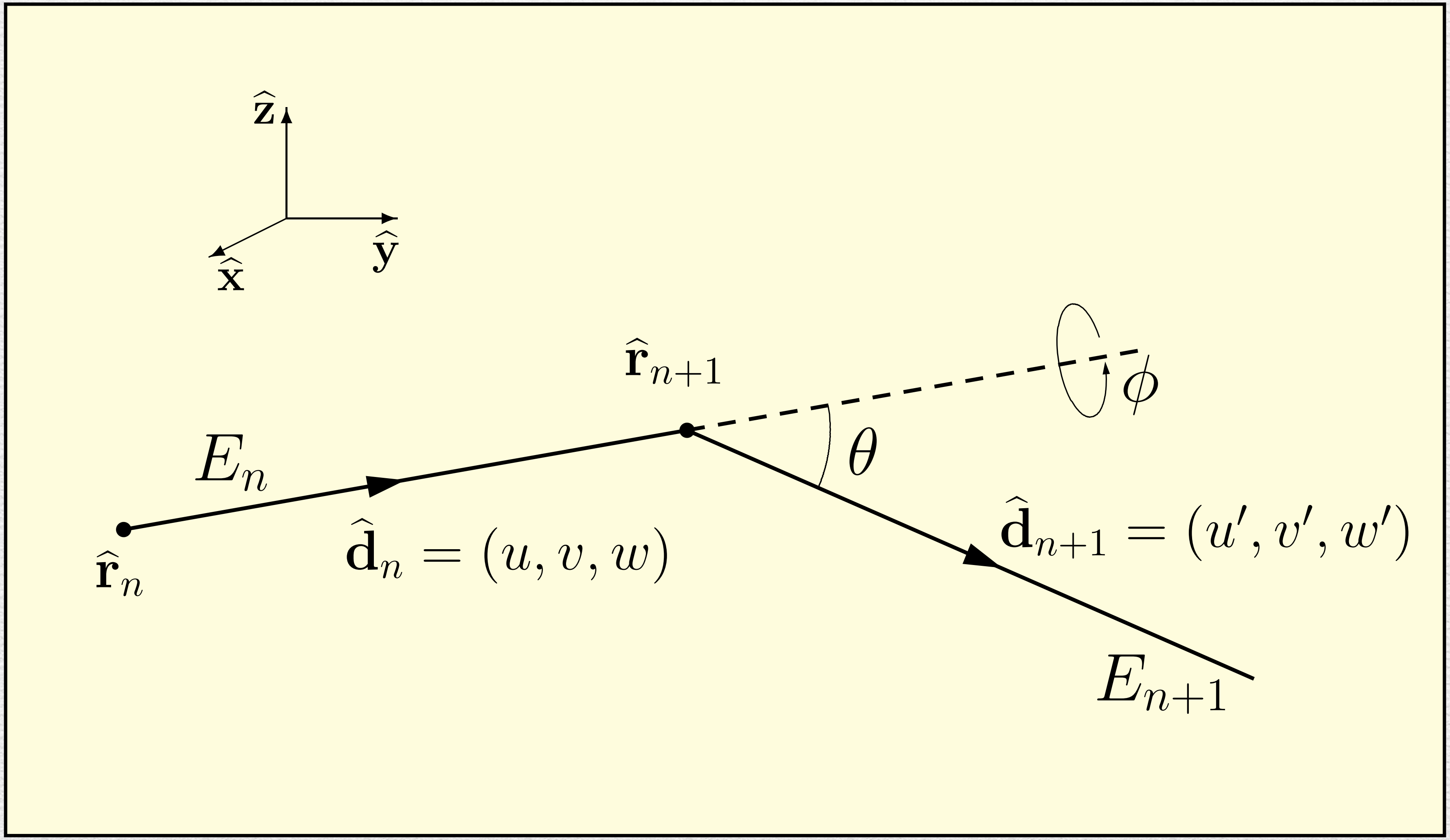
-total scattering cross section:

$$\sigma_T(E) = \sum_{\alpha \equiv \text{A,B}} \sigma_\alpha(E)$$

6. Simulating particle transport in matter



6. Simulating particle transport in matter

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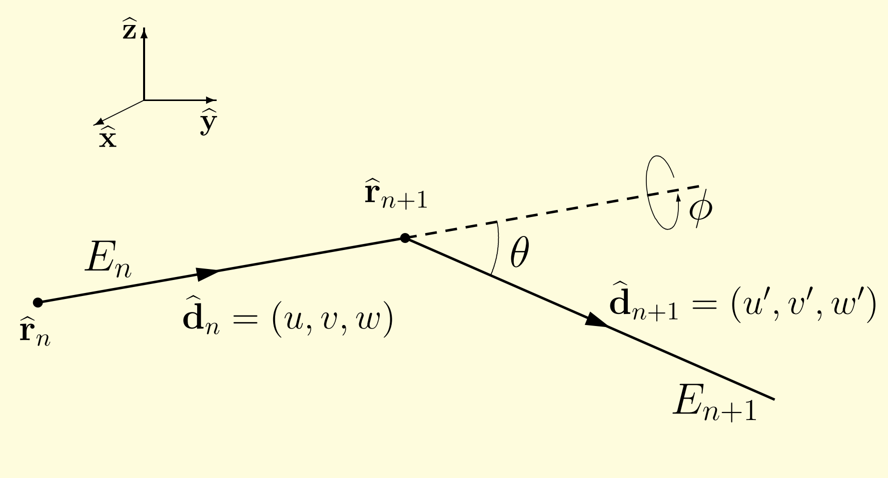
$$s = -\lambda_{\mathrm{T}} \ln \xi\,, \quad \xi \in \mathrm{U}(0,1)$$

$$\mathbf{r}_{n+1} = \mathbf{r}_n + s\,\widehat{\mathbf{d}}_n$$



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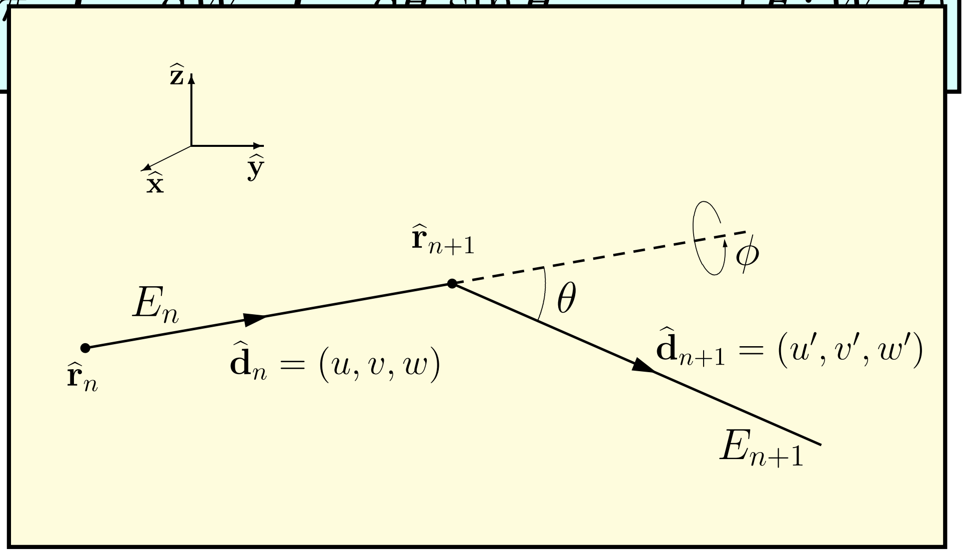
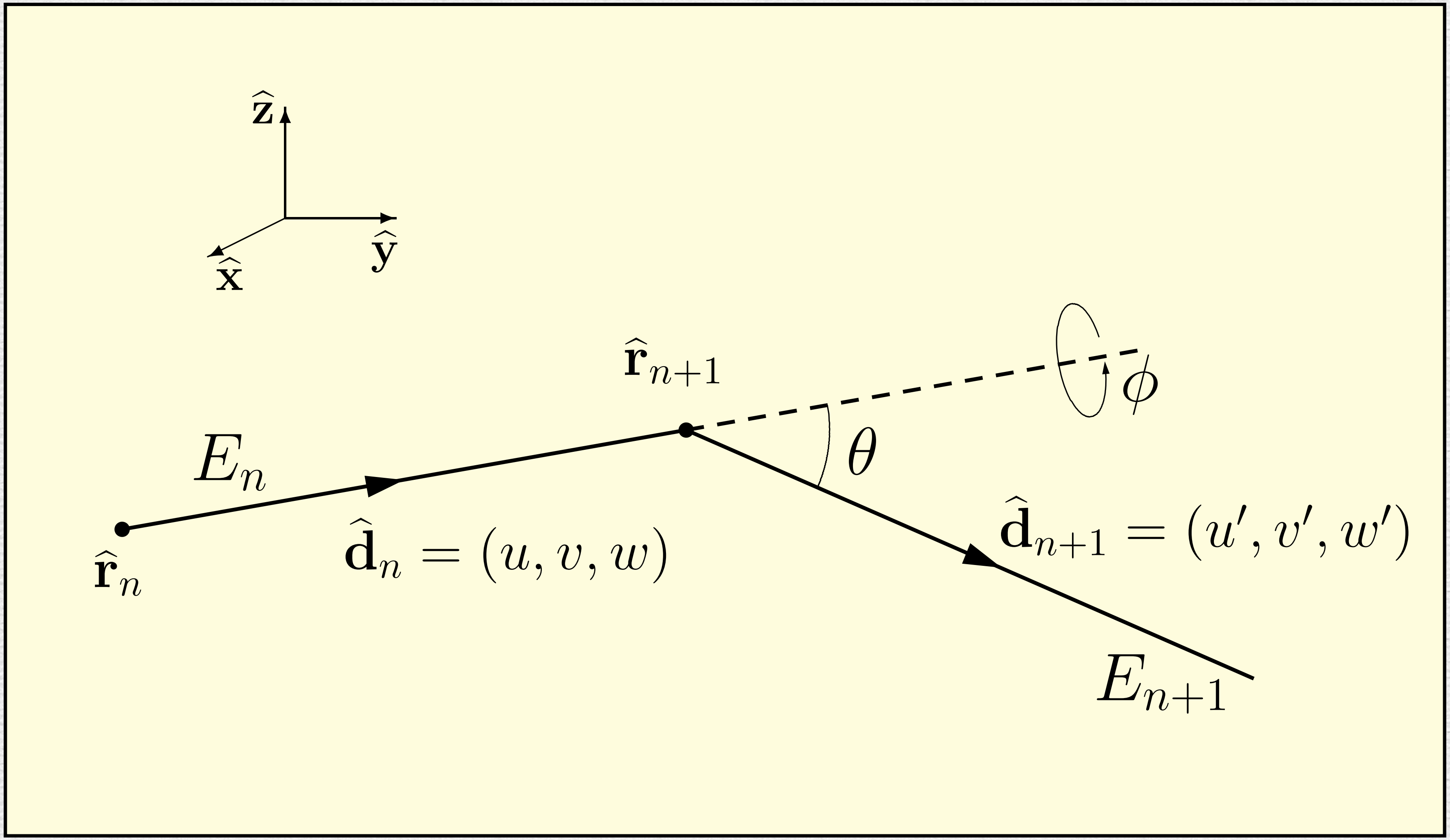


$$E_{n+1} = E_n - W$$

$$\widehat{\mathbf{d}}_{n+1} = \mathcal{R}(\theta,\phi)\,\widehat{\mathbf{d}}_n$$


$\widehat{\mathbf{z}}$
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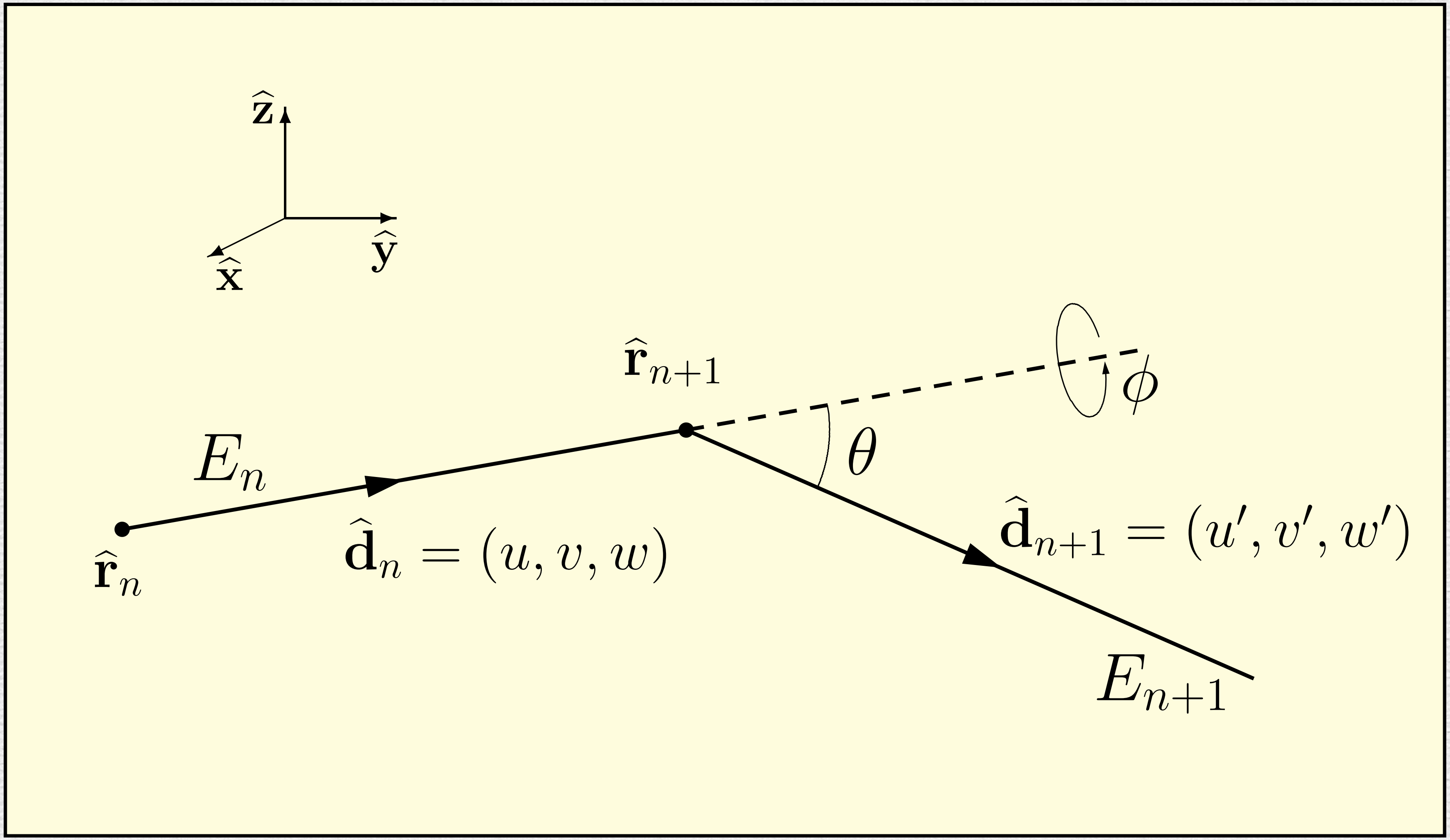
E_{n+1}

- the algorithm is iteratively repeated until
  - the particle energy is below the absorption energy (fixed by the user)
  - the particle moves out of the material medium



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6. Simulating particle transport in matter

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