Introduction to Medical Imaging – Chapter 1
Radiation and the Atom – Chapter 2
Interaction of Radiation and Matter – Chapter 3

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a copy of this lecture may be found at:

http://faculty.washington.edu/bstewart

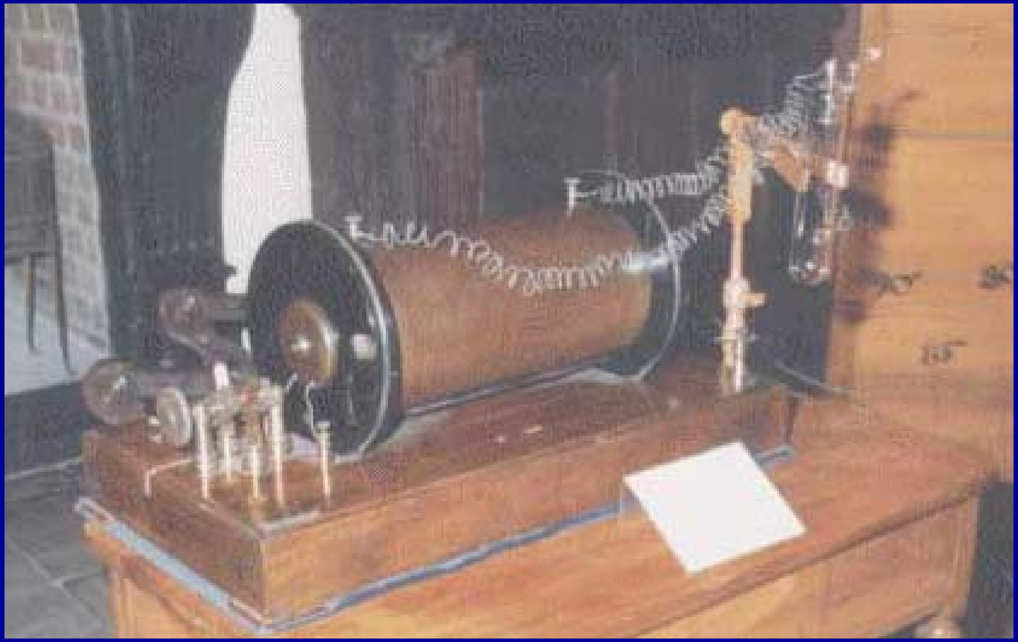
Outline

- Radiation
- Structure of the Atom
- Particle Interactions
- X-ray Interactions with Matter
- Attenuation of X-rays
- Absorption of Energy from X-rays
- Imparted Energy, Equivalent Dose and Effective Dose (introduction to dosimetric principles)

Radiation

- The propagation of energy through
  - space
  - matter
- Can be thought of as either
  - corpuscular
  - acoustic
  - electromagnetic
- Acoustic radiation awaits the ultrasound session later on in the course

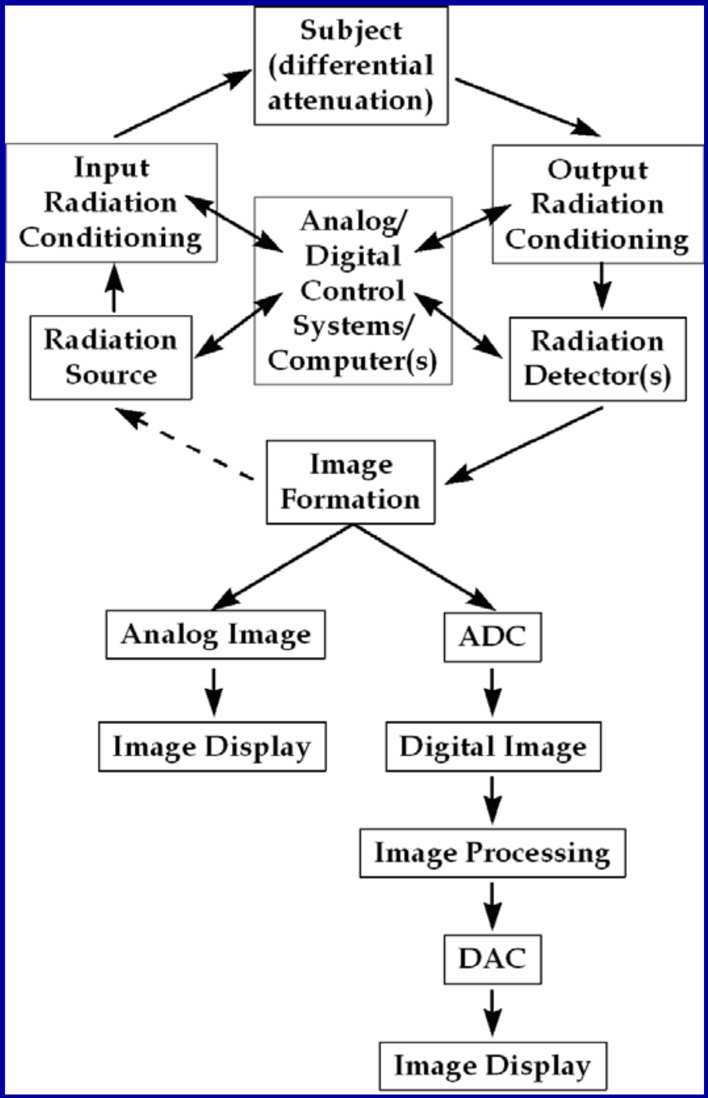
X-rays – the Basic Radiological Tool



Roentgen's experimental apparatus (Crookes tube) that led to the discovery of the new radiation on 8 Nov. 1895 – he demonstrated that the radiation was not due to charged particles, but due to an as yet unknown source, hence "x" radiation or "x-rays"

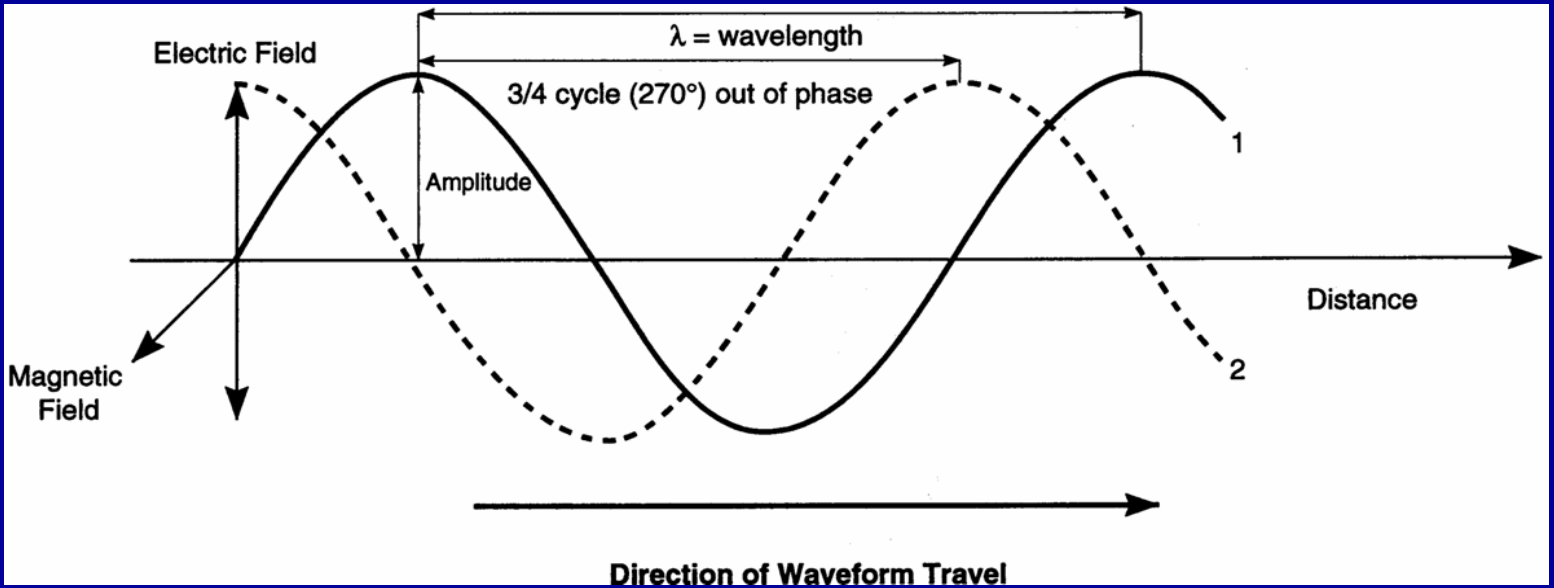
Known as "the radiograph of Bera Roentgen's hand" taken 22 Dec. 1895

A Systematic Approach to Medical Imaging



Modality	Radiation	Generator	Detector
Radiography Fluroscopy Comput. Tomo.	x-rays	HV anode	film, ion. chamber scintillation det.
Ultrasound	ultrasonic waves	piezoelec. crystal - xmt	piezoelec. crystal - rcv
Nuclear Medicine	γ, α, β, x-rays	nuclear disintegration	scintillation det. PMT
Magnetic Resonance	radiowaves	RF antenna - xmt	RF antenna - rcv
Microscope	visible light electrons	heat. filament	eye, film, and video camera

Characterization of Waves

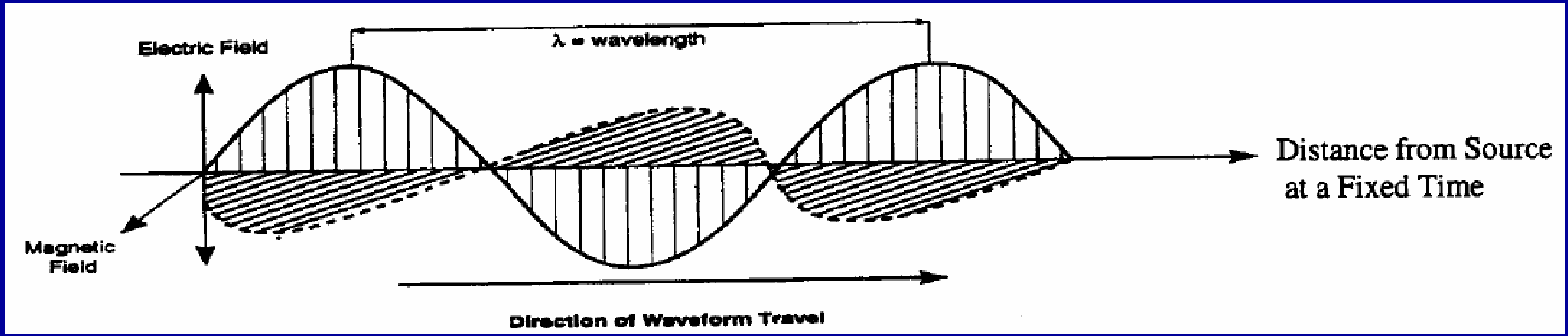


- Amplitude: intensity of the wave
- Wavelength (λ): distance between identical points on adjacent cycles [m, nm] (1 nm = 10^{-9} m)
- Period (τ): time required to complete one cycle (λ) of a wave [sec]
- Frequency (ν): number of periods per second = ($1/\tau$) [Hz or sec^{-1}]
- Speed of radiation: $c = \lambda \cdot \nu$ [m/sec]

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.18.

Electromagnetic ($\mathcal{EM}$) Radiation

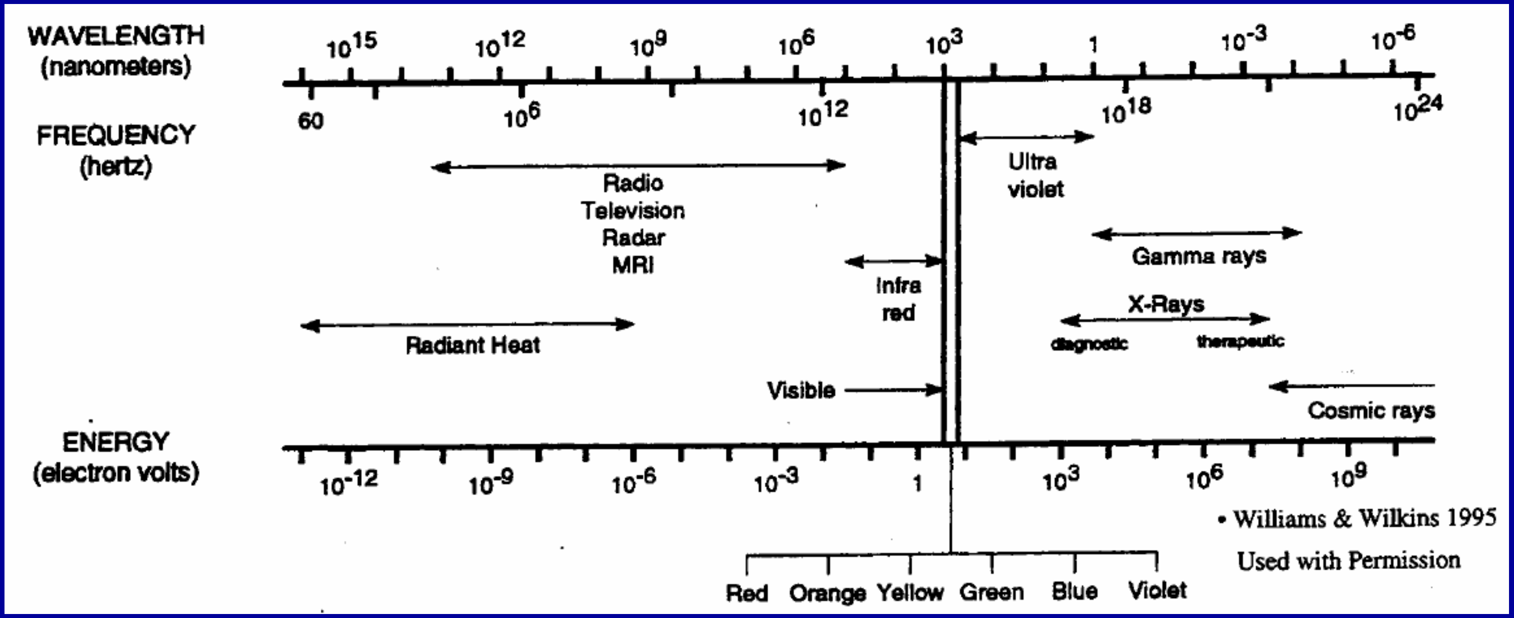
- $\mathcal{EM}$ radiation consists of the transport of energy through space as a combination of an electric ($\mathcal{E}$) and magnetic ($\mathcal{M}$) field, both of which vary sinusoidally as a function of space and time, e.g., $\mathcal{E}(t) = \mathcal{E}_0 \sin(2\pi ct/\lambda)$, where λ is the wavelength of oscillation and c is the speed of light



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.19.

The Electromagnetic (ℰℳ) Spectrum

- Physical manifestations are classified in the ℰℳ spectrum based on energy (E) and wavelength (λ) and comprise the following general categories:
  - Radiant heat, radio waves, microwaves
  - "Light" – infrared, visible and ultraviolet
  - X-rays and gamma-rays (high energy ℰℳ emitted from the nucleus)



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.18.

ℰℳ Radiation Share the Following

- Velocity in vacuum (c) = 3×10^8 m/sec
- Travel directional in nature, esp. for shorter λ
- Interaction with matter via either absorption or scattering
- Unaffected by external ℰ or ℳ fields
- Characterized by λ, frequency (ν), and energy (E)
- So-called wave-particle duality, the manifestation depending on E and relative dimensions of the detector to λ. All ℰℳ radiation has zero mass.
- *X-rays are ionizing radiation, removing bound electrons - can cause either immediate or latent biological damage

$\mathcal{EM}$ Wave and Particle Characteristics

- Wave characteristics – used to explain interference and diffraction phenomena: c [m/sec] = λ [m] · ν [1/sec]
  - As c is essentially constant, then $\nu \approxeq 1/\lambda$ (inversely proportional)
  - Wavelength often measured in nanometers (nm = 10^{-9} m) or Angstroms (Å = 10^{-10} m, not an SI unit)
  - Frequency measured in Hertz (Hz): 1 Hz = 1/sec or sec^{-1}
- Particle characteristics – when interacting with matter, high E $\mathcal{EM}$ radiation act as quanta of energy called "photons": E [Joule] = $h\nu = hc/\lambda$, where h = Planck's constant (6.62×10^{-34} Joule-sec = 4.13×10^{-18} keV-sec)
- When E expressed in keV and λ in nm:

$$E\ [\text{keV}] = 12.4/\lambda\ [\text{Å}] = 1.24/\lambda\ [\text{nm}]$$

Transparency of Human Body to $\mathcal{EM}$ Radiation

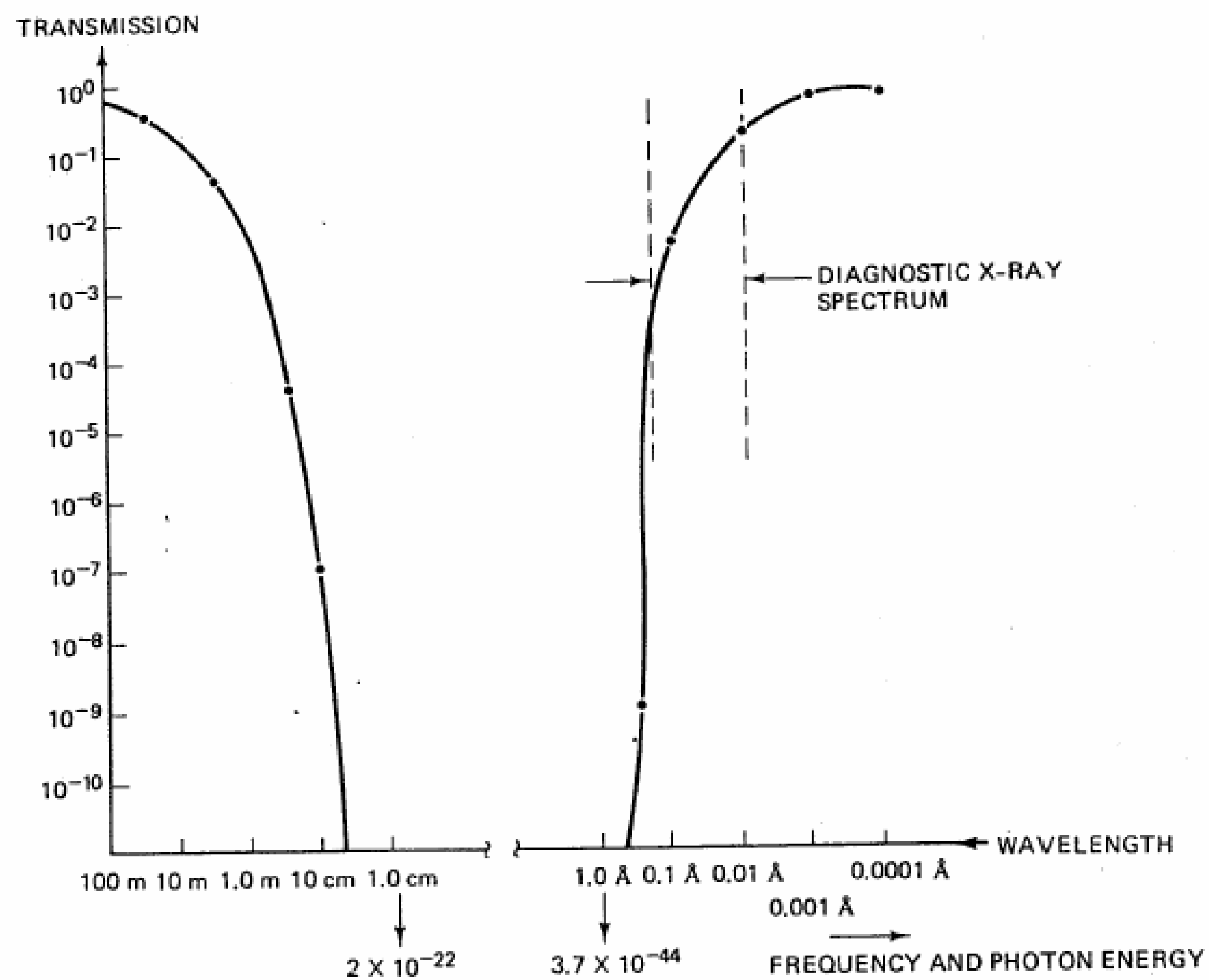


FIG. 1.1 Transmission of EM waves through 25 cm of soft tissue.

c.f. Macovski, A. Medical Imaging Systems, p. 3.

Raphex 2000 Question: $\mathcal{EM}$ Radiation

- **G46**. Regarding electromagnetic radiation:
  - A. Wavelength is directly proportional to frequency.
  - B. Velocity is directly proportional to frequency.
  - C. Energy is directly proportional to frequency.
  - D. Energy is directly proportional to wavelength.
  - E. Energy is inversely proportional to frequency.

Raphex 2001 Question: $\mathcal{EM}$ Radiation

- **G51.** Which of the following has the highest photon energy?
  - A. Radio waves
  - B. Visible light
  - C. Ultrasound
  - D. X-rays
  - E. Ultraviolet

Raphex 2001 Question: $\mathcal{EM}$ Radiation

- **G52.** Which of the following has the longest wavelength?
  - A. Radio waves
  - B. Visible light
  - C. Ultraviolet
  - D. X-rays
  - E. Gamma rays

Raphex 2002 Question: $\mathcal{EM}$ Radiation

- **G51**. Visible light has a wavelength of about 6 x 10^{-7} m. ^{60}Co gammas have a wavelength of 10^{-12} m and an energy of 1.2 MeV The approximate energy of visible light is:
  - A. 720 MeV
  - B. 72 keV
  - C. 2 eV
  - D. 2 x 10^{-6} eV
  - E. 7.2 x 10^{-4} eV
- $E_1 = hc/\lambda_1$ and $E_2 = hc/\lambda_2$, so $E_1\lambda_1 = hc = E_2\lambda_2$
- $E_2 = E_1\lambda_1/\lambda_2 = (1.2 \times 10^6 \text{ eV})(10^{-12} \text{ m})/(6 \times 10^{-7} \text{ m}) = 2 \text{ eV}$

Particulate Radiation

- Corpuscular radiations are comprised of moving particles of matter and the energy of which is based on the mass and velocity of the particles
- Simplified Einstein mass-energy relationship $E = mc^2$
- Kinetic energy (KE) $= \frac{1}{2} mv^2$ (for non-relativistic velocities)

- The most significant particulate radiations of interest are:
- Alpha particles α^{2+}
- Electrons e^-
- Positron β^+
- Negatrons β^-
- Protons p^+
- Neutrons n^0
- Interactions with matter are collisional in nature and are governed by the conservation of energy (E) and momentum ($p = mv$).

PERIODIC TABLE OF THE ELEMENTS

PSE.Menu

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.0079																	2 He 4.0026
2	3 Li 6.941	4 Be 9.0122											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
3	11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.066	17 Cl 35.453	18 Ar 39.948
4	19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.64	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
5	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
6	55 Cs 132.91	56 Ba 137.33	57 - 71 La-Lu	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
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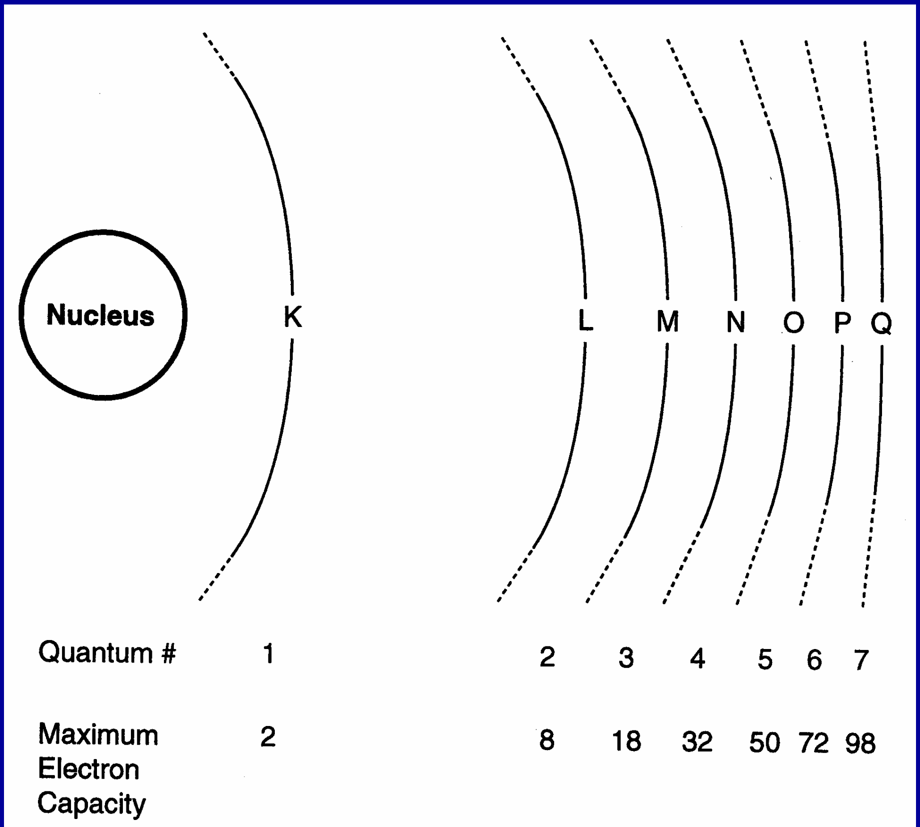
Lanthanide	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
Actinide	89 Ac (227)	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

ENIG. HOME

SOLID | LIQUID | GAS | 100 °C 101 kPa | SYNTHETIC ELEMENT

c.f. http://www.ktf-split.hr/periodni/en/

Electronic Structure – Electron Orbits



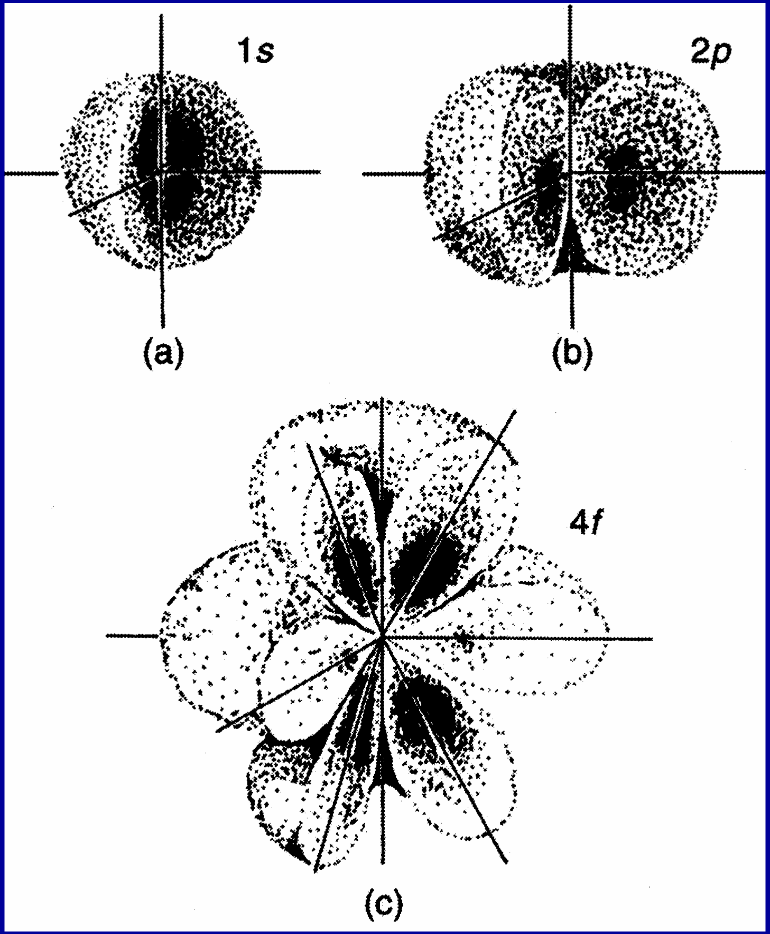
- Pauli exclusion principle
  - No two electrons can have the same energy
  - → $2n^2$ electrons per shell
- quantum numbers
  - n: principal q.n. – which e^- shell
  - ℓ: azimuthal – angular momentum q.n. (ℓ = 0, 1, ... , n-1)
  - m_ℓ: magnetic q.n. – orientation of the e^- magnetic moment in a magnetic field ($m_\ell = -\ell, -\ell+1, ..., 0, ... \ell-1, \ell$)
  - m_s: spin q.n. – direction of the e^- spin (m_s = +½ or -½)

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.21.

Electronic Structure – Electron Orbits (2)

ELEMENT	n	ℓ	m_ℓ	m_s
Helium (Z = 2)	1	0	0	$-1/2$
	1	0	0	$+1/2$
Carbon (Z = 6)	1	0	0	$-1/2$
	1	0	0	$+1/2$
	2	0	0	$-1/2$
	2	0	0	$+1/2$
	2	1	-1	$-1/2$
	2	1	-1	$+1/2$
Sodium (Z = 11)	1	0	0	$-1/2$
	1	0	0	$+1/2$
	2	0	0	$-1/2$
	2	0	0	$+1/2$
	2	1	-1	$-1/2$
	2	1	-1	$+1/2$
	2	1	0	$-1/2$
	2	1	0	$+1/2$
	2	1	1	$-1/2$
	2	1	1	$+1/2$
	3	0	0	$-1/2$

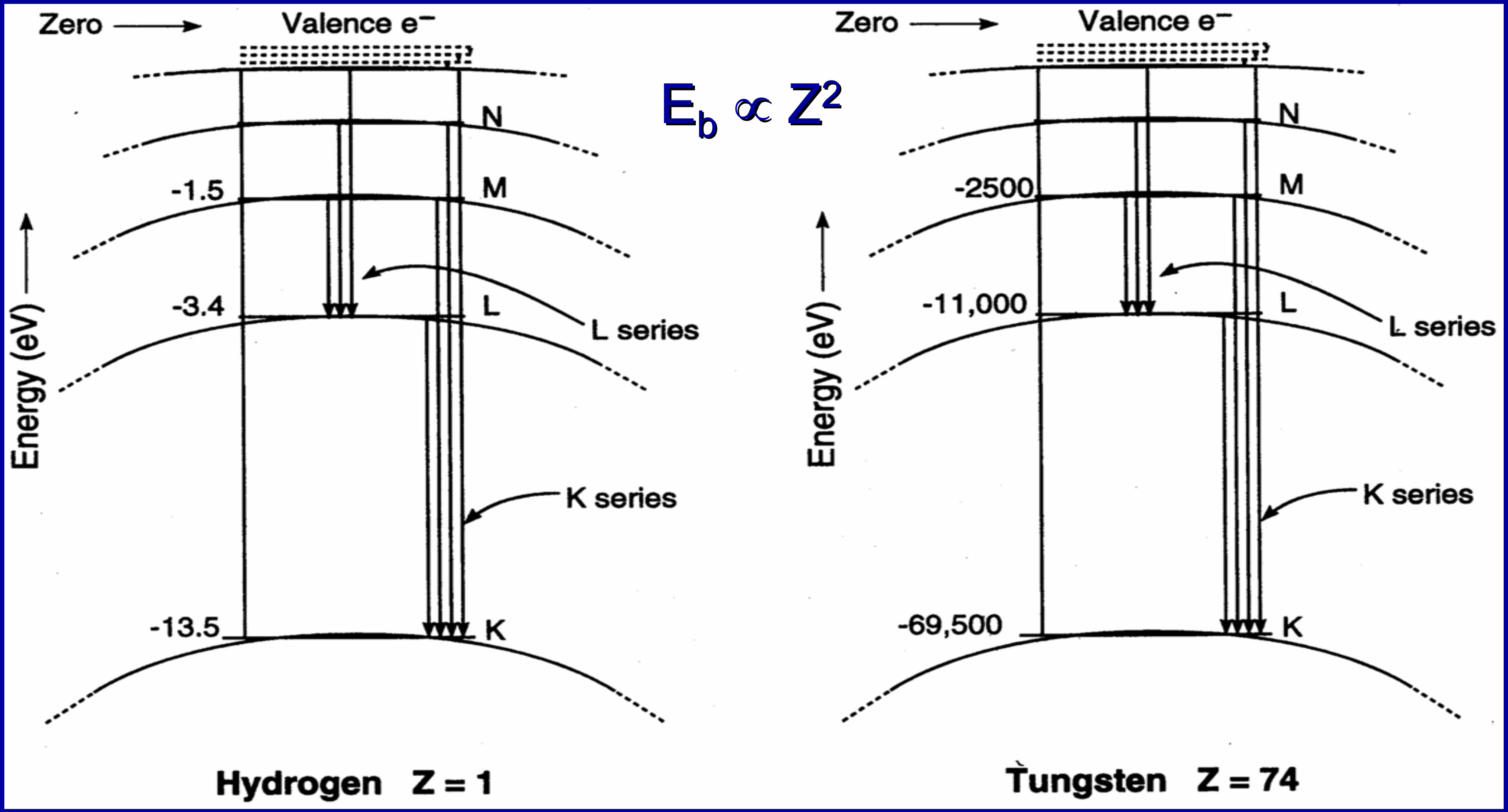
c.f. Hendee, et al. Medical Imaging Physics, 2nd ed., p.4.



c.f. Hendee, et al. Medical Imaging Physics, 4th ed., p.13.

Electronic Structure – Electron Binding Energy

$E_b \propto Z^2$



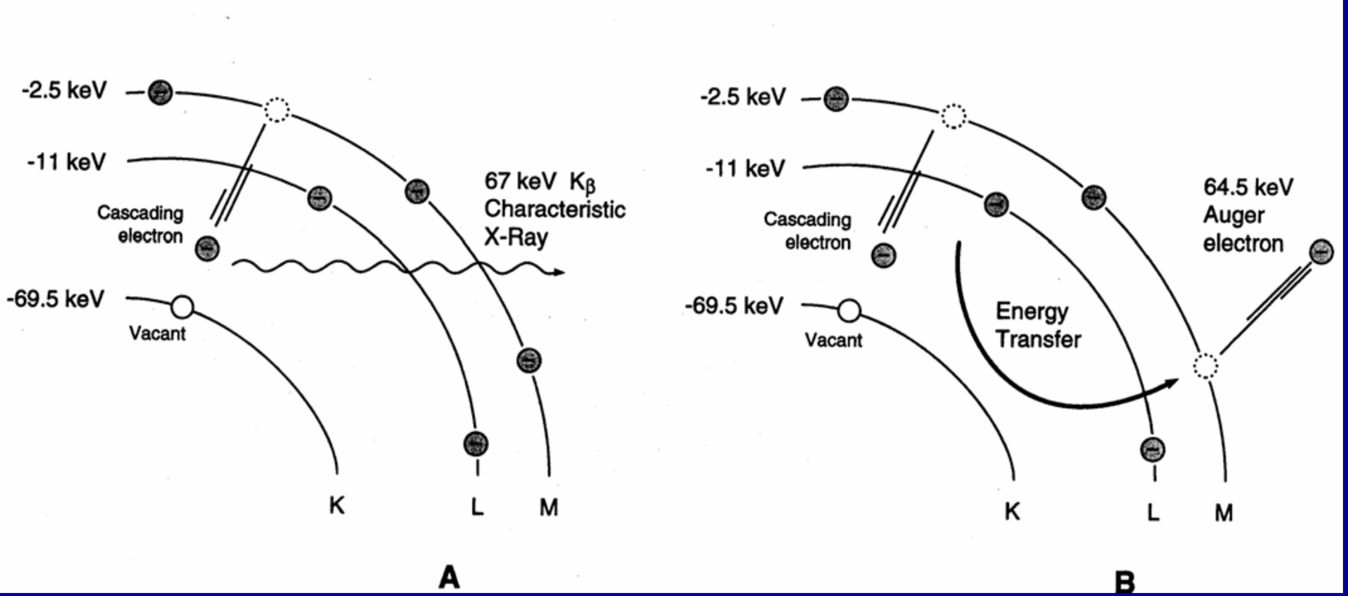
c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.22.

Radiation from Electron Transitions

- Characteristic X-rays
- Auger Electrons and Fluorescent Yield (characteristic x-rays/total)

$$E(K_\beta) = E_{bK} - E_{bM}$$

$$E(K_\beta) = 69.5 \text{ keV} - 2.5 \text{ keV} = 67 \text{ keV}$$



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.23.

The Atomic Nucleus

- Mostly covered in Nuclear Medicine course (August)
- Composition of the Nucleus
  - Protons and Neutron
  - Number of protons = Z
  - Number of neutrons = N
  - Mass number = A = Z + N
  - Chemical symbol = X
  - Isotopes: same Z, but different A
  - Notation: ${}^{A}_{Z}X_{N}$, but ${}^{A}X$ uniquely defines an isotope (also written as X-A) as X $\rightarrow$ Z and N = A - Z
    - For example ${}^{131}I$ or I-131

Raphex 2000 Question: Atomic Structure

- **G10-G14.** Give the charge carried by each of the following:
  - A. +4
  - B. +2
  - C. +1
  - D. 0
  - E. -1
- **G10**. Alpha particle
- **G11**. Neutron
- **G12**. Electron
- **G13**. Positron
- **G14**. Photon

Raphex 2002 Question: Atomic Structure

- **G17.** Tungsten has a K-shell binding energy of 69.5 keV. Which of the following is true?
  - A. The L-shell has a higher binding energy.
  - B. Carbon has a higher K-shell binding energy.
  - C. Two successive 35 keV photons could remove an electron from the K-shell.
  - D. A 69 keV photon could not remove the K-shell electron, but could remove an L-shell electron.

Raphex 2001 Question: Atomic Structure

- **G18.** How many of the following elements have 8 electrons in their outer shell?
  - Element: Sulphur Chlorine Argon Potassium
  - Z: 16 17 18 19
  - A. None
  - B. 1
  - C. 2
  - D. 3
  - E. 4

Raphex 2001 Question: Atomic Structure

- **G18.** **B** The n^{th} shell can contain a *maximum* of $2n^2$ electrons, but no shell can contain more than 8 if it is the outer shell. The shell filling is as follows:

	Z	K shell	L shell	M shell	N shell
Sulphur	16	2	8	6	0
Chlorine	17	2	8	7	0
Argon	18	2	8	8	0
Potassium	19	2	8	8	1

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EniG. HOME

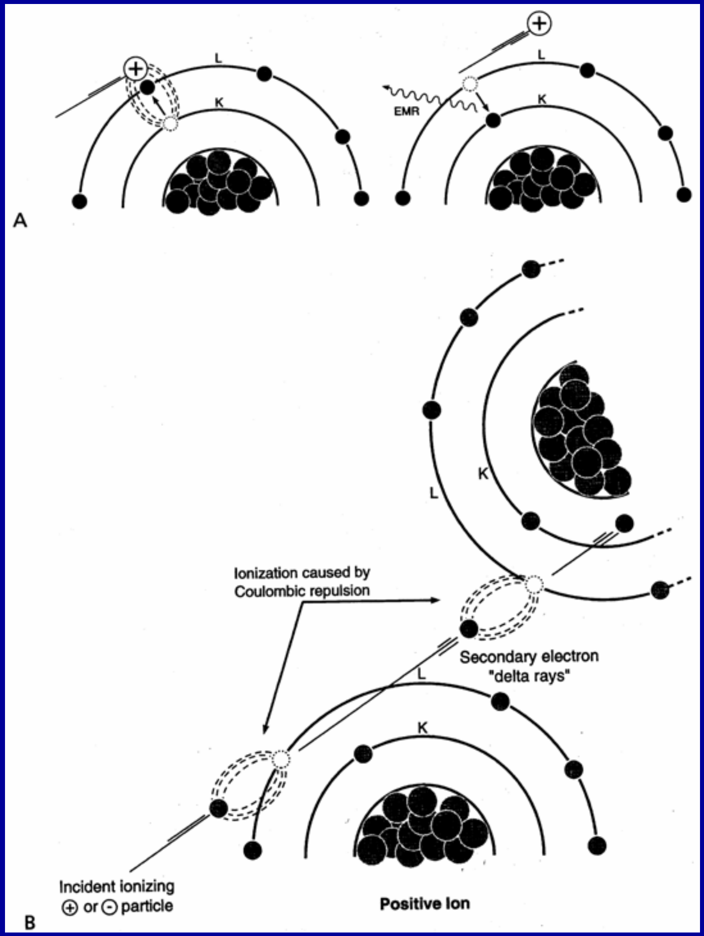
SOLID | LIQUID | GAS | 100 °C 101 kPa | SYNTHETIC ELEMENT

c.f. http://www.ktf-split.hr/periodni/en/

Raphex 2002 Question: Atomic Structure

- **G15.** $^{226}_{88}Ra$ contains 88 ___________ .
  - A. Electrons
  - B. Neutrons
  - C. Nucleons
  - D. Protons and neutrons

Excitation, Ionization and Radiative Losses

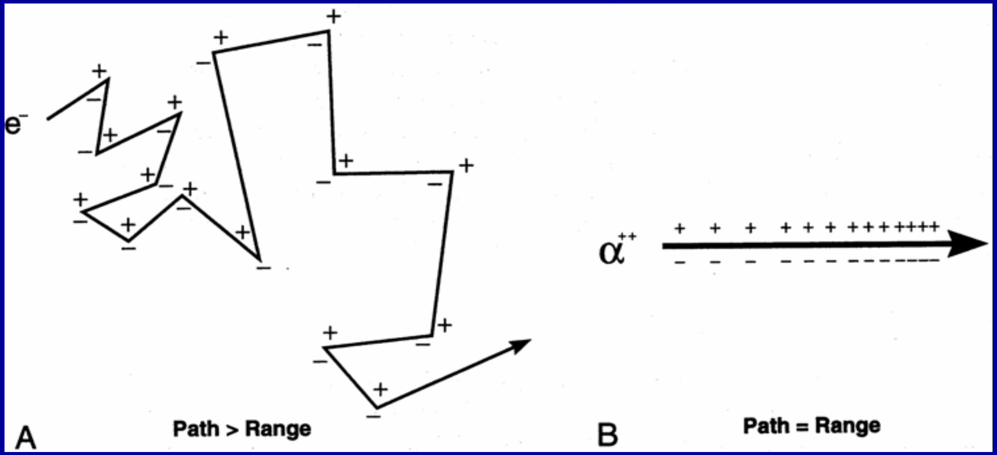


- Energetic charged particles interact via electrical forces
- Lose KE through excitation, ionization and radiative losses
- Excitation: imparted E < E_b → emits $\mathcal{EM}$ or Auger e^- (de-excitation)
- Ionization: imparted E > E_b → sometimes e^- with enough KE to produce further ionizations (secondary ionizations)
  - Such e^- are called 'delta rays'
- Approx. 70% of e^- E deposition leads to non-ionizing excitation

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.32.

Charged Particle Tracks

- e^- follow tortuous paths through matter as the result of multiple Coulombic scattering processes
- An α^{2+}, due to it's higher mass follows a more linear trajectory
- Path length = actual distance the particle travels in matter
- Range = actual penetration depth the particle in matter
- Range ≤ path length



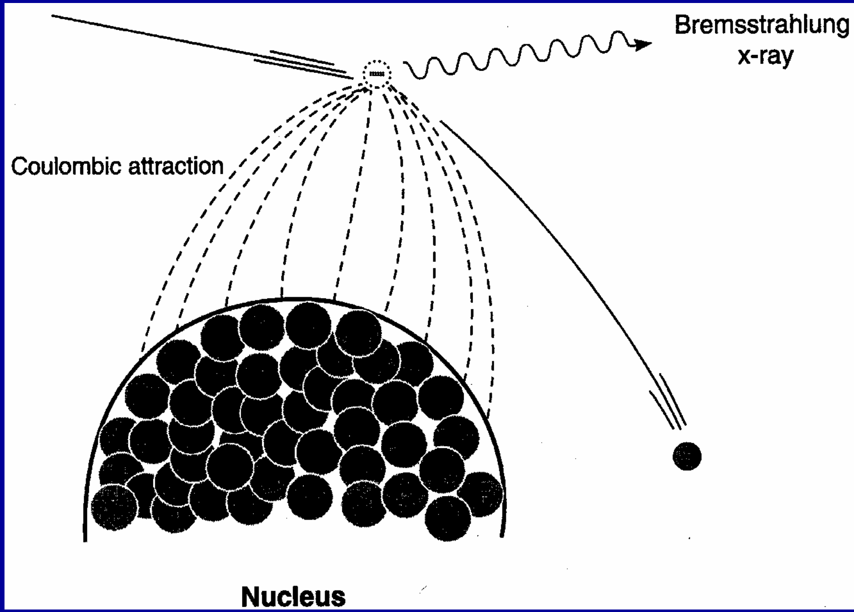
c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.34.

Linear Energy Transfer (LET)

- Amount of energy deposited per unit length (eV/cm)
- LET $\propto Q^2/KE$
- Basically describes the energy deposition density which largely determines the biologic consequence of radiation exposure
- High LET radiation: α^{2+}, p^+, and other heavy ions
- Low LET radiation:
  - Electrons (e^-, β^- and β^+)
  - $\mathcal{EM}$ radiation (x-rays or γ-rays)
- High LET >> damaging than low LET radiation

Radiative Interactions - Bremsstrahlung

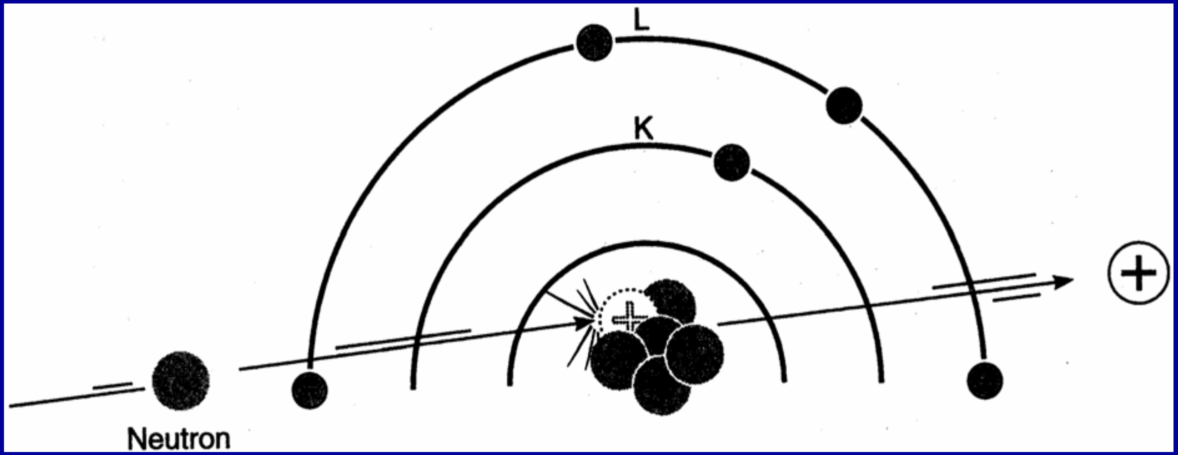
- Deceleration of an e^- around a nucleus causes it to emit $\mathcal{EM}$ radiation or bremsstrahlung (G.): "breaking radiation"
- Probability of bremsstrahlung emission $\propto Z^2$
- Ratio of e^- energy loss due to bremsstrahlung vs. excitation and ionization = KE[MeV]·Z/820
- Thus, for an 100 keV e^- and tungsten (Z=74) ≈ 1%



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.35.

Neutron Interactions and Scattering

- Neutrons: no external charge → no excitation or ionization
- Can interact with nuclei to eject charged particles (e.g., p^+ or α^{2+})
- In tissue (or water) neutrons eject p^+ (recoil protons)
- Scattering: deflection of particle or photon from original trajectory
- Elastic: scattering event in which the total KE is unchanged
- Inelastic: scattering event with a loss of KE



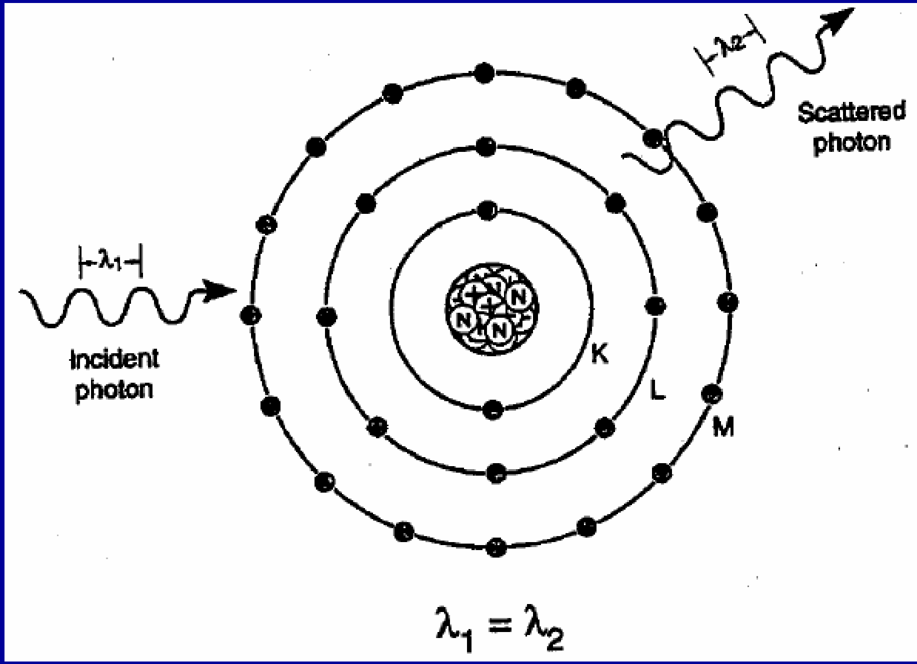
c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.36.

X-ray Interactions with Matter

- There are several means of x-rays and gamma rays being absorbed or scattered by matter
- Four major interactions are of importance to diagnostic radiology and nuclear medicine, each characterized by a probability (or "cross-section") of interaction
- Classical (Rayleigh or elastic) scattering
- Compton scattering
- Photoelectric effect
- Pair production

Classical (Rayleigh or elastic) Scattering

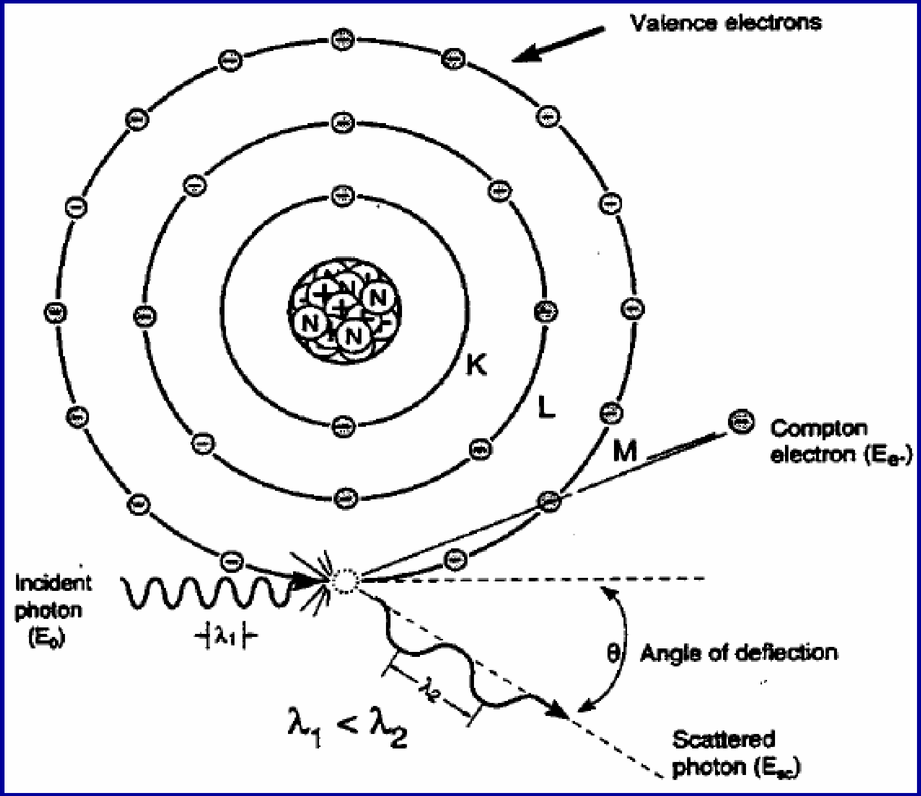
- Excitation of the total complement of atomic electrons occurs as a result of interaction with the incident photon
- No ionization takes place
- The photon is scattered (re-emitted) in a range of different directions, but close to that of the incident photon
- No loss of E
- Relatively infrequent probability ≈ 5%



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 37.

Compton Scattering

- Dominant interaction of x-rays with soft tissue in the diagnostic range and beyond (approx. 30 keV - 30MeV)
- Occurs between the photon and a "free" e^- (outer shell e^- considered free when E_γ >> binding energy, E_b of the e^-)
- Encounter results in ionization of the atom and probabilistic distribution of the incident photon E to that of the scattered photon and the ejected e^-
- A probabilistic distribution determines the angle of deflection



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 38.

Compton Scattering (2)

- Compton interaction probability is dependent on the total no. of e^- in the absorber vol. ($e^-/cm^3 = e^-/gm \cdot$ density)
- With the exception of ^1H, e^-/gm is fairly constant for organic materials ($Z/A \cong 0.5$), thus the probability of Compton interaction proportional to material density (ρ)
- Conservation of energy and momentum yield the following equations:
  - $E_o = E_{sc} + E_{e-}$
  - $E_{sc} = \dfrac{E_0}{1+\dfrac{E_0}{m_e c^2}\left(1-\cos\theta\right)}$, where $m_e c^2 = 511$ keV

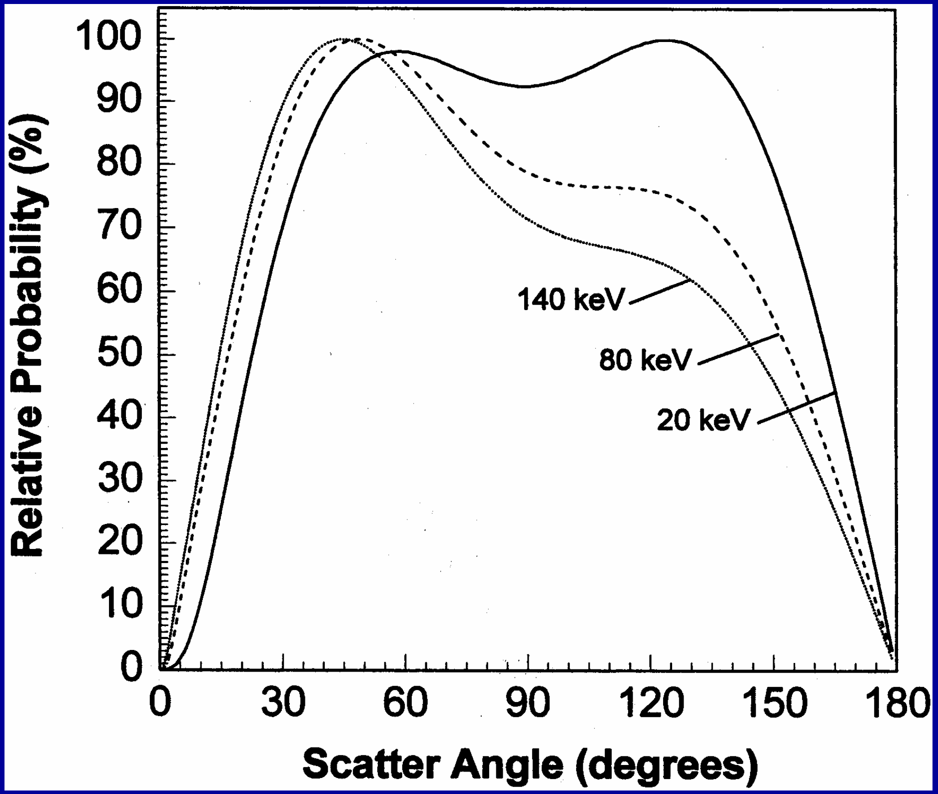
Compton Scattering (3)

E_{sc} as a function of E_0 and angle (θ) – Excel spreadsheet

Eo (keV)	10	20	50	100	200	500	1000	10000
Angle (deg)								
0	10	20	50	100	200	500	1000	10000
5	9.999	19.997	49.981	99.926	199.703	498.145	992.608	9306.934
10	9.997	19.988	49.926	99.704	198.818	492.676	971.128	7708.292
20	9.988	19.953	49.707	98.834	195.388	472.139	894.440	4586.770
30	9.974	19.896	49.353	97.445	190.035	442.051	792.279	2761.049
45	9.943	19.773	48.607	94.579	179.431	388.625	635.657	1485.494
60	9.903	19.616	47.668	91.087	167.267	335.742	505.440	927.236
75	9.857	19.436	46.619	87.333	155.028	289.817	408.088	644.973
90	9.808	19.247	45.544	83.633	143.741	252.720	338.187	486.157
105	9.760	19.061	44.517	80.235	133.986	224.042	288.730	390.100
120	9.715	18.891	43.601	77.307	126.017	202.617	254.102	329.444
135	9.677	18.747	42.844	74.958	119.894	187.241	230.377	290.637
150	9.648	18.639	42.280	73.251	115.584	176.938	214.975	266.545
180	9.623	18.548	41.817	71.871	112.184	169.093	203.505	249.135

Compton Scattering (4)

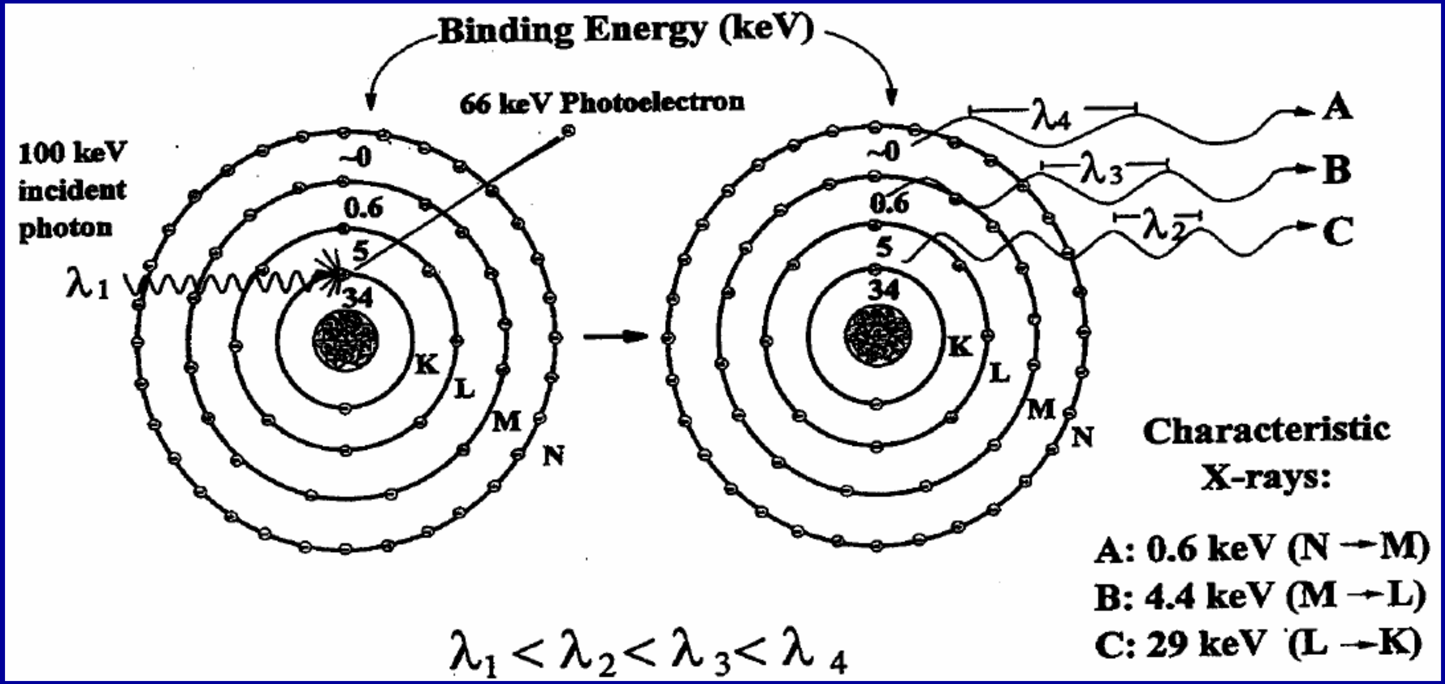
- As incident E_0 ↑ both photon and e^- scattered in more forward direction
- At a given ∠ fraction of E transferred to the scattered photon decreases with ↑ E_0
- For high energy photons most of the energy is transferred to the electron
- At diagnostic energies most energy to the scattered photon
- Max E to e^- at ∠ of 180°; max E scattered photon is 511 keV at ∠ of 90°



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 39.

Photoelectric Effect (1)

- Interaction of incident photon with inner shell e^-
- All E transferred to e^- (ejected photoelectron) as kinetic energy (E_e) less the binding energy: $E_e = E_0 - E_b$
- Empty shell immediately filled with e^- from outer orbitals resulting in the emission of characteristic x-rays (E_γ = differences in E_b of orbitals), for example, Iodine: E_K = 34 keV, E_L = 5 keV, E_M = 0.6 keV

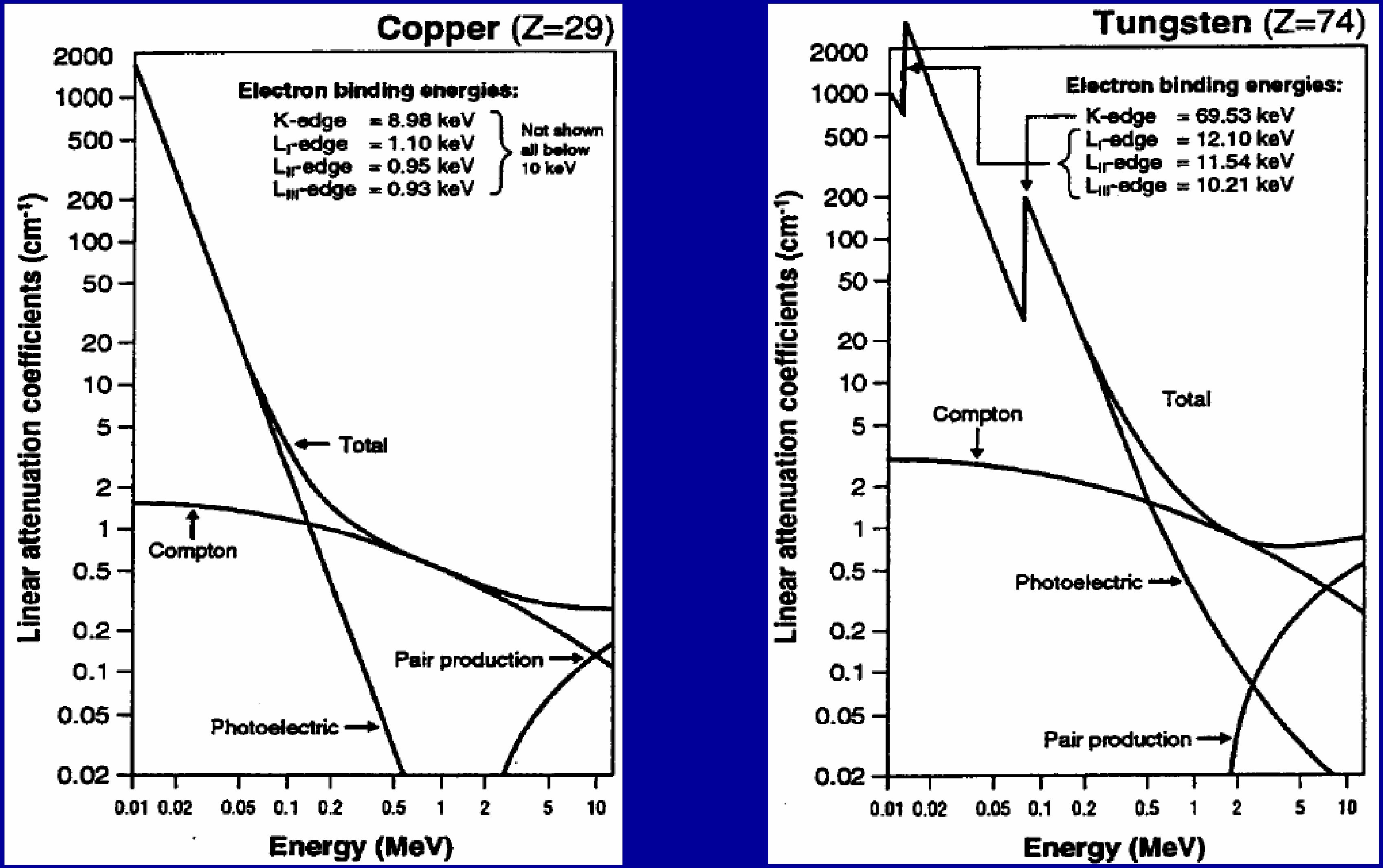


c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 41.

Photoelectric Effect (2)

- $E_b \propto Z^2$
- Characteristic x-rays and/or Auger e^-; photoe^- and cation
- Probability of photoe^- absorption $\propto Z^3/E^3$ (Z=atomic no.)
- Explains why contrast ↓ as higher energy x-rays are used in the imaging process
- Due to the absorption of the incident x-ray without scatter, maximum subject contrast arises with a photoe^- effect interaction
- Increased probability of photoe^- absorption just above the E_b of the inner shells cause discontinuities in the attenuation profiles (e.g., K-edge)

Photoelectric Effect (3)



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 1st ed., p. 26.

Photoelectric Effect (4)

- Edges become significant factors for higher Z materials as the E_b are in the diagnostic energy range:
  - Contrast agents – barium (Ba, Z=56) and iodine (I, Z=53)
  - Rare earth materials used for intensifying screens – lanthanum (La, Z=57) and gadolinium (Gd, Z=64)
  - Computed radiography (CR) and digital radiography (DR) acquisition – europium (Eu, Z=63) and cesium (Cs, Z=55)
  - Increased absorption probabilities improve subject contrast and quantum detective efficiency
- At photon E << 50 keV, the photoelectric effect plays an important role in imaging soft tissue, amplifying small differences in tissues of slightly different Z, thus improving subject contrast (e.g., in mammography)

PERIODIC TABLE OF THE ELEMENTS

PSE.Menu

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.0079																	2 He 4.0026
2	3 Li 6.941	4 Be 9.0122											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
3	11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.066	17 Cl 35.453	18 Ar 39.948
4	19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.64	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
5	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
6	55 Cs 132.91	56 Ba 137.33	57 - 71 La-Lu	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 -103 Ac-Lr	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (277)	109 Mt (268)	110 Uun (281)	111 Uuu (272)	112 Uub (285)		114 Uuq (289)				

Lanthanide	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
Actinide	89 Ac (227)	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

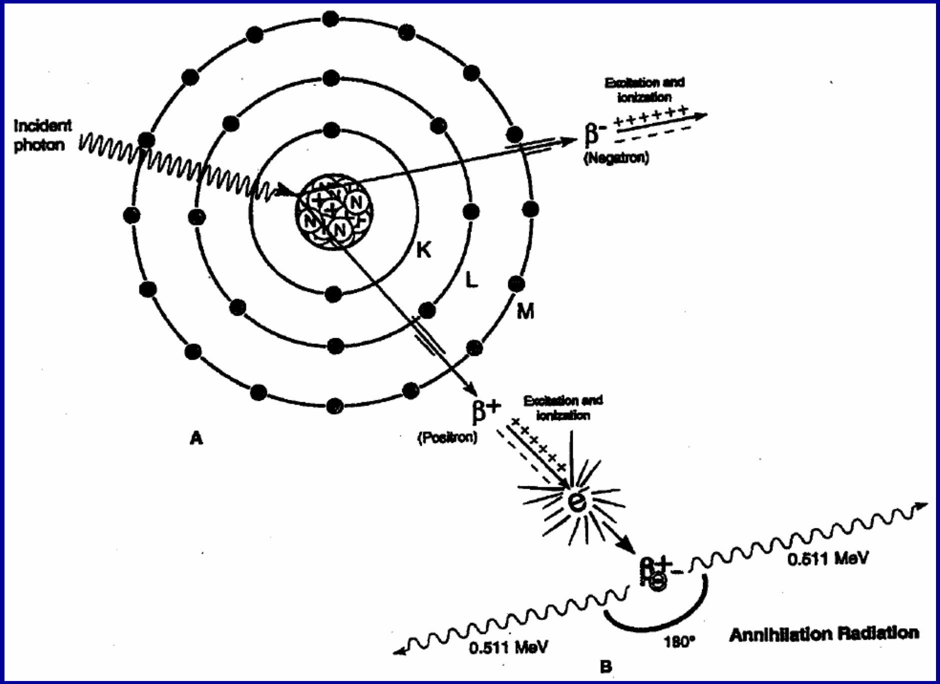
EniG. HOME

SOLID | LIQUID | GAS | 100 °C 101 kPa | SYNTHETIC ELEMENT

c.f. http://www.ktf-split.hr/periodni/en/

Pair Production

- Conversion of mass to E occurs upon the interaction of a high E photon (> 1.02 MeV; rest mass of e^- = 511 keV) in the vicinity of a heavy nucleus
- Creates a negatron (β^-) - positron (β^+) pair
- The β^+ annihilates with an e^- to create two 511 keV photons separated at an ∠ of 180°



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 44.

Linear Attenuation Coefficient

- Cross section is a measure of the probability ("apparent area") of interaction: $\sigma(E)$ measured in barns (10^{-24} cm^2)
- Interaction probability can also be expressed in terms of the thickness of the material – linear attenuation coefficient: $\mu(E)$ [cm^{-1}] = Z [e$^-$ /atom] · N_{avg} [atoms/mole] · 1/A [moles/gm] · ρ [gm/cm^3] · $\sigma(E)$ [cm^2/e$^-$]
- $\mu(E) \downarrow$ as E $\uparrow$, e.g., for soft tissue
  - μ(30 keV) = 0.35 cm^{-1} and μ(100 keV) = 0.16 cm^{-1}
- $\mu(E)$ = fractional number of photons removed (attenuated) from the beam by absorption or scattering
- Multiply by 100% to get % removed from the beam/cm

Linear Attenuation Coefficient (2)

- An exponential relationship between the incident radiation intensity (I_0) and the transmitted intensity (I) with respect to thickness:
- $I(E) = I_0(E)\, e^{-\mu(E)\cdot x}$
- $\mu_{total}(E) = \mu_{PE}(E) + \mu_{CS}(E) + \mu_{RS}(E) + \mu_{PP}(E)$
- At low x-ray E: $\mu_{PE}(E)$ dominates and $\mu(E) \propto Z^3/E^3$
- At high x-ray E: $\mu_{CS}(E)$ dominates and $\mu(E) \propto \rho$
- Only at very-high E (> 1MeV) does $\mu_{PP}(E)$ contribute
- The value of $\mu(E)$ dependent on the phase state:

$$\mu_{water\ vapor} < \mu_{ice} < \mu_{water}$$

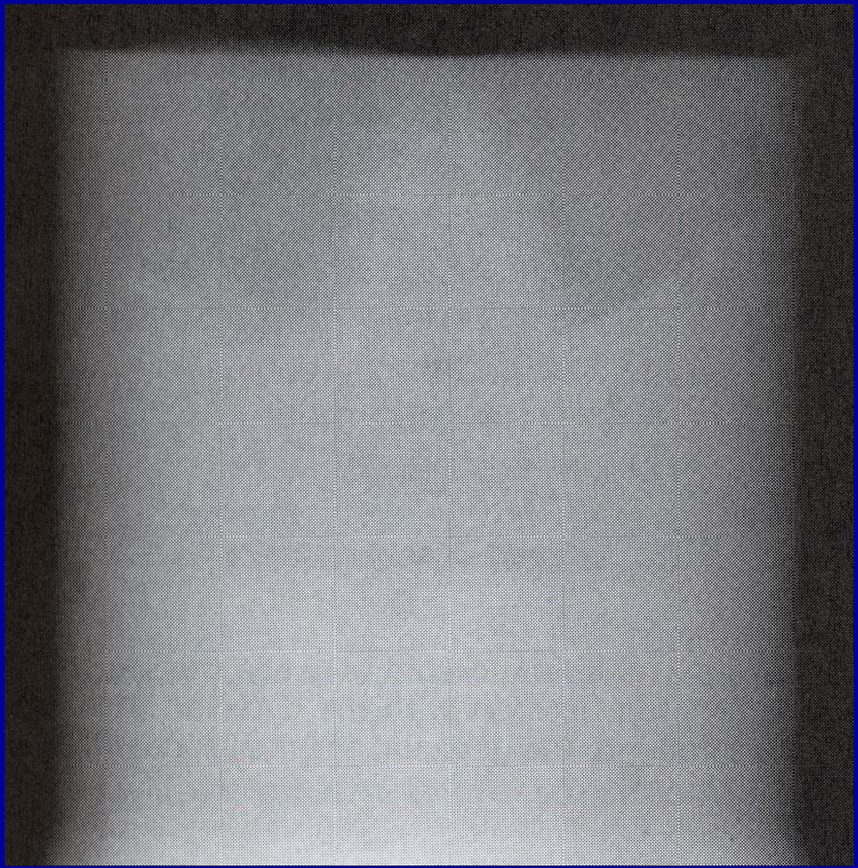
Linear Attenuation Coefficient (3)

Material	Effective Atomic Number (Z_{eff})	Density (g/cm^3)	Electrons per mass (e/g) x 10^{23}	Electron Density (e/cm^3) x 10^{23}	μ @ 50 keV (cm^{-1})
Hydrogen	1.0	0.000084	5.97	0.0005	0.000028
Water Vapor	7.51	0.000598	3.34	0.002	0.000128
Air	7.78	0.00129	3.006	0.0038	0.000290
Fat	6.46	0.91	3.34	3.04	0.193
Ice	7.51	0.917	3.34	3.06	0.196
Water	7.51	1	3.34	3.34	0.214
Compact Bone	13.80	1.85	3.192	5.91	0.573

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 46.

Mass Attenuation Coefficient

- Mass attenuation coefficient $\mu_m(E)$ [cm^2/gm] – normalization for ρ: $\mu_m(E) = \mu(E)/\rho$
- Independent of phase state (ρ) and represents the fractional number of photons attenuated per gram of material
- $I(E) = I_0(E)\, e^{-\mu_m(E) \cdot \rho \cdot x}$
- Represent "thickness" as g/cm^2 - the thickness of 1 cm^2 of material weighing a specified amount



125 kVp Radiograph of "Scotch on the rocks"

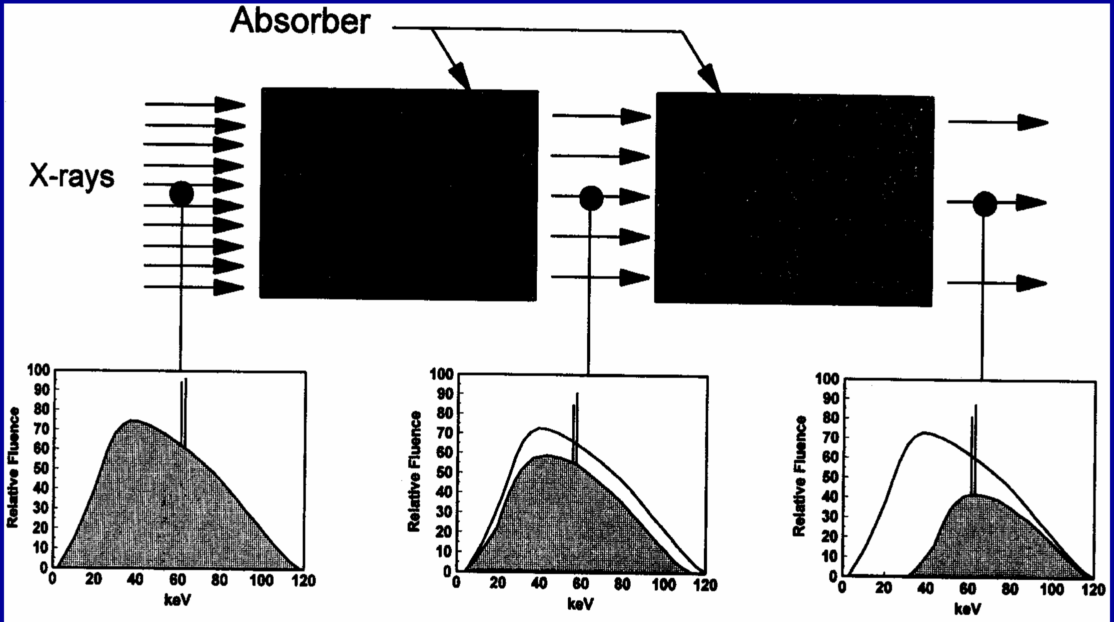
c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 47.

Half Value Layer

- Thickness of material required to reduce the intensity of the incident beam by ½
- $\frac{1}{2} = e^{-\mu(E)\cdot HVL}$ or HVL = $0.693/\mu(E)$
- Units of HVL expressed in mm Al for a Dx x-ray beam
- For a monoenergetic incident photon beam (i.e., that from a synchrotron), the HVL is easily calculated
- Remember for any function where $dN/dx \propto N$ which upon integrating provides an exponential function (e.g., $I(E) = I_0(E)\, e^{-k\cdot x}$), the doubling (or halving) dimension x is given by 69.3%/k% (e.g., 3.5% CD doubles in 20 yr)
- For each HVL, I ↓ by ½: 5 HVL → I/I_0 = 100%/32 = 3.1%

Mean Free Path and Beam Hardening

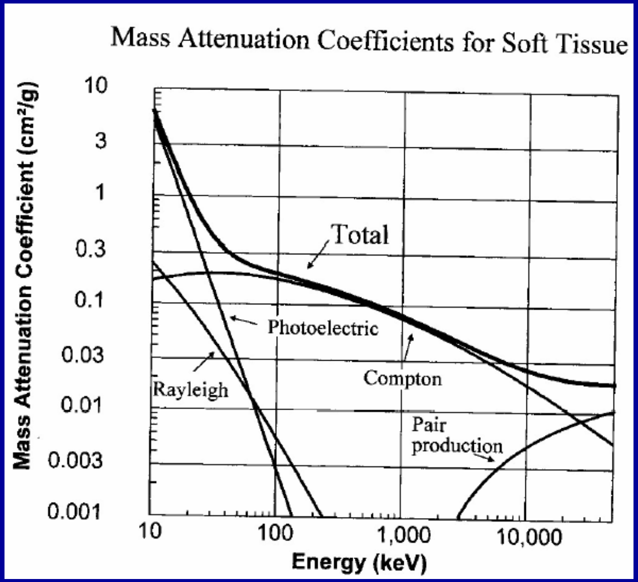
- Mean free path (avg. path length of x-ray) = $1/\mu$ = HVL/0.693
- Beam hardening
  - The Bremsstrahlung process produces a wide spectrum of energies, resulting in a polyenergetic (polychromatic) x-ray beam
  - As lower E photons have a greater attenuation coefficient, they are preferentially removed from the beam
  - Thus the mean energy of the resulting beam is shifted to higher E



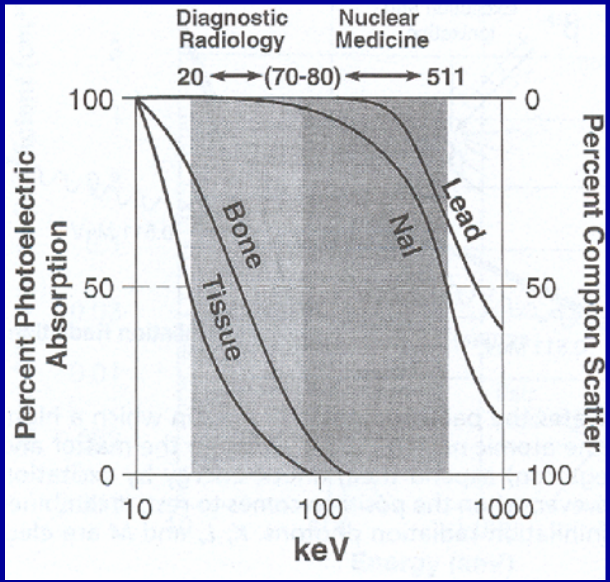
c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 1st ed., p. 281.

Homogeneity Coefficient and Effective Energy

- Homogeneity coefficient = 1st HVL/2nd HVL
  - A summary description of the x-ray beam polychromaticity
  - $HVL_1 < HVL_2 < \dots HVL_n$; so the homogeneity coefficient < 1
- The effective (avg.) E of an x-ray beam is ⅓ to ½ the peak value (kVp) and gives rise to an μ_{eff}, the $\mu(E)$ that would be measured if the x-ray beam were monoenergetic at the effective E



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 45.



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p. 43.

Raphex 2000 Question: Inter. Rad. & Matter

- **D1**. In comparison to 20 keV photons, the probability of photoelectric interaction in bone at 60 keV is approximately:
  - A. 27 times as great.
  - B. 3 times as great.
  - C. The same.
  - D. 3 times less.
  - E. 27 times less.

Raphex 2000 Question: Inter. Rad. & Matter

- **D2**. Compared with an iodine IVP exam, a barium exam produces better contrast resolution because:
  - A. The mass attenuation coefficient of barium is much greater than that of iodine.
  - B. The K-edge of barium is much greater than the K-edge of iodine.
  - C. The diameter of the bowel is bigger than the diameter of the ureter.
  - D. The atomic number of barium is significantly greater than the atomic number of iodine.
  - E. A higher concentration of barium can be achieved than with iodine.

Raphex 2001 Question: Inter. Rad. & Matter

- **D3.** Carbon dioxide can be used as an angiographic contrast medium because:
  - A. The K absorption edges of CO_2 are significantly higher than tissue.
  - B. The K absorption edges of CO_2 are significantly lower than tissue.
  - C. The linear attenuation coefficient of CO_2 is significantly higher than tissue.
  - D. The linear attenuation coefficient of CO_2 is significantly lower than tissue.
  - E. Of differences between the mass attenuation coefficients.

Raphex 2000 Question: Inter. Rad. & Matter

- **G50**. If the linear attenuation coefficient is 0.05 cm^{-1}, the HVL is:
  - A. 0.0347 cm
  - B. 0.05 cm
  - C. 0.693 cm
  - D. 1.386 cm
  - E. 13.86 cm
- HVL = $0.693/\mu = 0.693/0.05\ cm^{-1} \approx 0.7 \times 20\ cm = 14\ cm$

Raphex 2000 Question: Inter. Rad. & Matter

- **G64**. Electrons lose energy when passing through matter by:
  - 1. Production of bremsstrahlung.
  - 2. Photoelectric interactions.
  - 3. Collisions with other electrons.
  - 4. Production of delta rays.

  - A. 1 and 2
  - B. 3 and 4
  - C. 1, 3 and 4
  - D. 1, 2 and 3
  - E. All of the above.

Raphex 2001 Question: Inter. Rad. & Matter

- **G57.** The intensity of a beam is reduced by 50% after passing through x cm of an absorber. Its attenuation coefficient, μ, is:
  - A. $(0.693)\cdot x$
  - B. $x/0.693$
  - C. $0.693/x$
  - D. $2x$
  - E. $(0.693)\cdot x^2$

Raphex 2003 Question: Inter. Rad. & Matter

- **G56**. If a technologist were to stand 2 meters away from a patient during fluoroscopy (outside the primary beam) the dose received by the technologist would be mainly due to:
  - A. Compton electrons.
  - B. Photoelectrons.
  - C. Compton scattered photons.
  - D. Characteristic x-rays generated in the patient.
  - E. Coherent scatter.

Fluence, Flux and Energy Fluence

- Fluence (Φ) = number of photons/cross sectional area [cm^{-2}]
- Flux ($d\Phi/dt$) = fluence rate = fluence/sec [cm^{-2}-sec^{-1}]
- Energy fluence (Ψ) = (photons/area)·(energy/photon) = $\Phi \cdot E$ [keV-cm^{-2}] or [J-m^{-2}]
- Energy flux ($d\Psi/dt$) = energy fluence rate = energy fluence/sec [keV-cm^{-2}-sec^{-1}]

Kerma

- A beam of ionizing radiation deposits energy in the medium through a two-step process
  - Photon energy is transformed into KE of charged particles
  - These particles deposit energy through excitation and ionization
- Kerma = Kinetic Energy Released in MAtter
  - KE transferred to charged particles from x-rays
- Mass Energy Transfer Coefficient (μ_{tr}/ρ)
  - Discount attenuation coefficient (absorption only, no scattered γ)
- Kerma [$J\text{-}kg^{-1}$] = Ψ [$J\text{-}m^{-2}$] $\cdot(\mu_{tr}/\rho)$ [$m^2\text{-}kg^{-1}$]

Absorbed Dose

- Absorbed Dose = $\Delta E / \Delta m$ [$J\text{-}kg^{-1}$]
- SI units of absorbed dose = gray (Gy); 1 Gy = 1 J/kg
- Traditional dose unit = rad = 10 mGy; 100 rads = 1 Gy
- Mass Energy Absorption Coefficient
  - $(\mu_{en}/\rho) \leq\approx (\mu_{tr}/\rho)$ since at diagnostic E and low Z bremsstrahlung production probability is low)
- Calculation of Dose
  - $D = \Psi \cdot (\mu_{en}/\rho)$ [Gy]

Exposure and Dose

- Exposure (X) = $\Delta Q/\Delta m$ [$C\text{-}kg^{-1}$]
- Roentgen (R) = 2.58×10^{-4} C/kg; also mR = 10^{-3} R
- Measured using an air-filled ionization chamber
- Output intensity of an x-ray tube (I) = X/mAs [mR/mAs]
- Dose (Gy) = Exposure (R) · (R to Gray conversion factor)
  - R to Gray conversion factor = 0.00876 for air (8.76 mGy/R)
  - R to Gray conversion factor ≈ 0.009 for muscle and water
  - R to Gray conversion factor ≈ 0.02 – 0.04 for bone (PE)
- As $D = \Psi\cdot(\mu_{en}/\rho)$ and the Z_{eff} (air) ≈ Z_{eff} (soft tissue)
  - We can use the ionization chamber reading to provide dose (D)

Imparted Energy and Equivalent Dose

- Imparted Energy [J] = Dose [$J\text{-}kg^{-1}$] · mass [kg]
- Equivalent Dose (H) [Sievert or Sv]
  - In general, "high LET" radiation (e.g., alpha particles and protons) are much more damaging than "low LET" radiation, which include electrons and ionizing radiation such as x-rays and gamma rays and thus are given different radiation weighting factors (w_R)
    - X-rays/gamma rays/electrons: LET ≈ 2 keV/μm; $w_R = 1$
    - Protons (<2MeV): LET ≈ 20 keV/μm; w_R = 5-10
    - Neutrons (E dep.): LET ≈ 4-20 keV/μm; w_R = 5-20
    - Alpha Particle: LET ≈ 40 keV/μm; $w_R = 20$
  - $H = D \cdot w_R$
- Replaced the quantity formerly known as dose equivalent

Effective Dose

- Not all tissues equally radiosensitive
- ICRP publication 60 (1991): tissue weighting factors (w_T)
- Equivalent dose to each organ (H_T) [Sv]
- Effective Dose (E) [Sv]
- $E = \sum w_T \cdot H_T$
- Replaces the quantity formerly known as effective dose equivalent (H_E) using different w_T as per ICRP publication 26 (1977)

Tissue or Organ	Tissue Weighting Factor, w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01[a]
Bone surface	0.01
Remainder	0.05[b,c]
Total	**1.00**

[a] Applied to the mean equivalent dose over the entire skin.
[b] For purposes of calculation, the remainder is composed of the following additional tissues and organs: adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, and uterus.
[c] In those exceptional cases in which a single one of the remainder tissues or organs receives an equivalent dose in excess of the highest dose in any of the 12 organs for which weighting factor is specified, a weighting factor of 0.025 should be applied to that tissue or organ and weighting factor of 0.025 to the average dose in the rest of the remainder as defined above.
Adapted from *1990 Recommendations of the International Commission on Radiological Protection.* ICRP publication no. 60. Oxford: Pergamon, 1991.

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.58.

Summary

TABLE 3-6. RADIOLOGICAL QUANTITIES, SYSTEM INTERNATIONAL (SI) UNITS, AND TRADITIONAL UNITS

Quantity	Description of Quantity	SI Units (Abbreviations) and Definitions	Traditional Units (Abbreviations) and Definitions	Symbol	Definitions and Conversion Factors
Exposure	Amount of ionization per mass of air due to x- and gamma rays	$C\ kg^{-1}$	Roentgen (R)	X	$1R = 2.58 \times 10^{-4}\ C\ kg^{-1}$ 1R = 8.708 mGy air kerma @ 30 kVp 1R = 8.767 mGy air kerma @ 60 kVp 1R = 8.883 mGy air kerma @ 100 kVp
Absorbed dose	Amount of energy imparted by radiation per mass	Gray (Gy) $1\ Gy = J\ kg^{-1}$	rad $1\ rad = 0.01\ J\ kg^{-1}$	D	1 rad = 10 mGy 100 rad = 1 Gy
Kerma	Kinetic energy transferred to charged particles per unit mass	Gray (Gy) $1\ Gy = J\ kg^{-1}$	—	K	—
Air kerma	Kinetic energy transferred to charged particles per unit mass of air	Gray (Gy) $1\ Gy = J\ kg^{-1}$	—	K_{air}	1 mGy = 0.115 R @ 30 kVp 1 mGy = 0.114 R @ 60 kVp 1 mGy = 0.113 R @ 100 kVp 1 mGy ≅ 0.014 rad (dose to skin) 1 mGy ≅ 1.4 mGy (dose to skin)
Imparted energy	Total radiation energy imparted to matter	Joule (J)	—	D_I	Dose ($J\ kg^{-1}$) × mass (kg) = J
Equivalent dose (defined by ICRP in 1990 to replace dose equivalent)	A measure of radiation specific biologic damage in humans	Sievert (Sv)	rem	H	$H = w_R D$ 1 rem = 10 mSv 100 rem = 1 Sv
Dose equivalent (defined by ICRP in 1977)	A measure of radiation specific biologic damage in humans	Sievert (Sv)	rem	H	$H = Q D$ 1 rem = 10 mSv 100 rem = 1 Sv
Effective dose (defined by ICRP in 1990 to replace effective dose equivalent)	A measure of radiation and organ system specific damage in humans	Sievert (Sv)	rem	E	$E = \Sigma_T w_T H_T$
Effective dose equivalent (defined by ICRP in 1977)	A measure of radiation and organ system specific damage in humans	Sievert (Sv)	rem	H_E	$H_E = \Sigma_T w_T H_T$
Activity	Amount of radioactive material expressed as the nuclear transformation rate.	Becquerel (Bq) (sec^{-1})	Curie (Ci)	A	$1\ Ci = 3.7 \times 10^{10}\ Bq$ 37 kBq = 1 μCi 37 MBq = 1 mCi 37 GBq = 1 Ci

ICRP, International Commission on Radiological Protection.

c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p.59.

Raphex 2002 Question: $\mathcal{EM}$ Radiation

- **G46-G50**. Match the type of radiation with its description.
  - A. Ionizing elementary particles
  - B. Non-ionizing elementary particles
  - C. Ionizing photons
  - D. Non-ionizing photons
  - E. Other

  - **G46**. Betas
  - **G47**. Heat radiation
  - **G48**. Visible light
  - **G49**. X-rays
  - **G50**. Ultrasound

Raphex 2000 Question: Radiological Units

- **G2-G4.** Match the quality factor (Q) or radiation weighting factor (w_R) used in radiation protection with the type of radiation:
  - A. 10
  - B. 2
  - C. 1
  - D. 0.693
  - E. 20

  - **G2**. 1.25 MeV gammas
  - **G3**. 100 keV x-rays
  - **G4**. 200 keV neutrons

Raphex 2001 Question: Radiological Units

- **G3-G6.** Match the following units with the quantities below:
  - A. Bq
  - B. Sv
  - C. C/kg
  - D. Gy
  - E. J

  - **G3**. Absorbed dose
  - **G4**. Activity
  - **G5**. Exposure
  - **G6**. Dose equivalent

Raphex 2003 Question: Radiological Units

- **G9.** Dose equivalent is greater than absorbed dose for ___________.
  - A. X-rays above 10 MeV
  - B. Kilovoltage x-rays
  - C. Electrons
  - D. Neutrons
  - E. All charged particles

Raphex 2002 Question: Radiological Units

- **G2-G5.** Match the unit with the quantity it measures. (Answers may be used more than once or not at all.)
  - A. Frequency.
  - B. Wavelength.
  - C. Power.
  - D. Absorbed dose.
  - E. Energy.

  - **G2**. Electron volt
  - **G3**. Hertz
  - **G4**. Joule
  - **G5**. Gray