Advance Medical Physics

BASIC PHYSICS

The Atom

- Individual Entities
- Makes the elements different from each other
- Originally thought to be the smallest and indivisible particle, but … ..
  - Radius is approximately 10^{-10} m
- Small Central Core – nucleus
  - Radius approximately 10^{-15} m

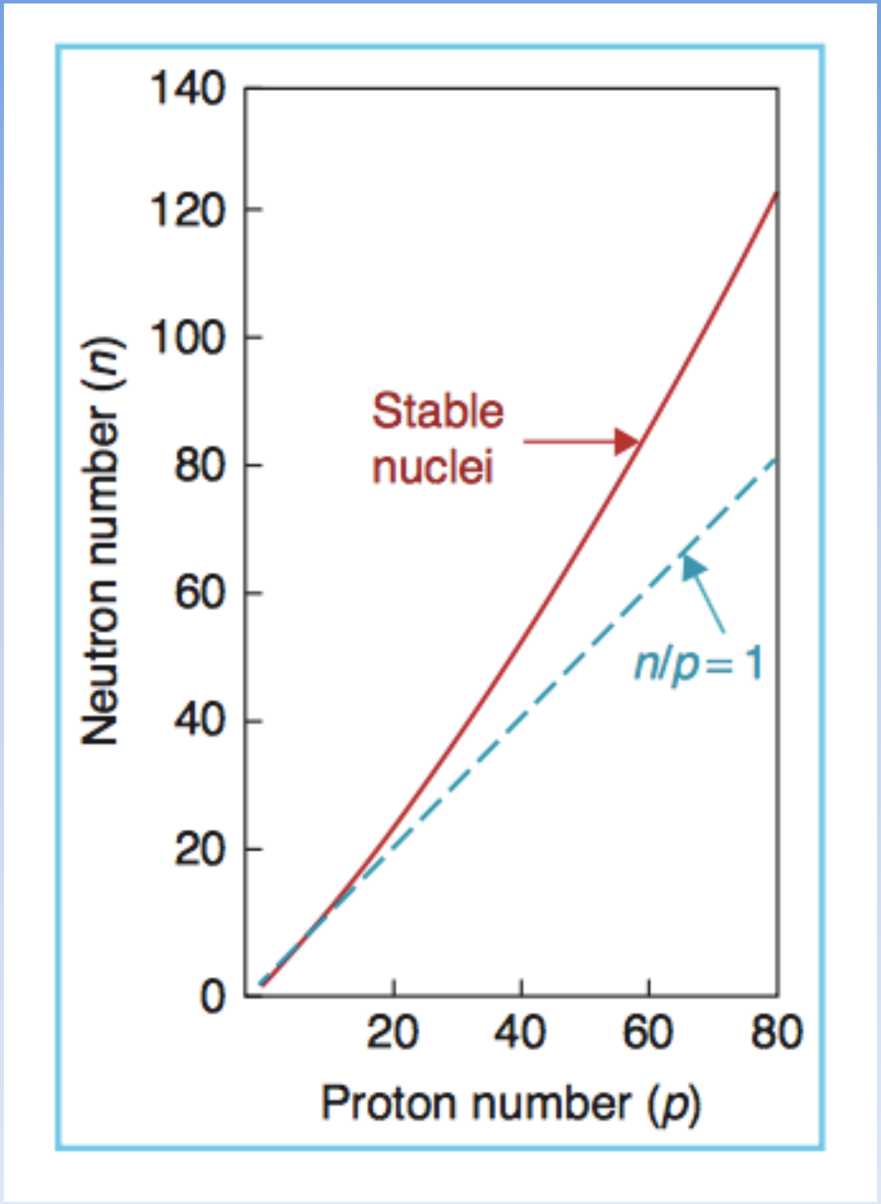
The Nucleus

- Contain two fundamental particles
- Positively charged protons and neutral neutrons

$$^{A}_{Z}X$$

A is the mass number, denoting the number of protons, Z is the atomic number

A plot of neutrons versus protons in stable nuclei



Masses of atoms and atomic particles are conveniently given in terms of atomic mass unit (amu). An amu is defined as 1/12 of the mass of a $^{12}_{6}C$ atom. Thus, the $^{12}_{6}C$ atom is arbitrarily assigned the mass equal to 12 amu. In basic units of mass,

$$1 \text{ amu} = 1.66 \times 10^{-27} \text{ kg}$$

The mass of an atom expressed in terms of amu is known as *atomic mass* or *atomic weight*. Another useful term is *gram atomic weight*, which is defined as the mass in grams numerically equal to the atomic weight. According to Avogadro's law, every gram atomic weight of a substance contains the same number of atoms. The number, referred to as *Avogadro number* or *Avogadro constant* (N_A), has been measured by many investigators, and its currently accepted value is 6.0221×10^{23} atoms per gram atomic weight (or mole).

From the previous definitions, one can calculate other quantities of interest such as the number of atoms per gram, grams per atom, and electrons per gram. Considering helium as an example, its atomic weight (A_W) is equal to 4.0026.

Therefore,

$$\text{Number of atoms/g} = \frac{N_A}{A_W} = 1.505 \times 10^{23}$$

$$\text{Grams/atom} = \frac{A_W}{N_A} = 6.646 \times 10^{-24}$$

$$\text{Number of electrons/g} = \frac{N_A \cdot Z}{A_W} = 3.009 \times 10^{23}$$

The masses of atomic particles, according to the amu, are electron = 0.000548 amu, proton = 1.00727 amu, and neutron = 1.00866 amu.

- Atomic structure:
  - Atom consists of a positively charged nucleus surrounded by a cloud of negatively charged electrons.
  - Atomic dimensions: radius of atom ~10^{-10} m, radius of nucleus ~10^{-15} m.
- An atom is specified by the formula: ${}^{A}_{Z}X$, where X is the symbol for the element, A is the mass number (number of protons + neutrons), and Z is the atomic number (number of protons).
- Classification of atoms:
  - Isotopes—atoms with the same Z but different number of neutrons
  - Isotones—atoms with the same number of neutrons but different Z
  - Isobars—atoms with the same A but different Z
  - Isomers—atoms with the same A and same Z but different nuclear energy states
- Nuclear stability:
  - Certain combinations of number of neutrons (n) and protons (p) in the nucleus show more stability than others.
  - Most stable nuclei contain even numbers of n and even numbers of p.
  - Least stable nuclei contain odd numbers of n and odd numbers of p.
  - A high n/p ratio gives rise to β^- decay, while a low n/p ratio can result in electron capture and β^+ decay (to be discussed in Chapter 2).

- Atomic mass:
  - amu = 1/12 of mass of $^{12}_{6}C$ atom.
  - Atomic mass or atomic weight may be expressed in amu.
  - Number of electrons per gram = $N_A \cdot Z/A_W$, where N_A is Avogadro number, Z is atomic number, and A_W is atomic weight.
- Mass–energy equivalence, $E = mc^2$:
  - Energy equivalent of an electron at rest (E_0) = 0.511 MeV.
  - Energy equivalent of 1 amu = 931.5 MeV.
  - Equivalent masses of particles may also be expressed in units of GeV/c^2 (see Fig. 1.6).
- Atomic energy levels:
  - The innermost electron orbit in an atom is the K shell. The next shells are L, M, N, and O. The maximum possible number of electrons in any orbit is given by $2n^2$, where n is the orbit number.
  - Binding energy of electrons in various orbits depends on the magnitude of the Coulomb force of attraction between the positively charged nucleus and the negatively charged electrons. The closer the orbit is to the nucleus, the greater the binding energy.
  - Potential energy is the binding energy with a negative sign.

- Nuclear energy levels:
  - Nucleons are arranged in discrete energy states of the nucleus.
  - Energy level diagram for the decay of ^{60}Co nucleus (Fig. 1.5) shows beta particle emission followed by two gamma ray photons emitted per disintegration with energies of 1.17 and 1.33 MeV.
- Elementary particles:
  - There are 12 fundamental particles of matter: six quarks and six leptons. Correspondingly, there are six quarks and six leptons of antimatter. All these particles are called fermions. In addition, there are 13 messenger particles, called bosons, that mediate the four forces of nature.
  - Fermions have noninteger spin; bosons have integer spin.
  - The Higgs field permeates all space and is responsible for giving mass properties to matter. The messenger particle for the Higgs field is the Higgs boson.
- Forces of nature:
  - There are four forces of nature. In order of their strengths, they are strong nuclear, electromagnetic, weak nuclear, and gravitational.
  - All forces of nature are mediated by specific messenger particles, the bosons.
- Electromagnetic radiation:
  - Electromagnetic radiations are characterized by oscillating electric and magnetic fields, always perpendicular to each other and to the direction of their energy propagation.
  - Wavelength (λ), frequency (ν), and velocity (c) of EM waves are related by $c = \nu\lambda$.
  - Quantum model relates energy of a photon with its frequency of oscillation by $E = h\nu$, where h is Planck's constant.

The Periodic Table

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-71	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Nuclear Transformation

- Radioactivity
- Decay Constant
- Activity
- The Half Life and the mean life
- Radioactive Series
- Radioactive equilibrium
- Modes of Radioactive Decay
- Solve Example 1,2 3, FM Khan Ch # 2

EXAMPLE 2

1. Calculate the decay constant for cobalt-60 ($T_{1/2} = 5.26$ years) in units of month^{-1}.
2. What will be the activity of a 5,000-Ci ^{60}Co source after 4 years?
   a. From Equation 2.5, we have

$$\lambda = \frac{0.693}{T_{\frac{1}{2}}}$$

since $T_{\frac{1}{2}} = 5.26$ years $= 63.12$ months. Therefore,

$$\lambda = \frac{0.693}{63.12} = 1.0979 \times 10^{-2}\ \text{month}^{-1}$$

   b. $t = 4$ years $= 48$ months. From Equation 2.4, we have

$$\begin{aligned} A &= A_0 e^{-\lambda t} \\ &= 5{,}000 \times e^{-1.0979 \times 10^{-2} \times 48} \\ &= 2{,}952\ \text{Ci} \end{aligned}$$

Alternatively,

$$t = 4\ \text{years} = \frac{4}{5.26} T_{\frac{1}{2}} = 0.760\, T_{\frac{1}{2}}$$

Therefore,

$$A = 5{,}000 \times \frac{1}{2^{0.760}} = 2{,}952\ \text{Ci}$$

Alternatively, reading the fractional activity from the universal decay curve given in Figure 2.2 at time $= 0.760 T_{1/2}$ and then multiplying it with the initial activity, we get the desired answer.

Nuclear Reactions

- The Alpha, p Reaction
- The alpha, n reaction
- Proton Bombardment
- Deuteron Bombardment
- Neutron Bombardment
- Photodisintegration
- Fission
- Fusion

- Radioactivity:
  - Emission of radiation from a nucleus in the form of particles, γ rays, or both is called radioactivity.
  - Activity A of a radioactive element is the rate of disintegration or decay and is given by $A = A_0 e^{-\lambda t}$, where A is activity at time t, A_0 is activity at the start of time t, and λ is the disintegration constant.
  - Half-life $T_{1/2}$ and λ are related by $T_{1/2} = 0.693/\lambda$.
  - Average or mean life $T_a = 1/\lambda = 1.44\ T_{1/2}$.
  - The SI unit for activity is Becquerel (B_q). 1 Bq = 1 dps.
  - A practical unit of activity is curie (Ci). 1 Ci = 3.7×10^{10} dps.
  - Activity of 1 g of radium is 0.975 Ci.
- All of the naturally occurring radioactive elements have been grouped together into three series: uranium, actinium, and thorium. The rest ($Z = 93$ to 118) are produced artificially.
- Radioactive equilibrium:
  - If half-life of the parent nuclide is larger than that of the daughter nuclide, a condition of equilibrium occurs after a certain amount of time. At equilibrium, the ratio of daughter activity to parent activity becomes constant.
  - Transient equilibrium occurs when the half-life of the parent (T_1) is not much longer than that of the daughter (T_2) (e.g., decay of ^{99}Mo to ^{99m}Tc). At transient equilibrium, the daughter activity A_2 and the parent activity A_1 are related by $A_2 = A_1 \times T_1/(T_1 - T_2)$.
  - Secular equilibrium occurs when the half-life of the parent is much longer than that of the daughter (e.g., decay of ^{226}Ra to ^{222}Rn). At secular equilibrium, $A_2 \approx A_1$.

- Modes of decay:
  - α particles are helium nuclei and are emitted by high atomic number radionuclides ($Z > 82$).
  - β^- particle is a negatively charged electron (negatron) emitted from a nucleus.
  - β^+ particle is a positively charged electron (positron) emitted from a nucleus.
  - β particle does not exist as such in the nucleus but is emitted at the instant of a neutron or a proton decay in the nucleus:

$$n \rightarrow p^+ + \beta^- + \text{antineutrino}$$
$$p^+ \rightarrow n + \beta^+ + \text{neutrino}$$

  - β particles are emitted with a spectrum of energies, ranging from zero to a maximum. They share the available kinetic energy with the accompanying neutrino.
  - The average energy of β particles is about one-third of the maximum energy.
  - Electron capture is a process in which a nucleus captures an orbital electron, thus transforming one of its protons into a neutron:

$$P^+ + e^- \rightarrow n + \nu$$

  - Electron capture creates a vacancy in the electron orbit involved which, when filled by an outer orbit electron, gives rise to characteristic x-rays (fluorescent radiation) and/or Auger electrons. The process is likened to "internal photoelectric effect."
  - Internal conversion is a process in which a nucleus in the excited state transfers its excess energy to one of the orbital electrons, causing it to be ejected from the orbit. The ejected electron creates a vacancy in the involved shell and, as mentioned in the electron capture process, causes the emission of characteristic x-rays (fluorescent radiation) or Auger electrons.
  - Fluorescent yield is Z dependent, increasing from lower Z to higher Z.

- Isomeric transition involves an excited nucleus in the metastable state decaying to the ground state. Example: ^{99m}Tc decaying to ^{99}Tc with a half-life of 6 hours.

- Nuclear reactions:
  - Nuclear reactions can be produced by bombarding heavier nuclides with lighter nuclides or particles.
  - Examples of bombarding particles are α particles, protons, neutrons, deuterons, and γ-ray photons.
  - The photodisintegration process is responsible for contamination of the high-energy x-ray beams generated by linear accelerators.
  - Radioactive sources used in radiation therapy are produced by bombarding nuclides in nuclear reactors or particle accelerators.
  - Nuclear fission is a process of splitting high Z nucleus into two lower Z nuclei. The process results in the release of a large amount of energy. Example: fission of ^{235}U nucleus by bombarding it with thermal neutrons (i.e., neutrons of energy < 0.025 eV). A chain reaction is possible with a critical mass of fissionable material.
  - Nuclear fusion is the reverse of nuclear fission—lighter nuclei are fused together into heavier ones. Again, a large amount of energy is released in the process.
  - Fusion of hydrogen nuclei into helium nuclei is the source of our sun's energy.

Clinical Radiation Generators

- Up to about 1950, most of the external beam radiotherapy was carried out with x-rays generated at voltages up to 300 kVp. Subsequent development of higher-energy machines and the increasing popularity of the cobalt-60 units in the 1950s and the 1960s resulted in a gradual demise of the conventional kilovoltage machines. However, these machines have not completely disappeared. Even in the present era of the megavoltage beams, there is still some use for the lower-energy beams, especially in the treatment of superficial skin lesions.

Grenz-Ray Therapy	20 kV
Contact Therapy	40 to 50 kV
Superficial Therapy	50 to 150 kV
Orthovoltage Therapy or Deep Therapy	150 to 500 kV
Supervoltage Therapy	500 to 1000 kV
Mega Voltage Therapy	Greater than 1 MV

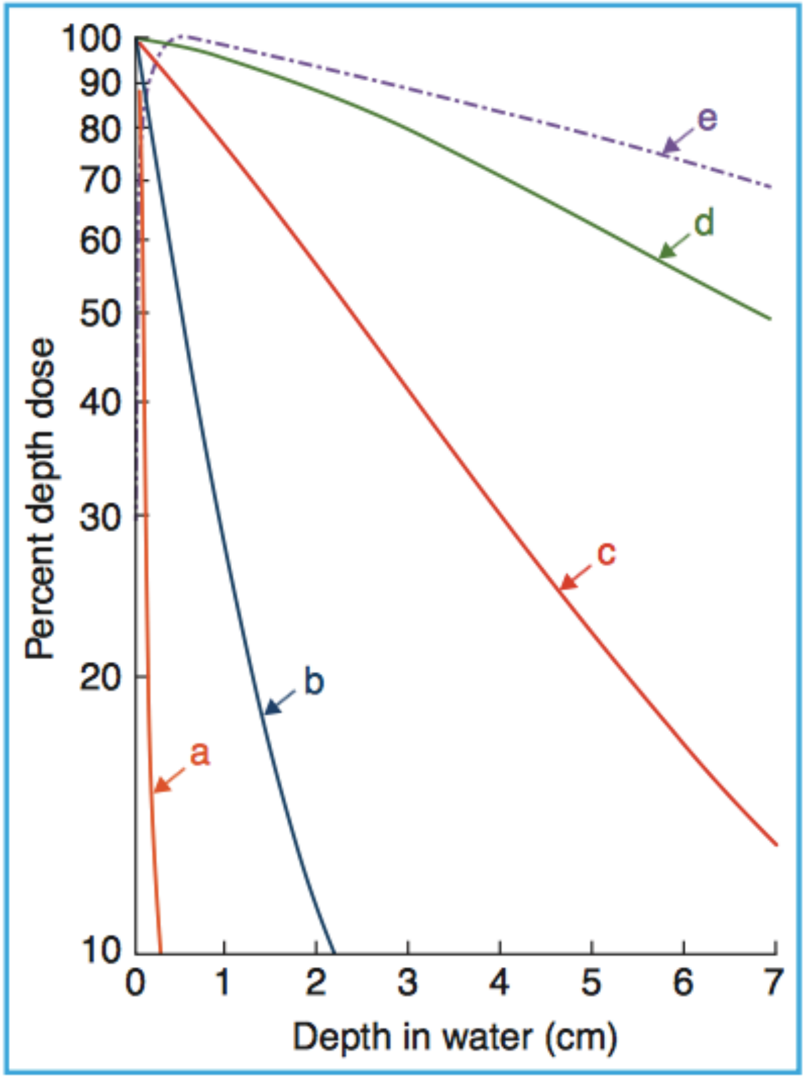
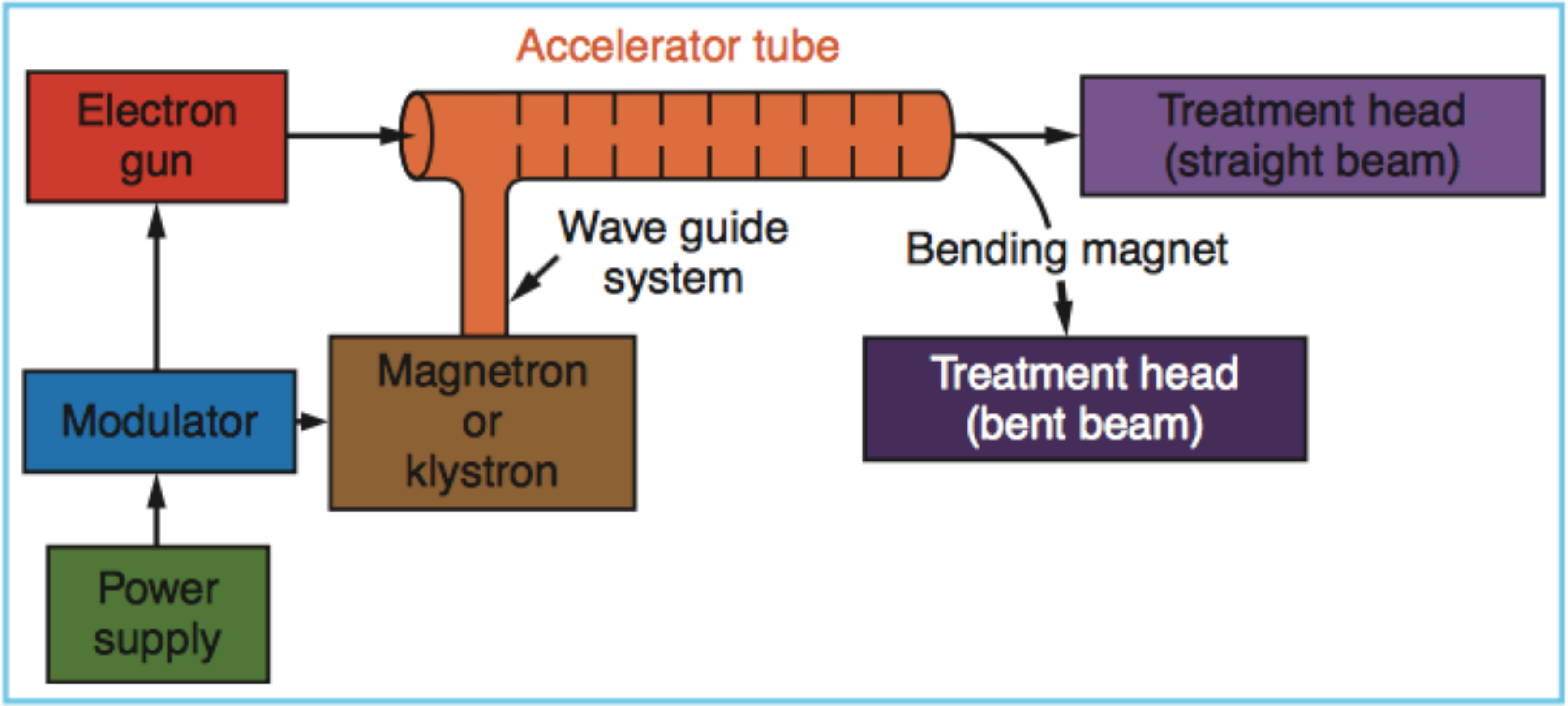
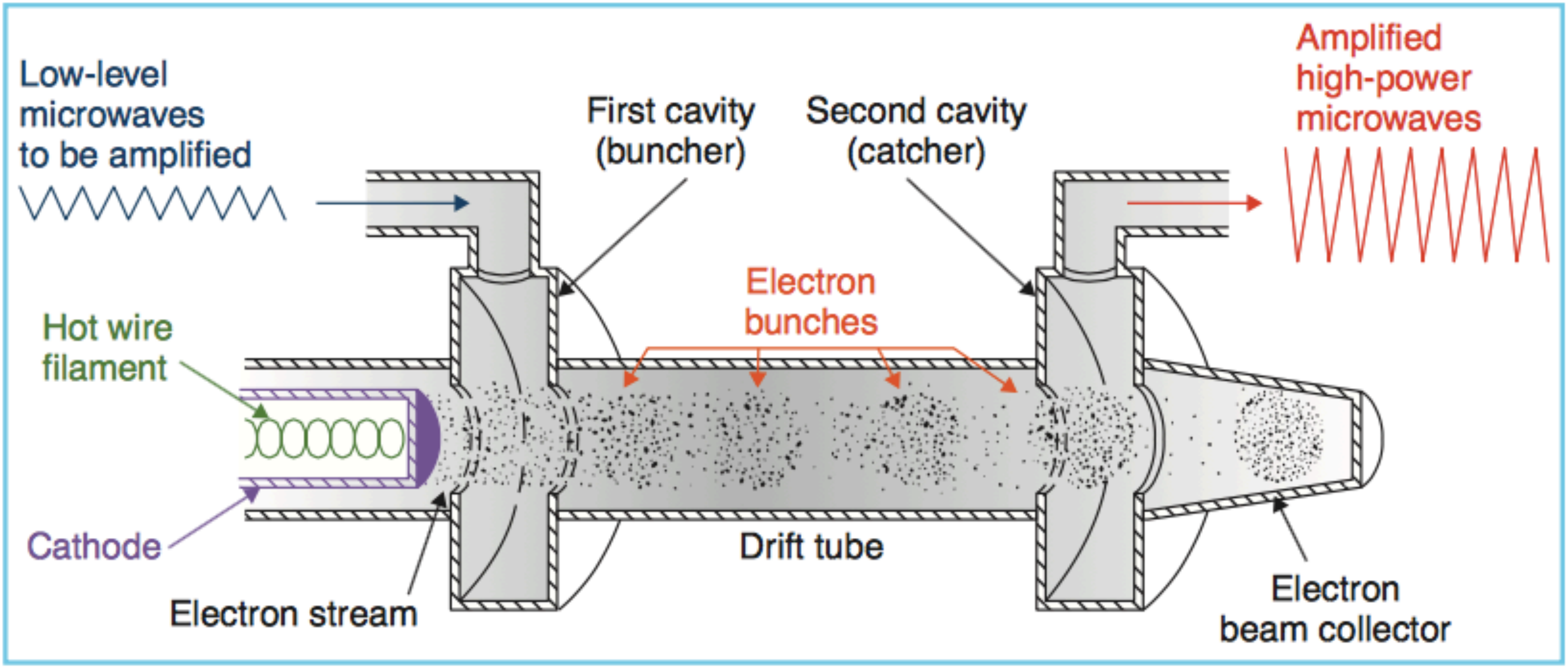


Figure 4.1. Depth–dose curves in water or soft tissues for various quality beams. **Line a:** Grenz rays, HVL = 0.04 mm Al, field diameter = 33 cm, SSD = 10 cm. **Line b:** Contact therapy, HVL = 1.5 mm Al, field diameter = 2.0 cm, SSD = 2 cm. **Line c:** Superficial therapy, HVL = 3.0 mm Al, field diameter = 3.6 cm, SSD = 20 cm. **Line d:** Orthovoltage, HVL = 2.0 mm Cu, field size = 10 × 10 cm, SSD = 50 cm. **Line e:** Cobalt-60 γ rays, field size = 10 × 10 cm, SSD = 80 cm. (Plotted from data in Cohen M, Jones DEA, Green D, eds. Central axis depth–dose data for use in radiotherapy. *Br J Radiol.* 1978[suppl 11]. The British Institute of Radiology, London, with permission.)

Linear Accelerators




Low-level
microwaves
to be amplified
First cavity
(buncher)
Second cavity
(catcher)
Amplified
high-power
microwaves
Electron
bunches
Hot wire
filament
Cathode
Electron stream
Drift tube
Electron
beam collector

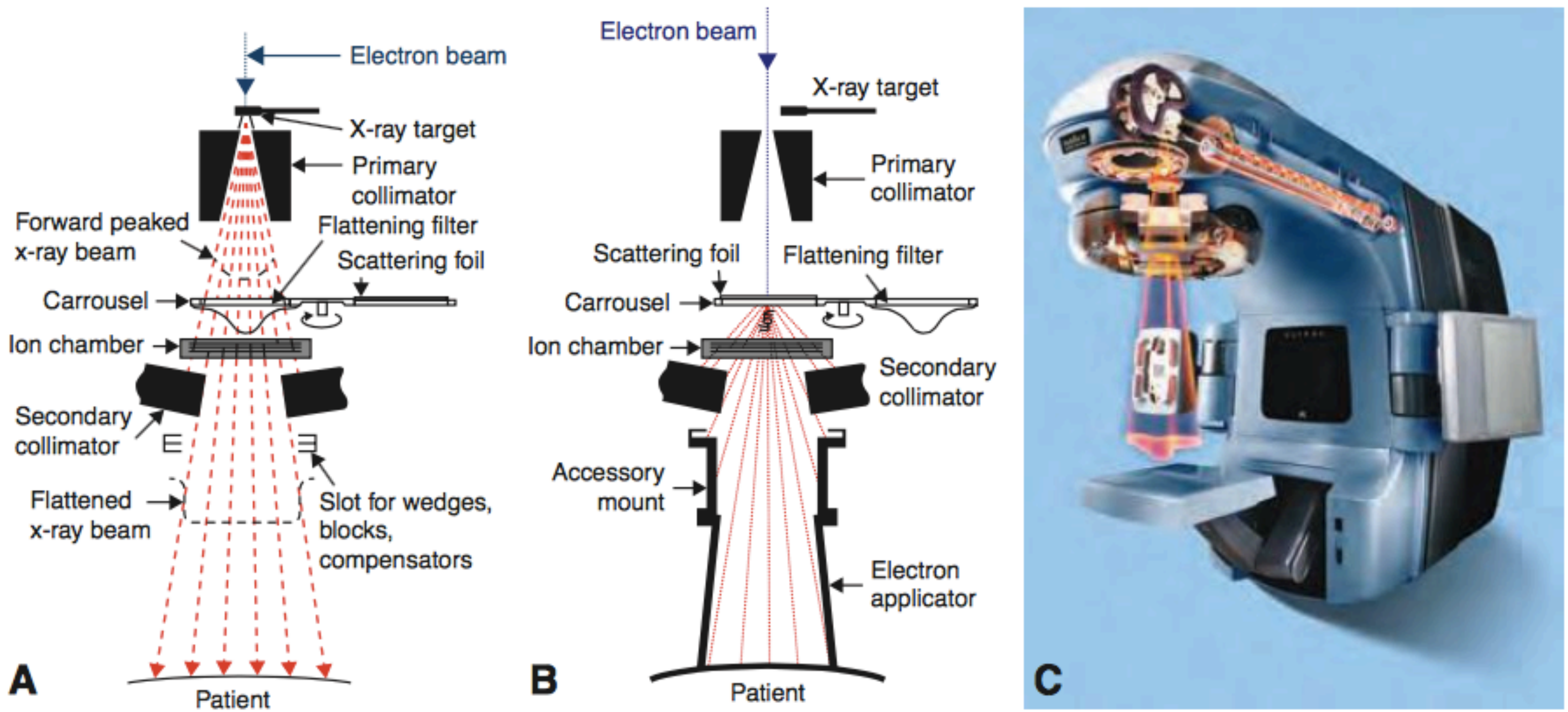


Figure 4.9. Components of treatment head. **A:** X-ray therapy mode. **B:** Electron therapy mode. (From Karzmark CJ, Morton RJ. *A Primer on Theory and Operation of Linear Accelerators in Radiation Therapy*. Rockville, MD: U.S. Department of Health and Human Services, Bureau of Radiological Health; 1981, with permission.). **C:** A cut-away diagram of the linac. (From Vaian Medical systems: www.varian.com, with permission.)

TABLE 4.1 Teletherapy Source Characteristics

Radionuclide	Half-Life (y)	γ-Ray Energy (MeV)	Γ-Value[a] $\left(\frac{Rm^2}{Ci-h}\right)$	Specific Activity Achieved in Practice (Ci/g)
Radium-226 (filtered by 0.5 mm Pt)	1,622	0.83 (avg.)	0.825	~0.98
Cesium-137	30.0	0.66	0.326	~50
Cobalt-60	5.26	1.17, 1.33	1.30	~200

[a]Exposure rate constant (Γ) is discussed in Chapter 8. The higher the Γ value, the greater the exposure rate or output per curie of the teletherapy source.