Structure of matter

Khan chapter 1

1.1. The Atom

- 105 elements exists and 92 of them occur naturally
- Each atom has dense nucleus with radius of $\sim 10^{-14}$ m and a cloud of electrons with radius of $\sim 10^{-10}$ m
- Comparative sizes of nucleus to atom is like a pin in a room
- Because of 'emptiness' of atom, high energy photons, electrons and nuclei readily penetrate many atoms before collisions
- Atoms differ by the composition of the nuclei and number of electrons
- Atomic number (Z) is the number of protons in the atom and chemical properties of atom are determined by Z

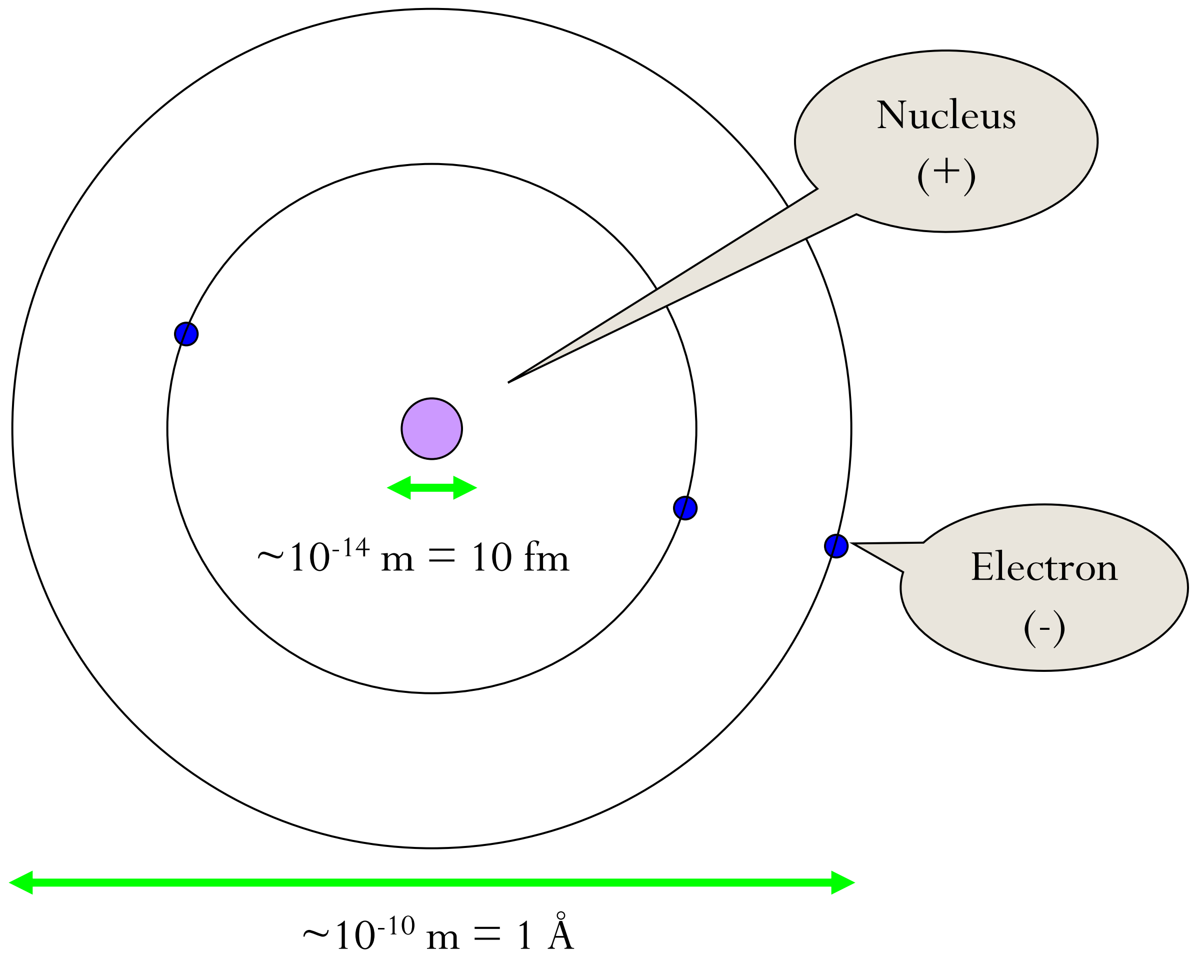
Structure of atoms

Nucleus

Electron (-)

Electron charge

$e = 1.602 \times 10^{-19}$ C



1.2. Nucleus

- Nucleus (핵), Nuclei (pl.): comprised of protons and neutrons
- Nuclear (핵의)
- ________ (핵종): an atomic species characterized by the specific constitution of its nucleus, i.e., by its number of protons *Z*, its number of neutrons *N*, and its energy state (ex, C-12, C-13)
- ________ (핵자): a collective name for two particles: the neutron and the proton
- Protons have positive charge and Neutrons have no charge
- Protons and neutrons have nearly same mass which is ~1800 times the mass of an electron
- In a neutral atom, the no. of protons = no. of electrons

- **Atomic number** (Z): the number of protons in nucleus or number of electrons around nucleus

- **Mass number** (A): total number of protons and neutrons in the nucleus

- **Isotopes**: Atoms with _________ but _________, i.e., atoms of the same element with different numbers of neutrons

  - ✓ Isotopes have the same chemical properties
  - ✓ Isotopes can be stable or unstable
  - ✓ "Unstable" means that nucleus exists in an excited energy level
  - ✓ Unstable nucleus eventually drops to a lower level by emitting energy of a form of a particle
  - ✓ Nuclear disintegration is the ejection of a particle from the nucleus

- Symbol for nucleus and its composition:

$^{A}_{Z}X$ where X is the element, A is the mass number, and Z is the atomic number

➔ e.g., $^{60}_{27}Co$ $^{1}_{1}H$

- Alternative symbol: X-A ➔ e.g. Co-60, H-1, etc

- Example: Three isotopes of hydrogen

$^{1}_{1}H$: Stable nucleus consists of 1 proton : hydrogen

$^{2}_{1}H$: Stable nucleus consists 1 proton and 1 neutron : deuteron (중양자)
The atom is deuterium (중수소)

$^{3}_{1}H$: Unstable nucleus (half life = 12.26 yr): triton (3중양자)
The atom is tritium (삼중수소)

- __________: same number of neutrons, different number of protons

$$^{131}_{53}I \qquad ^{132}_{54}Xe$$

- __________: same number of nucleons (or mass), different number of protons

Mo-99 Tc-99

- __________: same number of neutrons, same number of protons, different energy states

$$^{131m}_{54}Xe \qquad ^{131}_{54}Xe$$

Summary

- Isotopes: $p_1 = p_2$, $n_1 \neq n_2$
- Isotones: $p_1 \neq p_2$, $n_1 = n_2$
- Isobars: $p_1 \neq p_2$, $p_1+n_1 = p_2+n_2$
- Isomers: $p_1 = p_2$, $n_1 = n_2$, $E_1 \neq E_2$

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

X: chemical symbol for the element

A: mass number

Z: atomic number

Characteristics of Stable Nuclei

- Nuclear stability

  1) Z = 1~20 : n/p ratio = 1

  2) Z > 20 : ___________

  3) 300 isotopes

     1. >1/2 : even Z, even N

     2. only 4 : odd Z , odd N

     3. 20% : odd Z, even N

     4. 20% : even Z, odd N

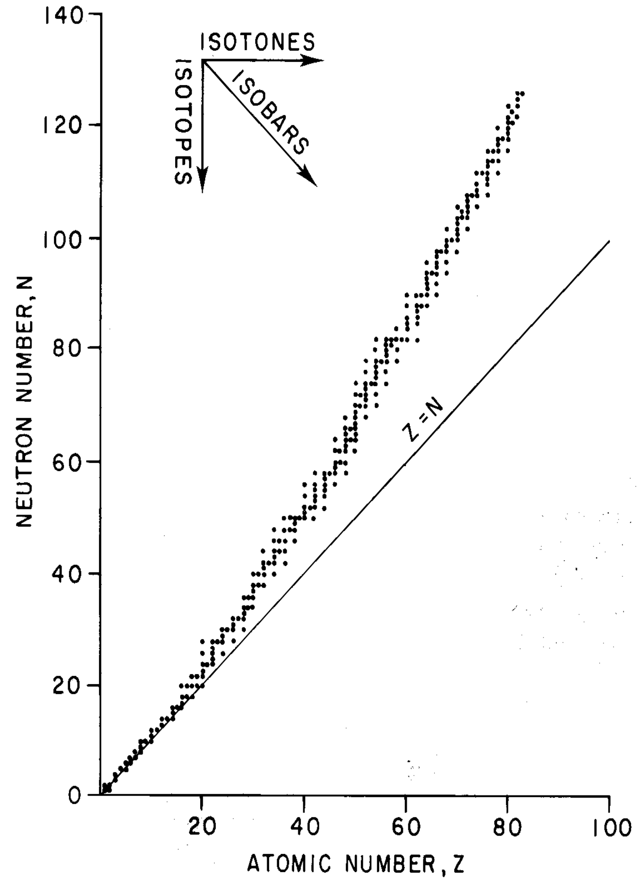


Fig. 1-7. Atomic number Z versus neutron number N for the stable nuclides. They are clustered around an imaginary line called the line of stability, $N \approx Z$ for light elements; $N \approx 1.5Z$ for heavy elements.

1.3. Atomic mass and energy units

- Atomic mass are given in terms of the mass of carbon nucleus (mass number 12), C-12
- Atomic masses are very near the sum of constituent particles
- ____________________(amu): 1/12 of the mass of C-12 nucleus (i.e., C-12 has 12 amu)

  1 amu = 1.66 x 10^{-27} kg

- However, atomic masses cannot be obtained by adding masses of constituent particles
- Mass of the whole nucleus is always less than the sum of its constituent parts
- Example: mass of nucleus for He-4 = 4.0015 amu

  mass of (2 proton + 2 neutron) = 4.0319 amu

- Gram atomic weight: the mass in grams numerically equal to the atomic weight

  (e. g., He ➔ 4.0026 gram)

- ______________: every gram atomic weight of a substance contains the same number of atoms

- $N_A = 6.0228 \times 10^{23}$ atoms per gram atomic weight

- Example ➔ Helium: its atomic weight (A_w) = 4.0026

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

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

Number electrons/g $$= \frac{N_A \bullet Z}{A_w} = 3.009 \times 10^{23}$$

Energy Unit

- 1 eV = 1V x 1.602 x 10^{-19} C = 1.602 x 10^{-19} J
- Einstein's principle of equivalence of mass and energy: $E = mc^2$
- Rest mass energy of electron: E =___________
- Amu to Energy: **1 amu = _________**

Nuclear Binding Energy

Protons	2 x 1.007277 u =	2.014554 u
Neutrons	2 x 1.008665 u =	2.017330 u
		~ 4.032 u

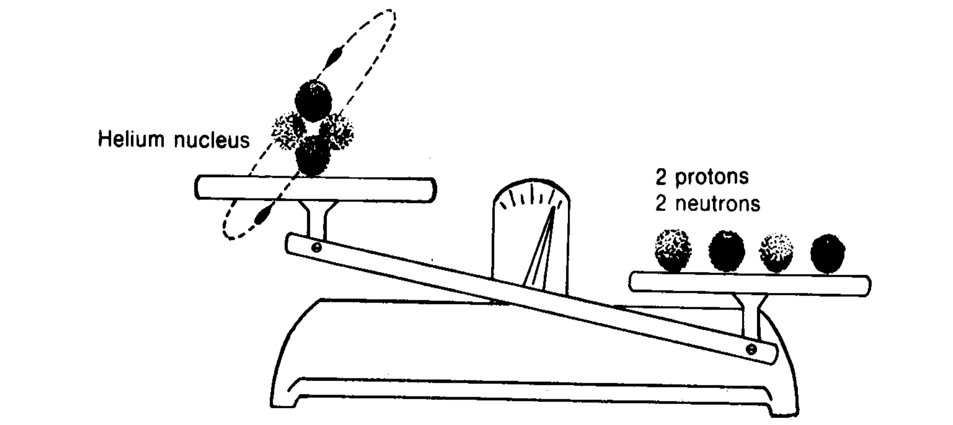


Fig. 2-6. Proof of nuclear binding energy. Intact helium 4 nucleus weighs less than individual components weighed separately. This suggests that some nuclear mass has been converted to binding energy.

4.032 – 4.002= 0.03 u ➔ Δm (mass defect)

$\mathbf{E_B = \Delta mc^2} = 0.03 \times 931.5 = \sim 28\ \text{MeV}$

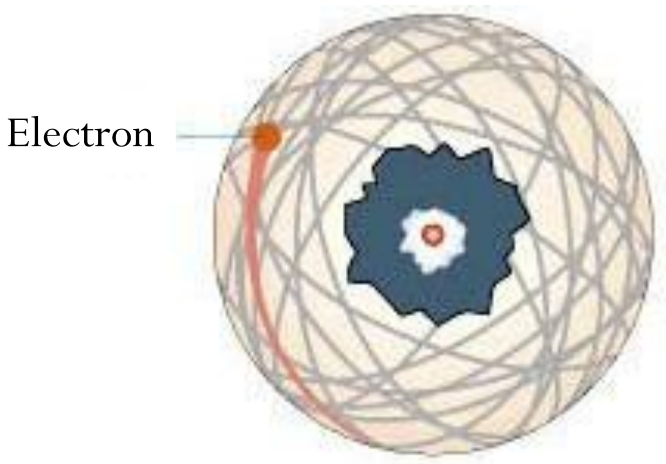
1.4 &5 Atomic energy levels & orbital electrons

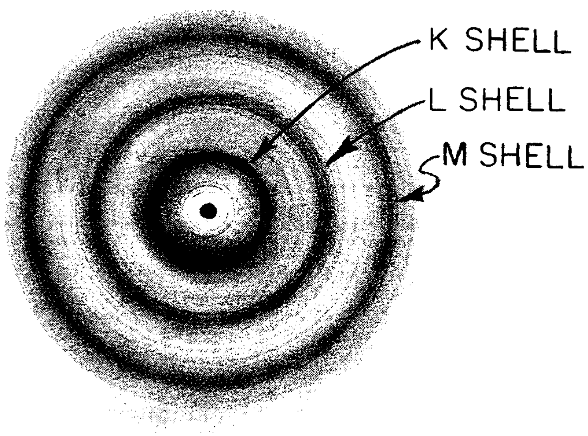
- Stable electron orbits are called "shells"
- Diameters of these shells are determined by quantum number (integer values)
- Innermost shell (n=1) called K shell

  next the L shell (n=2)

  M shell (n=3)

  N shell (n=4) ····





Pauli Exclusion Principle (1)

- Pauli's exclusion principle: "No two electrons in an atom may have the same set of quantum numbers (n, ℓ, m_ℓ, m_s)"

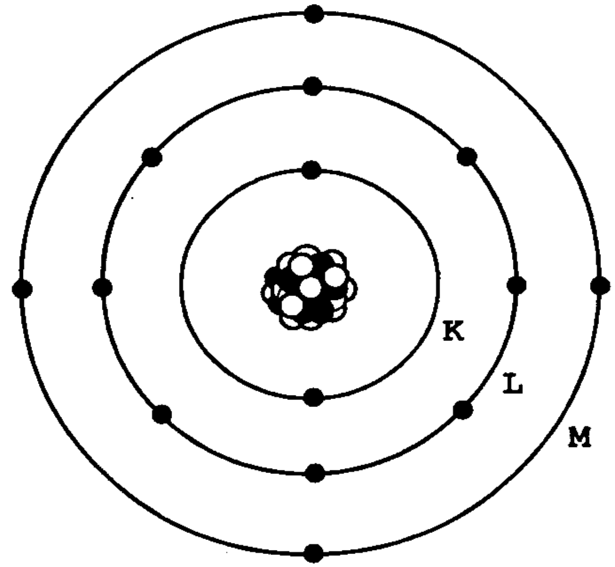
- It applies to all particles of half-integer spin, which are called *fermions*

- The periodic table can be understood by the Pauli Exclusion Principle

- The electrons in an atom tend to occupy the lowest energy levels available to them

Pauli Exclusion Principle (2)

- Maximum number of electrons allowed in each shell ➔ _____
- K shell n=1 : 2
- L shell n=2 : 8



Electron Binding Energy and Energy Levels

- The amount of energy required to completely remove an electron from a given shell in an atom is called the binding energy of that shell

- Notation K_B for the K shell

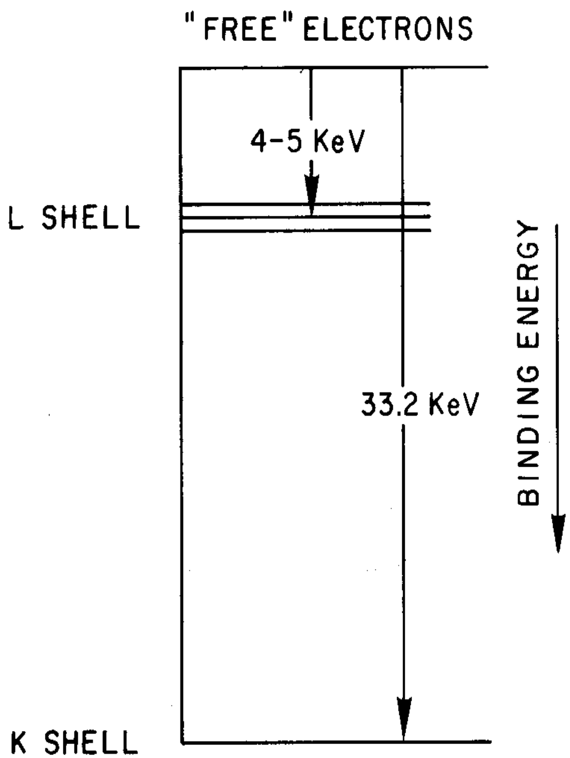
  L_B for the L shell

- $K_B > L_B > M_B \cdots\cdots$

- Heaviest element means that "it has greatest binding energy"

- Energy required to move from K to L is K_B-L_B

Binding energy and Energy Level Diagram



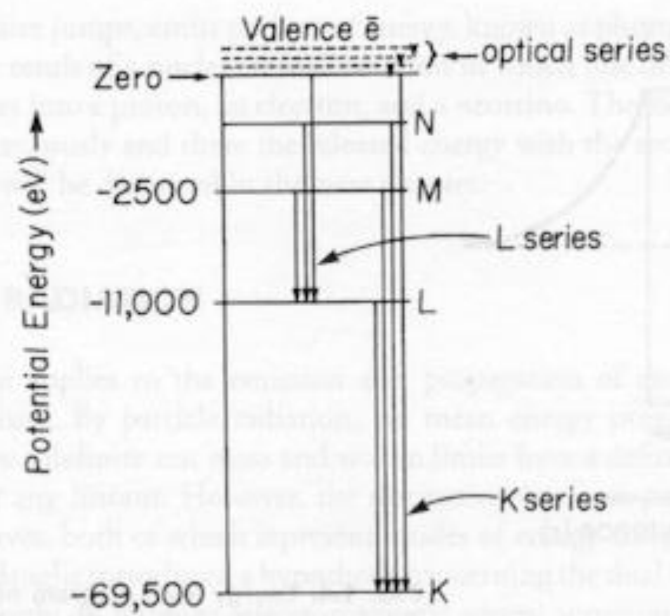


FIG. 1.3. A simplified energy level diagram of the tungsten atom (not to scale). Only few possible transitions are shown for illustration. Zero of the energy scale is arbitrarily set at the position of the valence electrons when the atom is in the unexcited state.

Iodine atom

Tungsten atom

1.6. Nuclear forces

- Nucleus (neutral neutrons and positive protons) are held together in spite of repulsive electrostatic forces
- Forces in nature: gravitational, electromagnetic, weak nuclear force, strong nuclear force
- While gravitational and magnetic force are very weak forces, electrostatic force is quite strong
- ____________________: very strong: => it accounts for nuclear binding energy, short range potential barriers

Forces in nucleus and Energy levels

- Repulsive Electrical forces

    → exist between positively charged protons

- Attractive Strong forces

    ✓ exist between any two nucleons

    ✓ are effective in very short distances

    ✓ hold the nucleus together

    (strong forces >> electrical forces)

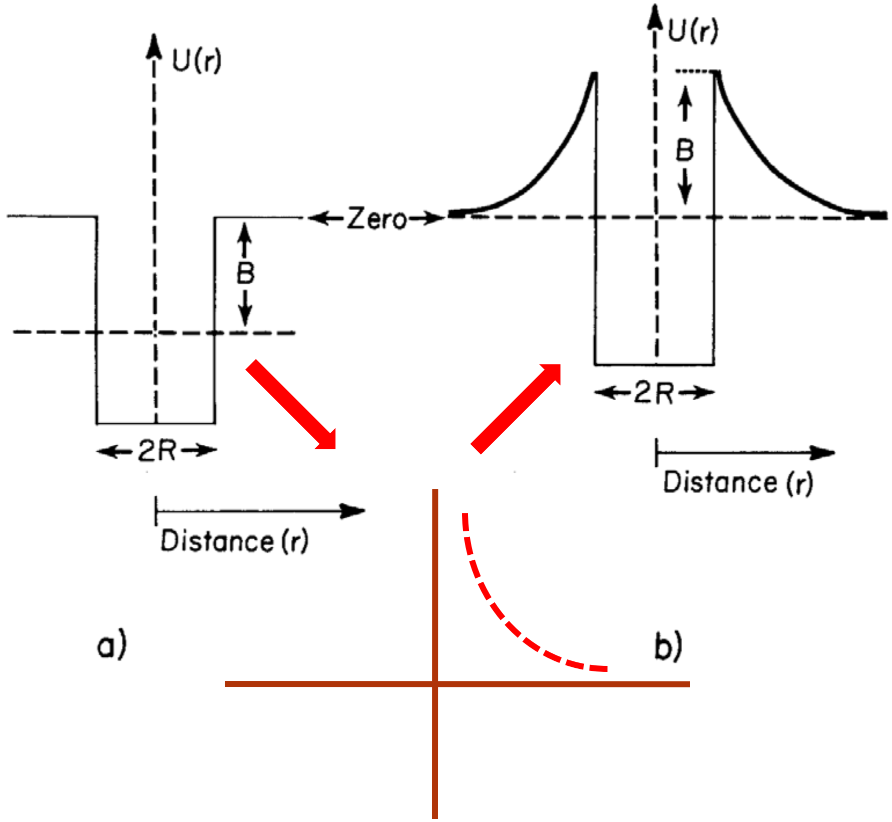


FIG. 1.4. Energy level diagram of a particle in a nucleus: **a,** particle with no charge; **b,** particle with positive charge; *U(r)* is the potential energy as a function of distance *r* from the center of the nucleus. *B* is the barrier height; *R* is the nuclear radius.

Electric potential by nucleus for positive particle

1. If a nucleon moves to certain range (< 2R), it falls in to the nuclear potential well.
2. Negative potential energy means you should give an energy if you want to take a nucleon from the nucleus.
3. If a nucleon with positive charge moves to nucleus, there will be additional force which is electric force between the nucleus and a positive nucleon.
4. Positive potential means that if you do nothing to the particle, it will have that potential energy as an kinetic energy.

1.7. Nuclear energy levels

- Most stable arrangement of nucleon is called the ground state

- Other arrangements

  two categories:

  - ✓ Excited states
  - ✓ Meta-stable states (relatively long time)

* dividing line for life time : about 10^{-12} sec

Co–59 + n ➔ Co-60 ➔ Ni-60 (neutron → proton)

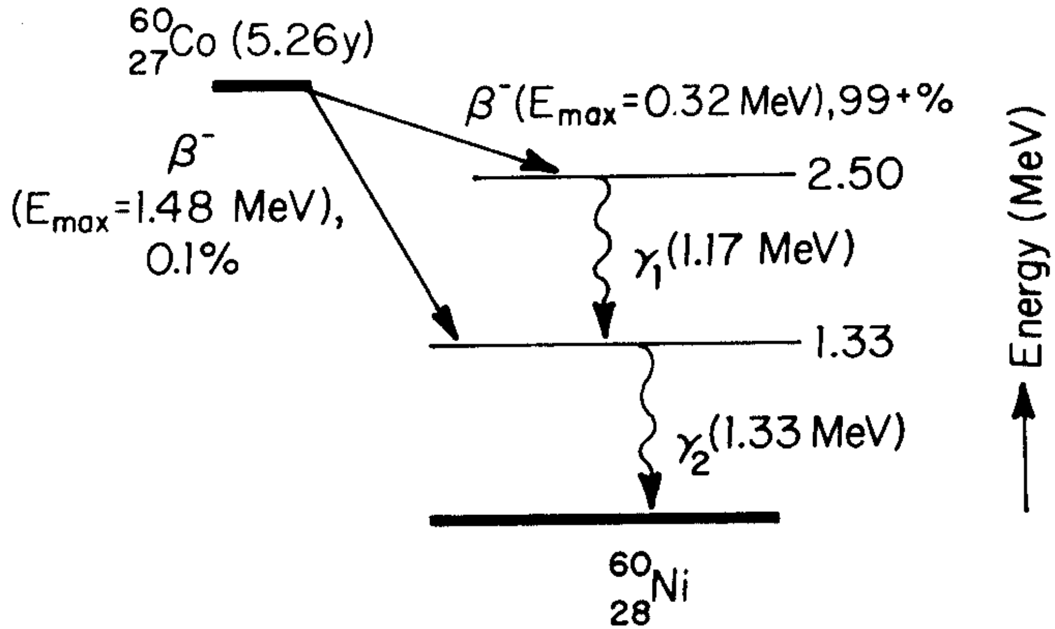


FIG. 1.5. Energy level diagram for the decay of $^{60}_{27}$Co nucleus.

1.8. Particle radiation

- Definition of Radiation: ___________ is the emission and propagation of energy through space or a material medium (Energy in transit)

- There are two specific forms of radiation

  1. Particle radiation

     ➔ Energy is carried in form of kinetic energy of mass in motion

  2. Electromagnetic radiation

     ➔ Energy is carried by oscillating electrical and magnetic fields traveling through space at the speed of light

Example of Particle Radiation

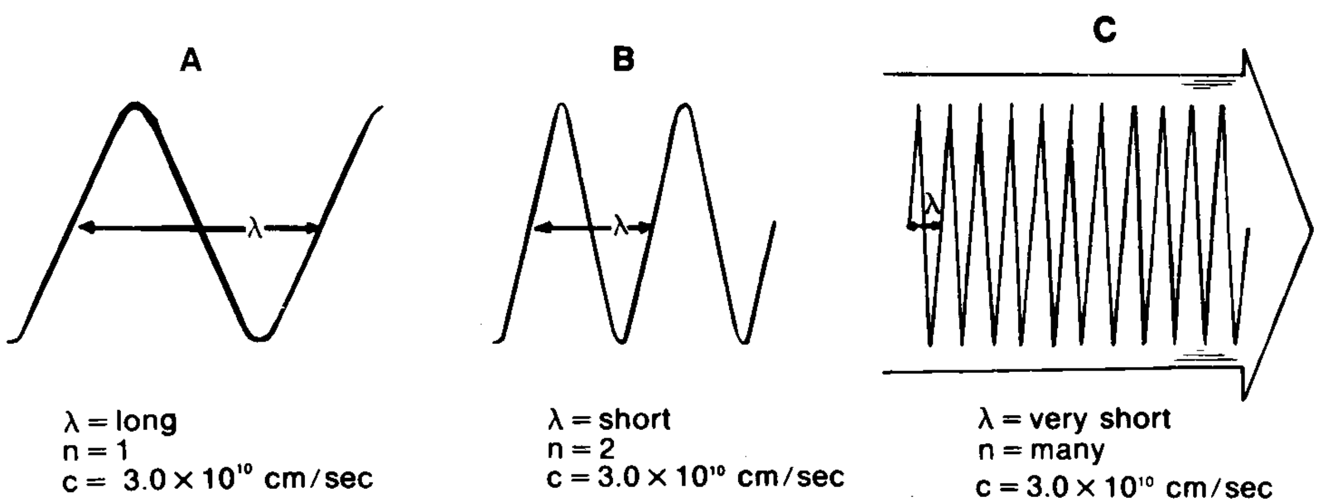
- Electron (e^-), Positron (e^+)
  - β ray, thermal electrons → LINAC
  - Proton (p)
    - ✓ from hydrogen gas, accelerated by cyclotron
- Neutron (n)
  - from nuclear reactor
- Heavy ion (^{12}C)
- Muon (m), Pion (p)
  - Leptons and mesons

1.9. Elementary Particles

- There are two classes of particles: fermions and bosons
- Fermion is a particle whose spin is an odd half-inter (1/2, 3/2,..)
- Boson is a particle whose spin is an integer number (1,2,3,..)
- The fundamental particles of matter are of two kinds: Quarks and leptons
  - ✓ Quarks: up (u), down (d), charm (c), strange (s), top (t), and bottom (b)
  - ✓ Leptons: electron (e), electron neutrino (ν_e), muon (μ), muon neutrino (ν_μ), tau (τ) and tau neutrino (ν_τ)
- There are 13 messenger particles that mediate the four forces of nature
  - ✓ Electromagnetism -------- Photon
  - ✓ Strong force -------------- Eight gluons
  - ✓ Weak force --------------- W^+, W^-, Z^0
  - ✓ Gravity ---------------- graviton (not yet detected)

1.10. Electromagnetic Radiation

- wavelength : λ
- frequency : ν
- velocity of light : $c = 3 \times 10^8$ m/s



$\underline{\lambda\nu = c,}$ $\underline{\lambda = c/\ \nu,}$ $\underline{\nu = c/\lambda}$

Propagation & Collision of EM field

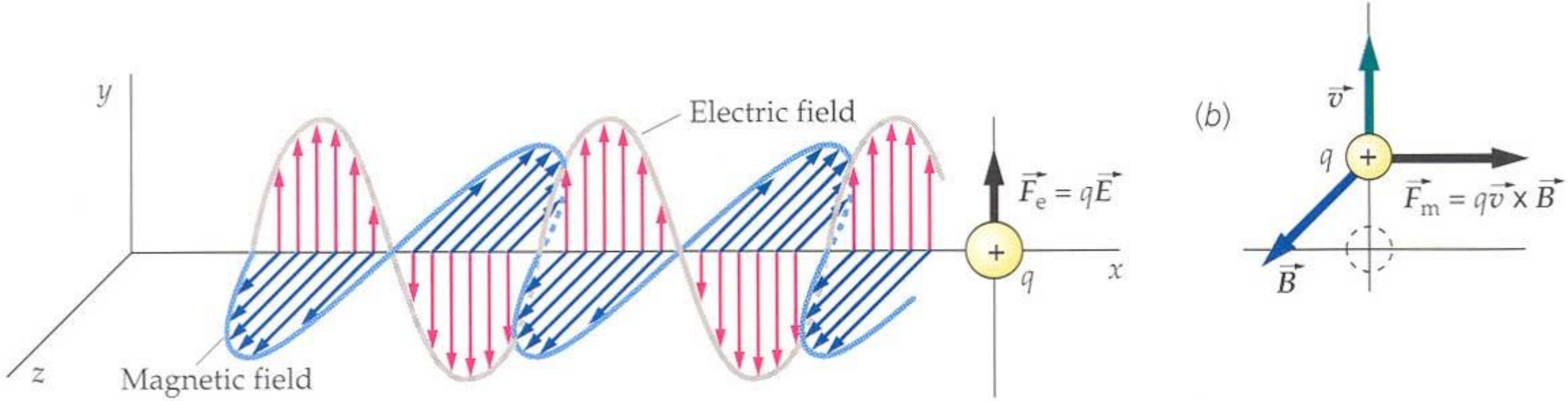


Figure An electromagnetic wave incident on a point charge that is initially at rest on the x axis. (a) The electric force $q\vec{E}$ accelerates the charge in the upward direction. (b) When the velocity of the charge is $\vec{v}$ upward, the magnetic force $q\vec{v} \times \vec{B}$ accelerates the charge in the direction of the wave.