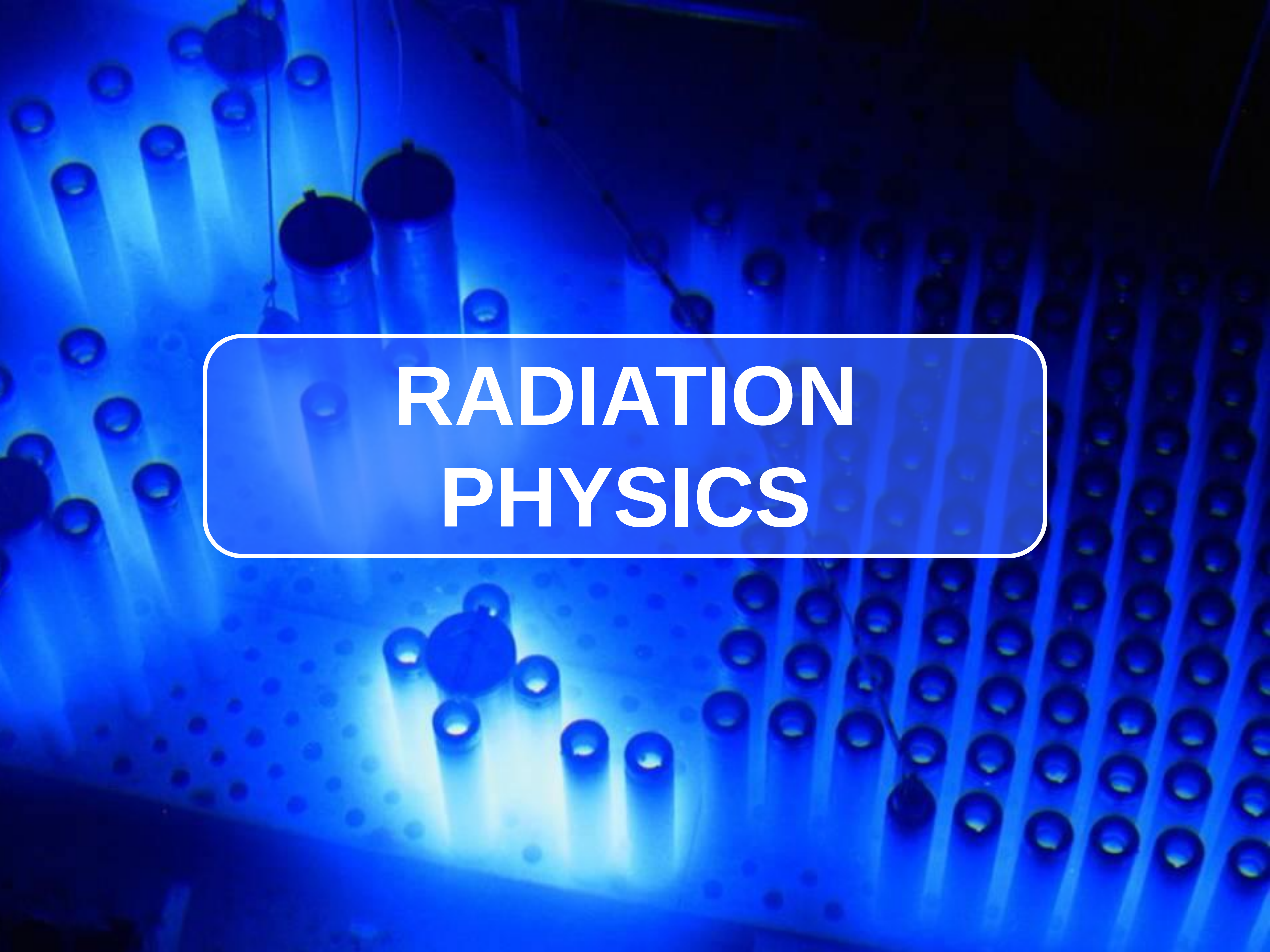


RADIATION PHYSICS

RADIATION PHYSICS

Introduction

- Element - a substance that cannot be broken down by ordinary chemical processes into simpler substances
  - 92 naturally occurring elements
  - Another dozen or so elements have been produced artificially, best known is plutonium

- Compound - two or more elements chemically linked in definite proportions, e.g. water, H_2O

- Atom - matter consists of atoms, each element having its own characteristic atom

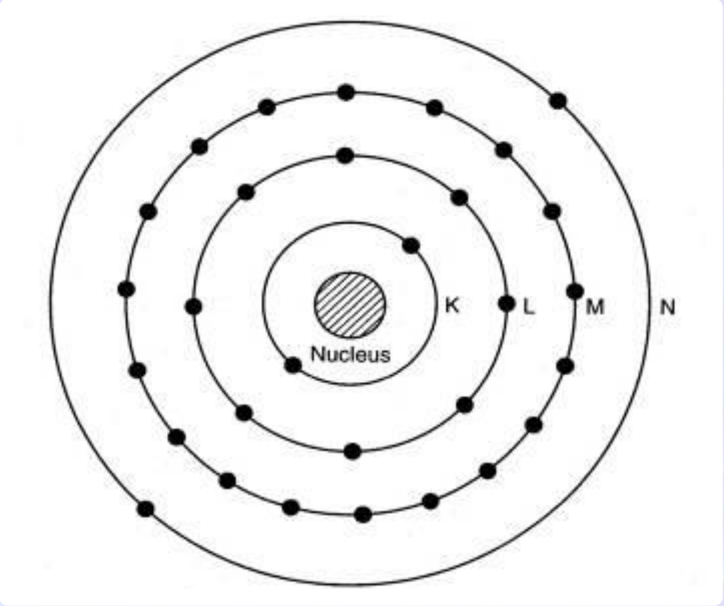
Structure of the Atom

- Every atom consists of protons, neutrons and electrons
- Proton – one unit of positive electrical charge and mass of approximately one atomic mass unit (1u)
- Electron - one unit of negative charge and mass of 1/1840 u
- Neutron - electrically neutral and mass of approximately 1 u

The positive and negative charges of the proton and electron, respectively, are equivalent to 1.6 x 10-19 Coulomb. One atomic mass unit (1u) is about 1.66 x 10-27 kg or 1.66 x 10-24 g.

Model of the Atom

- Neutrons and protons form central nucleus
- Electrons rotate around nucleus in various orbits, normally referred to as shells
- K shell - 2 electrons
- L shell - 8 electrons
- M shell -18 electrons
- N shell - 32 electrons



Atomic Number

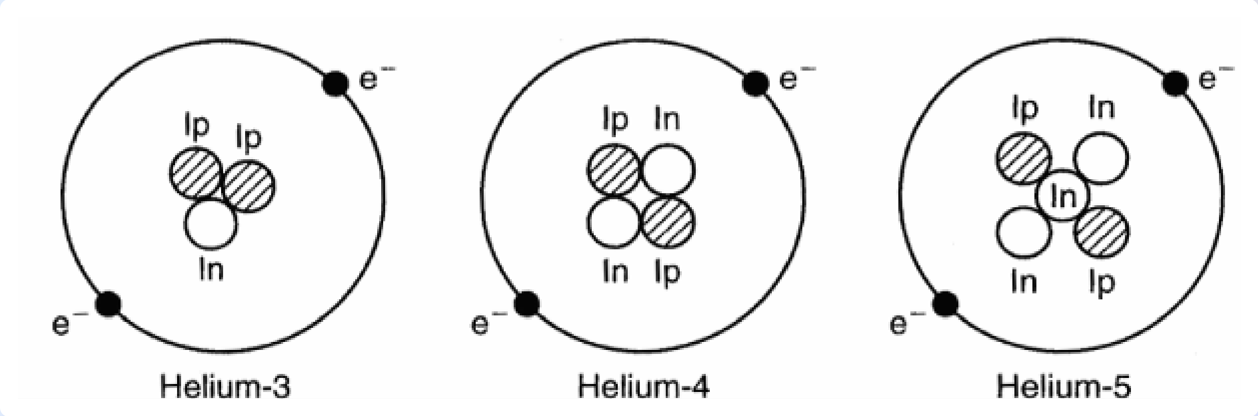
- Atomic number (Z) – number of protons in an atom. Determines chemical properties of atom and hence defines the element
  - All atoms with Z = 1 are hydrogen (H) atoms
  - All atoms with Z = 2 are helium (He) atoms
  - All atoms with Z = 3 are lithium (Li) atoms
  - All atoms with Z = 4 are beryllium (Be) atoms
  - All atoms with Z = 92 are uranium (U) atoms

Isotopes and Mass Number

- All atoms of an element have the same number of protons but they can occur with different numbers of neutrons
- So an element can have several types of atoms – these are called isotopes and differ from each other in terms of their mass number (A)
- A = Z + number of neutrons

The Isotopes of Helium

- Helium can occur in three isotopic forms:



  - Helium - 3 (He-3) contains 2 protons and 1 neutron
  - Helium - 4 (He-4) contains 2 protons and 2 neutrons
  - Helium - 5 (He-5) contains 2 protons and 3 neutrons
- The term nuclide means any isotope of any element
- Note: All isotopes of an element are *chemically* identical

Neutron to Proton Ratio

- Apart from the few lightest elements the number of neutrons always exceeds the number of protons in an atom
- Difference greater as Z increases, e.g

^{4}He has 2 protons and 2 neutrons

^{31}P has 15 protons and 16 neutrons

^{238}U has 92 protons and 146 neutrons

- All known isotopes in Chart of the Nuclides

Most isotopes have more neutrons than protons. As protons are positively charged, the more protons there are the more repulsive the nuclear forces become. The neutrons exert a stabilising force to counteract the repulsive forces of the protons.

Radioactivity and radiation

Atomic Instability

- Radioactivity is a process by which an unstable nucleus (parent) decays into a new nuclear configuration (daughter) that may be stable or unstable. If the daughter is unstable, it will decay further through a chain of decays until a stable configuration is attained
- Atoms of a few naturally-occurring elements are unstable - undergo spontaneous transformation into more stable atoms by a process known as radioactive decay
- Such substances are said to be radioactive
- In radioactive decay three main types of radiation are emitted: alpha, beta and gamma
- Natural radioactivity was first recognized by Becquerel in 1896. He gives his name to the SI unit of activity

Alpha, Beta, Gamma Radiations

- Alpha (α) radiation consists of helium nuclei (2 protons + 2 neutrons)
- α particle – mass 4 u, charge +2
- Beta (β) radiation consists of high-speed electrons originating in nucleus
- β particle - mass 1/1840 u, charge -1
- Gamma (γ) radiation results from changes in nucleus: consists of quanta of energy
- Gamma rays - electromagnetic radiation, energy inversely proportional to wavelength, $E \propto 1/\lambda$

Wavelengths of EM Radiations

Type of radiation	**Wavelength, λ (m)**
Radio waves, long wave	1500
Radio waves, VHF (Very High Frequency)	3
Visible light	10^{-6} to 10^{-7}
X-rays, 50 keV energy	2.5×10^{-11}
γ-rays, 1 MeV energy	1.2×10^{-12}

Radiation Energy

- Radiation energy: in electron volts(eV)
- One eV - energy gained by electron passing through electrical potential of 1 volt
- 1 keV = 1000 eV
- 1 MeV = 1000 keV = 10^6 eV
- Energies of other radiations also expressed in eV
- Kinetic energy (E_k) of particle of mass m travelling with velocity v is $E_k = ½ mv^2$

Radiation is alpha or beta particles, or gamma / X-ray photons

Radioactive Decay Mechanisms

- α-emission in which number of protons and neutrons in nucleus are each reduced by 2
- β-emission - a neutron changes into a proton by emitting a high-speed electron(β particle):

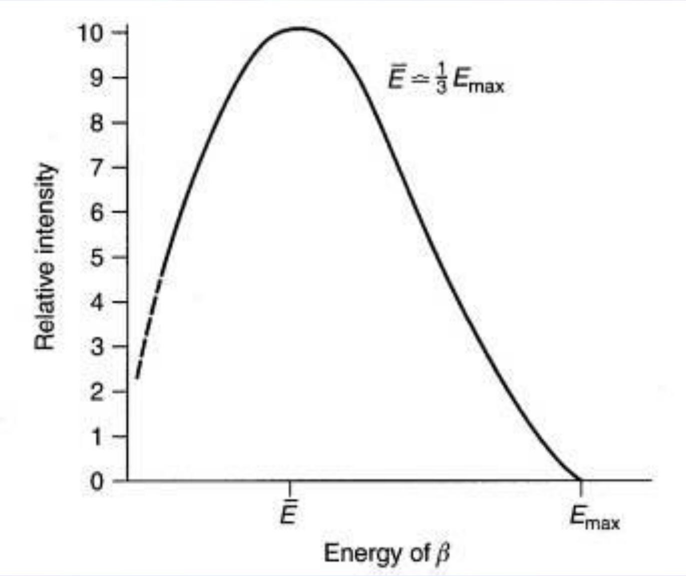
$$^{1}_{0}n \longrightarrow ^{1}_{1}p + \beta^{-}$$

- Positron emission - proton in nucleus ejects positive electron(β^{+}) to become neutron
- Electron capture - an inner electron is captured by nucleus resulting in conversion of a proton into a neutron:

$$^{1}_{1}p + e^{-} \longrightarrow ^{1}_{0}n$$

Typical β Spectrum

- Electrons emitted during β-decay have a continuous energy distribution from zero to E_{max}
- E_{max} is characteristic of the particular nuclide
- Most probable β energy is about 1/3 E_{max}



Natural Radioactive Series

Series name	Final stable nucleus	Longest-lived member
Thorium	^{208}Pb	^{232}Th ($T_{½}$ = 1.39 x 10^{10} y)
Uranium-radium	^{206}Pb	^{238}U ($T_{½}$ = 4.50 x 10^{9} y)
Actinium	^{207}Pb	^{235}U ($T_{½}$ = 8.52 x 10^{8} y)
Neptunium	^{209}Bi	^{237}Np ($T_{½}$ = 2.20 x 10^{6} y)

Induced Radioactivity

- Lighter elements can be made radioactive by bombarding them with nuclear particles, e.g. neutrons in a nuclear reactor
- A neutron may be captured by a nucleus, with the emission of a γ-photon, known as an (n,γ) reaction
- An important example is

$$^{59}Co\ (n,\gamma)\ ^{60}Co \xrightarrow{\beta^-} {}^{60}Ni$$

Radioactive Decay Law

- Radioactive decay - a random, statistical process governed by the mathematical law

$$N_t = N_0 e^{-\lambda t}$$

- The half-life ($T_{½}$) of a radioactive species is the time required for ½ of nuclei in sample to decay

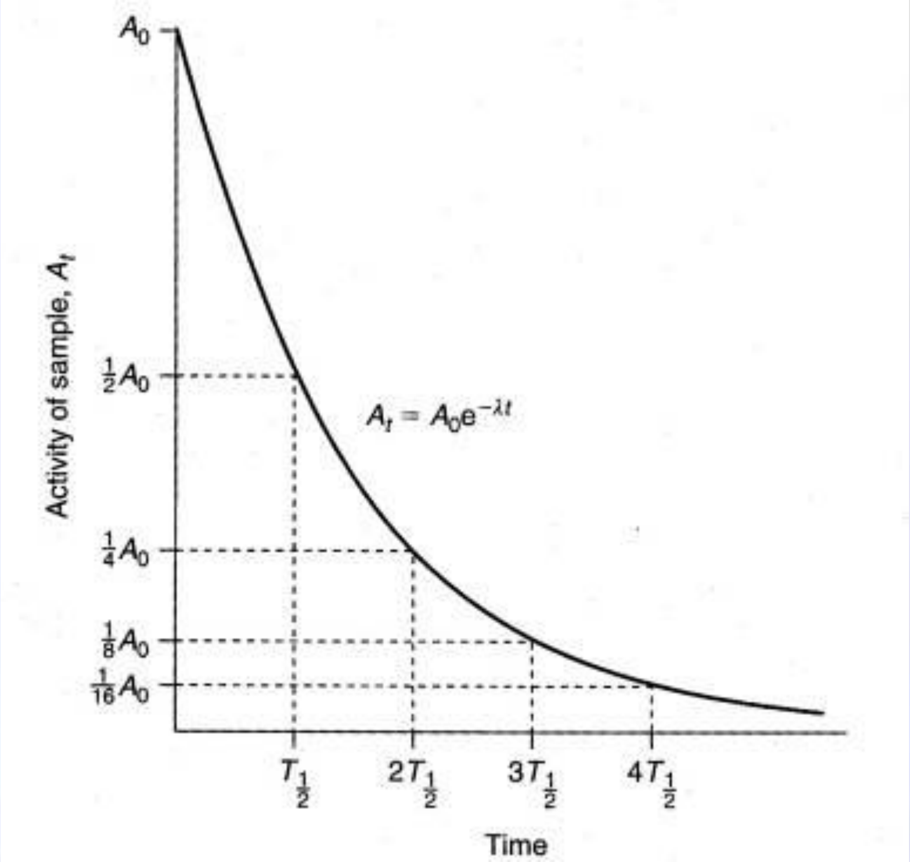
$$T_{½} = 0.693/\lambda$$

- The disintegration rate (activity) is proportional to the number of unstable nuclei

$$A_t = A_0 e^{-\lambda t}$$

Variation of Activity with Time

- In one half-life activity decays to ½ A_0
- In two half-lives activity decays to ¼ A_0
- Half-life of a particular radioactive isotope is constant and its measurement helps to identify unknown samples



The half-lives of radioactive isotopes vary enormously, e.g. ^{32}P, 14.3 days; ^{192}Ir, 74 days; ^{60}Co, 5.25 years; ^{137}Cs, 30 years; ^{14}C, 5760 years; and ^{238}U, 4.5×10^9 years.

The Unit of Radioactivity

- Original unit of radioactivity was the curie (Ci)
- The curie was originally related to the activity of 1 gram of radium but it was later standardized to

  1Ci = 3.7×10^{10} disintegrations/sec

- Modern, SI unit is becquerel (Bq)

  1Bq = 1 disintegration/sec

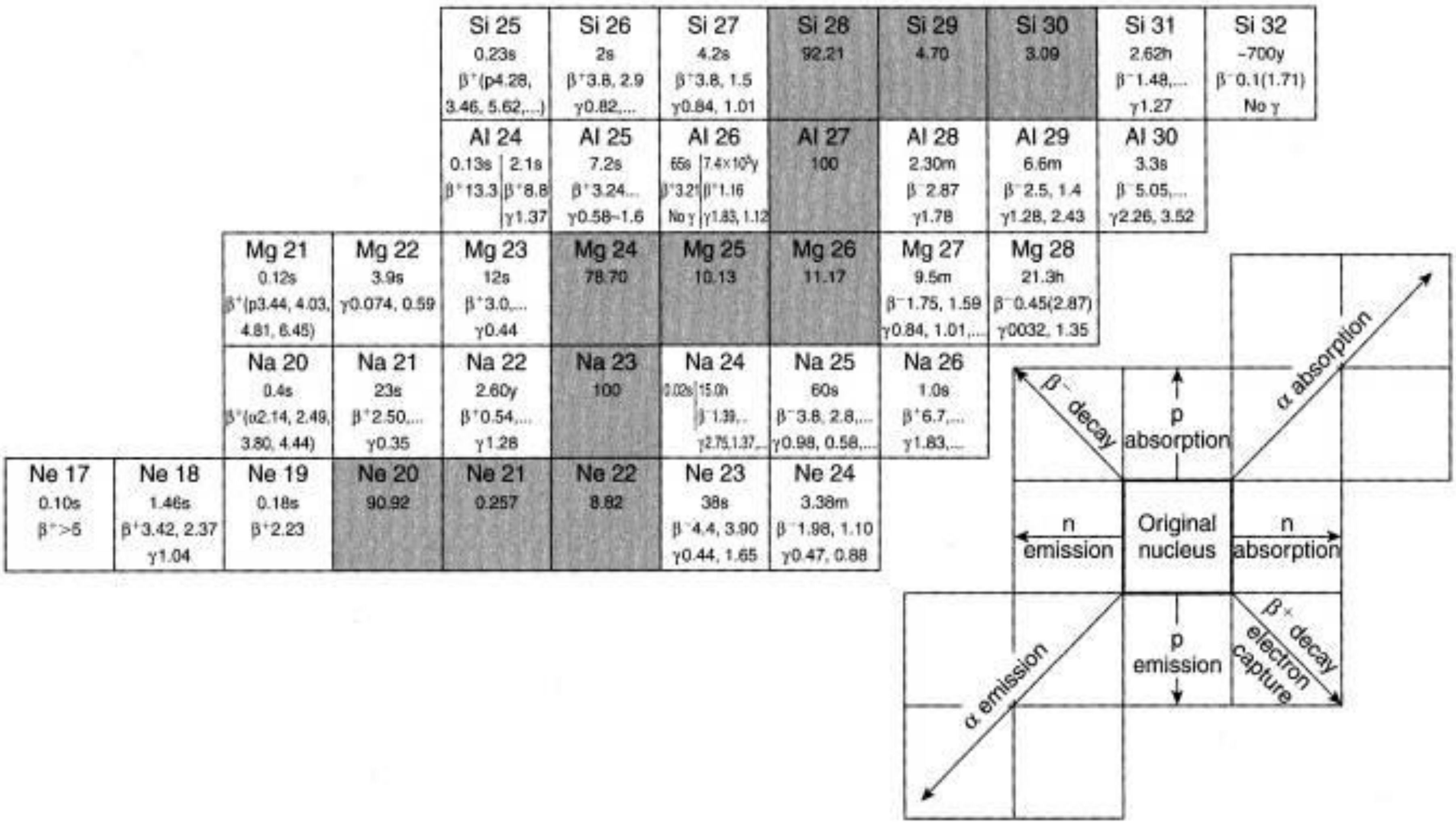
  1kBq = 10^3 Bq = 10^3 dis/s

  1MBq = 10^6 Bq = 10^6 dis/s

  1TBq = 10^{12} Bq = 10^{12} dis/s

The Nuclide Chart

Nuclide chart - compilation of info. on all known stable and unstable nuclides (small section below)



Interaction of Radiation with Matter

- Charged particles (α, β) lose energy mainly by interacting with atomic electrons. Transferred energy causes either excitation or ionization
- Bremsstrahlung X-rays: released when charged particles slow down rapidly in vicinity of nucleus
- X and γ radiation interactions: photoelectric effect, Compton scattering and pair-production
- Neutrons cannot cause ionization directly. They lose energy through elastic and inelastic scattering and various capture processes

Interaction of Nuclear Radiations

Radiation	**Process**	**Remarks**
Alpha	Collisions with atomic electrons	Leads to excitation and ionization
Beta	(a) Collisions with atomic electrons	Leads to excitation and ionization
	(b) Slowing-down in field of nucleus	Leads to emission of bremmstrahlung X-rays
X and γ radiation	(a) Photoelectric effect (b) Compton scattering (c) Pair-production	Photon is totally absorbed Only part of photon energy is absorbed in (b) and (c)
Neutron	(a) Elastic scattering (b) Inelastic scattering (c) Capture processes	These processes will be discussed in a later lecture

Penetrating Powers of Nuclear Radiations

- α particles – massive, travel slowly, high probability of interacting with atoms along their path. Lose energy rapidly and only travel very short distances
- β particles - very much smaller than α particles, travel much faster. Undergo fewer interactions per unit length of path and travel further than α's in dense media
- X and γ radiation loses energy mainly by interacting with atomic electrons. Travels very large distances and is very difficult to absorb completely
- Neutrons – interactions are energy dependent. Very penetrating - travel large distances even in dense media

Properties of Nuclear Radiations

Radiation	Mass (u)	Charge	Range in air	Range in tissue
Alpha	4	+2	0.03 m	0.04 mm
Beta	1/1840	-1 (positron +1)	3m	5mm
X,γ radiation	0	0	Very large	Through body
Fast neutron	1	0	Very large	Through body
Thermal neutron	1	0	Very large	0.15 m

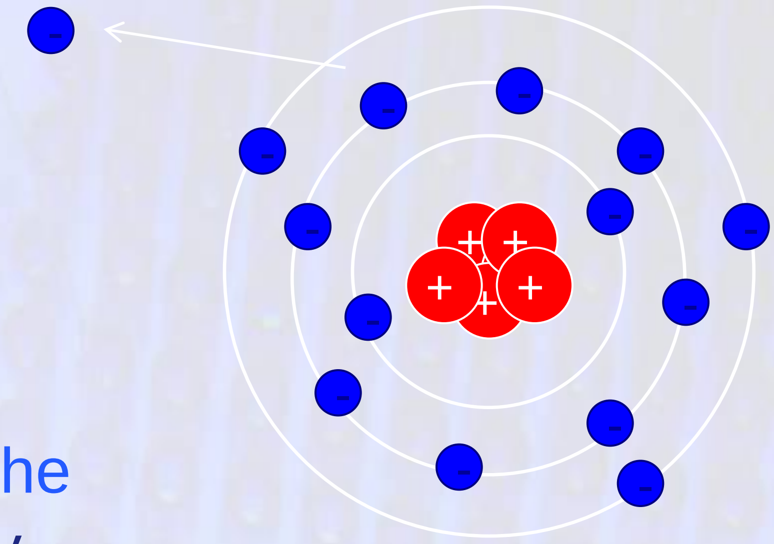
Radiation Units

Absorption of Energy

- Energy from a heat source can be absorbed by matter and increase its temperature
- Nuclear radiation can transfer energy from a radiation source to an absorbing medium
- The body can detect harmful levels of heat, <u>but</u> it can not detect absorbed energy from nuclear radiation – even in lethal quantities
- Nuclear radiation differs from heat and other types of radiation in that it has sufficiently high energy to cause ionization

Ionization

- Removal of an orbital electron from an atom gives
  - an electron
  - remainder of atom (an ion) positively charged



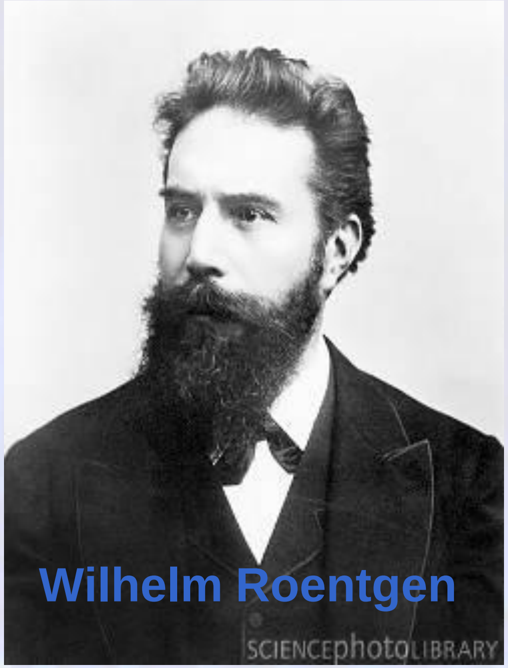
- This is an ion pair
- The energy needed to remove the electron is the ionization energy
- Ionization energy is supplied by the absorption of radiation energy in the medium
- The radiation loses its energy to the medium in the process
- Alpha, beta, gamma and X-ray radiation is termed ionizing radiation

Exposure

The quantity of electronic charge in coulombs (C) produced by ionization per kilogram (kg) of AIR

(either the positive or negative charge – not both)

SI units are C / kg



1 Roentgen = 2.58×10^{-4} C / kg

KERMA

- Kinetic Energy Released per unit MAss
- Units are: Joules per kilogram (J kg^{-1})
- Energy deposited (NOT absorbed) in unit mass of a material (e.g. air) by exposure to radiation
- Only different to Absorbed Dose at high keVs (more than 200 keV) due to:
  - Long range of secondary electrons
  - Bremsstrahlung
- Air KERMA is replacing exposure as standard

Absorbed Dose (D)

$$\frac{\text{Energy imparted to matter in a small volume (J)}}{\text{Mass of the small volume (kg)}}$$

Hal Gray

Courtesy of the LH Gray Trust

- SI unit is the gray (Gy)
- 1 Gy = 1 Joule of energy absorbed in 1 kg of matter = 1 J/kg

Conversion factor: 1 gray ≈ 100 rads

Organ or Tissue Dose

$$D_T = \frac{\text{Energy imparted to organ or tissue}}{\text{Mass of the organ or tissue}}$$

More useful for radiation protection purposes

Units: Gray (Gy)

Linear Energy Transfer (LET)

- Rate at which energy transferred from radiation beam to the medium
- Density of ionization along the track of radiation
- High LET radiations are more easily stopped

Radiation	LET (keV per μm)
1 MeV gamma rays	0.5
100 keV x-rays	6
20 keV betas	10
5 MeV alphas	50

Relative Biological Effectiveness (RBE)

- Different types of radiation can be more or less damaging

$$RBE = \frac{\text{Dose of 220 kV x-rays}}{\text{Dose of radiation under test}}$$

- Both doses cause same biological end point e.g. 10% cell survival
- RBE increases with LET

Radiation Weighting Factors

(from ICRP103)

Type of radiation	wR
X-rays, γ-rays and electrons	1
Protons	5
Thermal neutrons	2.5
Fast neutrons	2.5 to 20 *
Alpha particles, fission fragments	20

* Depending on energy

ICRP: International Commission on Radiological Protection

Equivalent Dose (H)

$$H = \text{Absorbed Dose (in Grays)} \times \text{Radiation Weighting Factor } (w_R)$$

Strictly speaking this is the absorbed dose averaged over the organ or tissue

Dimensionless quantity

$$\text{Total } H_T = \sum w_R \times D_{T,R}$$

where $D_{T,R}$ is the average absorbed dose to the organ for a particular radiation type

Unit: Sievert (Sv)

Still dimensionally J / kg as w_R is just a number

Conversion factor: 1 Sv $\approx$ 100 rem

(rem: roentgen equivalent man)

Rolf Sievert – 1929

Example No. 1

- What is the total equivalent dose to the organ (H_T) if the absorbed dose to the lungs is 0.2 mGy from x-rays?

H_T = Absorbed Dose x radiation weighting factor

Radiation weighting factor for x-rays (w_R) = 1 (for any energy)

$$H_T = 0.2 \times w_R = 0.2 \times 1 = 0.2 \text{ mSv}$$

Note that the units change from mGy to mSv

Effective Dose (E)

- Accounts for uneven irradiation of the body and represents overall risk from whole body exposure

$$E = \sum_{T} w_T \times H_T$$

H_T = Equivalent dose to tissue or organ 'T'
w_T = tissue weighting factor

- Tissue weighting factors represent risks of detrimental radiation effects to different organs or tissue

Tissue Weighting Factors (from ICRP103)

Organ	w_T for organ
Gonads	0.08
Red bone marrow, colon, lung, stomach, breast	0.12
Bladder, liver, oesophagus, thyroid	0.04
Skin, bone surface, brain, salivary glands	0.01
Remainder (in total)	0.12

Example

- A patient receives the following equivalent (organ) doses as a result of a chest PA x-radiograph:

Bone Marrow	0.01 mSv	(W_T=0.12)
Thyroid	0.05 mSv	(W_T=0.04)
Lungs	0.17 mSv	(W_T=0.12)
Breast	0.09 mSv	(W_T=0.08)

- What is the effective dose resulting from this examination?

$$E = \sum w_T \times H_T$$

$$E_T = 0.01 \times 0.12 + 0.05 \times 0.04 + 0.17 \times 0.12 + 0.09 \times 0.08 = 0.0308 \text{ mSv or } 30.8 \ \mu\text{Sv}$$

Dose Rate

- The Gray and Sievert are units expressing an amount of radiation received over some period of time
- In controlling hazards, it is usually necessary to know the rate at which the radiation is being received – the DOSE RATE

Dose = Dose Rate x Time

- For example: if someone works in an area for 2 hours and receives a dose of 4 mSv, then the dose rate in that areas will be 2 mSv/h

Committed Equivalent Dose

$H_T(50)$ = Equivalent dose summed over a 50 year period

Note: 70 year period for children

Also: Committed Effective Dose

Collective Dose

- If a group of the population is exposed to radiation then the collective effective dose is:

$$S = E_m \times N$$

where:
E_m = mean effective dose to individual in group
N = number of individuals in the group

Units: man Sieverts (man Sv) or
person Sieverts (person Sv)