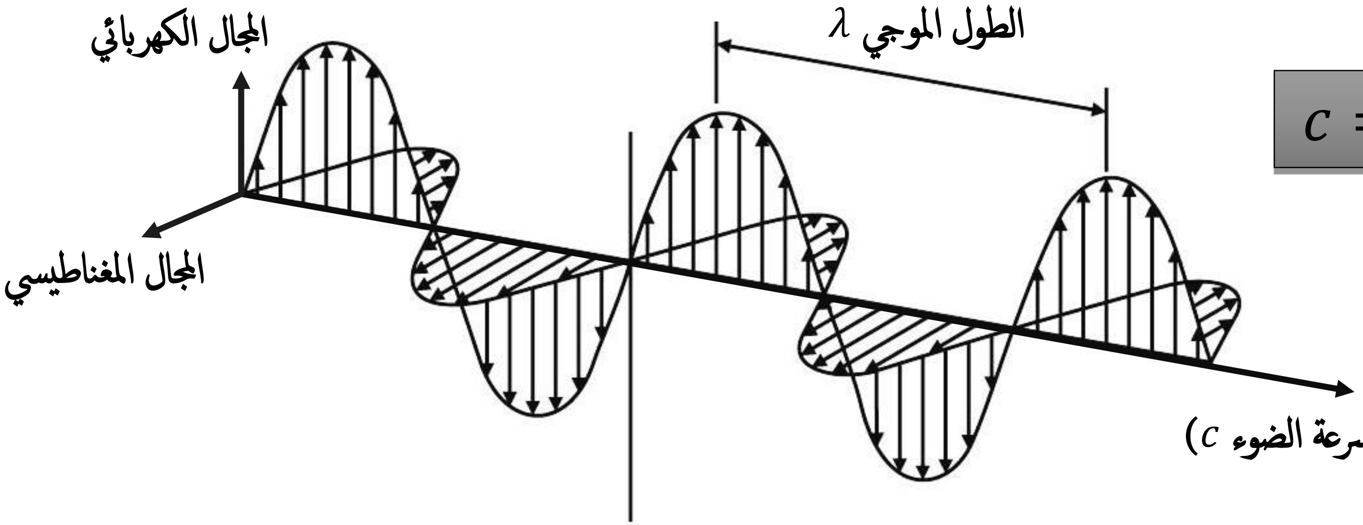
Chapter 26

Particle Properties of Light: The Photon

Kane & Sternheim, Physics, 3rd Edition

الموجات الكهرومغناطيسية

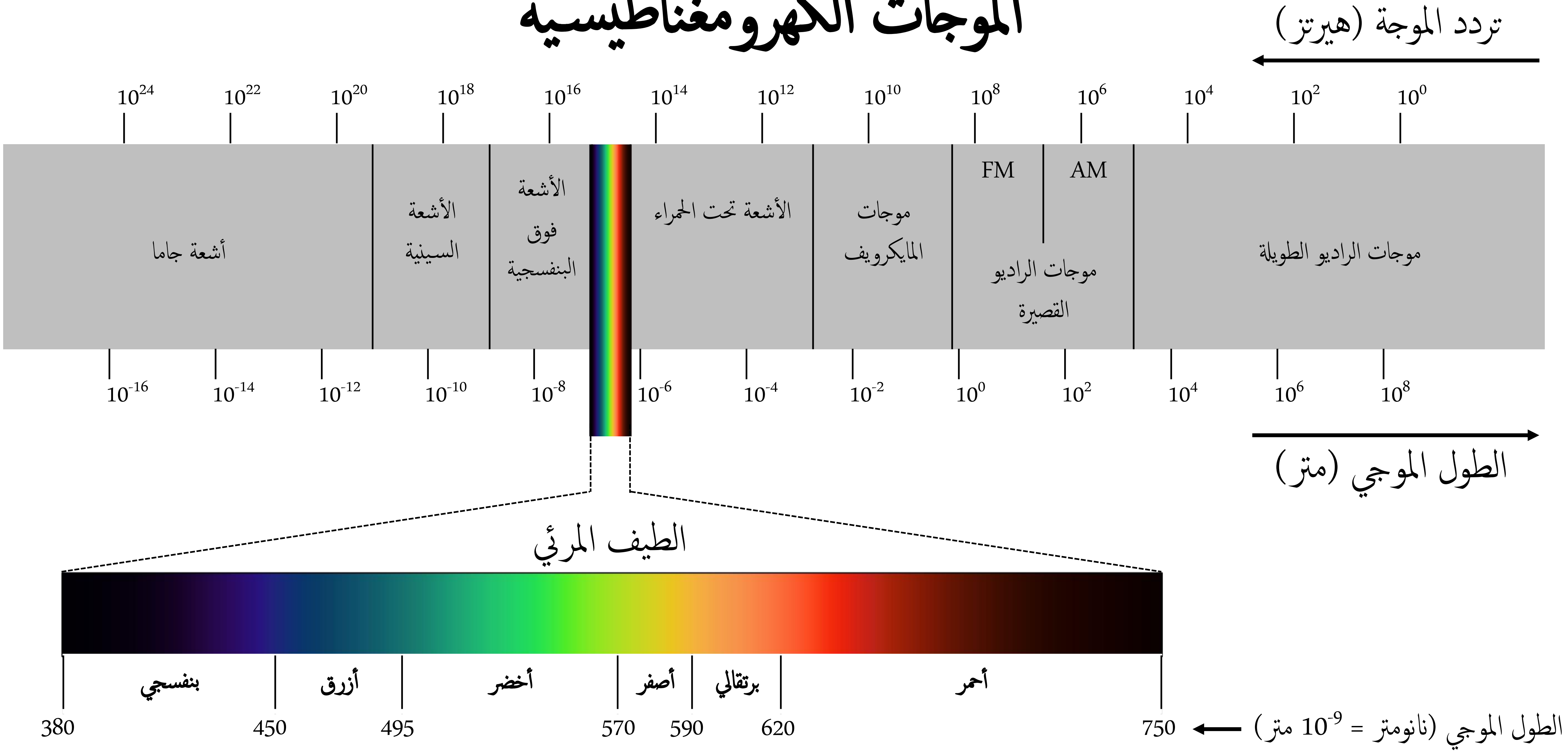


$$\boxed{c = \lambda f}$$

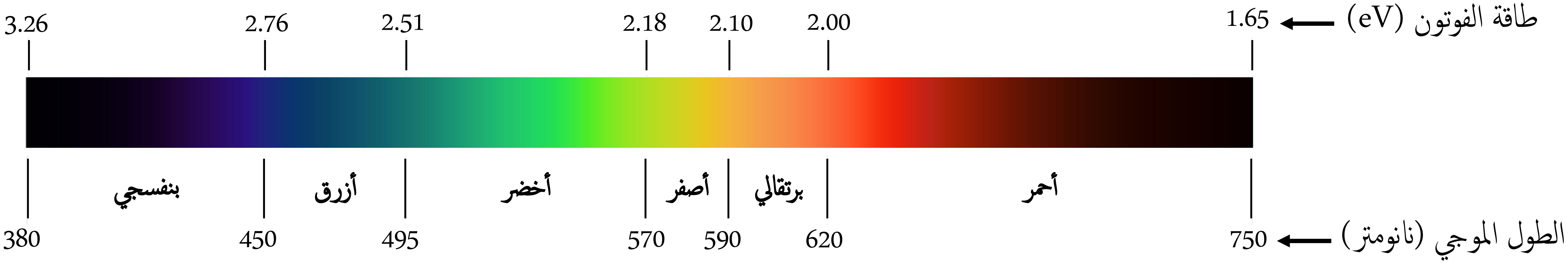
التردد f: عدد الدورات في الثانية المارة بنقطة ثابتة على خط اتجاه الموجة

$$\boxed{E = hf = \frac{h\,c}{\lambda}}$$

الموجات الكهرومغناطيسية



الطيف الكهرومغناطيسي المرئي



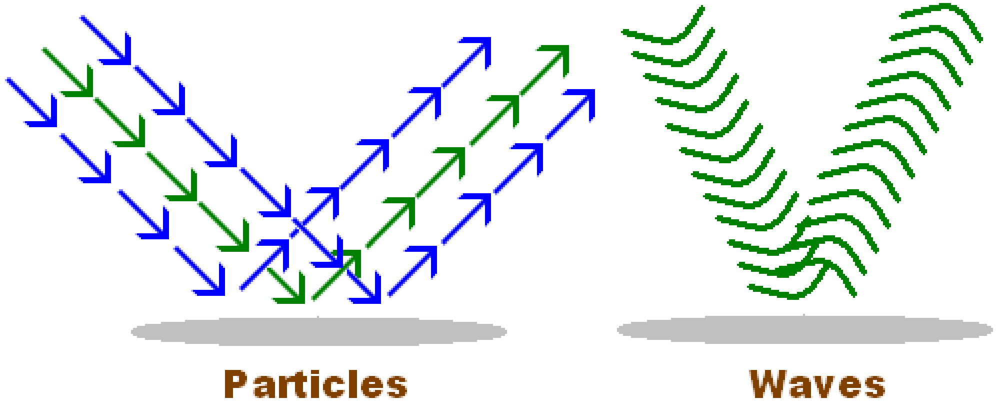
3.26 2.76 2.51 2.18 2.10 2.00 1.65 ⟵ طاقة الفوتون (eV)

بنفسجي أزرق أخضر أصفر برتقالي أحمر

380 450 495 570 590 620 750 ⟵ الطول الموجي (نانومتر)

The Dual Nature of Light

- Light can be considered as a wave, and can be considered as a particle.
- All light phenomena (reflection, diffraction, refraction, propagation..etc) can be explained by any of the two pictures of light; this is called the “wave-particle duality” of light.
- The absolute true nature of light is still not completely understood.



Particles and wave Reflected by a Mirror

www.entrancei.com

Light as Particles (Photons)

- Considering light as particles (called *photons*) could solve many puzzled light experiments in the 20th century, e.g. blackbody radiation, the photoelectric effect, Compton effect…etc (see the textbook for further readings).
- The frequency of light determines the energy of each photon, according to the following equation:

$$E = hf = \frac{h\,c}{\lambda}$$

- For energy in eV and λ in nm, one might use the following simplified equation:

$$E(\text{eV}) = \frac{1240}{\lambda\,(\text{nm})}$$

- Remember: 1 eV = 1.6×10^{-19} Joule ; 1 Joule = 6.24×10^{24} eV

Example 1: What is the energy (in eV) of a red photon whose wavelength is 633 nm?

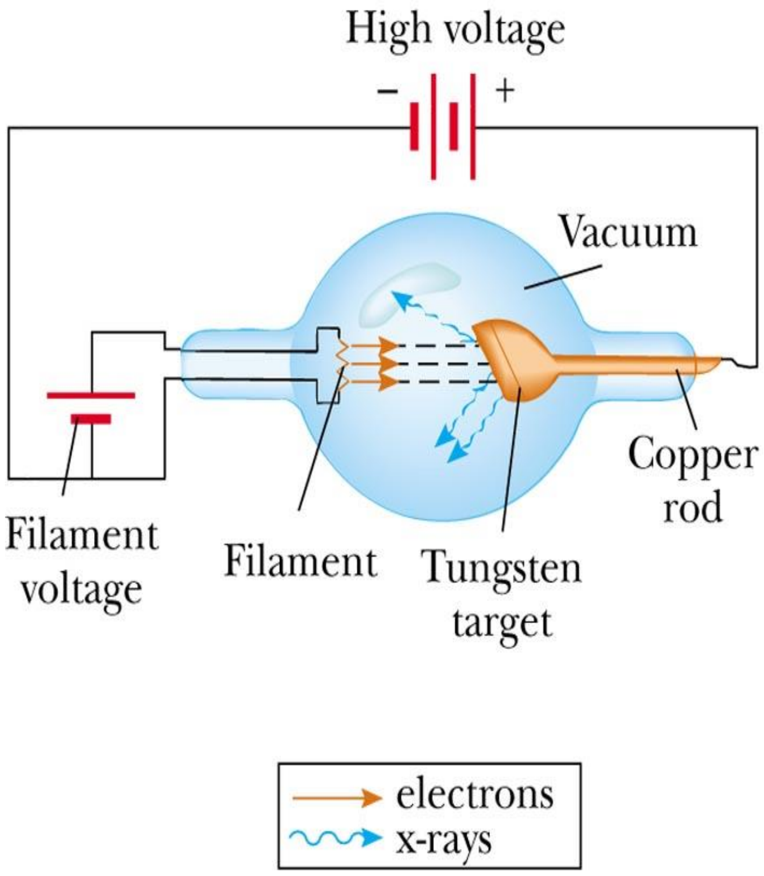
Example 2: What is the wavelength (in cm) of a 100 MHz radio wave?

Example 3: An X-ray machine delivers 1 Joule of x-ray photons for one film imaging? How many x-ray photons are produced assuming an average x-ray photon wavelength of 0.1 nm?

Example 4: Excimer laser (wavelength = 193 nm) 1 mJ pulses are used for remodeling the corneal stroma. How many photons are there in each pulse?

Example 5: UV-B radiation (~ 280 nm – 315 nm), although can be harmful to the skin, is necessary for vitamin D synthesis in the body. What is the ratio of photon energy between a 300 nm UVB photon and 600 nm red photon?

Production of X-Rays



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(a)

- A current in the filament causes electrons to be emitted.
- These free electrons are accelerated in vacuum (by a high voltage ΔV in ~ tens of kV) towards a dense metal target.
- Notice that the freed electrons make an electric current (in vacuum), which is usually in the range of ~ tens of mA.
- The power generated is equal to the multiplication of voltage and current ($P = \Delta V \times I$)
- The free electrons bombard the target material and produce x-ray photons. This process is very inefficient; only less than 1% of electron energy is transferred to produce x-ray photons.
- The x-ray photons produced vary greatly in their energies (see next slide).
- The maximum energy of an x-ray photon can have is when the x-ray photon absorbs the full energy of the electron i.e. ($e\,\Delta V$)

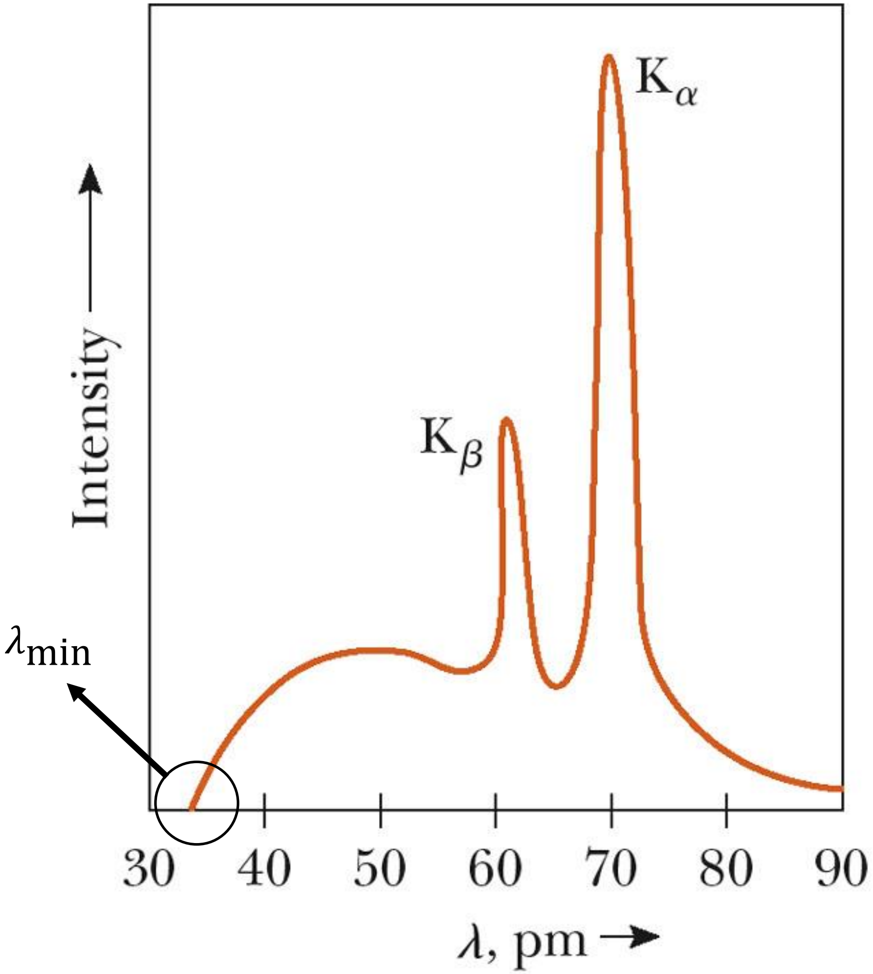
Example 6: An electron is accelerated by a medical x-ray machine through 50 kV. What is the minimum wavelength photon it can produce when striking a target?

X-Ray Spectrum

The x-ray spectrum has two distinct components:

1) Bremsstrahlung: the German word for "*braking radiation*". A continuous broad spectrum that depends on voltage applied to the tube. The amount of kinetic energy lost in any given interaction can vary from zero up to the entire kinetic energy of the electron (e ΔV). Therefore, the wavelength of radiation from these interactions lies in a continuous range.

2) Characteristic X-Ray Emission: these are sharp, intense lines, which depend on the nature of the target material. Each line comes from the energy difference between two atomic orbitals in the target material.



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Chapter 30

Nuclear Physics

Kane & Sternheim, Physics, 3rd Edition

Facts and Definitions

- The atom is made of a *nucleus* at the center and *electrons* orbiting the nucleus.
- The nucleus is made of two kinds of *nucleons*: *protons* and *neutrons*.
- Neutrons are ~ 0.1% heavier than protons.
- Protons are positively charged while neutrons are neutral.
- The positive proton charge and the negative electron charge are equal in magnitude.
- The number of protons in the nucleus is called the *atomic number* Z.
- The total number of protons and neutrons in the nucleus is called the *mass number* A.
- The number of neutrons in the nucleus is then given by N = A – Z
- An element with a specific number of protons and neutrons is called a *nuclide.*

Symbols for Nuclides

- A nuclide X can be symbolized as:

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

Examples:

$^{238}_{92}U$ (Uranium with 92 protons and 146 neutrons)

$^{131}_{53}I$ (Iodine with 53 protons and 78 neutrons)

$^{14}_{6}C$ (Carbon with 6 protons and 8 neutrons)

- Nuclides can alternatively be symbolized as: $X - A$

Examples: U-238 ; I-131 ; C-14

Isotopes

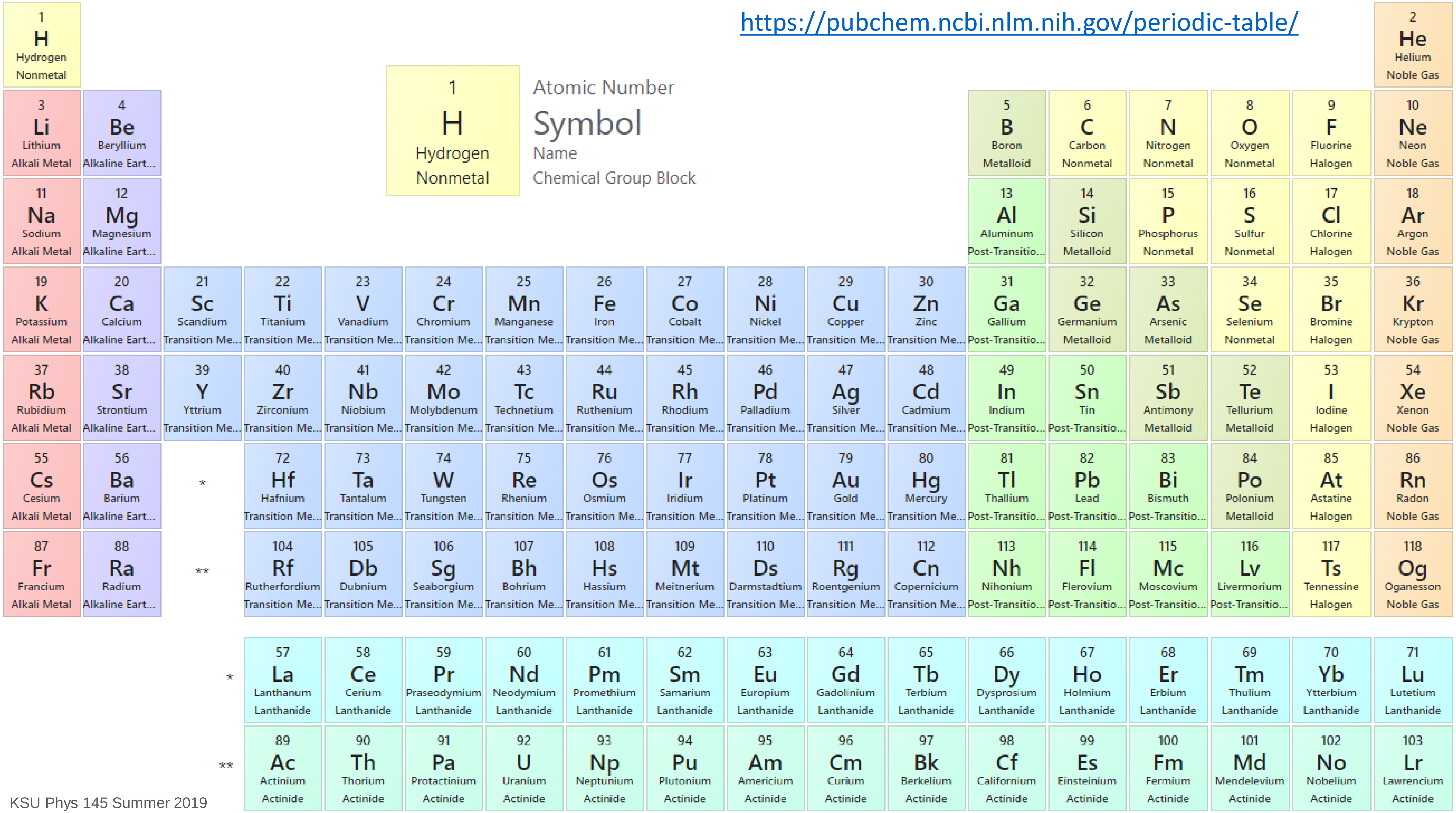
- Nuclides with the same number of protons but different numbers of neutrons are called *isotopes*.

Examples:

$^{238}_{92}U$ and $^{235}_{92}U$ are isotopes (or you may write U-238 and U-235)

$^{131}_{53}I$ and $^{127}_{53}I$ are isotopes (or you may write I-131 and I-127)

$^{14}_{6}C$ and $^{12}_{6}C$ are isotopes (or you may write C-14 and C-12) https://pubchem.ncbi.nlm.nih.gov/periodic-table/



1
H
Hydrogen
Nonmetal

Atomic Number
Symbol
Name
Chemical Group Block

1 H Hydrogen Nonmetal																	2 He Helium Noble Gas
3 Li Lithium Alkali Metal	4 Be Beryllium Alkaline Eart...											5 B Boron Metalloid	6 C Carbon Nonmetal	7 N Nitrogen Nonmetal	8 O Oxygen Nonmetal	9 F Fluorine Halogen	10 Ne Neon Noble Gas
11 Na Sodium Alkali Metal	12 Mg Magnesium Alkaline Eart...											13 Al Aluminum Post-Transitio...	14 Si Silicon Metalloid	15 P Phosphorus Nonmetal	16 S Sulfur Nonmetal	17 Cl Chlorine Halogen	18 Ar Argon Noble Gas
19 K Potassium Alkali Metal	20 Ca Calcium Alkaline Eart...	21 Sc Scandium Transition Me...	22 Ti Titanium Transition Me...	23 V Vanadium Transition Me...	24 Cr Chromium Transition Me...	25 Mn Manganese Transition Me...	26 Fe Iron Transition Me...	27 Co Cobalt Transition Me...	28 Ni Nickel Transition Me...	29 Cu Copper Transition Me...	30 Zn Zinc Transition Me...	31 Ga Gallium Post-Transitio...	32 Ge Germanium Metalloid	33 As Arsenic Metalloid	34 Se Selenium Nonmetal	35 Br Bromine Halogen	36 Kr Krypton Noble Gas
37 Rb Rubidium Alkali Metal	38 Sr Strontium Alkaline Eart...	39 Y Yttrium Transition Me...	40 Zr Zirconium Transition Me...	41 Nb Niobium Transition Me...	42 Mo Molybdenum Transition Me...	43 Tc Technetium Transition Me...	44 Ru Ruthenium Transition Me...	45 Rh Rhodium Transition Me...	46 Pd Palladium Transition Me...	47 Ag Silver Transition Me...	48 Cd Cadmium Transition Me...	49 In Indium Post-Transitio...	50 Sn Tin Post-Transitio...	51 Sb Antimony Metalloid	52 Te Tellurium Metalloid	53 I Iodine Halogen	54 Xe Xenon Noble Gas
55 Cs Cesium Alkali Metal	56 Ba Barium Alkaline Eart...	*	72 Hf Hafnium Transition Me...	73 Ta Tantalum Transition Me...	74 W Tungsten Transition Me...	75 Re Rhenium Transition Me...	76 Os Osmium Transition Me...	77 Ir Iridium Transition Me...	78 Pt Platinum Transition Me...	79 Au Gold Transition Me...	80 Hg Mercury Transition Me...	81 Tl Thallium Post-Transitio...	82 Pb Lead Post-Transitio...	83 Bi Bismuth Post-Transitio...	84 Po Polonium Metalloid	85 At Astatine Halogen	86 Rn Radon Noble Gas
87 Fr Francium Alkali Metal	88 Ra Radium Alkaline Eart...	**	104 Rf Rutherfordium Transition Me...	105 Db Dubnium Transition Me...	106 Sg Seaborgium Transition Me...	107 Bh Bohrium Transition Me...	108 Hs Hassium Transition Me...	109 Mt Meitnerium Transition Me...	110 Ds Darmstadtium Transition Me...	111 Rg Roentgenium Transition Me...	112 Cn Copernicium Transition Me...	113 Nh Nihonium Post-Transitio...	114 Fl Flerovium Post-Transitio...	115 Mc Moscovium Post-Transitio...	116 Lv Livermorium Post-Transitio...	117 Ts Tennessine Halogen	118 Og Oganesson Noble Gas
		*	57 La Lanthanum Lanthanide	58 Ce Cerium Lanthanide	59 Pr Praseodymium Lanthanide	60 Nd Neodymium Lanthanide	61 Pm Promethium Lanthanide	62 Sm Samarium Lanthanide	63 Eu Europium Lanthanide	64 Gd Gadolinium Lanthanide	65 Tb Terbium Lanthanide	66 Dy Dysprosium Lanthanide	67 Ho Holmium Lanthanide	68 Er Erbium Lanthanide	69 Tm Thulium Lanthanide	70 Yb Ytterbium Lanthanide	71 Lu Lutetium Lanthanide
		**	89 Ac Actinium Actinide	90 Th Thorium Actinide	91 Pa Protactinium Actinide	92 U Uranium Actinide	93 Np Neptunium Actinide	94 Pu Plutonium Actinide	95 Am Americium Actinide	96 Cm Curium Actinide	97 Bk Berkelium Actinide	98 Cf Californium Actinide	99 Es Einsteinium Actinide	100 Fm Fermium Actinide	101 Md Mendelevium Actinide	102 No Nobelium Actinide	103 Lr Lawrencium Actinide

Radioactivity

- Some nuclides are *radioactive*; they are called *radionuclides*.
- A radionuclide nucleus is unstable and thus disintegrates into more stable components.
- An example of radioactivity: $^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$
  Note the conservation of proton and mass numbers.
- This disintegration process has a random nature, and it is called *radioactive nuclear decay*.

Half-Life of Radionuclides

- Each radionuclide has a half-life time T, after which half of the nuclei will have had undergone a nuclear decay.
- In other words, if at t = 0, we have N_0 nuclei, then one half-life later at t = T, an average of $N_0/2$ will remain, and so on.
- At any time t, one can find the number of remaining nuclei by using the following formula:

$$N = N_0 e^{-0.693\,\frac{t}{T}}$$

- The above formula can sometimes be written as: $N = N_0 e^{-\lambda t}$
  where $\lambda = \frac{0.693}{T}$ and is called the *decay constant*.

Biological and Effective Half-Life

- When used in medical treatment, radionuclides are steadily excreted from the human body with another half-life called the biological half-life.
- The effective half-life T_{eff} is then the combination of both the physical half-life (T_p) and the biological half-life (T_b) half-lives and is given according to the following formula:

$$\frac{1}{T_{eff}} = \frac{1}{T_p} + \frac{1}{T_b}$$

Table 30.1: Examples of Radionuclides used in medicine and biology

Nuclide	Organ Where Concentrated	Half-Life (days)	
		Physical	Biological
$^{3}_{1}H$	Total body	4.6×10^3	19
$^{14}_{6}C$	Fat	2.09×10^6	35
	Bone	2.09×10^6	180
$^{24}_{11}Na$	Total body	0.62	29
$^{32}_{15}P$	Bone	14.3	1200
$^{35}_{16}S$	Skin	87.1	22
$^{36}_{17}Cl$	Total body	1.6×10^8	29
$^{42}_{19}K$	Muscle	0.52	43
$^{45}_{20}Ca$	Bone	152	18000
$^{59}_{26}Fe$	Blood	46.3	65
$^{64}_{29}Cu$	Liver	0.54	39
$^{131}_{51}I$	Thyroid	8.1	180

Example 1

Iodine I-131 is used in the treatment of thyroid disorders. Its half-life is 8.1 days.

a) If a patient ingests a small quantity of ^{131}I and assuming none is excreted from the body, what fraction N/N_0 remains after 8.1 days, 16.2 days, 60 days?

b) If the ingested ^{131}I quantity is naturally excreted from the body with a biological half-life of 180 days, what will be the fraction N/N_0 after 60 days?

Example 2

^{59}Fe is administrated to a patient to diagnose blood anomalies. The physical and biological half-lives of ^{59}Fe are 46.3 and 65 days respectively. Find its effective half-life?

Example 3

Tritium has a half life of 12.3 years. How many years will it take for 88.0 grams to decay to 5.50 grams?

What happens in a radioactive decay process?

(types of radioactive decays)

1. **α decay:** In an α decay, an α particle ($^{4}_{2}$He nucleus) is emitted, leaving behind a residual nucleus that has lost two protons and two neutron.

   Example: $^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$

2. **β± decay:** In a β decay, an electron (e^-) or in few cases a positron (e^+) is emitted by a nucleus. The two decays are respectively called β^- and β^+ decays. $\beta^\pm$ decays result in the following conversions:

   $n \rightarrow p + e^- + \nu$ (β^- decay)

   $p \rightarrow n + e^+ + \nu$ (β^+ decay)

   where ν is the neutrino (a massless uncharged particle)

   Example: $^{60}_{27}Co \rightarrow {}^{60}_{28}Ni^* + e^- + \nu$

3. **γ decay:** In γ decays, the nucleus releases a high energy photon (γ rays) as means to approach a lower more stable energy state. The nucleus does not change in its atomic or mass number.

   Examples: $^{60}_{28}Ni^* \rightarrow {}^{60}_{28}Ni^* + \gamma$ (1.1732 MeV)

   $^{60}_{28}Ni^* \rightarrow {}^{60}_{28}Ni + \gamma$ (1.3325 MeV)

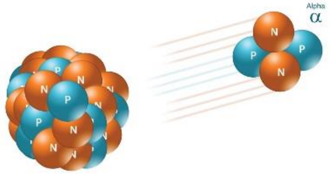
Each α, β or γ particle has energy of ~ few MeV ! When they pass through matter or through human body, they can ionize atoms in their way and make a lot of damage (*ionizing radiation*).

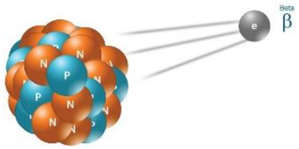
Chapter 31

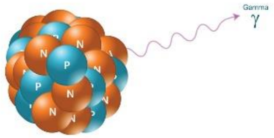
Ionizing Radiation

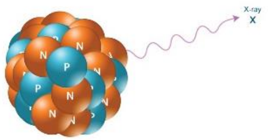
Kane & Sternheim, Physics, 3rd Edition

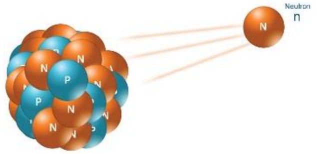
Types of Ionizing Radiation أنواع الإشعاع المُؤَيِّن



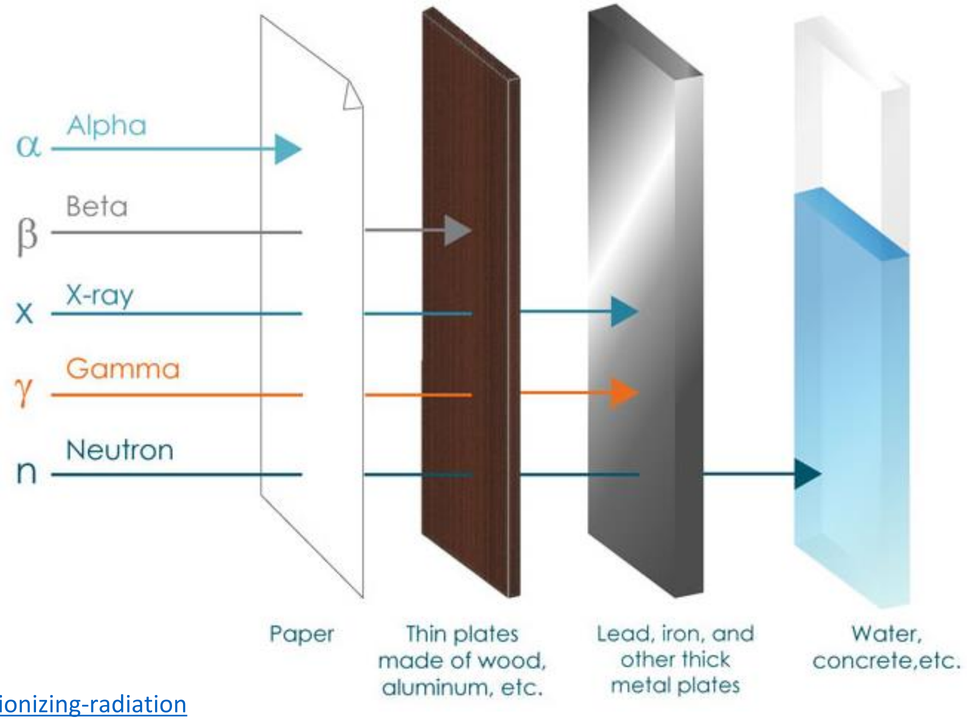








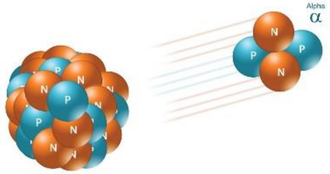
α Radiation	β Radiation	γ Radiation	X-ray Radiation	Neutron Radiation
~ 4 - 9 MeV	~ 10 keV - 4 MeV	~ 100 keV – 3 MeV	~ 100 eV – 200 keV	~ 0.5– > 20 MeV



Images from:
https://www.mirion.com/learning-center/radiation-safety-basics/types-of-ionizing-radiation

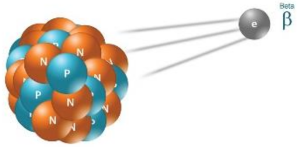
Energy Loss of Ionizing Radiation كيف تفقد جسيمات الإشعاع المُؤَيِّـــن طاقتها؟

$$\Delta K\ \alpha\ -\frac{m\,q^2}{2K}$$



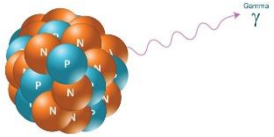
α Radiation

- An α particle moves almost straight for a short distance ionizing atoms in their way until its energy is ~ 1 MeV.
- At ~ 1 MeV it acquires two electrons and becomes a neutral Helium (He) atom.
- The neutral atom comes to rest after a few more collisions.

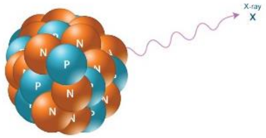


β Radiation

- A β particle has a longer range than α particles, with a random movement.
- Similar to α particles, they lose energy by exciting atoms in their way until they are finally captured by an atom.
- After loosing enough energy, β^- particles (electrons) are captured by atoms. On the other hand, (β^+ particles come close to an electron and annihilate producing γ rays.

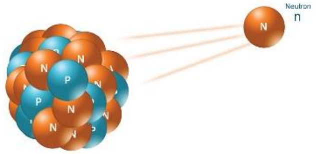


γ Radiation



X-ray Radiation

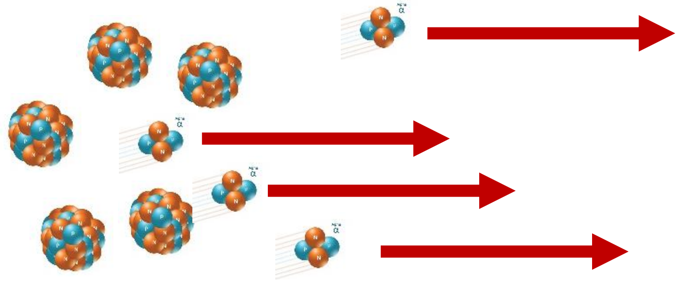
- Photons (both γ and x-rays) don't directly ionize atoms. Instead, they lose energy to electrons, which in turn ionize atoms.
- Photons have a much loner range than α and β particles.
- Energy loss of photons to electrons take place by one of three processes:
  1) **The photoelectric effect** (at energies below 0.1 MeV): Here a photon is absorbed by an atom, and an atomic electron is ejected.
  2) **Compton Scattering** (at ~ 1 MeV): the photon transfers some but not all of its energy to an atomic electron.
  3) **Electron-Positron Pair** (for energies > 1.02 MeV): here a photons produces an electron and a positron.



Neutron Radiation

- Neutrons are uncharged and so cannot directly ionize atoms. The range of neutrons is subsequently very long.
- Fast neutrons loose energy by (1) direct collisions with the nuclei OR (2) by nuclear reactions. These processes can produce secondary harmful emissions (e.g. γ rays).

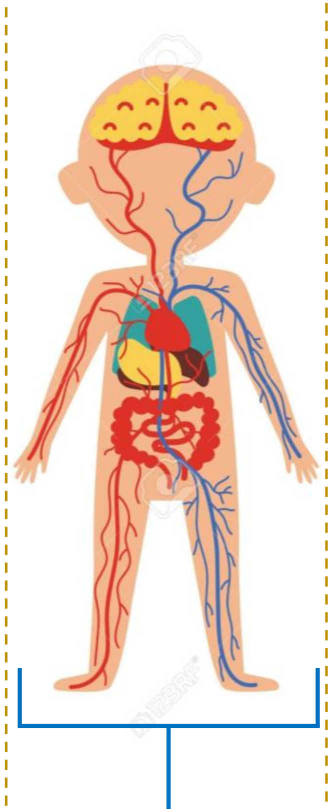
Radiation Units الوحدات الإشعاعية



Source Activity (A)
Disintegrations/time
نشاط المصدر الإشعاعي: عدد الانقسامات الإشعاعية في وحدة زمنية معينة

$$A = \frac{0.693}{T} N$$

Units:
Becquerel (Bq) = 1 disintegration per second
Curie (Ci) = 3.70×10^{10} disintegrations per second



Exposure (Ionized charge/mass)
التعرض الإشعاعي: كم ذرة تأينت في الكيلوجرام الواحد؟

Units:
Rontgen (R) = 2.58×10^{-4} C of ions in a kilogram of air
***Note:** only for x-rays and γ-rays below 3 MeV

Absorbed dose (Absorbed energy/mass)
جرعة الطاقة الممتصة: مقدار الطاقة (بالجول) التي امتصها كل كيلوجرام

Units:
Gray (Gy) = 1 joule per kilogram of absorbed energy
Rad = 0.01 Gy

Biologically equivalent dose
Biologically equivalent dose = absorbed dose × QF

الجرعة المكافئة حيوياً = جرعة الطاقة الممتصة × معامل الجودة (QF)

Units:
Sievert (Sv) = QF × (dose in grays)
Rem = QF × (dose in grays)

Quality Factor (QF): effect compared to 200 keV x-ray.
- QF ~ 1 for x-rays, γ-rays and most β particles.
- QF ~ 10-20 for α particles.
- QF ~ 2-10 for neutrons.

Example 1

Carbon makes ~ 20% of our body. In other words, a 75-kg adult will have 15 kg of carbon. The radioactive nuclide ^{14}C (lifetime of 5730 years) naturally exists in our body; one kilogram of carbon contains ~ 6.5×10^{13} ^{14}C atoms. In one year, how many radioactive disintegrations take place inside a 75-kg human body?

Example 2

The present activity of nuclear radiation source was found to be 1.7×10^7 Bq. What is the present activity in mCi?

Example 3

A cancer is irradiated with 10^5 Grays of ^{60}Co γ-rays, which has a quality factor of 0.7. Find the biologically equivalent dose in Sievert?

Example 4

A laboratory experiment in a physics class uses a 10 μCi ^{137}Cs source. Each decay emits 0.66 MeV γ-ray.

(a) How many decays occur per hour?

(b) A 60-kg student standing nearby absorbs 10% of the γ-rays. What is his absorbed dose in rads in 1 hour?

(c) The quality factor is 0.8. Find the biologically equivalent dose in rems.