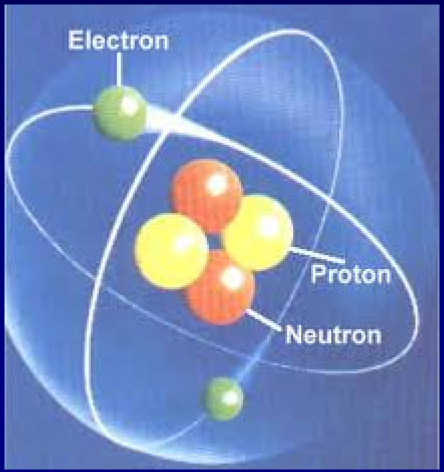
Chapter 3

HP Fundamentals

Objectives

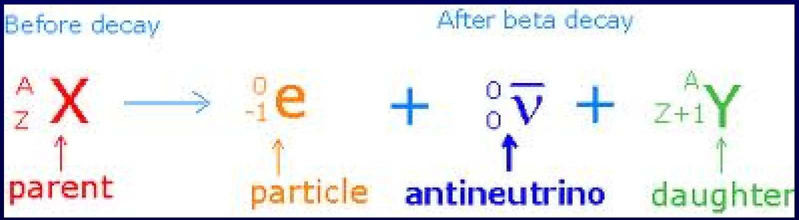
- Describe basic atomic structure
- Describe the atomic number, neutron number and atomic mass
- Define the terms isotope, ionization, radiation and radioactive material
- Discuss the difference between radiation and contamination
- Discuss the particulate and non-particulate types of radiation



Objectives

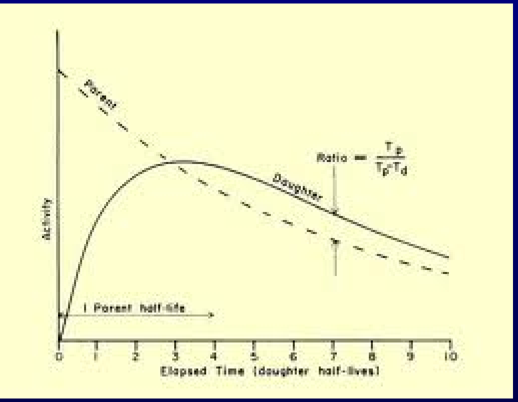
- Explain alpha, beta, positron and gamma decay

- Define the terms activity and half-life
- Define decay constant and relate it to activity
- Utilize the decay equation to calculate the number of atoms in a sample or activity of a sample



Objectives

- Define and calculate specific activity
- Define serial decay
- Discuss the types of radioactive equilibrium

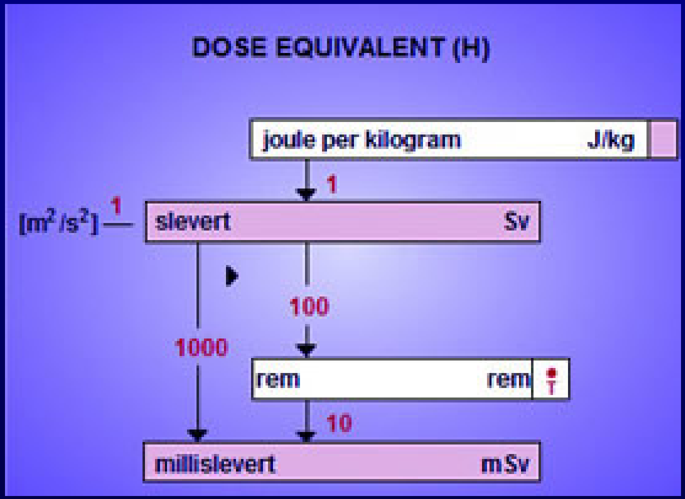


Objectives

- Discuss the concept of exposure
- State three fundamental limitations of the roentgen
- Define absorbed dose and its traditional and SI units
- Discuss limitations of the rad
- Define the term quality factor

Objectives

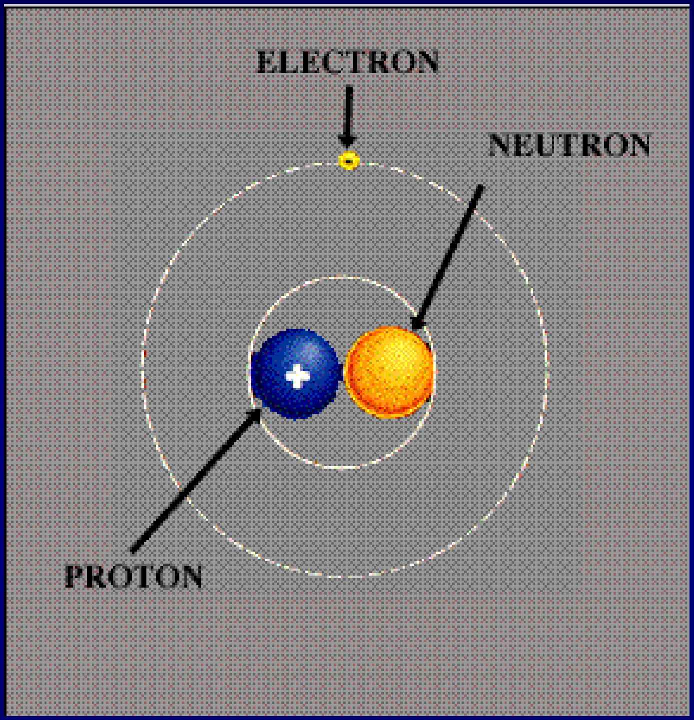
- Define the term dose equivalent including the SI and conventional units
- State the relationship between roentgen, rad, and rem for photon dose to human tissue



Atomic Structure

- Atoms have orbital electrons, which have a negative charge, and a nucleus comprised of neutrons and protons.

- Protons have a positive charge. Typically there is an orbital electron for each proton in the nucleus.



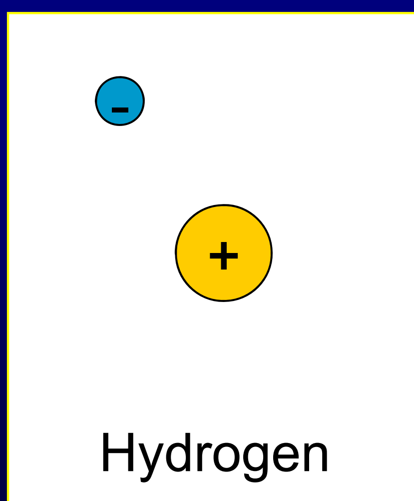
- The element is determined by the number of protons in the nucleus.

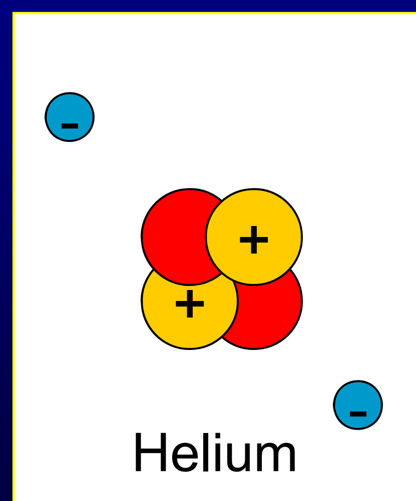
Elements

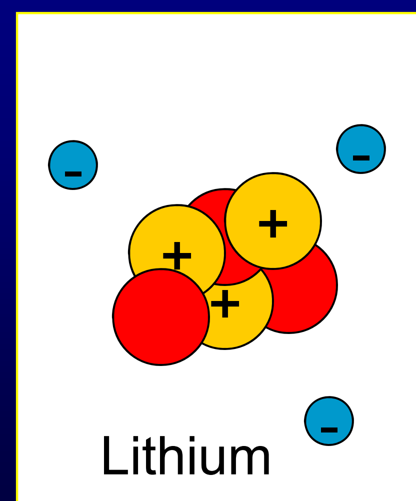
"Of course the elements are earth, water, fire and air. But what about uranium? Surely you can't ignore uranium."

Atomic Structure

- A hydrogen (H) atom has one proton in its nucleus and one orbital electron.
- A helium (He) atom has two protons in its nucleus, so it has two electrons…and so on…
- All electrically neutral atoms have one negative electron for each positive proton in the nucleus.

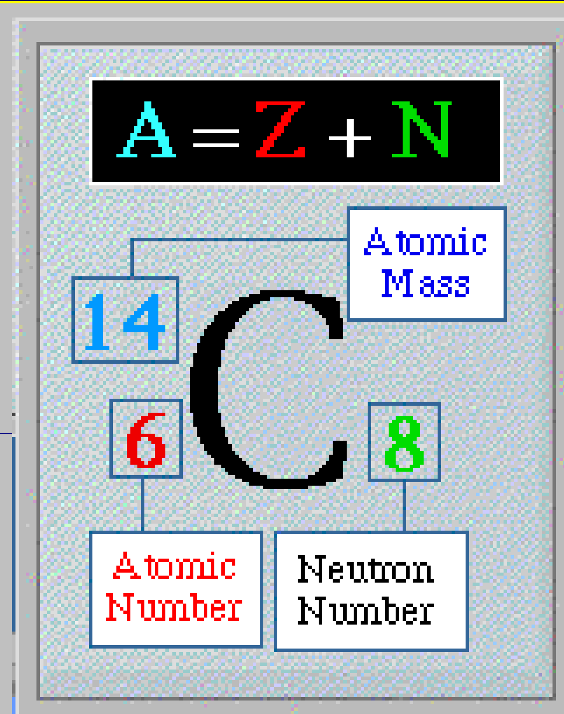






Nuclear Notation

- The number of protons in the nucleus is called the atomic number, Z, which determines the element.
- The neutron number, N, is the number of neutrons in the nucleus.
- The atomic mass, A, is the sum of the atomic number, Z, and neutron number, N.

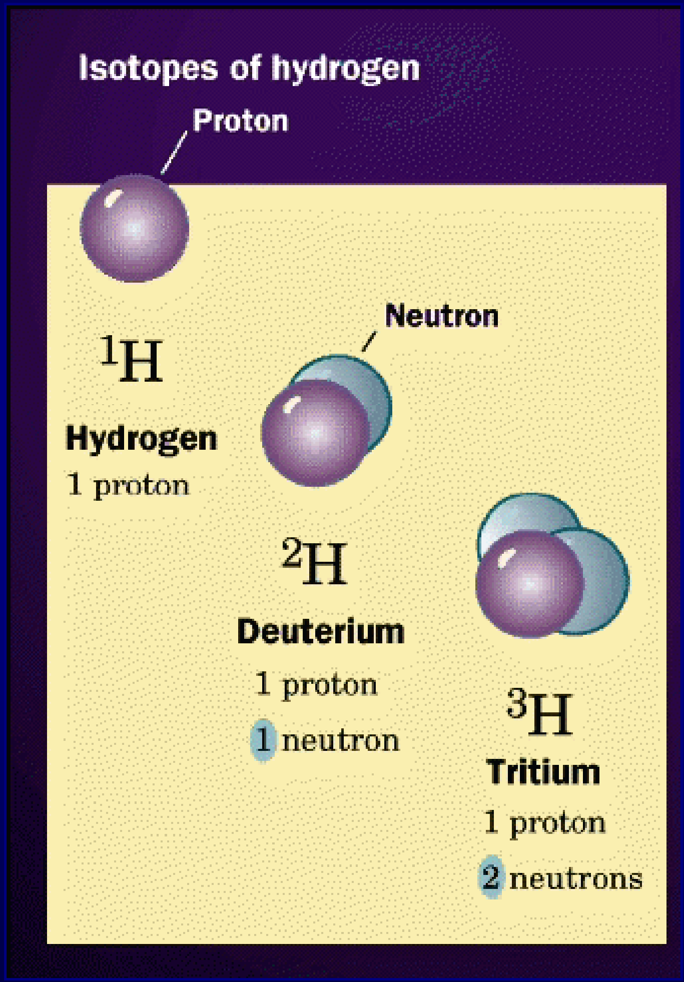


Commonly Written:

C-14 or ^{14}C

Definitions

- Atoms with the same number of protons but a different number of neutrons are called isotopes.
- Some isotopes have an unstable nucleus. They try to rearrange themselves into a more stable configuration by emitting energy or particles which we call radiation.
- Isotopes that emit ionizing radiation are called radioactive.
- This slide shows isotopes of hydrogen. Of these, H-3, or tritium, is radioactive.

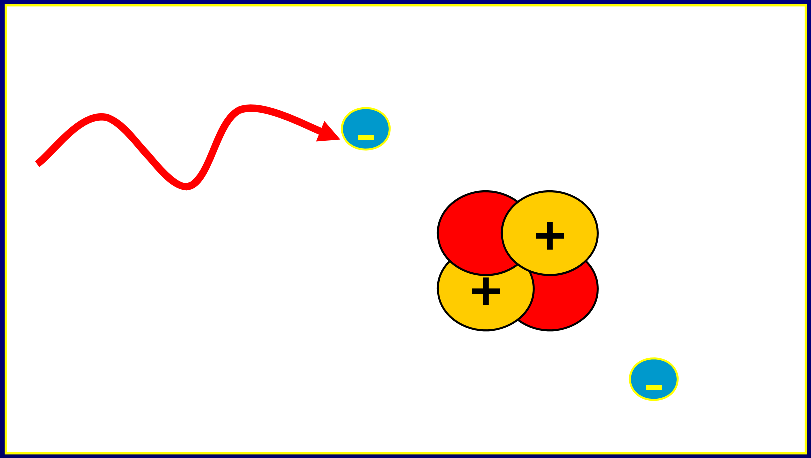


Radioactive Decay

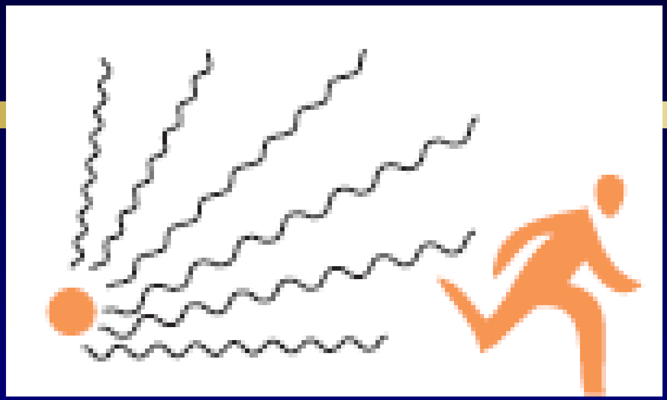
- Radioactive decay is a spontaneous change in the nucleus of an unstable atom
- Accompanied by the release of ionizing radiation in the form of particles or energy
- May result in the formation of new elements (either stable or unstable)
- Nuclear instability is related to either the neutron-to-proton ratio being too high or too low, or the nucleus being in an excited state (excess energy)

Ionizing Radiation

- Radioactive decay releases ionizing radiation
- Ionizing radiation is energetic enough to remove orbital electrons from atoms or molecules with which it interacts.



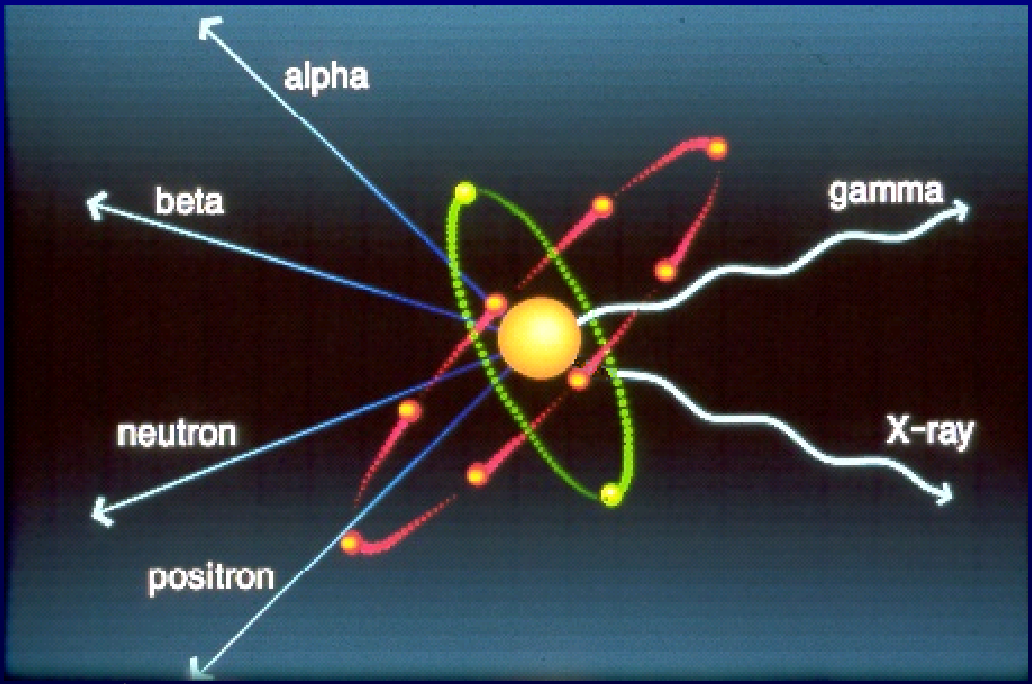
- Non-ionizing radiation (e.g., visible light, microwaves) does not have sufficient energy to remove orbital electrons from the atoms with which it interacts.



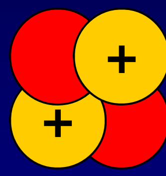
Radiation vs. Contamination

Types of Ionizing Radiation

- Ionizing radiation can be in the form of particles or electromagnetic waves (photons).
- The particulate forms are alpha, beta, neutrons, and positrons.
- The non-particulate forms are gamma rays and X-rays.



Alpha Radiation (α)



- Alpha particles consist of two protons and two neutrons.
- Heavier atoms such as transuranics emit alpha particles.
- Because of their double positive charge and relatively large size, alpha particles are slow (< 2E9 cm/sec) and have a limited range – no more than a couple of inches in air. They ionize other atoms by removing orbital electrons and can create relatively high numbers of ionizations in a very small volume.
- Alpha particles are not a hazard if they are outside of the body (cannot penetrate the skin's dead layer), but can cause a lot of damage if they enter your body.

$$^{241}_{95}Am \longrightarrow {}^{237}_{93}Np + {}^{4}_{2}He^{++}$$

Beta Radiation (β^-)

- Beta radiation is also particulate. A beta particle is the same as an electron and has a single negative charge.
- Since they are less massive than alpha particles and have less charge, they travel much faster and further in material. The distance depends upon their energy.
- An energetic (~1 MeV) beta particle travels near the speed of light (3E10 cm/s), up to 12 feet in air, and has the ability to penetrate the skin and the lens of an eye.

Beta Emission

- Emission of an electron from the *nucleus* of a radioactive atom

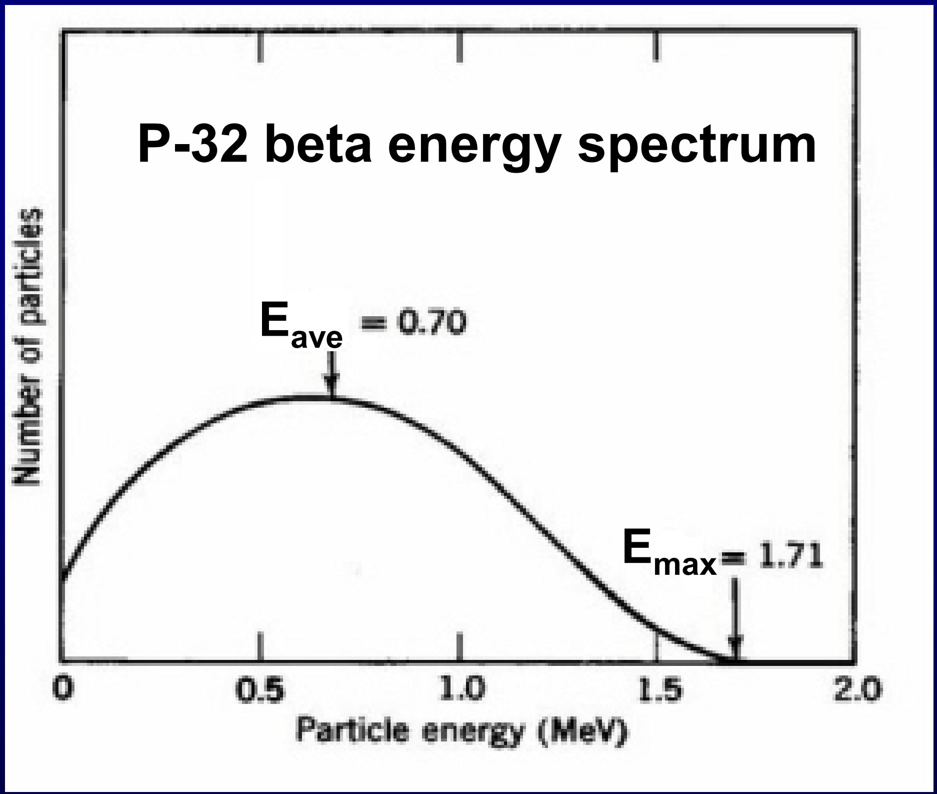
- Occurs when neutron to proton ratio is too high, i.e., a surplus of neutrons:

$$n \rightarrow p^{+} + \beta^{-} + \overline{\nu}$$

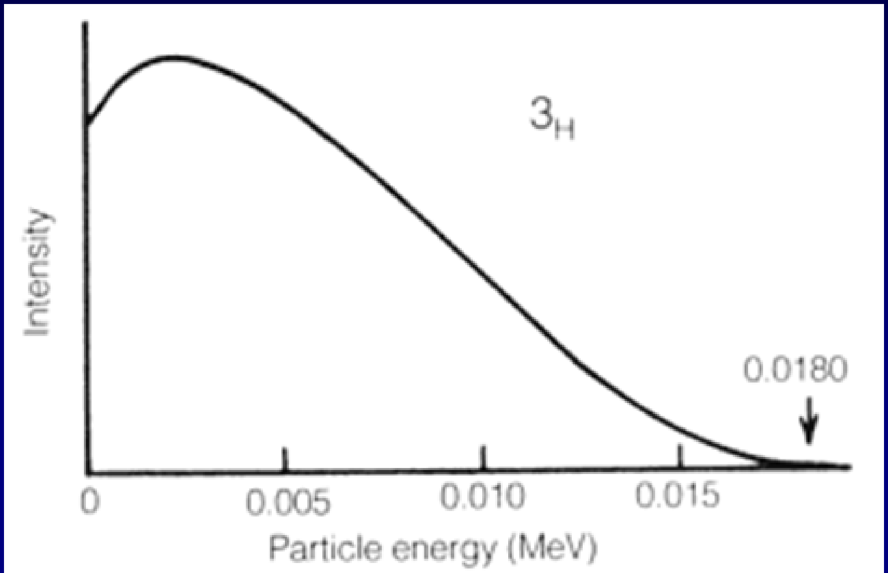
$$ {}_{1}^{3}\mathrm{H} \longrightarrow {}_{2}^{3}\mathrm{He} + e^{-} + \overline{\nu}$$

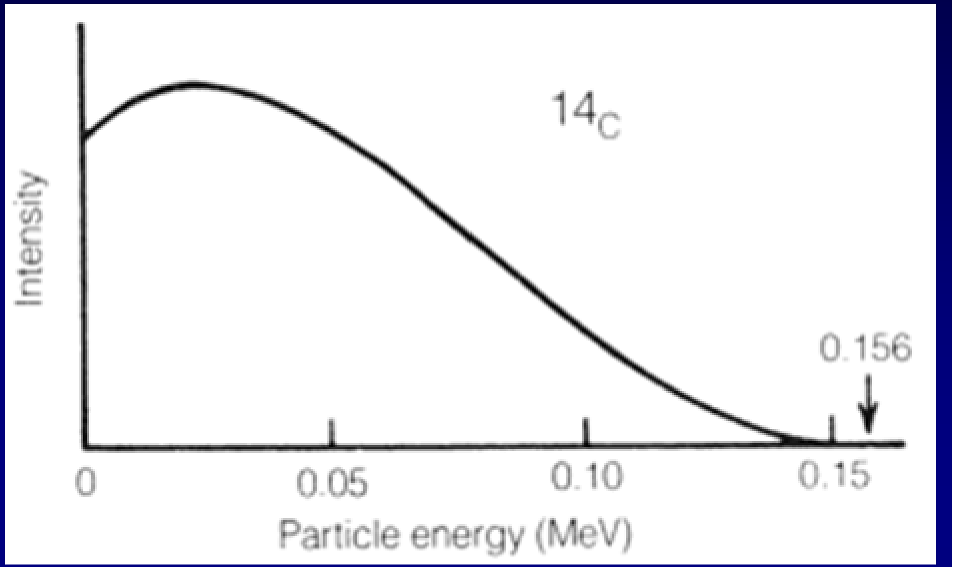
Beta Energy Spectrum

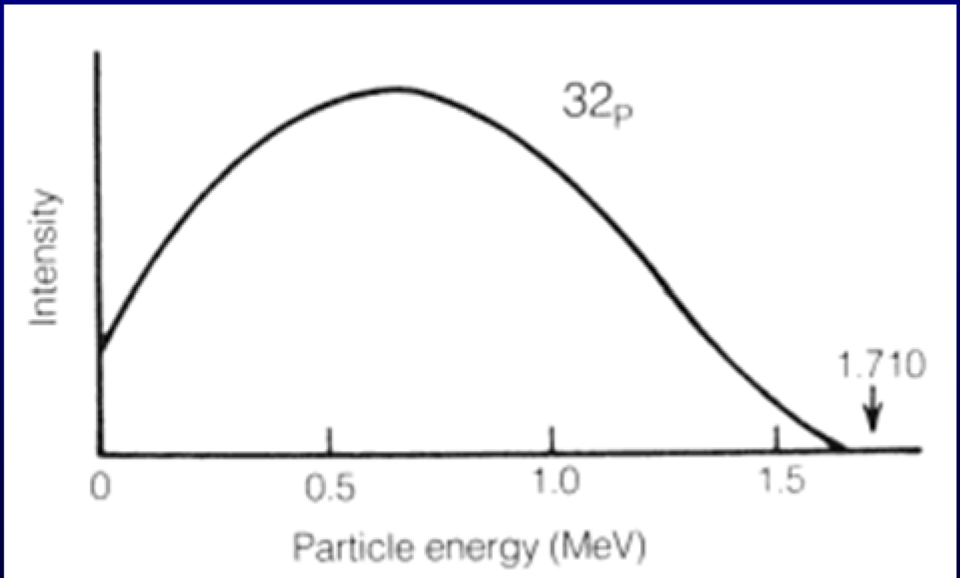
Beta particles are emitted with a spectrum of energies (unlike alpha particles) since their energy is shared with an antineutrino.



Additional Beta Spectra



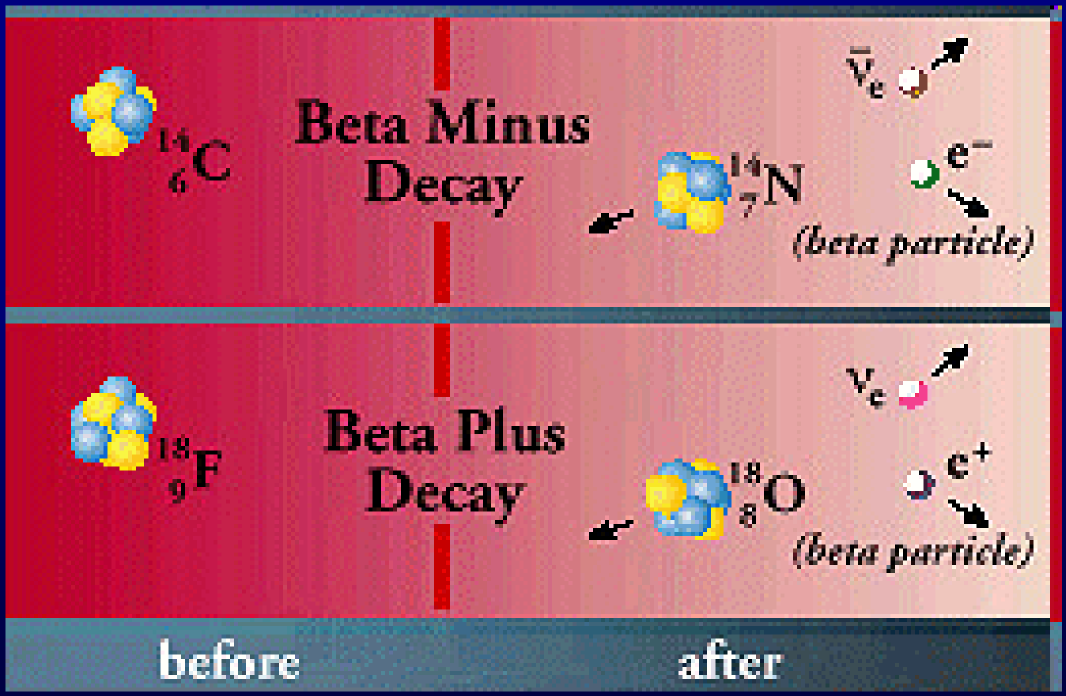




Positron (β^+) Radiation

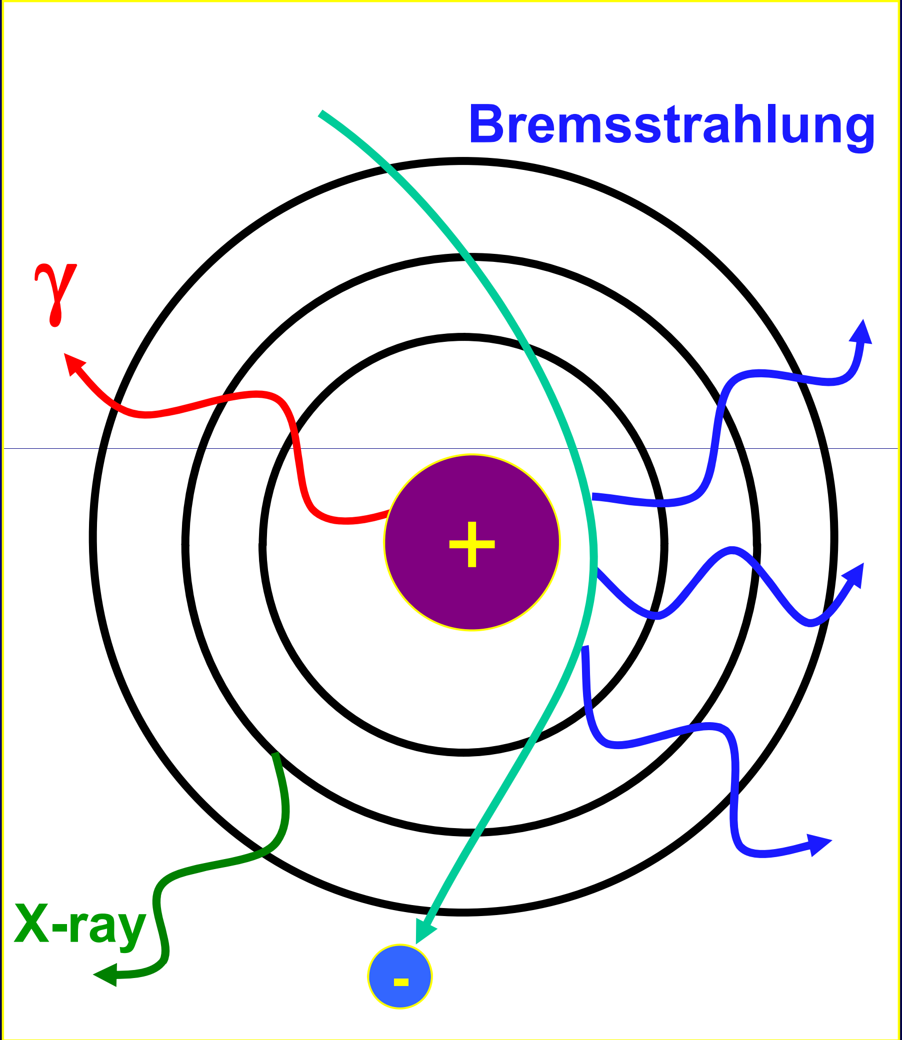
- Occurs when the nucleus contains too many protons (neutron to proton ratio is too low)

- Nucleus emits a positron (a beta particle with a positive charge) and a neutrino $p^+ \rightarrow n + \beta^+ + \nu$



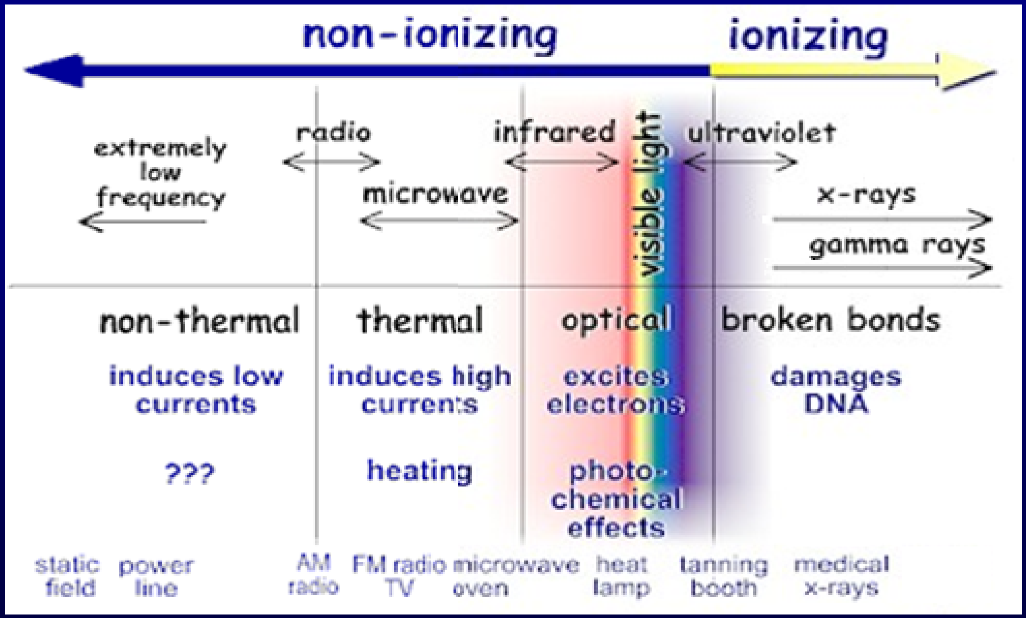
Photon Emissions

- Photons, γ, have no mass or charge - they are pure energy.
- Characteristic X-rays are produced outside of the nucleus.
- Gamma rays originate in the nucleus of a radioactive atom.
- Bremsstrahlung photons are emitted when an electron is deflected by a nucleus.



Gamma and X-ray radiation

- Photons (electromagnetic radiation) are grouped by wavelength. The shorter the wavelength, the higher the energy.
- Not all forms of radiation are ionizing.
- No defined energy cut-off between x-rays and gamma rays

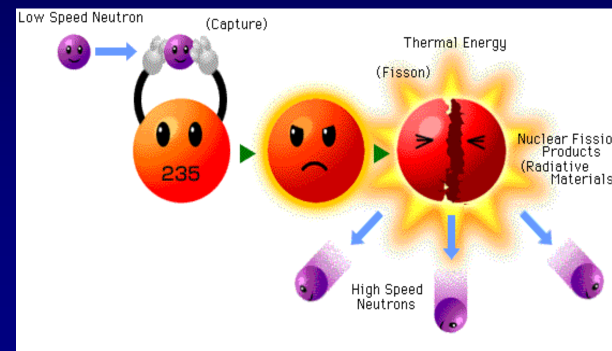


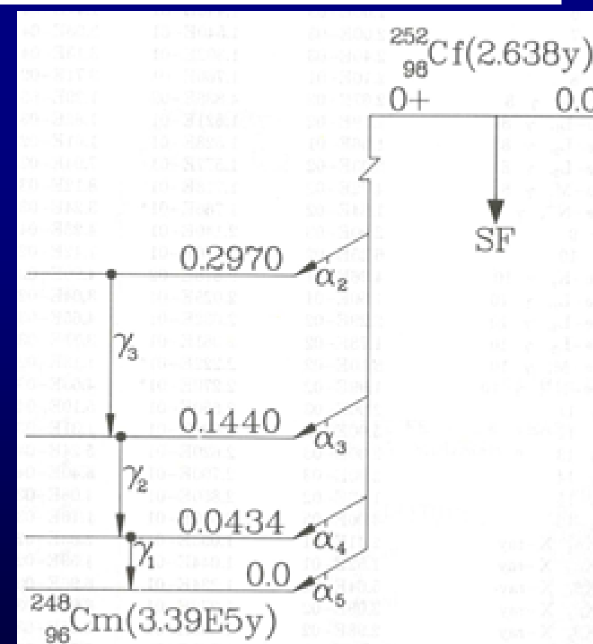
Gamma Rays

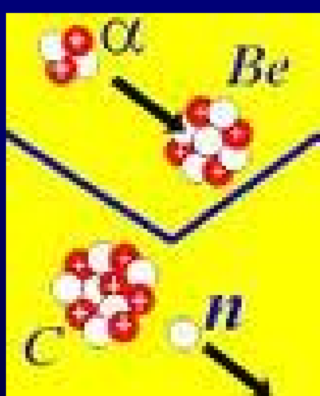
- Gamma rays are photon usually emitted from the nucleus of an atom following radioactive decay to rid the nucleus of excess energy
- Gamma rays are electromagnetic radiation just like visible light and UV rays, but they are more penetrating
- Gamma rays have characteristic energies that can be used to identify the radionuclide, e.g., Cs-137 decay results in the emission of 662 keV gamma rays

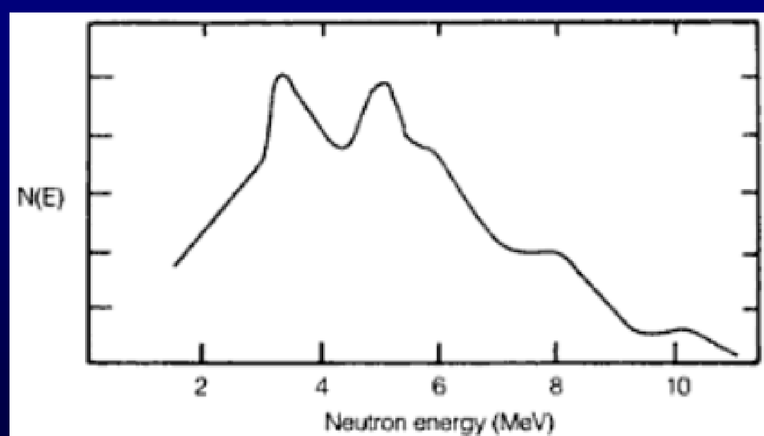
Neutrons

- Neutrons are particulate radiation with no charge.
- Neutrons are generated through:
  - fission in a reactor
  - decay via spontaneous fission (
  - neutron generators (deuterons into a tritium target: 14 MeV)
  - alpha – neutron interaction



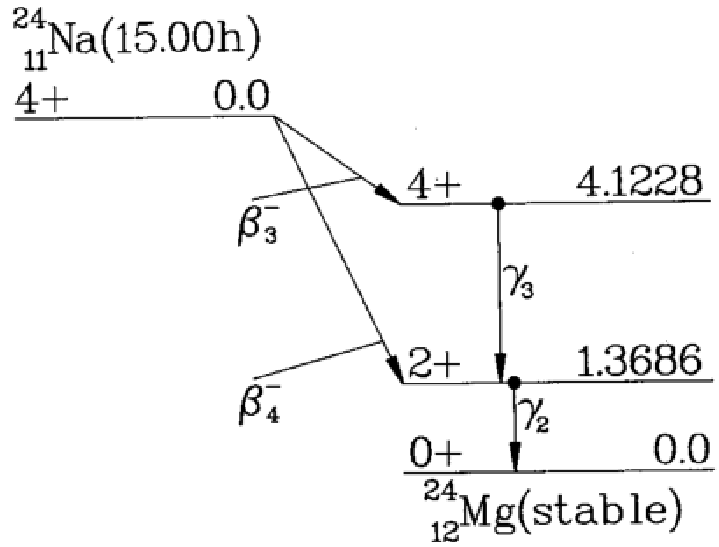






Decay scheme example

$^{24}Na \rightarrow {}^{24}Mg + \beta^-$



11-SODIUM-24

HALFLIFE = 15 HOURS 13-OCT-77
DECAY MODE(S): β^-

RADIATION	y(i) (Bq-s)$^{-1}$	E(i) (MeV)	y(i)×E(i)
β 3	9.99E-01	5.537E-01*	5.53E-01
γ 2	1.00E 00	1.369E 00	1.37E 00
γ 3	9.99E-01	2.754E 00	2.75E 00

LISTED X, γ AND γ± RADIATIONS	4.12E 00
OMITTED X, γ AND γ± RADIATIONS**	2.45E-03
LISTED β, ce AND Auger RADIATIONS	5.53E-01
OMITTED β, ce AND Auger RADIATIONS**	1.35E-04
LISTED RADIATIONS	4.67E 00
OMITTED RADIATIONS**	2.59E-03

* AVERAGE ENERGY (MeV)
** EACH OMITTED TRANSITION CONTRIBUTES <0.100% TO Σy(i)×E(i) IN ITS CATEGORY.
MAGNESIUM-24 DAUGHTER IS STABLE.

Activity

- Activity, A, is the term used to measure the decay rate of a radionuclide
- The activity of a sample is based on the total number of radioactive atoms, N, and the probability of each atom undergoing radioactive decay.
- The decay constant, λ, represents this probability and is dependent on the half-life of the nuclide.

$$A = \lambda N$$

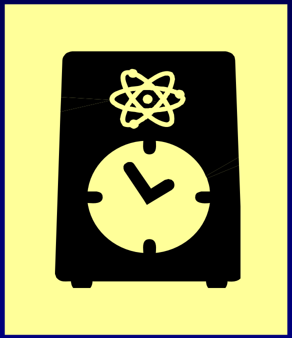
Activity Units

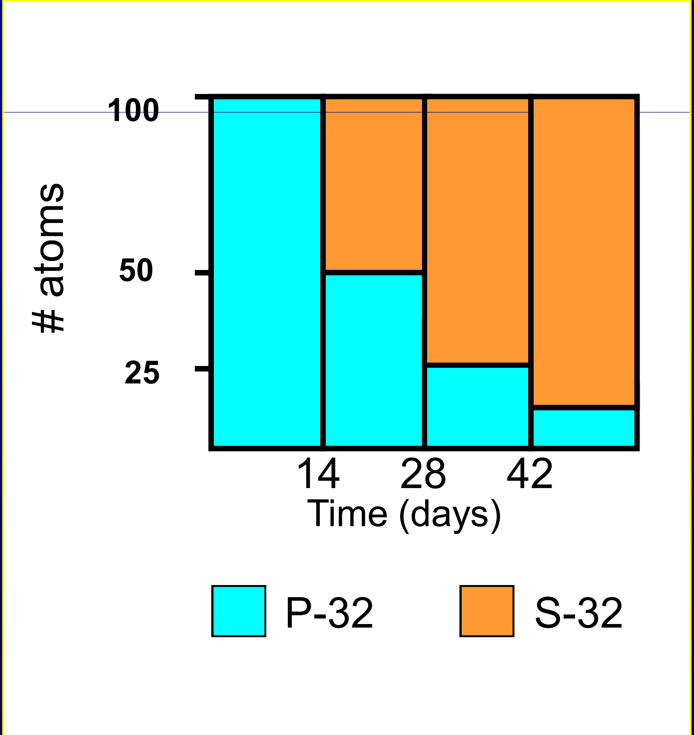
- Traditional unit is the curie, Ci
  1 Ci = 3.7 x 10^{10} dps (disintegrations per second)
- SI (International System) unit is becquerel, Bq
  1 Bq = 1 dps
- 1 Ci = 3.7 x 10^{10} dps = 37 GBq

Half-Life

- Half-life is the time required for half of the nuclei in a sample of radioactive material to undergo radioactive decay and is unique for each isotope.

- For example, radioactive P-32 decays with a half-life of 14 days to stable S-32.
  - Starting with 100 atoms of P-32
  - After 14 days, ½ of the atoms of P-32 will have decayed to S-32
  - After two half-lives, only 25 atoms of P-32 remain while the other 75 atoms are now S-32





Half-Life and the Decay Constant

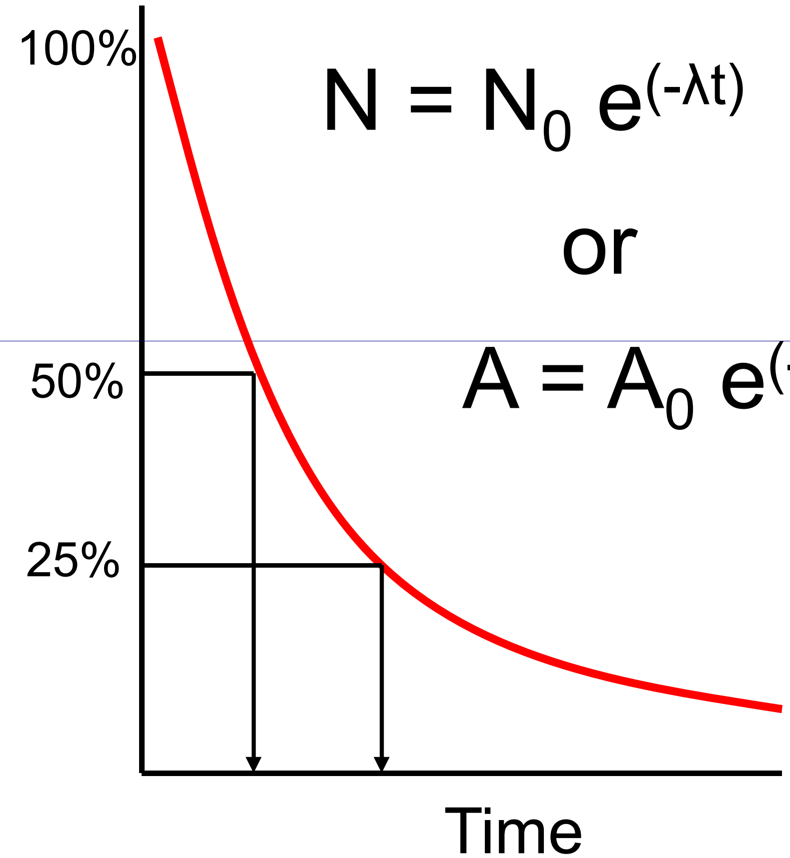
- **Half-life, $T_{1/2}$, is directly related to the decay constant, λ**

$$T_{1/2} = \frac{\ln(2)}{\lambda} \quad \text{or} \quad \lambda = \frac{0.693}{T_{1/2}}$$

where λ is in units of inverse time (e.g., s^{-1})

The Decay Equation

- Radioactive decay as a function of time decreases at a negative exponential rate.
- N_0 is the original number of radioactive atoms.
- N is the number remaining after time, t.
- This equation also applies to activity, A, as shown.
- The decay constant, λ, represents the probability that a radioactive atom will decay.



$$N = N_0\, e^{(-\lambda t)}$$

or

$$A = A_0\, e^{(-\lambda t)}$$

Half-Life Example

A vial contains 1E6 atoms of Cs-137.
Cs-137 has a half-life of 30 years.
After 15 years, how many atoms of Cs-137 remain?

1) **Using the Decay Equation:**

$$N = N_0\, e^{(-\lambda t)}$$

$$\lambda = \ln(2)/T_{1/2} = 0.693/T_{1/2}$$

$$\lambda = (0.693/30\ y) = 0.023\ y^{-1}, \text{ so}$$

$$N = (1E6 \text{ atoms})e^{[-(0.023\ 1/y)(15\ y)]}$$

$$N = 7.07E5 \text{ atoms}$$

2) **Using simplified equation:**

$N = N_0(1/2)^n$ **where n = number of elapsed half-lives**

15 years is ½ of the 30 year half-life of Cs-137

$$N = (1E6 \text{ atoms})(1/2)^{0.5} = 7.07E5 \text{ atoms}$$

Specific Activity

- Specific Activity is the activity of a radionuclide per unit mass.

$$SA = A/mass$$

$$SA = \frac{(0.693/T_{1/2})(N)}{mass}$$

- To determine the mass, use the Atomic Mass of a radionuclide in units of g/mole

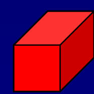
Note: The mole is a unit to determine the amount of a substance (6.02 E23 atoms/mole)

Specific Activity Comparison

0.001 g

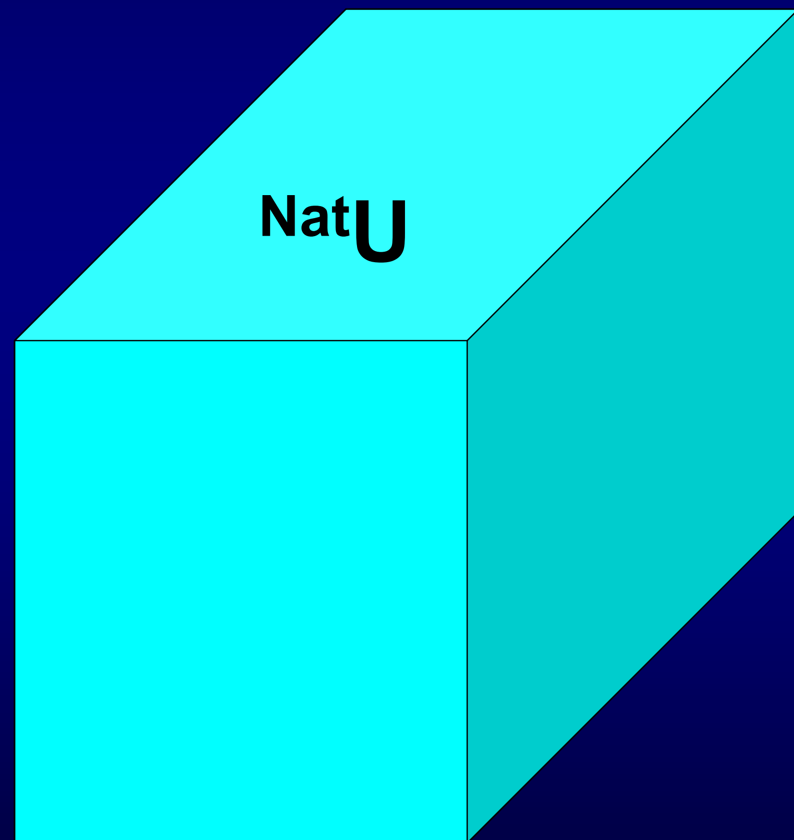
$^{60}_{27}Co$

1 g



$^{226}_{88}Ra$

1,428,571 g



Amount in grams of each isotope equaling one curie of activity

Serial Decay

- Some radioactive isotopes decay into daughter products that are also radioactive. An example is the uranium-238 decay series.
- As seen within the U-238 series, decay occurs through different mechanisms – alpha, beta and gamma.
- Each isotope within a series has its own unique half-life which can vary from fractions of a second to billions of years.

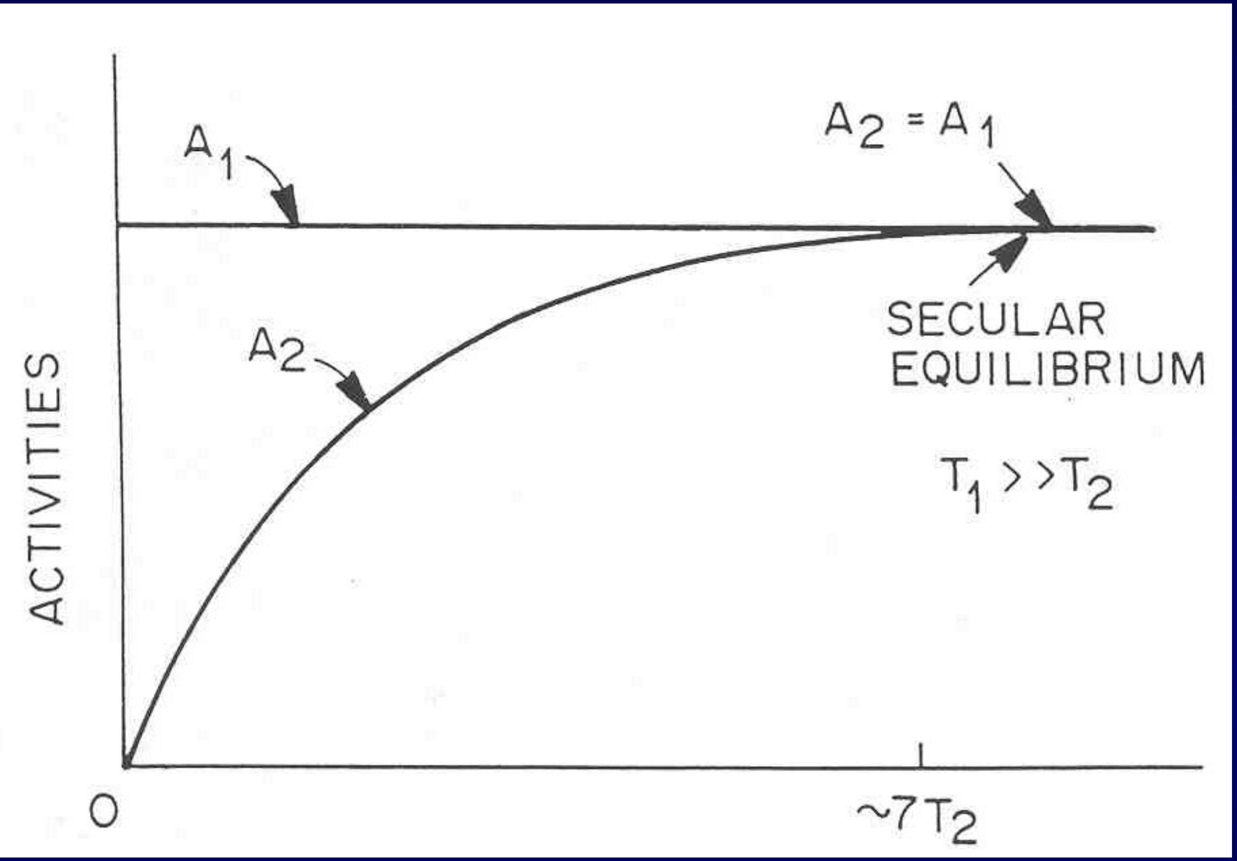
URANIUM 238 (U238) RADIOACTIVE DECAY

type of radiation	nuclide	half-life
	uranium-238	4.47 billion years
α		
	thorium-234	24.1 days
β		
	protactinium-234m	1.17 minutes
β		
	uranium-234	245000 years
α		
	thorium-230	8000 years
α		
	radium-226	1600 years
α		
	radon-222	3.823 days
α		
	polonium-218	3.05 minutes
α		
	lead-214	26.8 minutes
β		
	bismuth-214	19.7 minutes
β		
	polonium-214	0.000164 seconds
α		
	lead-210	22.3 years
β		
	bismuth-210	5.01 days
β		
	polonium-210	138.4 days
α		
	lead-206	stable

Equilibrium (Serial Decay)

- **Secular** — Half-life of parent <u>much greater</u> (>100 times) than that of daughter products
- **Transient** — Half-life of parent only <u>slightly greater</u> (~10 times) than that of decay product
- **No equilibrium** — Half-life of parent <u>less</u> than that of progeny

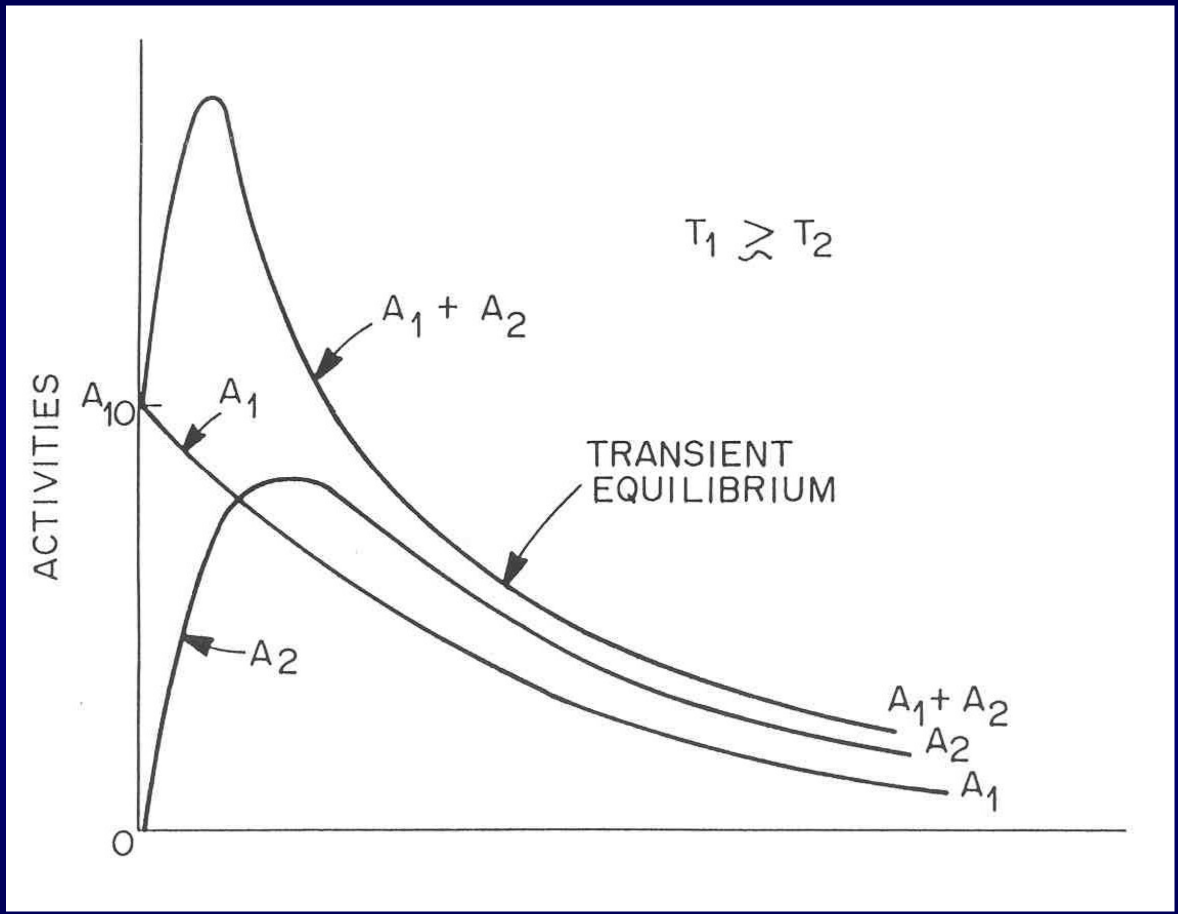
Secular Equilibrium



For example, Sr-90 → Y-90

T_1 for Sr-90 = 29 years and T_2 for Y-90 = 64 hours

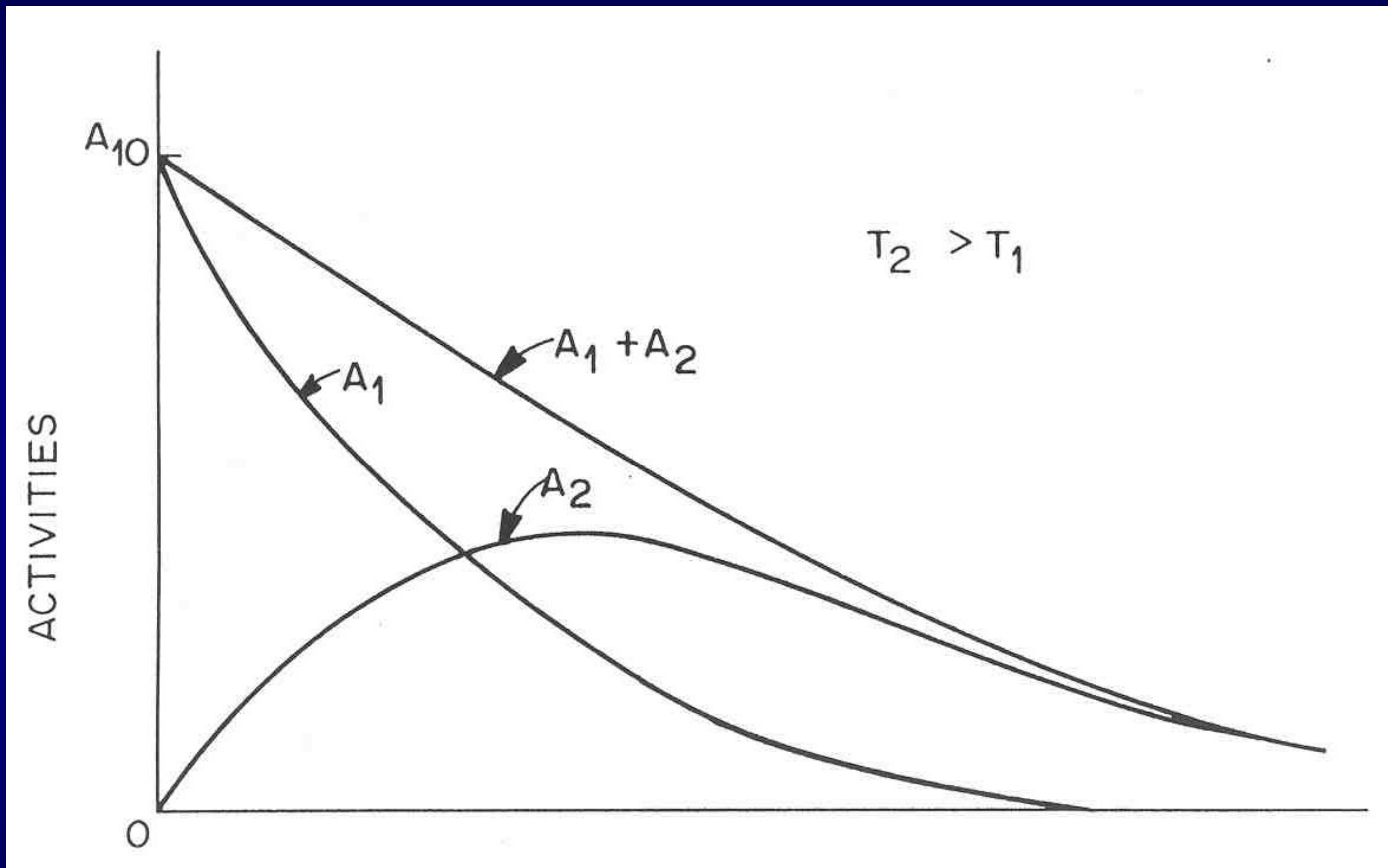
Transient Equilibrium



For example, Pb-212 → Bi-212

T_1 for Pb-212 = 10.6 hours and T_2 for Bi-212 = 1 hour

No Equilibrium



For example, Ce-146 → Pr-146

T_1 for Ce-146 = 14 min and T_2 for Pr-146 = 26 min

Radiation Quantities and Units

Unit Prefixes

Tera	1E12	TBq
Giga	1E9	GBq
Mega	1E6	MBq
kilo	1E3	kBq
milli	1E-3	mCi
micro	1E-6	µCi
nano	1E-9	nCi
pico	1E-12	pCi

Exposure

- Exposure is related to the amount of energy transferred from photons (X-rays and gamma rays) to a given mass of air
- Exposure is typically measured in roentgens, R
- 1 R = 2.58E-4 coulombs/kg
  = 87 ergs/g

Note: No similar unit in the International System (SI)

Limitations of the Roentgen

- Roentgen applies only to photons
- Roentgen applies only in air
- Roentgen is defined only for photon energies up to 3 MeV

(Limited) Use of the Roentgen

- Not used or defined in 10 CFR Part 20
- Not allowed as official record of dose (use rad or rem)
- Commonly found on survey instruments and used on radiation survey records

Absorbed Dose

- The energy deposited by radiation in a given mass of any material
- Traditional unit is the rad

  1 rad = 100 ergs/g
- SI unit is the gray, Gy

  1 Gy = 100 rad
- Absorbed dose applies to all ionizing radiations at all energies in all media, including human tissue

Roentgen and Rad Relationship

- Recall that an exposure of 1 R results in about 87 ergs/g in air
- Since 1 rad = 100 ergs/g
- Thus, in air, $1\ R = 87\ \text{ergs/g} \times \dfrac{1\ \text{rad}}{100\ \text{ergs/g}} = 0.87\ \text{rad}$
- In human tissue, 1 R results in about 96 ergs/g
- Thus, 1 R = 0.96 rad or …

1 R ≈ 1 rad for human tissue.

Limitations of the Rad

- Does not take into account differing biological effects of various types of radiations
- For example, in human tissue, 1 rad due to alpha exposure is NOT equal to 1 rad of beta exposure
- Since 1 rad from each radiation deposits the same amount of energy in tissue (100 ergs/g), the difference is related to energy distribution in tissue
- Thus, we need another factor that accounts for differing biological effects of the various types of radiation

Quality Factor and Dose Equivalent

- Quality Factor, Q, is the modifying factor by which absorbed dose can be multiplied to account for differing biological effects

- Absorbed Dose x Q = Dose Equivalent

Note that dose equivalent is only defined for human tissue

Quality Factors (10 CFR 20.1004)

Radiation Type	Quality Factor
beta	1
gamma	1
X-ray	1
neutron	2–11 (depending on energy)
alpha	20

Dose Equivalent

- Traditional unit for dose equivalent is rem
- Since Q = 1 for photons and betas,
  1 rad of these radiations equals 1 rem
- SI unit is sievert, Sv
  1 Sv = 100 rem
- 50 mSv = _____ mrem?

Rule of Thumb

- For X-rays and gamma rays in human tissue:

  1 R = 1 rad = 1 rem

Traditional Units and SI Units

Quantity	Traditional Unit	SI Unit	Conversion Factor
activity	curie (Ci)	becquerel (Bq)	3.7×10^{10} Bq/Ci
absorbed dose	rad	gray (Gy)	100 rad/Gy
dose equivalent	rem	sievert (Sv)	100 rem/Sv

QUESTIONS?

END OF
HP FUNDAMENTALS

Review Questions

- What two particles in the atomic nucleus have the same mass?
- Atomic mass is the sum of the number of _________ and __________ in the nucleus.
- Isotopes of the same element have the same number of __________ but differ in the number of __________.
- What happens when ionizing radiation interacts with an atom?
- An alpha particle is the same as the nucleus of a ________ atom.

Review Questions

- How far can an alpha particle travel in air?
- Can a beta particle penetrate your skin?
- How are X-rays similar to gamma radiation?
- What is the difference between gamma and an X-ray?
- Beta (-) particles are emitted by a nucleus that has too many __________ or too few __________.

Review Questions

- What are the SI and traditional units of activity?
- After one half-life, how much of the radioactive material remains?
- If you have 1,600 MBq of an isotope with a half-life of 5 years, how much remains after 15 years?
- If you now have 800 mCi of an isotope with a half-life of 10 days, how much was there 20 days before?

Review Questions

- What type of equilibrium condition exists when the daughter activity increases during in-growth to that of the parent nuclide?

- What type of equilibrium condition exists when the parent nuclide half-life is only slightly more than that of the daughter nuclide?

- What type of equilibrium condition exists between Ra-226 ($T_{1/2}$ = 1,600 y) decaying to Rn-222 ($T_{1/2}$ = 3.8 days)?

- What type of equilibrium condition exists when the half-life of the daughter product is more than that of the parent nuclide?

Review Questions

- What two particles in the atomic nucleus have the same mass?
- Atomic mass is the sum of the number of _________ and __________ in the nucleus.
- Isotopes of the same element have the same number of __________ but differ in the number of __________.
- What happens when ionizing radiation interacts with an atom?
- An alpha particle is the same as the nucleus of a ________ atom.

Review Questions

- How far can an alpha particle travel in air?
- Can a beta particle penetrate your skin?
- How are X-rays similar to gamma radiation?
- What is the difference between gamma and an X-ray?
- Beta (-) particles are emitted by a nucleus that has too many __________ or too few __________.

Review Questions

- What are the SI and traditional units of activity?
- After one half-life, how much of the radioactive material remains?
- If you have 1,600 MBq of an isotope with a half-life of 5 years, how much remains after 15 years?
- If you now have 800 mCi of an isotope with a half-life of 10 days, how much was there 20 days before?

Review Questions

- What type of equilibrium condition exists when the daughter activity increases during in-growth to that of the parent nuclide?
- What type of equilibrium condition exists when the parent nuclide half-life is only slightly more than that of the daughter nuclide?
- What type of equilibrium condition exists between Ra-226 ($T_{1/2}$ = 1,600 y) decaying to Rn-222 ($T_{1/2}$ = 3.8 days)?
- What type of equilibrium condition exists when the half-life of the daughter product is more than that of the parent nuclide?