

Fundamental Radiation Concepts

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What is radiation?

Radiation is energy that travels through space or matter in the form of a particle or wave

Energy is measured in electron volts (eV)

- $1 \text{ eV} = 1.6 \times 10^{-19} \text{ joules}$
- More common to see kilo electron volts used
($1 \text{ keV} = 1,000 \text{ eV}$)

Where does it come from?

Radiation can originate in one of two ways:

1. Radioactive decay of an unstable atom (radionuclide)
 - Spontaneous (can't cause it to happen)
 - Random (can't predict when it will happen)
 - Type of radiation emitted depends on the specific material (some materials may emit more than one type)
 - You cannot "turn it off"



Where does it come from?

2. Interaction of a particle with matter

- Source of particles may be radionuclide or machine
- We can predict the likelihood of a certain type of interaction if we know enough information about the particle and the material it hits
- This is the principle behind an x-ray tube
- You can “turn it off” if you can stop the incoming particles

Types of radiation

2 main categories

- Particulate radiation: consists of particles that have mass and energy, and may or may not have an electric charge
 - Alpha particles and protons (positive charge)
 - Beta particles (positive or negative charge)
 - Neutrons (uncharged)
- Electromagnetic radiation: consists of photons that have energy, but no mass or charge (just like light, but higher frequency)
 - X rays
 - Gamma rays

Ionizing Radiation

Radiation is called ionizing if it is capable of forming ion pairs in matter

- An ion pair is formed when an electron is removed from an atom, leaving a free electron and a positively charged atom

The ability to ionize depends on factors including energy, mass, and charge

Most non-ionizing radiation is not harmful

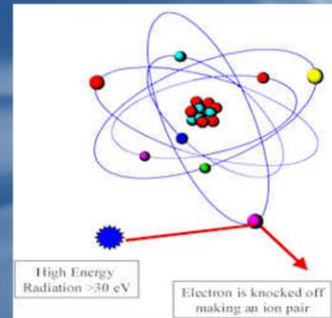


Figure taken from:
www.e-radiography.net/radsafety/rad_physics-1.jpg

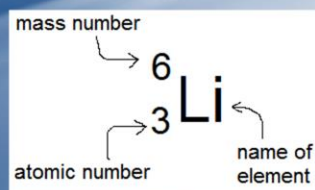
Basic Chemistry Review

Atomic number (Z): tells how many protons an atom has, is specific to that element



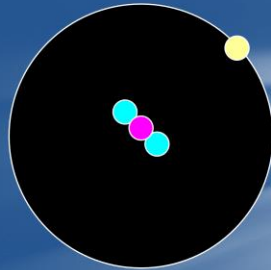
Mass number (A): equal to the sum of the protons and neutrons in the atom, can change without changing the element

- Atoms with the same atomic number but different mass numbers are called isotopes.
- Isotopes are commonly referred to by their element name and mass number, e.g. Li-6.



Free radical

Example: Isotopes of Hydrogen



H-1 Hydrogen
H-2 Deuterium
H-3 Tritium



Each isotope has the same number of protons, but an increasing number of neutrons.

Why is this important?

Usually, only certain isotopes of an element are radioactive

- Example: C-14 is radioactive, but C-12 and C-13 are stable
- For most common elements, all isotopes are found in nature in varying percentages
- Stable isotopes are usually the most common

Radioactive Decay

- Electron / Beta Minus Decay
- Positron / Beta Plus Decay
- Alpha Decay
- Electron Capture
- Nuclear / Isomeric Transition

Symbols

Alpha particle: α

Electron: β^- (or e^-)

Positron: β^+ (or e^+)

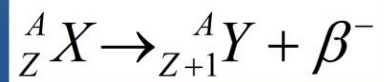
Neutron: n

Proton: p

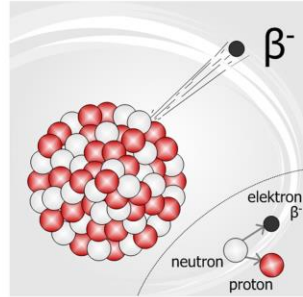
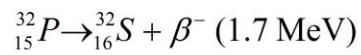
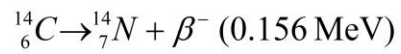
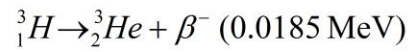
Photon (x ray or gamma ray): γ

Beta-minus decay

- Beta-minus particles are identical to electrons (same mass and negative charge)
- Beta-minus decay occurs when an atom has too many neutrons
- A neutron in the atom's nucleus converts into a proton and an electron
- The proton remains, so the atom's atomic number increases by 1
- The electron is ejected from the atom



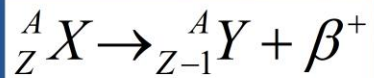
Examples of Beta-minus Decay



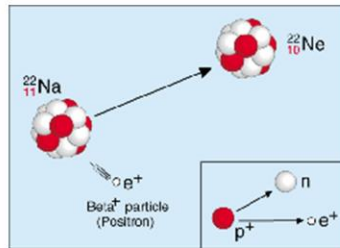
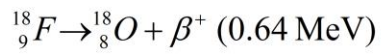
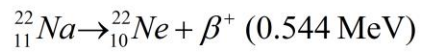
Energy in () is the maximum energy of the ejected particle.

Beta-plus (positron) decay

- A positron has the same mass as an electron, but with a positive charge
- Beta-plus decay happens when an atom has too many protons
- A proton in the atom's nucleus converts into a neutron and a positron
- The atom's atomic number decreases by 1
- The positron is ejected from the atom but quickly interacts with an electron and annihilation occurs. Two 0.511 MeV photons are produced and move away from each other in a straight line (180 degrees between them).

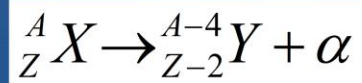


Examples of Beta-plus Decay

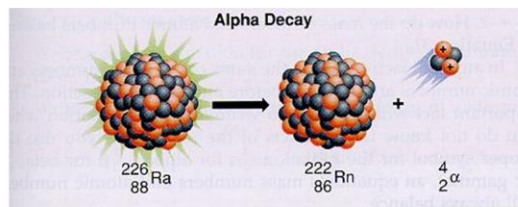
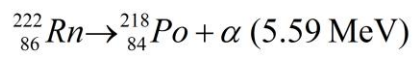
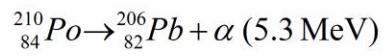


Alpha decay

- An alpha particle is the same as a helium nucleus (atomic number of 2, mass number of 4, and has a +2 charge because there are no electrons)
- Alpha decay can happen when an atom is too big to be stable (atomic number > 82)
- A particle consisting of two protons and two neutrons is ejected from the atom
- The atom's atomic number decreases by 2
- The atom's mass number decreases by 4

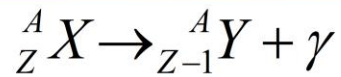


Examples of Alpha Decay

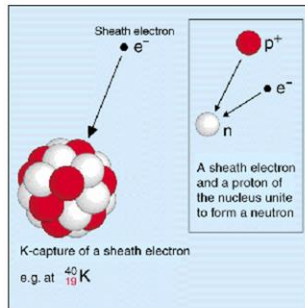
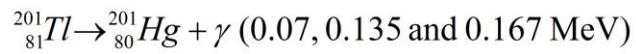
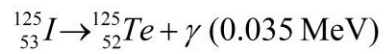


Electron capture decay

- An electron in an inner orbital gets “sucked into” the nucleus
- Like beta-plus decay, this happens when the nucleus has too many protons (electron capture and beta-plus decay are competing processes)
- The electron converts a proton into a neutron
- Once the lower orbital electron is captured, another electron from a higher orbital falls down to take its place
- The difference in energy is emitted as a photon
- The atom’s atomic number decreases by 1



Examples of electron capture decay

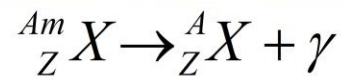


Te = tellurium

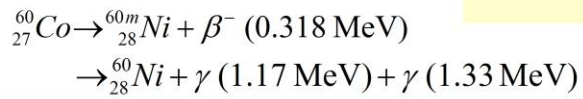
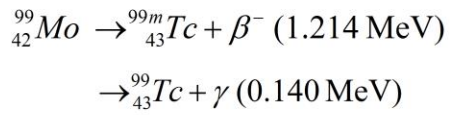
Tl = thallium

Nuclear/Isomeric transition

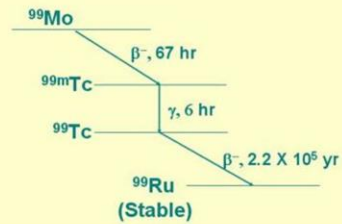
- Often the nucleus that results after one of the previous decays is not stable (in an excited state) – this is designated with an “m” after the mass number
- The nucleus undergoes an “internal rearrangement” to go from the excited state to a lower-energy state
- Gamma rays are emitted in the process to carry away the excess energy
- Atomic and mass numbers do not change



Examples of isomeric transition



Decay Scheme for ${}^{99}\text{Mo}$



A blue rectangular area with a black border. Inside, there are several bright, white, diagonal light rays or lens flares emanating from the right side, creating a sense of depth and focus.

Half-Life

Half-life ($T_{1/2}$): Time required for a radioactive substance to lose half of its atoms or half of its activity by decay.

Is specific to each radionuclide

The number of atoms N remaining after n half-lives is:

where N_0 = initial number of atoms

$$N = \frac{N_0}{2^n}$$

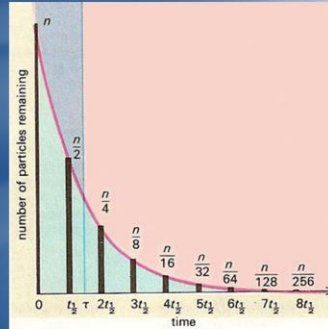
Example

A sample of radioactive material has a half-life of 1 week. What fraction remains after 3 weeks?

$$N = \frac{N_0}{2^n}$$

$$\frac{N}{N_0} = \frac{1}{2^3} = \frac{1}{8}$$

Answer: 1/8



Activity

Activity: the number of nuclear disintegrations (decay) occurring per unit time

$$A = \lambda N$$

where λ (decay constant) = $0.693/T_{1/2}$

Measured in the traditional unit Curies (Ci) or the SI unit Becquerels (Bq)

1 Bq = 1 disintegration/second (dps)

1 Ci = 3.7×10^{10} Bq

1 Ci is a huge amount! It is much more common to use microcuries (μ Ci) or millicuries (mCi)

- 1 Ci = 1000 mCi = 10^6 μ Ci
- 1 mCi = 37 MBq

Radioactive Decay Equation

Used if you know what the activity of a source was at some point in the past, and you need to know what it is now (or vice versa)

A = activity at time t

A_0 = initial activity

t = time since activity was known

λ = decay constant = $0.693/T_{1/2}$

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

Example

You have a source that was calibrated at 30 mCi on May 30, 2005. The half-life is 2.5 years. What is the activity on June 5, 2007?

- $A_0 = 30 \text{ mCi}$
- $t = 736 \text{ days} = 2.016 \text{ years}$
- $\lambda = 0.693/(2.5 \text{ years}) = 0.277 \text{ }^1/\text{years}$

$$A = (30 \text{ mCi}) * e^{-0.227 * 2.016}$$

Answer: $A = 17 \text{ mCi}$

A blue gradient background with light rays emanating from the right side, creating a sense of depth and movement.

Radiation Interactions

Interactions of Charged Particles

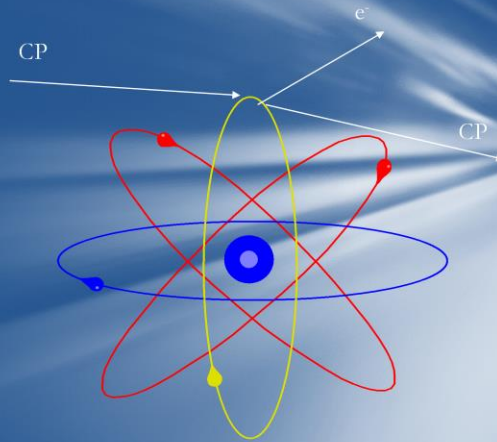
Alpha particles and Beta particles

Charged particles interact with matter in one of 3 ways:

- Ionization
- Excitation
- Radiative losses (Bremsstrahlung)

Ionization

- Charged particles interact with electrons in the atom's orbitals
- The energy transferred is enough to "kick" an electron out of its orbital
- This results in an ion pair: a negatively-charged electron and a positively-charged nucleus



Specific Ionization

Specific ionization is used to compare the ionizing power of different types of charged particles

It depends on the mass, energy and charge of the particle and the density of the absorbing material

- More mass or higher charge = higher S.I.
- More energy = lower S.I. (for particles of equal mass)
- Denser material = higher S.I.

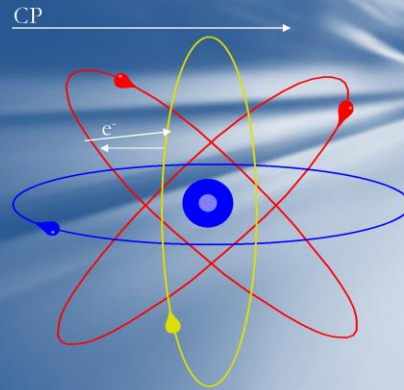
High S.I. means the particles do not travel far

$$\text{Specific ionization} = \frac{\text{\# ion pairs formed}}{\text{path length (cm)}}$$

Specific Ionization of Radiation			
Radiation	Range in air	Speeds	Specific ionization
Alpha	5 - 7 cm	3,200 - 32,000 km/sec	20,000 - 50,000 ion pairs/cm
Beta	200 - 800 cm	25 - 99% speed of light	50 - 500 ion pairs/cm
Gamma	Use of half-thickness	Speed of light 300,000 km/sec	5 - 8 ion pairs/cm

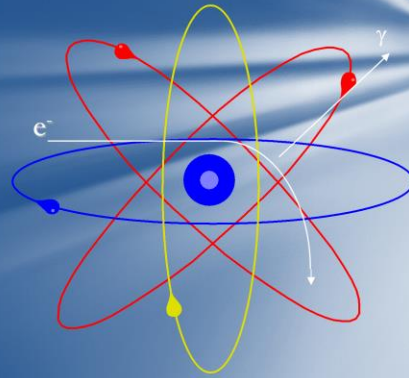
Excitation

- Like ionization, charged particles interact with electrons in the atom's orbitals
- The energy transferred is NOT enough to "kick" an electron out of its orbital
- The electron "jumps" to a higher energy state, then emits energy (a photon) when it "falls" back down



Bremsstrahlung Radiation

- Happens only with electrons
- Also called “braking” or “deceleration” radiation
- When an electron passes close to a nucleus, it slows down and loses energy
- This energy is emitted as a photon
- The higher the energy, the greater the deflection.
- This is how x-ray tubes work!

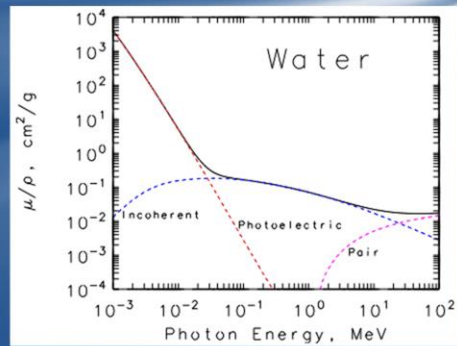


Interactions of Photons

X-rays and gamma rays

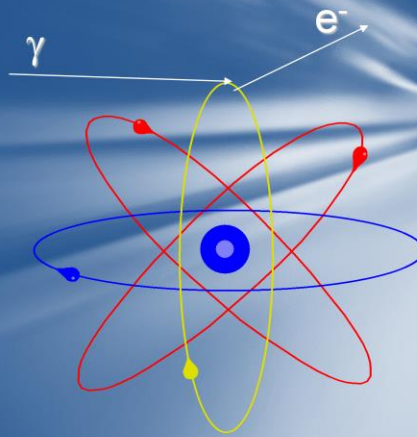
Photons interact with matter in one of 3 ways:

- Photoelectric effect
- Compton Scattering
- Pair Production



Photoelectric effect

- The incoming photon's energy is entirely transferred to an electron
- The electron is ejected from the atom and the photon is absorbed
- The nucleus is then left with a positive charge
- Dominant with low-energy photons, and probability decreases as energy increases



Compton Scattering

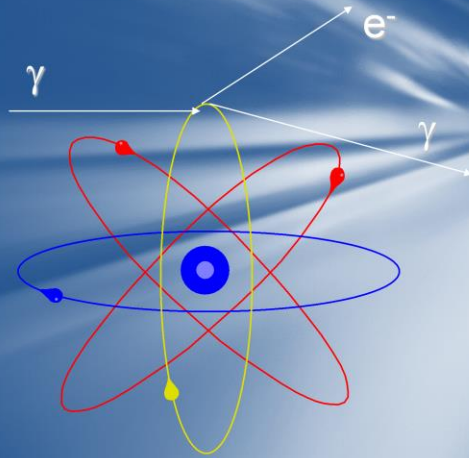
The incoming photon's energy is partially transferred to an electron

The electron is ejected from the atom and the photon scatters

The nucleus then has a positive charge

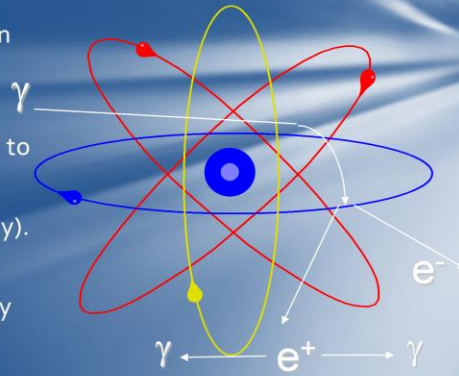
Dominant with mid-energy photons, but always present

A photon may scatter many times before it loses enough energy to be absorbed by the photoelectric effect

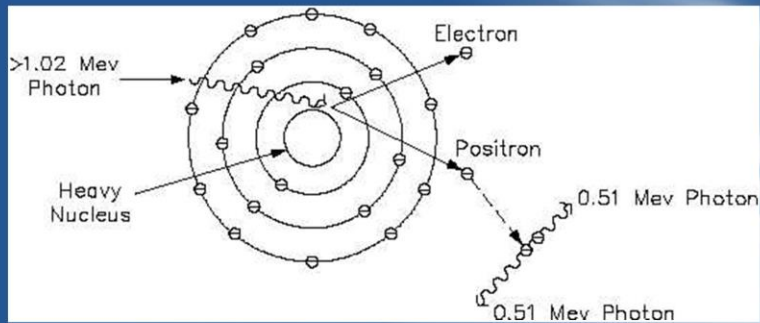


Pair Production

- The incoming photon interacts with the electric field of the nucleus
- The photon is transformed into an electron-positron pair
- This process results in the formation of 2 more photons due to positron annihilation
(remember beta-plus decay).
- Dominant with high-energy photons, minimum photon energy is 1.022 MeV



Pair Production / Annihilation

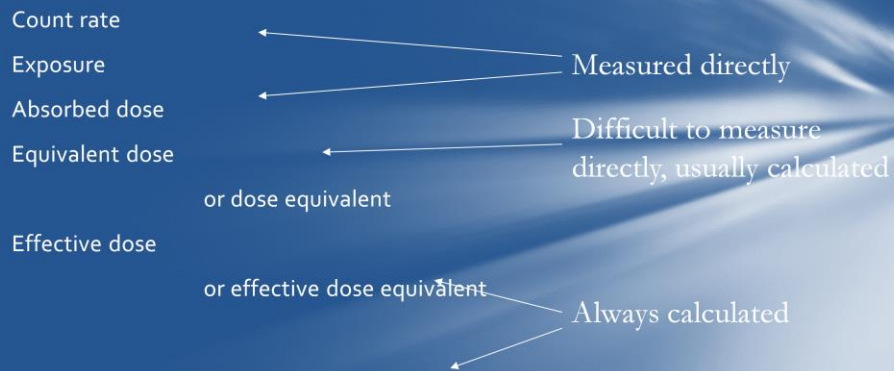


- The incident photon comes in and interacts with the electric field of the nucleus ($\gamma > 1.022 \text{ MeV}$)
- An electron-positron pair is formed
- The positron then finds/interacts with a free electron
- Annihilation occurs and two 0.511 MeV photons are produced



Radiation Quantities and Units

Radiation Measurement



Count rate

- Number of radiation interactions that occur in a detector in a period of time
- Units: count per second (cps) or counts per minute (cpm)
- Used for particulate radiation or small quantities of x-ray or gamma radiation
- 1 count $\neq$ 1 disintegration or decay, so cps $\neq$ dps



Exposure

- Exposure: the electric charge produced by photons (x rays or gamma rays) in a mass of air
- Traditional unit is the Roentgen (R)
- SI unit is Coulombs/kg air
- $1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg air}$
- Can be measured as a total exposure or an exposure rate

Absorbed Dose

- Absorbed dose: the energy deposited in a material by radiation per unit mass
- Traditional unit is the rad (radiation absorbed dose)
- 1 rad = 0.01 J/kg
- In SI units, rad has been replaced by Gray (Gy)
 - 1 Gy = 1 J/kg
 - 100 rad = 1 Gy
- You can convert exposure to dose *in air* using:

$$D_{air} \text{ (rad)} = 0.876 \text{ (rad/R)} \times X \text{ (R)}$$

- *In tissue*, 1 rad is approximately equal to 1 R

Equivalent Dose /Dose Equivalent

- Takes into account that some kinds of radiation cause more biological harm than others
- The traditional unit for this is the rem (stands for Roentgen Equivalent Man)
- In SI units, the rem has been replaced by the sievert (Sv), where $1 \text{ Sv} = 100 \text{ rem}$
- Equivalent dose: $H (\text{rem}) = \sum (D (\text{rad}) * w_R)$
- w_R = radiation weighting factor
- Dose equivalent (pre-1990): $H (\text{rem}) = \sum (D (\text{rad}) * Q)$
- Q = quality factor

Radiation Type	Quality Factor	Radiation Weighting Factor
x-rays, γ rays, or β particles	1	1
Neutrons (depends on energy)	2-11	5-20
Protons (high-energy)	10	2-5
Alpha particles	20	20

Example

What is an individual's equivalent dose from 200 mR of gamma rays, 10 mrad of β particles and 2 mrad of alpha particles? (m = milli = 1/1000). Assume 1 R = 1 rad.

Radiation Type	Quality Factor	Radiation Weighting Factor
x-rays, γ rays, or β particles	1	1
Neutrons (depends on energy)	2-11	5-20
Protons (high-energy)	10	2-5
Alpha particles	20	20

Equivalent Dose	= mrad	x	w_R	= mrem
Gamma equivalent dose	= 200	x	1	= 200
Beta equivalent dose	= 10	x	1	= 10
Alpha equivalent dose	= 2	x	20	= 40
			TOTAL	= 250 mrem

Effective Dose / Effective Dose Equivalent

- Takes into account that some tissues and organs in the human body are more sensitive to radiation than others
- Multiply the Equivalent Dose or Dose Equivalent to each organ/tissue by the tissue weighting factor (w_T) for that organ/tissue and add them all together
- Use equivalent dose and 1990 w_T values – get effective dose
- Use dose equivalent and 1977 w_T values – get effective dose equivalent
- The unit is still either rem or Sv

$$EDE = \sum H_T \times w_T$$

Tissue Weighting Factors

Tissue weighting factor: the proportion of the risk of stochastic effects resulting from irradiation of an organ or tissue to the total risk of stochastic effects when the whole body is irradiated uniformly

Stochastic effect: A health effect that occurs randomly and for which the probability of the effect occurring, rather than its severity, is assumed to be a linear function of dose without threshold (example: getting cancer)

Tissue or Organ	w_T (2007 recomm.)	w_T (ICRP 60 - 1990)	w_T (ICRP 23 - 1977)
Gonads	0.08	0.20	0.25
Bone marrow	0.12	0.12	0.12
Colon	0.12	0.12	N/A
Lung	0.12	0.12	0.12
Stomach	0.12	0.12	N/A
Bladder	0.04	0.05	N/A
Breast	0.12	0.05	0.15
Liver	0.04	0.05	N/A
Esophagus	0.04	0.05	N/A
Thyroid	0.04	0.05	0.03
Skin	0.01	0.01	N/A
Brain	0.01	N/A	N/A
Salivary glands	0.01	N/A	N/A
Bone surface	0.01	0.01	0.03
Remainder	0.12	0.05	0.30

Committed Effective Dose / Committed Effective Dose Equivalent

Committed Effective Dose (CED) or Committed Effective Dose Equivalent (CEDE): Product of the weighting factor applicable for the organ or tissue and the equivalent dose (for CED) or dose equivalent (for CEDE) from an intake of *radioactive material* integrated over the 50 years following the intake

Only applies to internal sources of radiation!

TED / TEDE

Total Effective Dose (TED) or

Total Effective Dose Equivalent (TEDE):

The sum of the doses from internal and external radiation sources.

$TED = ED + CED$ (all 1990 values)

$TEDE = EDE + CEDE$ (all 1977 values)

Table of Radiation Units

Quantity	Traditional Unit	S.I. Unit
Activity	Curie (Ci)	Becquerel (Bq)
Exposure	Roentgen (R)	Coulomb/Kilogram (C/kg)
Absorbed Dose	Rad	Gray (Gy)
Equivalent Dose	Rem	Sievert (Sv)

Examples:

1. What would the equivalent dose be to an individual receiving an exposure of:
 - 8 mR of gamma radiation
 - 5 mrad of beta particles
 - 2 mrad of alpha particles

Ans: $H = (8 \text{ mrad})(1) + (5 \text{ mrad})(1) + (2 \text{ mrad})(20)$
 $= 53 \text{ mrem}$

2. You are using a Cs-137 source that was calibrated at 80 mCi on June 5, 1977. The half-life of cesium is 30 years. What is the activity on June 5, 2007?

Ans: $A_0 = 80 \text{ mCi}$
 $t = 30 \text{ years}$
 $t_{1/2} = 30 \text{ years}$
 $A = A_0 e^{-\frac{0.693t}{t_{1/2}}} = 40 \text{ mCi}$

or

Recognize that $t = t_{1/2}$, therefore $A = 0.5A_0$

3. The activity of a radionuclide is 1 mCi
The half-life is 100 minutes. How many
atoms are present in the sample?

$$\text{Ans: } A = (1 \text{ mCi}) \left(3.7 * 10^7 \frac{\text{Bq}}{\text{mCi}} \right) = 3.7 * 10^7 \frac{1}{\text{s}}$$

$$\lambda = \frac{0.693}{T_{1/2}} = \frac{0.693}{6000 \text{ s}} = 1.16 * 10^{-4} \frac{1}{\text{s}}$$

$$N = \frac{A}{\lambda} = \frac{3.7 * 10^7 \frac{1}{\text{s}}}{1.16 * 10^{-4} \frac{1}{\text{s}}} = 3.2 * 10^{11} \text{ particles}$$

4. The specific ionization of an alpha particle in air is about 45,000 ion pairs/cm. An 8 MeV alpha particle produces about 228,000 ion pairs. How far will it travel in air?

Ans: $\text{Specific ionization} = \frac{\# \text{ ion pairs formed}}{\text{path length (cm)}}$

$$\text{path length (cm)} = \frac{\# \text{ ion pairs formed}}{SI}$$

$$\text{path length (cm)} = \frac{228,000 \text{ ip}}{45,000 \frac{\text{ip}}{\text{cm}}} = \mathbf{4.9 \text{ cm}}$$

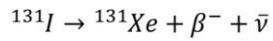
5. In one month, you are exposed to 52 mrem of external x-ray radiation. You also accidentally ingest some P-32, which gives you a CEDE of 83 mrem. What is your TEDE for the month?

Ans: $TEDE = EDE + CEDE$

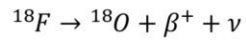
$$TEDE = 52 \text{ mrem} + 83 \text{ mrem} = \mathbf{135 \text{ mrem}}$$

6. What would be the end product in each of the following cases?

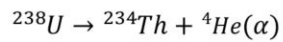
a) $^{131}_{53}\text{I}$ (beta-minus decay):



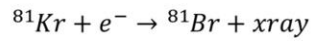
b) $^{18}_9\text{F}$ (beta-plus decay):



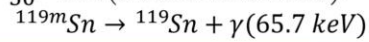
c) $^{238}_{92}\text{U}$ (alpha decay):



d) $^{81}_{36}\text{Kr}$ (electron capture):



e) $^{119\text{m}}_{50}\text{Sn}$ (nuclear transition):



Br = bromine

Sn = tin