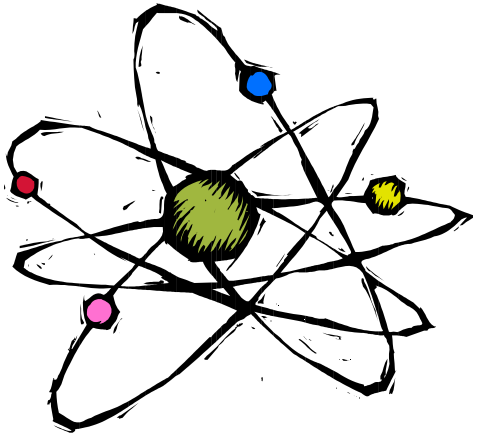
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

HRTD
Human Resources
Training & Development



Chapter 1:

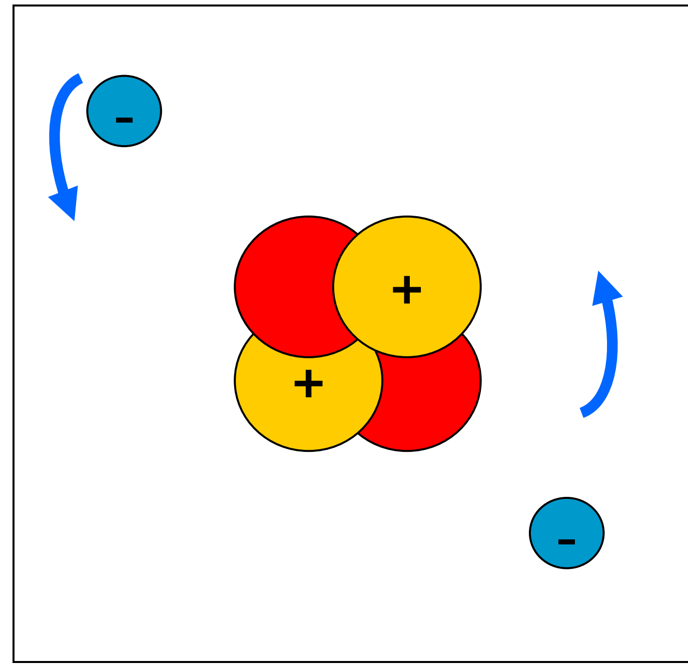
Fundamentals

Chapter 1 – Objectives:

- **Define radioactive material and ionizing radiation and the traditional and SI unit for activity.**
- **Define the concept of isotopes and describe the sources of fission and activation products in commercial reactors.**
- **Define half-life.**
- **Distinguish between particulate and non-particulate forms of ionizing radiation.**
- **Describe the meaning of absorbed dose, dose equivalent, and the associated traditional and SI units.**
- **Describe the concepts of dose, dose rate, and stay time.**

Atomic Structure

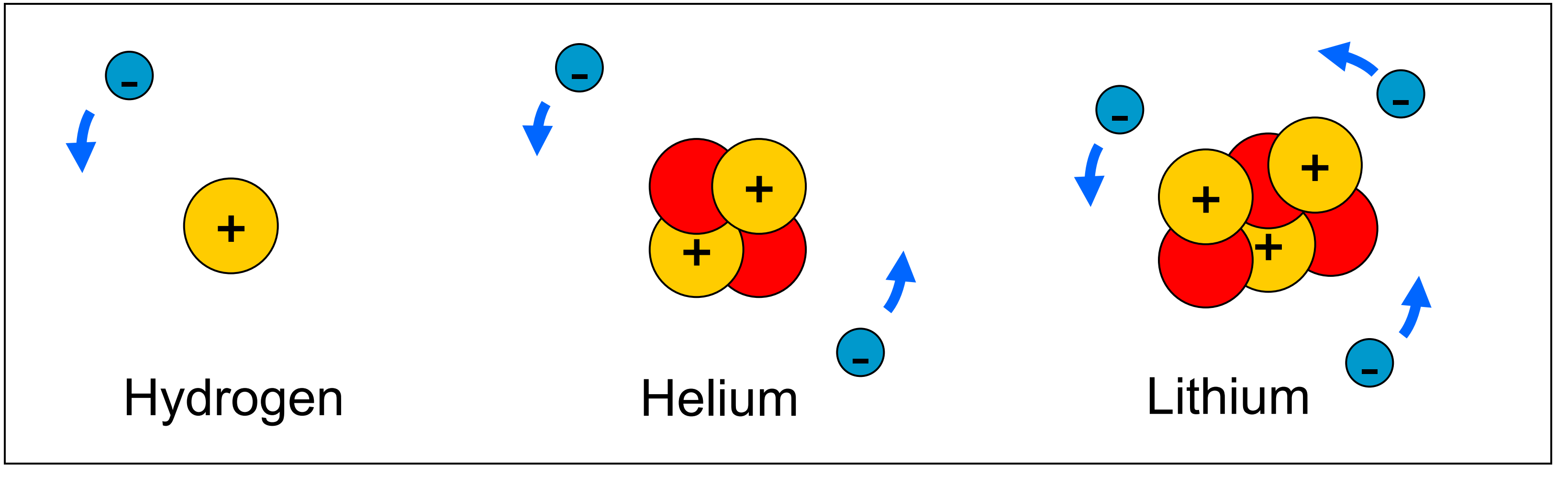
- Atoms have a nucleus comprised of protons (with a positive charge) and neutrons (usually), and orbital electrons (with a negative charge).
- The specific element is determined by the number of protons in the nucleus.



The atom represented here is Helium because it has two protons.

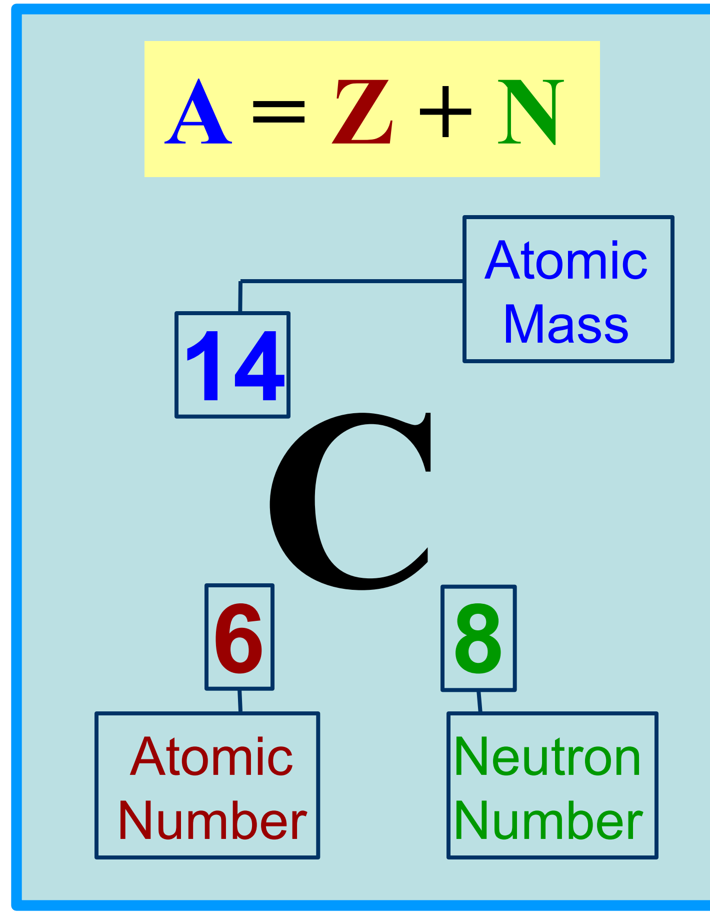
Atomic Structure

- Hydrogen (H) atoms have a single proton in the nucleus.
- Helium atoms (He) have two protons in the nucleus so they have two electrons in a neutral state.
- Lithium (Li) atoms have a nucleus consisting of three protons and, usually, three neutrons. In the electrically neutral atom there are three electrons - one negative electron for each positive proton in the nucleus.



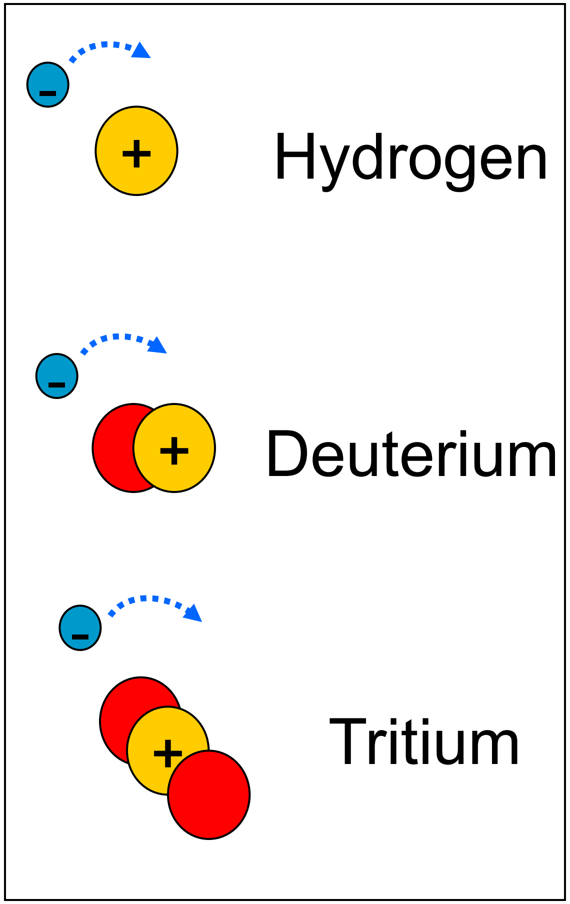
Atomic Notation

- Number of protons is the Atomic Number, "Z," and determines the element.
- Number of neutrons is the Neutron Number, "N."
- Sum of the Atomic Number (Z) and Neutron Number (N) is the Atomic Mass, "A."
- Protons & neutrons have similar mass and electrons are tiny, so Atomic Mass is used to describe the "weight" of an atom.



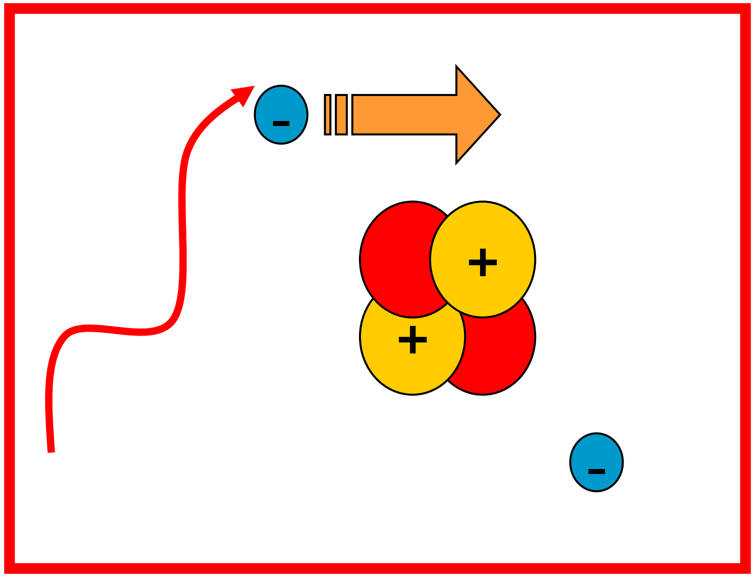
Isotopes & Radiation

- **Atoms with the same number of protons but different numbers of neutrons are called "isotopes."**
- **Some isotopes have unstable nuclei and try to achieve a stability (lower energy) by emitting energy or particles, called "radiation."**
- **Isotopes that emit radiation are "radioactive." All elements with Z > 83 are radioactive, all elements with Z > 80 have radioactive isotopes.**
- **Hydrogen has 3 isotopes. Of these, H-3, called "tritium," is radioactive. It emits beta radiation.**

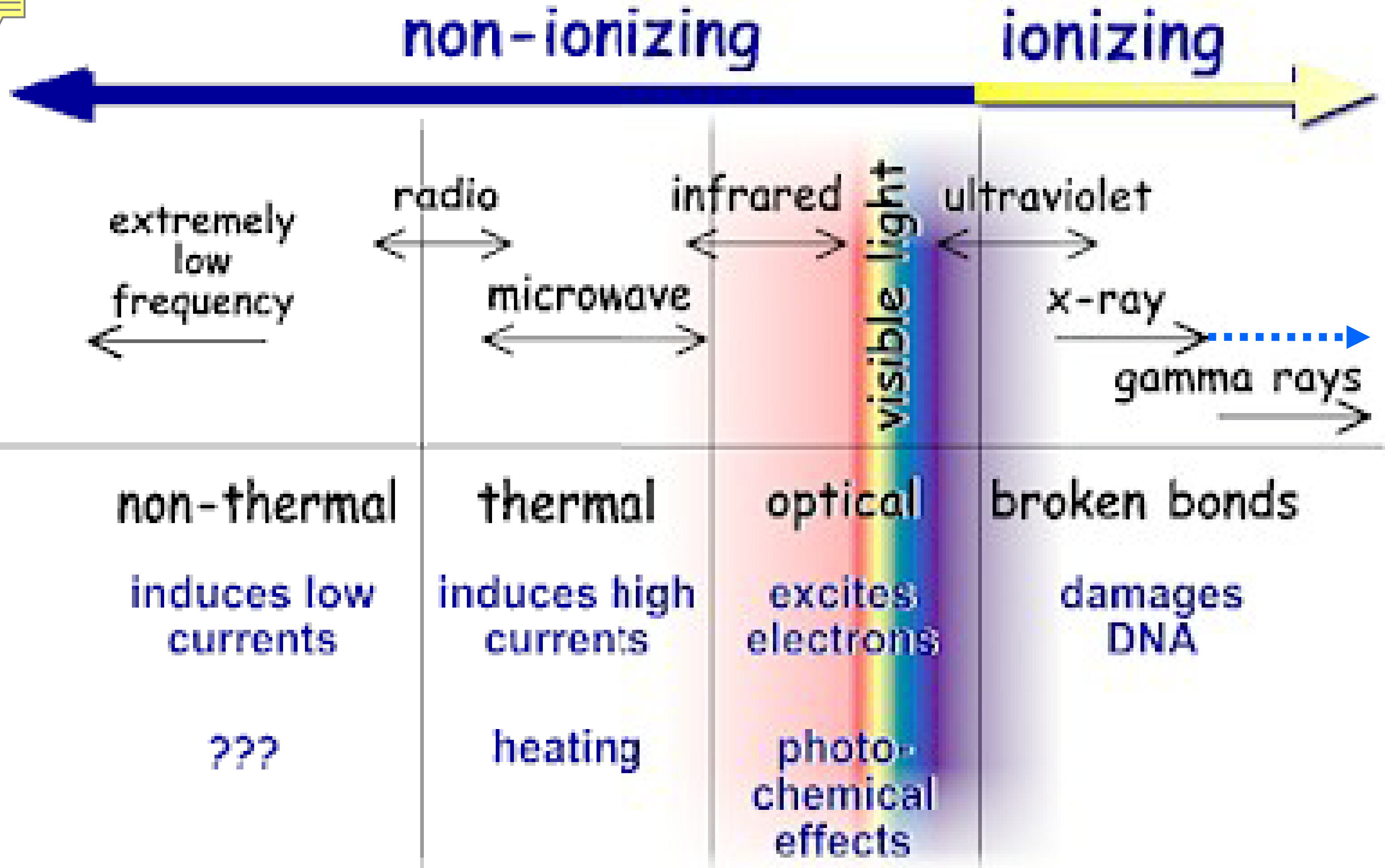


Ionizing Radiation & Radioactivity

- Unstable atoms undergo radioactive decay.
- Decaying atoms emit ionizing radiation.



- Ionizing radiation, often referred to simply as "radiation," removes (strips out) orbital electrons from atoms or molecules with which it interacts.



Note: Often you will see X-rays listed as being at a lower energy than γ rays – this is not necessarily always the case. X-rays can be generated with more energy than γ rays.

Activity

- CURIE is the traditional unit of the amount of radioactive material. One curie (abbreviated "Ci") gives 37 billion disintegrations every second. You may see activity represented in fractional units such as mCi, or "millicurie." 1 mCi = 1/1000th of a curie (0.001 Ci or 1E-3 Ci or 1×10^{-3} Ci).
- The SI (System International) unit of activity is the "Becquerel," abbreviated "Bq".
  - 1 Bq = 1 disintegration per second (so 1 Ci = 37 billion Bq = 0.037 TBq = 37 GBq = 3.7×10^{10} Bq).
  - 1 mCi = 37 MBq

Orders of Magnitude

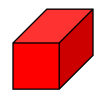
"Tera" TBq	1E12
"Giga" GBq	1E9
"Mega" MBq	1E6
"kilo" kBq	1E3
"milli" mCi	1E-3
"micro" μCi	1E-6
"nano" nCi	1E-9
"pico" pCi	1E-12

Mass vs. Activity

0.001 gm

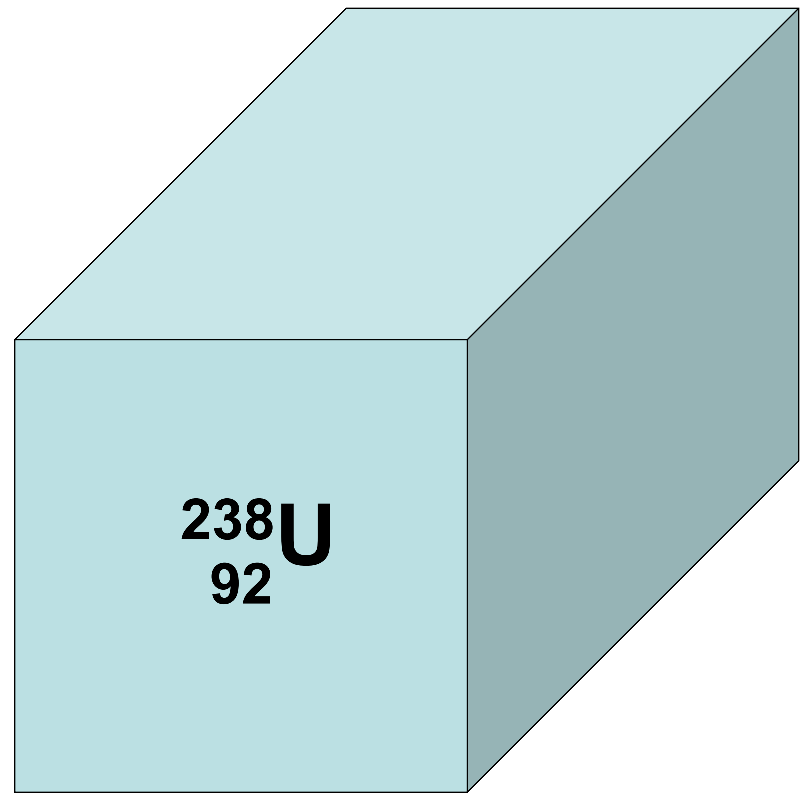
$^{60}_{27}Co$

1 gm



$^{226}_{88}Ra$

635,600 gm
(or ~1400 lbs)



Amount, in grams, of each isotope equaling one curie of activity.

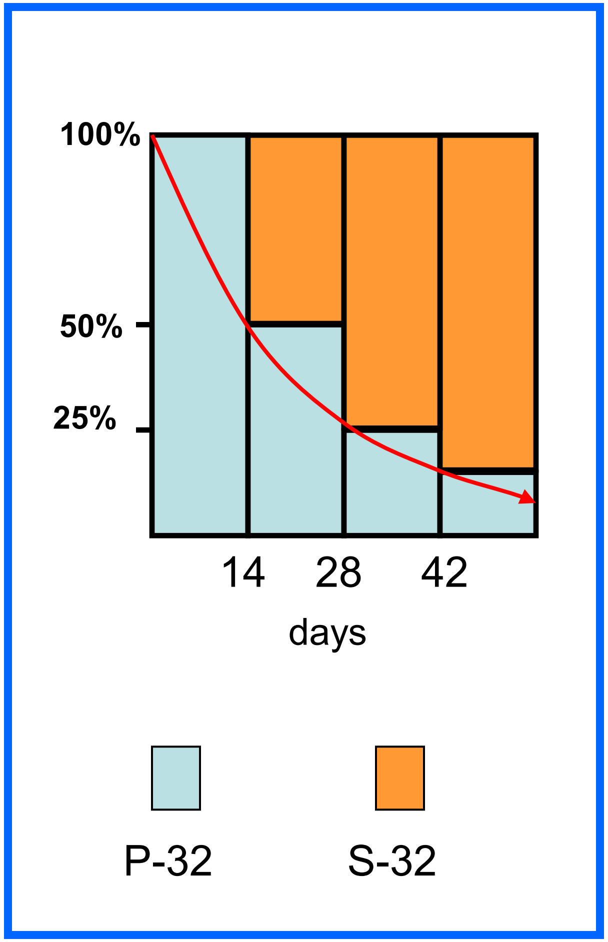
Decay Series

- Some radioactive isotopes decay into "daughter products" or "progeny" that are also radioactive.
- The Uranium-238 (U-238) decay series is one example of a decay chain.
- Each isotope has a unique half-life, varying from fractions of a second to billions of years.

Type	Nuclide	Half-life
α	Uranium - 238	4.5 billion years
β -	Thorium - 234	24 days
β -	Protactinium – 234m	1.2 minutes
α	Uranium-234	240,000 years
α	Thorium – 230	77,000 years
α	Radium – 226	1,600 years
α	Radon – 222	3.8 days
α	Polonium – 218	3.1 minutes
β -	Lead – 214	27 minutes
β -	Bismuth – 214	20 minutes
α	Polonium -214	160 μseconds
β -	Lead – 210	22 years
β -	Bismuth – 210	5 days
α	Polonium – 210	140 days
	Lead – 206	Stable

Half-Life

- Half-life is the time for half of the radioactive atoms to decay. Half lives are unique for each isotope.
- After one half-life ($t_{1/2}$) you will have 1/2 of the radioactive atoms you started with.
- For example, P-32 has a $t_{1/2}$ = 14 days and decays to S-32. Starting with 100 atoms of P-32, after 14 days only 50 atoms of P-32 remain while the other 50 atoms are now S-32. After another half-life, half of 50 atoms, or 25 atoms, of P-32 would remain. The other 75 atoms are S-32.
- After about 7-8 half-lives, the original radioactive material is about zero.

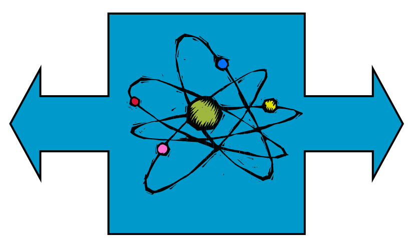


Radiation & Radioactivity

- Ionizing radiation is emitted in the form of particles and/or energy.
- The particulate forms are: alpha, beta (+ & -), and neutrons (they have mass).
- The non-particulate forms are called: gamma rays and X-rays. The energy is in the form of photons (packets of energy).

Particulate

Alpha - α
Beta - β
Neutron - n



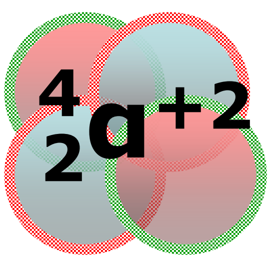
Non-Particulate

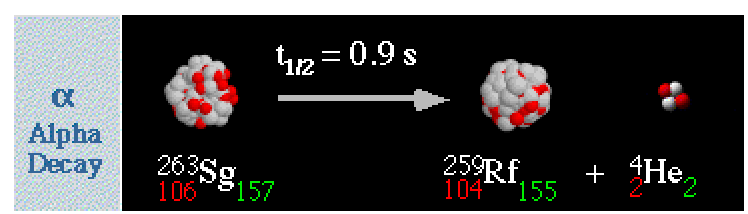
Gamma - γ
X-ray

“Alpha” Radiation (α)

- Alpha particles consist of two protons and two neutrons (the same as the nucleus of a helium atom) and are emitted by larger atoms such as Uranium, Americium, and Plutonium. Since they have two protons (a +2 charge) and are large, alpha particles do not travel far – no more than a few inches in air. They aren’t a hazard if they are outside of your body, but because they are a form of ionizing radiation, they can cause of lot of damage if they enter your body.
- The Greek symbol for alpha radiation is: α

$$^{A}{}_{Z}X = {}^{4}_{2}\alpha^{+2} + {}^{A-4}{}_{Z-2}Y$$





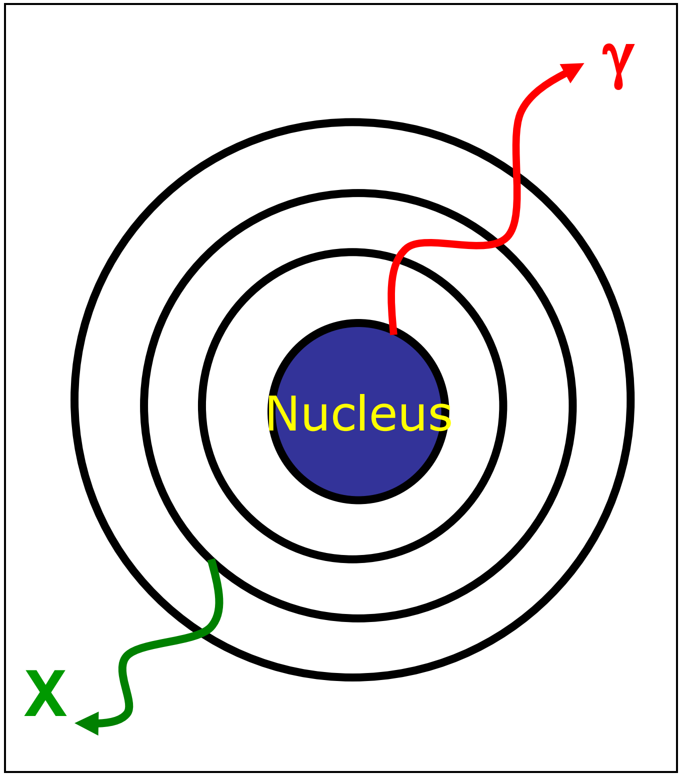
"Beta" Radiation (β)

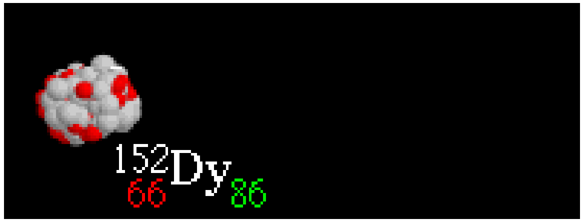
- Beta radiation (like alpha) is particulate. That is, it has mass. Beta particles are like an electron and so have a single +/- charge. Since they are smaller than alpha particles and have less of a charge, they travel further in material than alpha particles. The distance depends upon their energy. An energetic beta particle may travel about 12 feet in air and could penetrate your skin.
- Beta particles are ionizing radiation – they will remove orbital electrons from materials with which they interact.
- The Greek symbol for beta radiation is: β

$$ {}^{A}_{Z}X = {}^{0}_{-1}\beta + {}^{A}_{Z+1}Y $$

Radiation: Gamma & X-rays

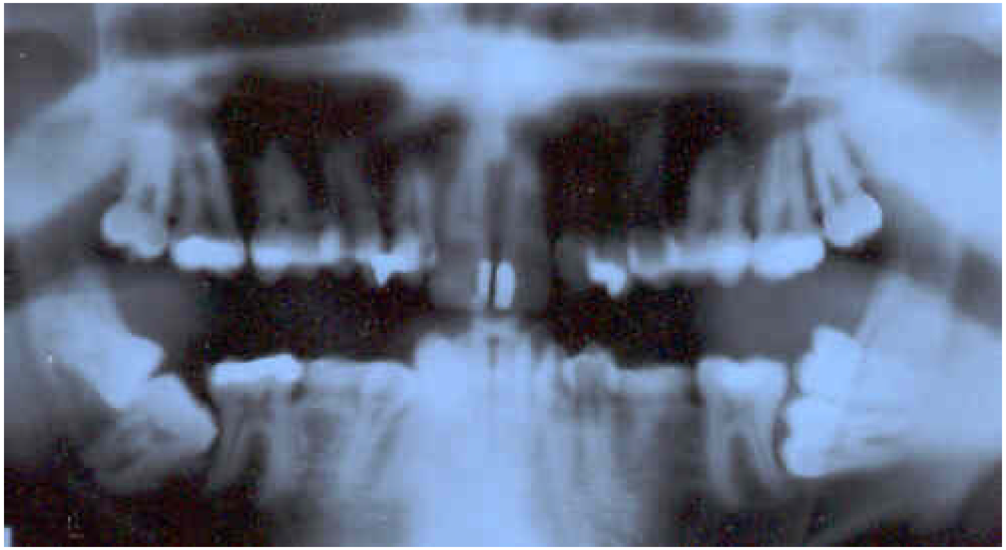
- Gamma “rays” and “X-rays” have no mass or charge; they are pure energy (photons).
- They differ in that gamma rays originate from the nucleus of a radioactive atom while X-rays originate in the electron orbitals of an atom.
- The Greek symbol for gamma radiation is: γ





X-ray Machines

- X-rays (like other ionizing radiation) do not make things radioactive; that is, your mouth or bones do not become radioactive from exposure to X-rays. When the current that produces the X-ray beam is stopped, the source of radiation ends – the X-ray machine that produces the X-rays is not radioactive. However, the X-ray (photon) CAN create ionizations in your body.
- These ionizations can cause biological damage.



Neutrons (n)

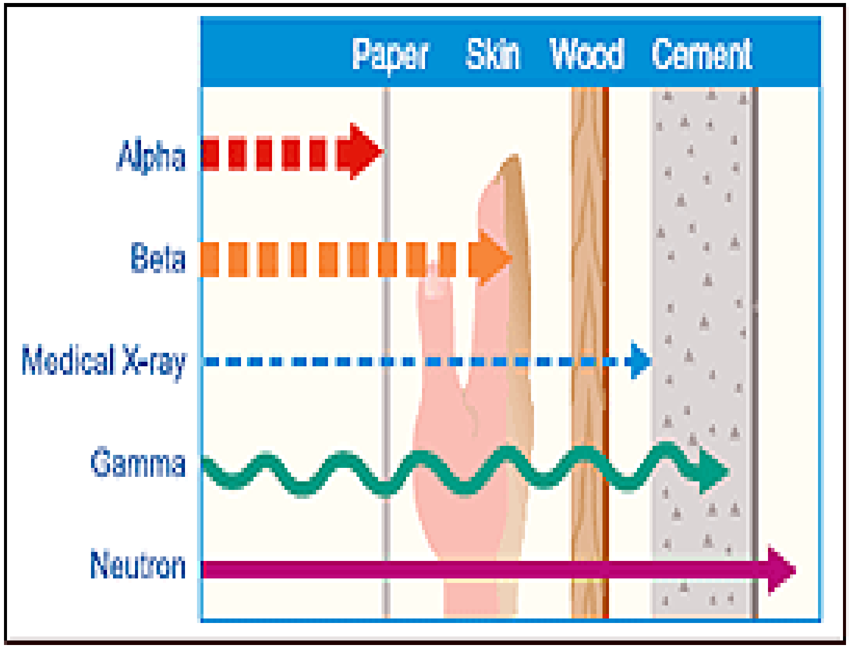
- Neutrons are considered particulate ionizing radiation.
- They are about the same size as a proton, but are neutral (have no charge).
- Because they have no charge, neutrons are termed indirect ionizing radiation. Their interaction with a material can cause activation or particle ejection that, then, causes the subsequent ionizations.
  - The neutron can be absorbed, creating a radioactive isotope that then emits ionizing radiation such as α, β, or γ.
  - The neutron can interact with a atom's nucleus and knock a proton out (spallation), and the proton causes ionizations.
- These subsequent ionizations can cause biological damage.
- Neutrons are <u>generally</u> encountered from a fission process, not from radioactive isotopes emitting a neutron.

Neutron Activation

- **Neutrons (usually produced by the fission process) may interact with stable atoms that are not radioactive.**
- **“Activation” is the term used to describe the process when stable, non-radioactive atoms absorb a neutron and become radioactive because their nucleus is in an unstable configuration.**

Radiation Interactions

- Charged particle radiation (α & β) does not travel far and can be stopped relatively easily.
  - Alpha particles can be stopped by a couple of inches of air, paper, or the outer layer of your skin.
  - Energetic beta particles can travel several feet in air, but can be stopped by <1" of plastic.



- Gamma or neutron radiation is very penetrating and therefore more difficult to shield. Dense materials (e.g. lead & steel) or large amounts of water are used to shield gamma radiation.
- Neutrons are best shielded with hydrogenous material, like water and paraffin.

Exposure

- The measurement for ionizing radiation was first developed to measure energy deposited from X-rays. It was decided that air should be used as the media in which to measure this deposited energy.
- The measure of "exposure" to X-rays in air was referred to as a Roentgen (abbreviated as "R" for Conrad Roentgen who discovered the X-ray in 1895).
- 1 R $\cong$ 1 rad.

Absorbed Dose

- The amount of energy deposited in material by ionizing radiation is called DOSE. The traditional or conventional unit of absorbed dose, which is applicable to any material, is called the rad. Lower doses are often expressed in units of millirad (mrad).
  - 1 rad = 1,000 mrad.
- The SI unit of absorbed dose is called the "Gray" (abbreviated Gy).
  - 1 Gy = 100 rad (or 1 rad = 0.01 Gy)

Easy way to remember: A…both Gr<u>a</u>y and R<u>a</u>d have A's!

Dose Equivalent

- The conventional unit of dose equivalent, the rem, was developed to adjust absorbed dose (rad) for the biological significance of the radiation. This dose, from different types of ionizing radiation, may be summed.
- Dose equivalent is the absorbed dose times a quality factor, Q or QF (considers biological significance of the radiation. Alpha particles are ~ 20 times as damaging to tissue as γ, X-ray, or β radiation. So 1 rad of alpha radiation has a dose equivalence of 20 rem (1 rad x 20 = 20 rem). (Remember: 1 rem = 1,000 mrem)
- The SI unit of dose equivalent is called the Sievert (abbreviated "Sv").
  - 1 Sv = 100 rem or 1 mSv = 100 mrem

Easy way to remember: E…both Si<u>e</u>v<u>e</u>rt and R<u>e</u>m have E's!

Dose Rate

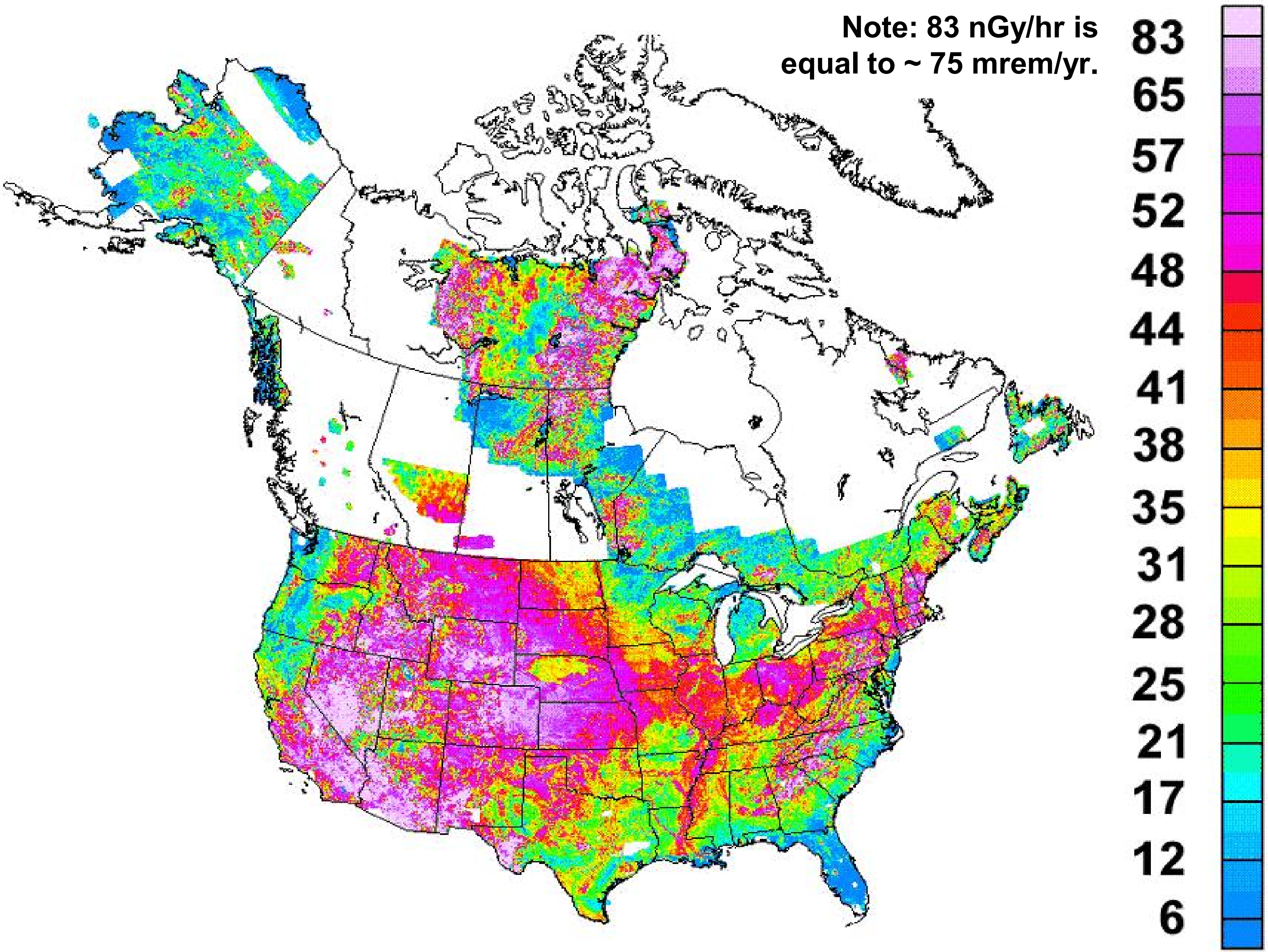
- The time-dependent rate of receiving a dose is called the "dose rate." It is often expressed in millirem per hour (mrem/hr).
- The total dose received is the dose-rate times the time of "exposure." For example, if the dose rate is 20 mrem/hr and you receive this exposure for 30 minutes, your total dose is then:
- (20 mrem/hr)(30 minutes)(1 hour/60 minutes) =
- (20 mrem/hr)(½ hour) = 10 mrem

Stay Time

- One of the requirements for entry into areas where ionizing radiation is present is to limit your dose to a specified level. The amount of time that you may remain in an area and not exceed the dose limit is called STAY TIME.

- Stay Time = (Dose Limit) / (Dose Rate)

- For example, if the administrative dose limit for an area is 50 mrem, and the dose rate in the area is 100 mrem/hour, then the stay time is:
  - (50 mrem)/(100 mrem/hr) = ½ hour

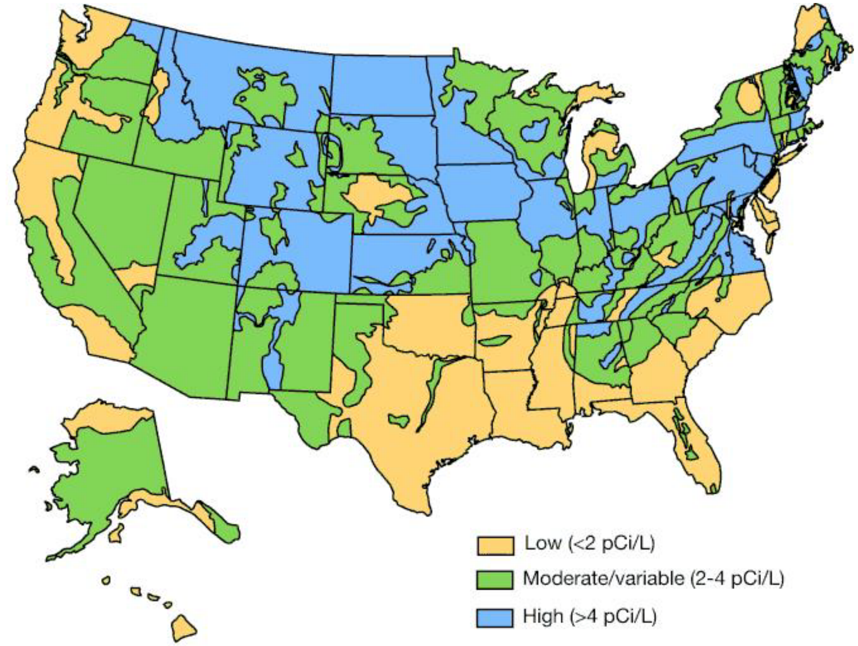


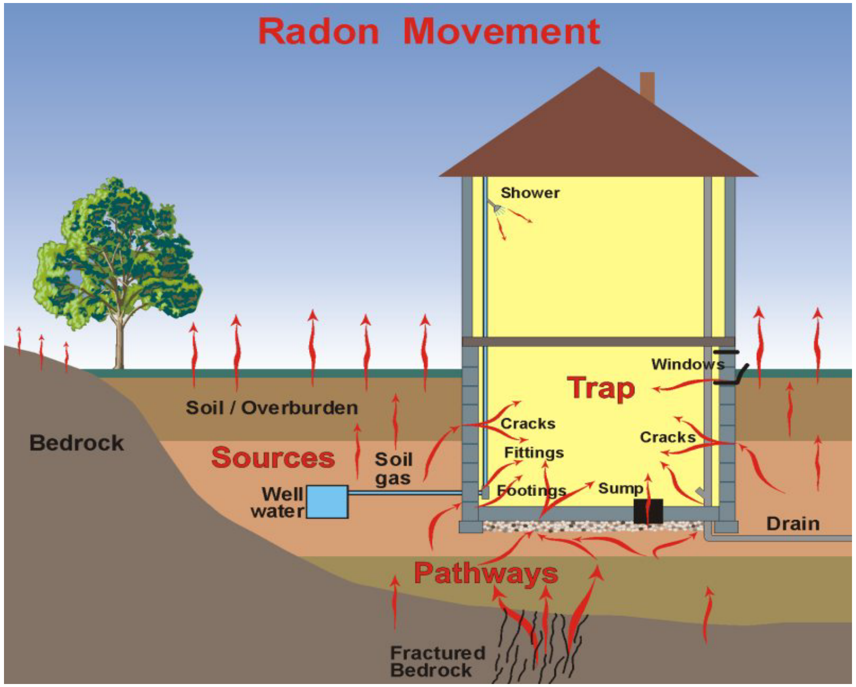
Gamma-ray Absorbed Dose (nGy/hr)

Dose (nGy/Hr)

Radon

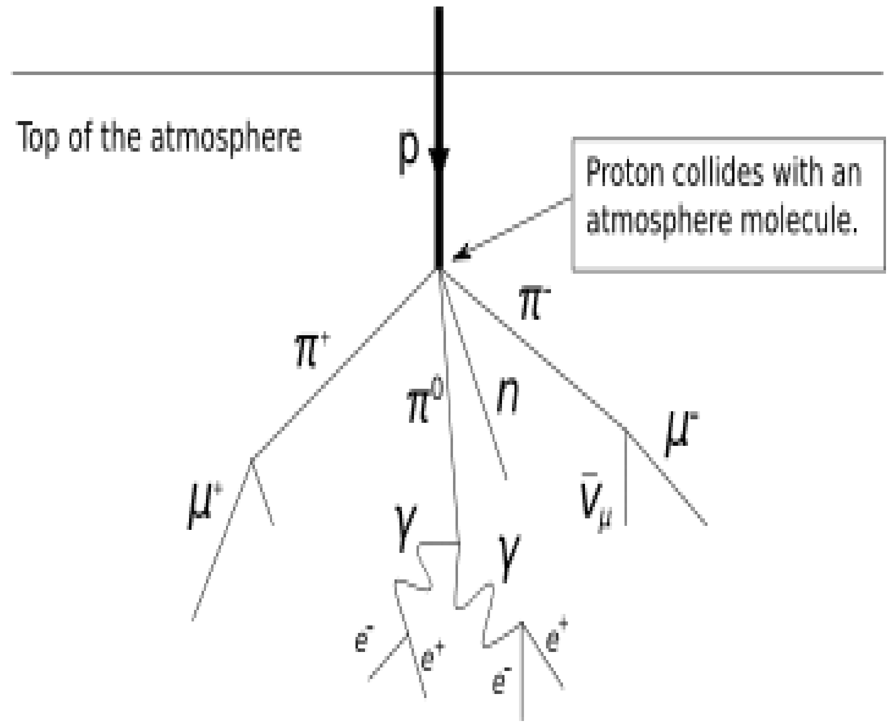
- Radon comes from decay of U-238, present in soil. Radon is a “noble gas” and does not interact with material so it can diffuse through soil into the foundation of homes. Radon and its decay products are radioactive. They are linked to higher risks of lung cancer by being present in the air of homes.





Cosmic Radiation

- Cosmic radiation interacts with molecules in the upper atmosphere of the Earth. These interactions produce, among other items, neutrons that can activate nitrogen atoms. Carbon-14, a radioactive isotope with a half-life of 5,730 years, is produced this way.
- "Carbon dating" is the process of measuring the C-14 content in material and comparing it with the expected levels. This provides a way of estimating the age of the material.



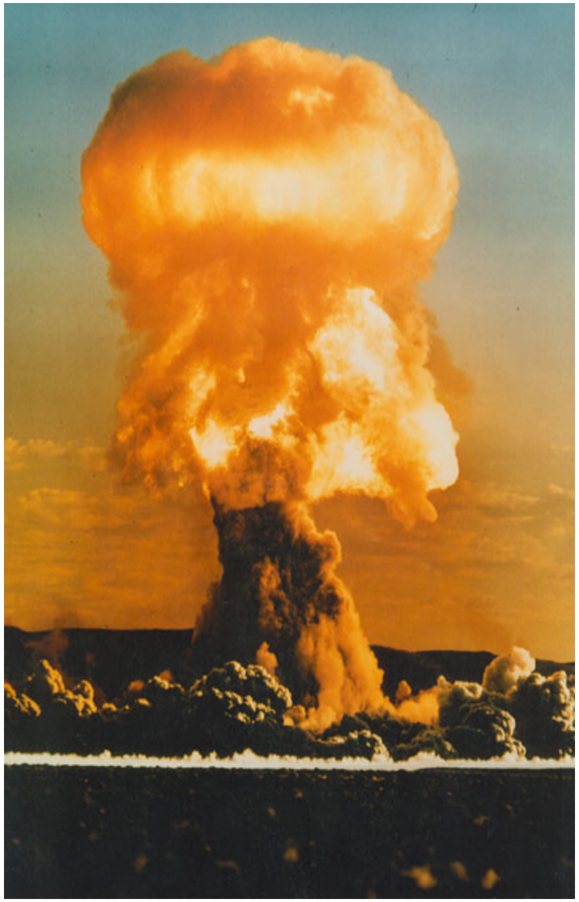
Cosmic Radiation

- Cosmic radiation is reduced as it interacts with the atmosphere. The higher in altitude you are, the higher the radiation levels will be from cosmic radiation. For this reason cosmic radiation is a potential concern for airline flight crews and astronauts.

- Space craft usually use equatorial orbits that use the earth's magnetic field to reduce the levels of radiation to orbiting space craft (about 5 mrem/day).
- The cosmic radiation levels are much higher for polar orbits and high altitude orbits (about 60 mrem/day at the International Space Station
  - ref. Health Physics, Vol. 79, No. 5, Nov. 2000, p. 485).

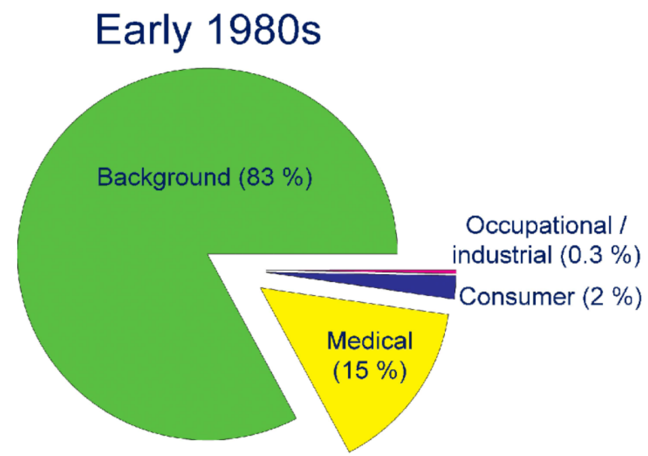
Fallout: Cs-137

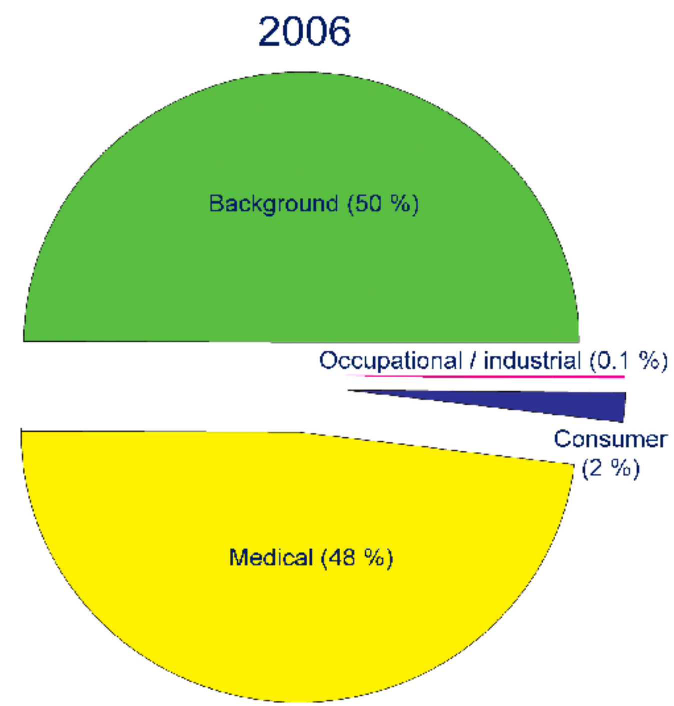
- Atmospheric testing of nuclear weapons in the 50's & 60's resulted in fission product dispersion to the environment. Short-lived isotopes (e.g. I-131 with an 8 day half-life) may no longer be present in the environment. Isotopes with long half-lives are still present and have associated doses.
- One fission product, Cs-137 (half life of about 30 years) is still present in the environment (of 1E18 Ci released, 90% is from weapons, 6% from Chernobyl on 4/26/86, 4% from fuel reprocessing, no data yet from Japan's recent accident).



Annual Exposure

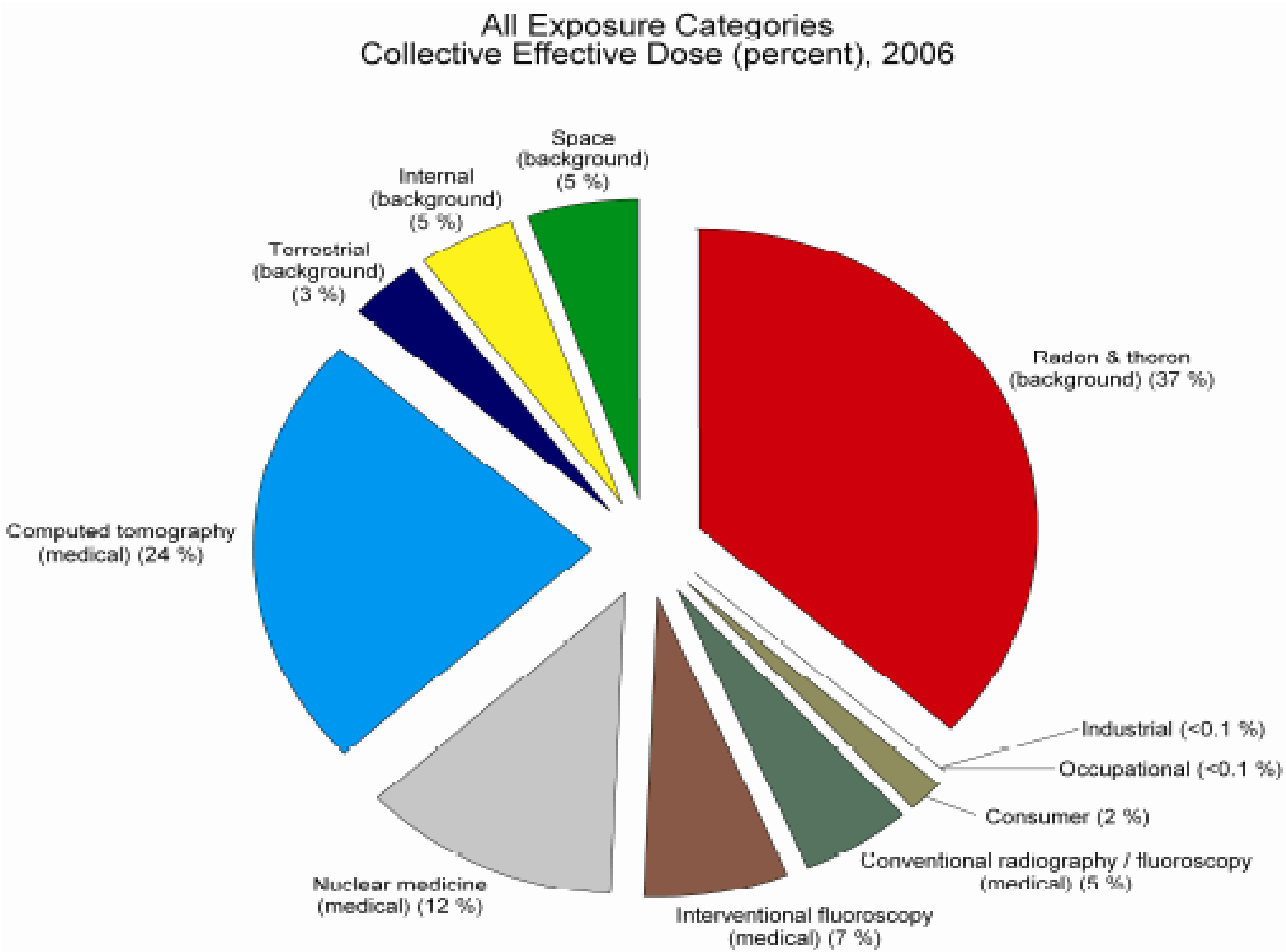
- The average, annual exposure from all sources of radiation is about 620 mrem*, (~ 2 mrem/day). Most of this is due to both environmental **radon** and **medical treatment**.
- Compare that to nuclear workers:
  - Average, annual, measurable dose to workers in commercial power reactors is about 160 mrem** . In '95, the average value was 310 mrem; in '96 it was 280 mrem.
- In contrast, the average dose to industrial radiographers in 2008 was 560 mrem.





* NCRP Report No. 160, *Ionizing Rad. Exp. of the Population of the US*

** NUREG-0713, Vol. 30, 2008


All Exposure Categories
Collective Effective Dose (percent), 2006
Space (background) (5 %)
Internal (background) (5 %)
Terrestrial (background) (3 %)
Radon & thoron (background) (37 %)
Computed tomography (medical) (24 %)
Industrial (<0.1 %)
Occupational (<0.1 %)
Consumer (2 %)
Conventional radiography / fluoroscopy (medical) (5 %)
Nuclear medicine (medical) (12 %)
Interventional fluoroscopy (medical) (7 %)

Review

- Particulate forms of ionizing radiation are:
  - Alpha
  - Beta
  - Neutron
- Non-particulate forms of ionizing radiation are:
  - gamma
  - X-rays
- Range of α particles is a few inches in air, β particles may travel several feet in air. γ and n are more penetrating.

Review

- Each radionuclide has a unique half-life (time for half the activity to decay). The traditional unit of activity is the Curie (Ci), the SI unit is the Becquerel (Bq).
  - 1 Ci = 37 billion Bq (37 GBq).
- The energy deposited by radiation is called dose. This absorbed dose applies to any material. The traditional unit of absorbed dose is the "rad," SI unit is the Gray (Gy).
  - 1 Gy = 100 rad

Review

- The dose equivalent is the absorbed dose adjusted for the "quality" or biological significance of the radiation. The traditional unit of dose equivalent is the rem, and the SI unit is the Sievert (Sv).
  - 1 Sv = 100 rem
  - so 50 mSv = 5,000 mrem = 5 rem
- The rate that you receive a dose is the "dose rate" which has units of mrem/hr.
- The "stay time" is the amount of time you may remain in an area and not exceed an established (administrative) dose.

Review

- The average background dose to a US citizen is about 620 mrem per year. Most of this dose is equally from radon-222 and medical treatment.
- The average, measurable occupational dose from commercial reactors is about 160 mrem per year which is from activation and fission products.
- Most of the dose in commercial reactors is from cobalt-60 (Co-60), an activation product.