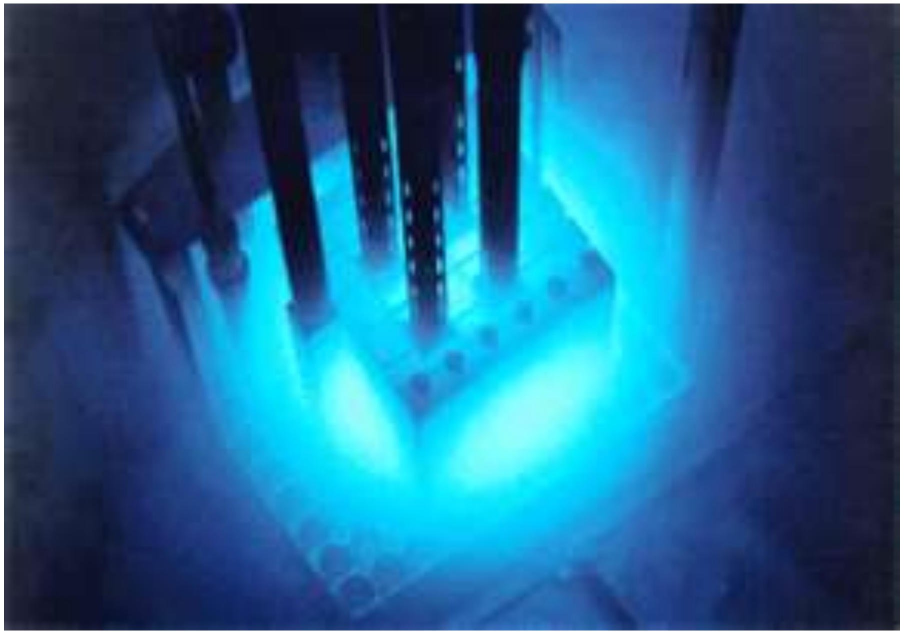
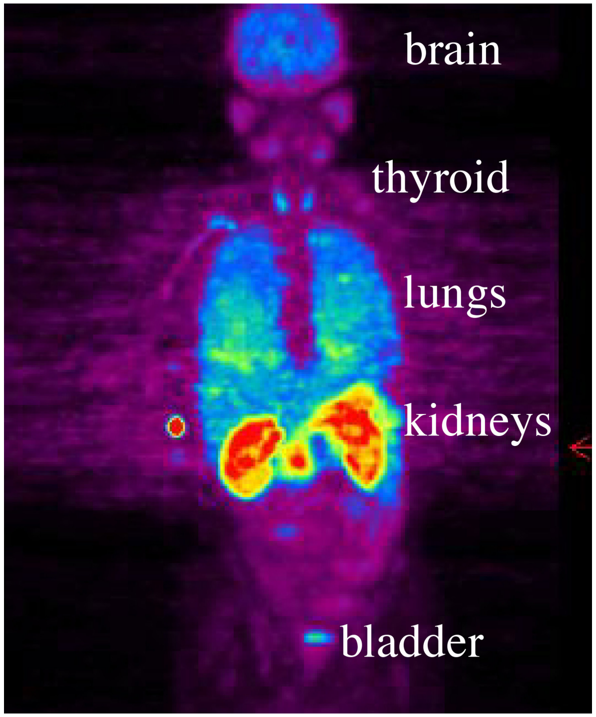
Lecture 23. Applications

Radiocarbon Dating
Nuclear Fission
Medical Imaging

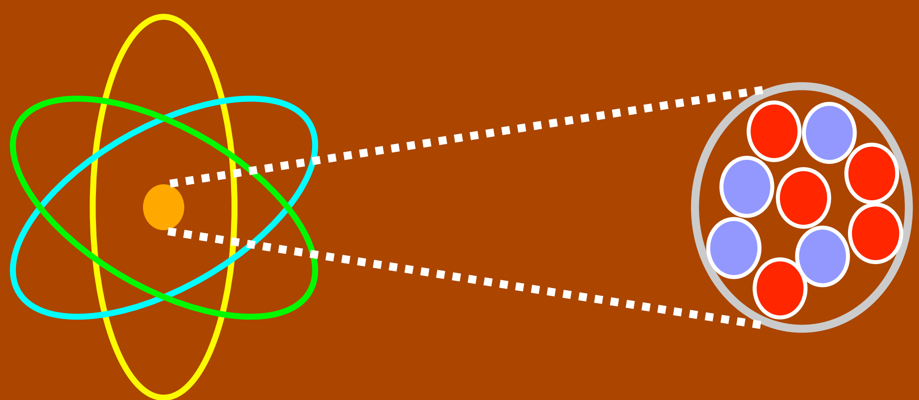




ConcepTest 30.1 The Nucleus

There are 82 protons in a lead nucleus. Why doesn't the lead nucleus burst apart?

1) Coulomb repulsive force doesn't act inside the nucleus
2) gravity overpowers the Coulomb repulsive force inside the nucleus
3) the negatively charged neutrons balance the positively charged protons
4) protons lose their positive charge inside the nucleus
5) none of the above

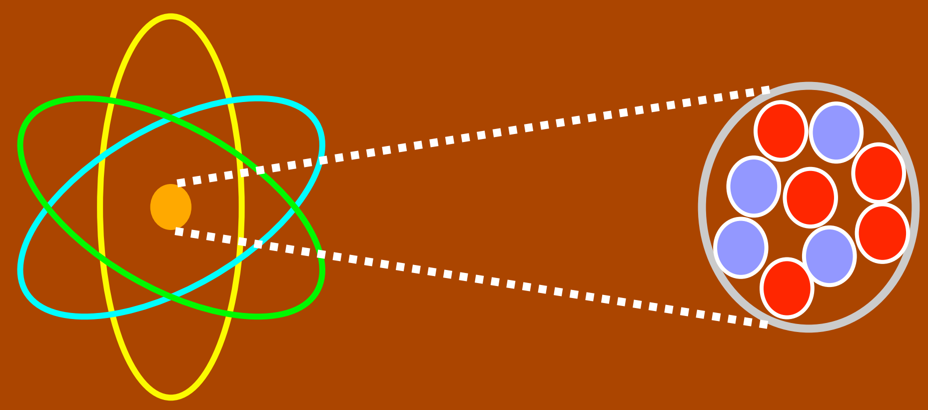


ConcepTest 30.1 The Nucleus

There are 82 protons in a lead nucleus. Why doesn't the lead nucleus burst apart?

1) Coulomb repulsive force doesn't act inside the nucleus
2) gravity overpowers the Coulomb repulsive force inside the nucleus
3) the negatively charged neutrons balance the positively charged protons
4) protons lose their positive charge inside the nucleus
5) none of the above

The Coulomb repulsive force is overcome by the even stronger ***Strong nuclear force***



30.11 Radio-Carbon Dating

- Radioactive dating can be done by analyzing the fraction of carbon in organic material that is carbon-14.

- The ratio of carbon-14 to carbon-12 in the atmosphere has been *roughly* constant over thousands of years. A living plant or tree will be constantly exchanging carbon with the atmosphere, and will have the same carbon ratio in its tissues.

- When the plant dies, this exchange stops. Carbon-14 has a half-life of about 5730 years; it gradually decays away and becomes a smaller and smaller fraction of the total carbon in the plant tissue.

- This fraction can be measured, and the age of the tissue deduced.

ConcepTest 30.7 Beta Decay

What element results when ^{14}C undergoes **beta decay**?

1) ^{15}C
2) ^{15}N
3) ^{14}C
4) ^{14}N
5) ^{15}O

ConcepTest 30.7 Beta Decay

What element results when ^{14}C undergoes beta decay?

1) ^{15}C
2) ^{15}N
3) ^{14}C
4) ^{14}N
5) ^{15}O

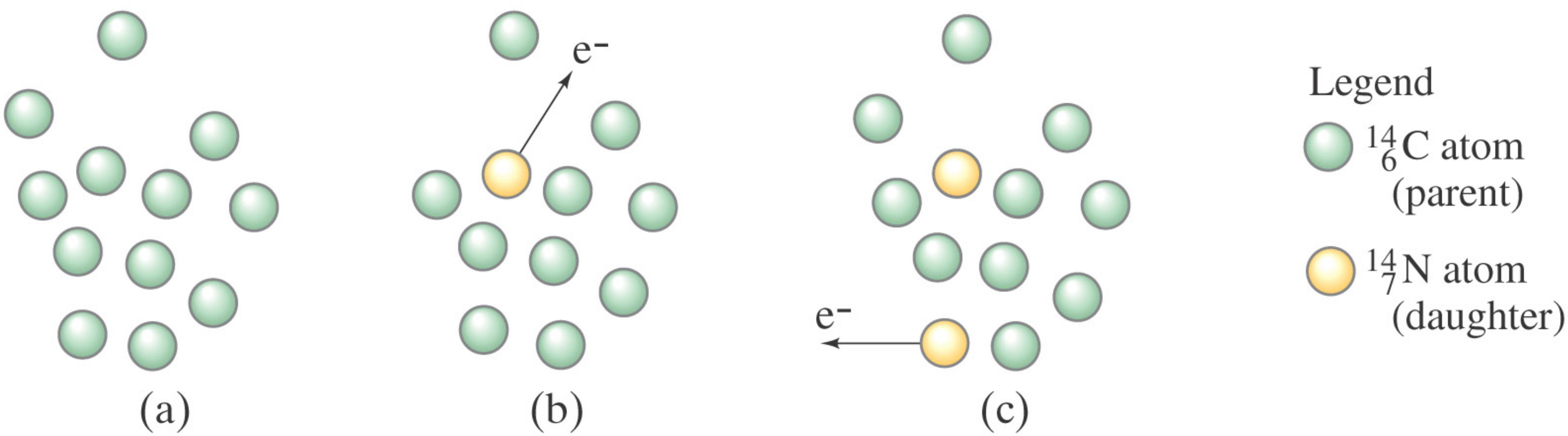
The reaction is: $^{14}_{6}C \rightarrow {}^{14}_{7}N + e^- + \text{neutrino}$

Inside the nucleus, the reaction $n \rightarrow p + e^- + \nu$ has occurred, changing a neutron into a proton, so the atomic number Z increases by 1. However the mass number (A = 14) stays the same.

Follow-up: How would you turn ^{14}C into ^{15}N?

30.8 Half-Life and Rate of Decay

Nuclear decay is a random process; the decay of any nucleus is not influenced by the decay of any other.



30.8 Half-Life and Rate of Decay

The number of decays in a short time interval is proportional to the number of nuclei present and to the time:

$$\Delta N = -\lambda N \, \Delta t$$

(30-3a)

Here, λ is a constant characteristic of that particular nuclide, called the decay constant.

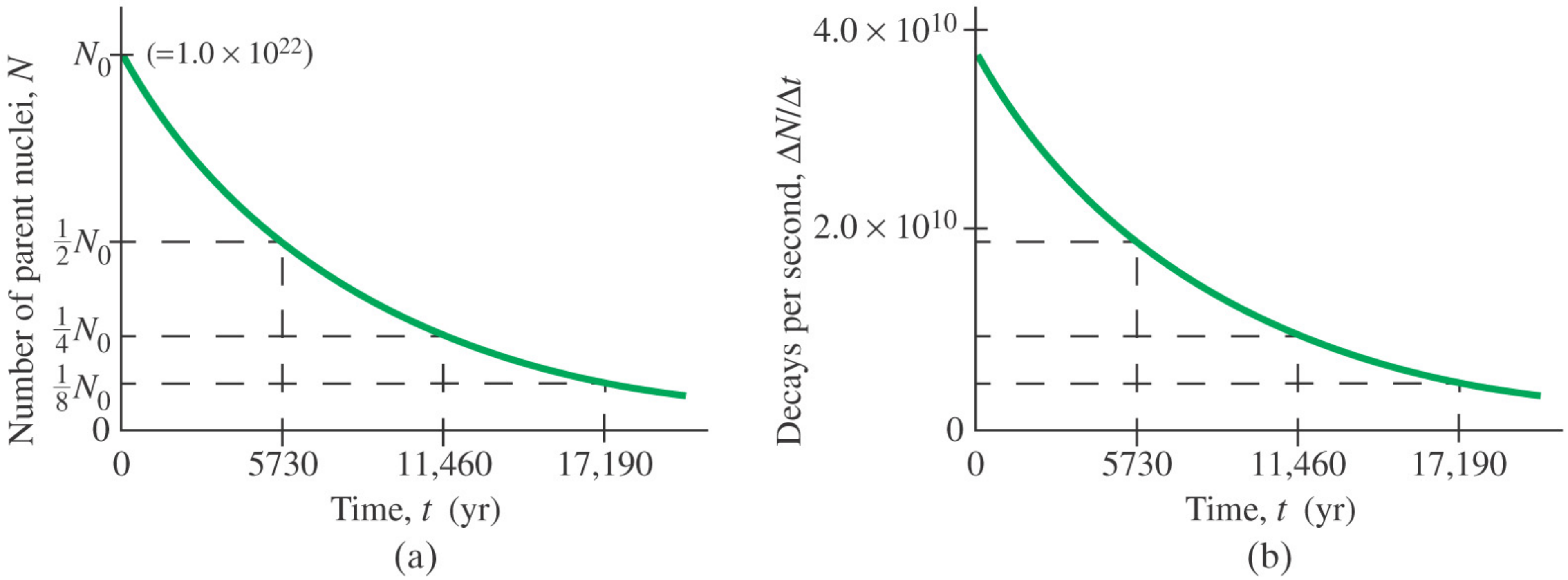
λ is really the probability that a given nucleus will decay at any particular instant.

If we had a known mass of the element, and a geiger counter, we could easily compute λ from the event rate (counts per sec).

30.8 Half-Life and Rate of Decay

The previous equation can be solved, using calculus, for N as a function of time to give the exponential radioactive decay law

$$N = N_0 e^{-\lambda t} \quad \text{(30-4)}$$



30.8 Half-Life and Rate of Decay

The half-life is the time it takes for half the nuclei in a given sample to decay. It is related to the decay constant:

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} \qquad \textbf{(30-6)}$$

Substituting into the previous eqn, it can be shown that there are 2 equivalent equations:

$$N = N_0 e^{-\lambda t} \qquad N = N_0\, 2^{-t/t_{1/2}}$$

ConcepTest 30.8a Radioactive Decay Law I

You have 16 kg of a radioactive sample with a certain half-life of 30 years. How much is left after 90 years?

(1) 8 kg

(2) 4 kg

(3) 2 kg

(4) 1 kg

(5) nothing

ConcepTest 30.8a Radioactive Decay Law I

You have 16 kg of a radioactive sample with a certain half-life of 30 years. How much is left after 90 years?

(1) 8 kg

(2) 4 kg

(3) 2 kg

(4) 1 kg

(5) nothing

The total time (90 years) is 3 half-lives.

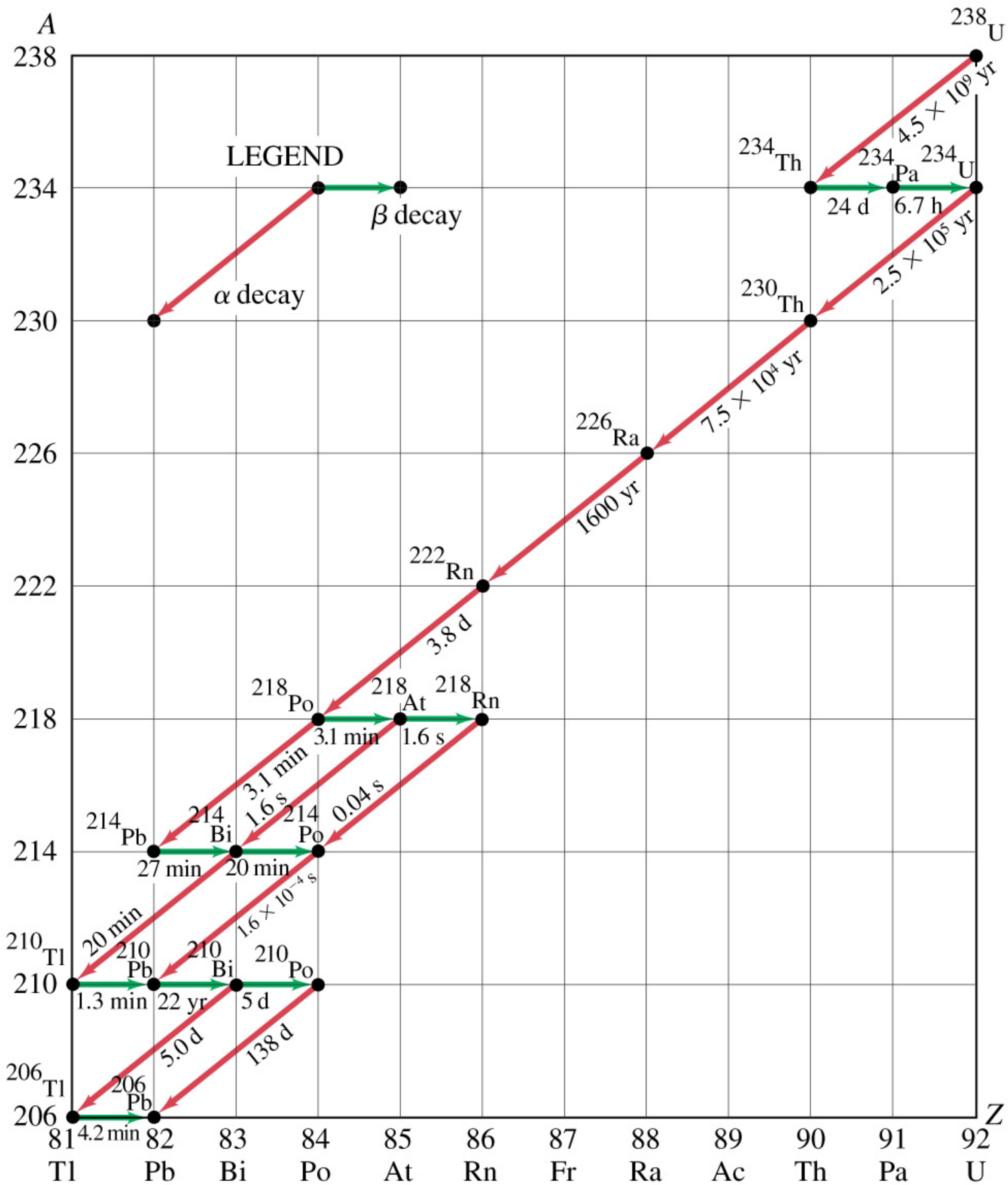
After one half-life ⇒ 8 kg left.

After two half-lives ⇒ 4 kg left.

After three half-lives ⇒ 2 kg left.

Follow-up: When will the sample be reduced to nothing?

- Carbon 14 is produced by the solar wind splitting atoms in the upper atmosphere (the same mechanism as the Aurora Borealis)
- Variations in the Sun, and Earth's magnetic Field cause the rate of C14 production to vary slightly.
- Atmospheric Nuclear Weapons use/testing greatly elevated the C14 rate for a while.
- Objects older than about 60,000 years (> ten half-lives) cannot be dated this way – there is too little carbon-14 left.



30.10 Decay Series

One unstable radioactive element decays into another, and so on….

For a given starting point there may be multiple generations of unstable daughter nuclei

From the relative abundance of the parent and daughters, accurate dates can be calculated

E.g. the age of the Earth 4.5 billion years

More advanced variations of radioactive dating have been developed

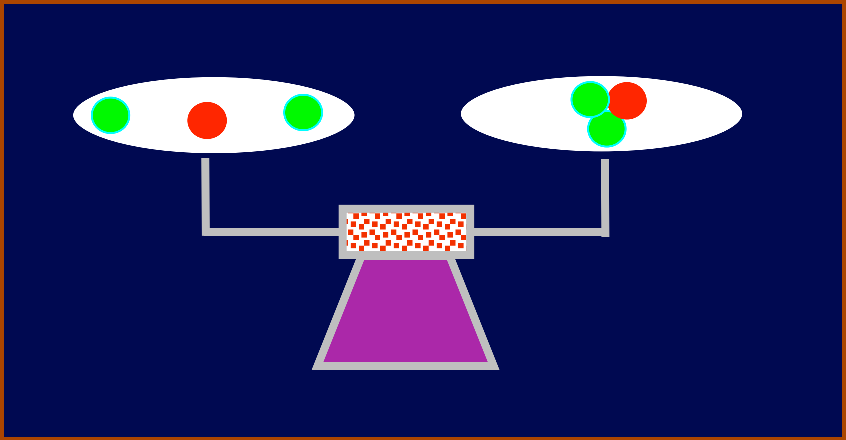
Leona Woods (August 9, 1919 – November 10, 1986), was an American physicist who helped build the first nuclear reactor and the first atomic bomb.

After WW2 she became interested in ecological and environmental issues, and devised the method of using the isotope ratios of in tree rings to study changes in temperature and rainfall patterns hundreds of years before records were kept, opening the door to the study of climate change

ConcepTest 30.2c Binding Energy III

On a balance scale, you put **2 neutrons** and **1 proton** on one side and you put a **tritium** nucleus (^3H) on the other. Which side weighs more?

1) the 2 neutrons and 1 proton
2) the tritium nucleus
3) they both weigh the same
4) it depends on the specific isotope of tritium

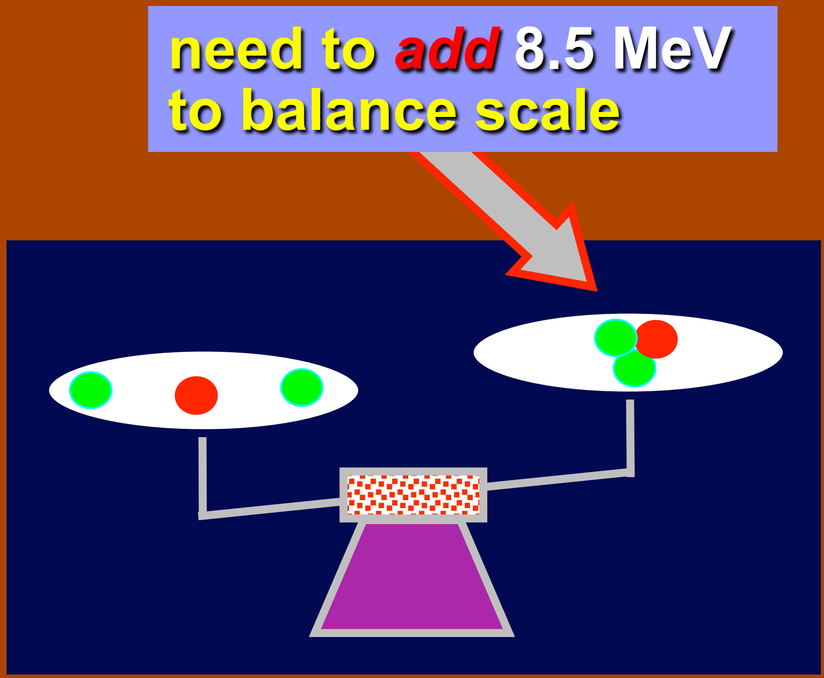


ConcepTest 30.2c Binding Energy III

On a balance scale, you put 2 neutrons and 1 proton on one side and you put a tritium nucleus (^3H) on the other. Which side weighs more?

1) the 2 neutrons and 1 proton
2) the tritium nucleus
3) they both weigh the same
4) it depends on the specific isotope of tritium

The mass of the 2 neutrons and 1 proton is *less* when they are bound together as tritium. **The mass difference is the binding energy.**



ConcepTest 30.9a Activity and Half-Life I

You have 10 kg each of a radioactive sample A with a half-life of 100 years, and another sample B with a half-life of 1000 years. Which sample has the higher activity?

1) sample A
2) sample B
3) both the same
4) impossible to tell

ConcepTest 30.9a Activity and Half-Life I

You have 10 kg each of a radioactive sample A with a half-life of 100 years, and another sample B with a half-life of 1000 years. Which sample has the higher activity?

1) sample A
2) sample B
3) both the same
4) impossible to tell

If a sample has a shorter half-life, this means that it decays more quickly (larger decay constant λ) and therefore has a higher activity:

$$\Delta N/\Delta t = -\lambda N$$

In this case, that is sample A.

Follow-up: What is the ratio of activities for the two samples?

Units of Chapter 31

- **Nuclear Reactions and the Transmutation of Elements**
- **Nuclear Fission; Nuclear Reactors**
- **Nuclear Fusion**
- **Passage of Radiation through Matter; Radiation Damage**
- **Measurement of Radiation – Dosimetry**
- **Radiation Therapy**
- **Tracers and Imaging in Research and Medicine**
- **Emission Tomography**
- **Nuclear Magnetic Resonance (NMR) and Magnetic Resonance Imaging (MRI)**

31.1 Nuclear Reactions and the Transmutation of Elements

A nuclear reaction takes place when a nucleus is struck by another nucleus or particle.

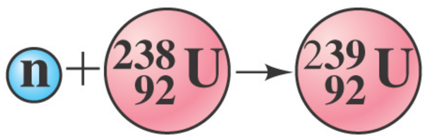
If the original nucleus is transformed into another, this is called transmutation.

An example:

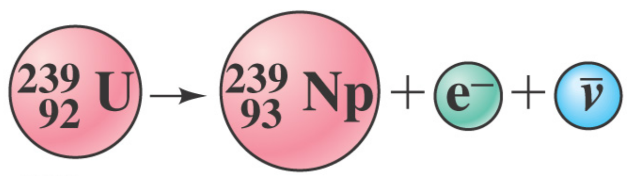
$$^{4}_{2}He + ^{14}_{7}N \rightarrow ^{17}_{8}O + ^{1}_{1}H$$

Reactions can be exothermic or endothermic - (just like in Chemistry)

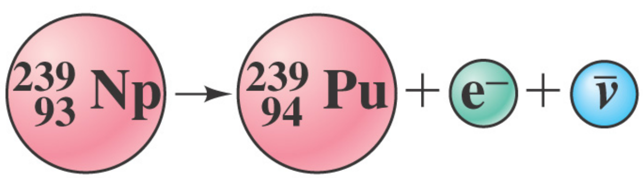
31.1 Nuclear Reactions and the Transmutation of Elements

(a) 

Neutron captured by $^{238}_{92}U$.

(b) 

$^{239}_{92}U$ decays by β decay to neptunium-239.

(c) 

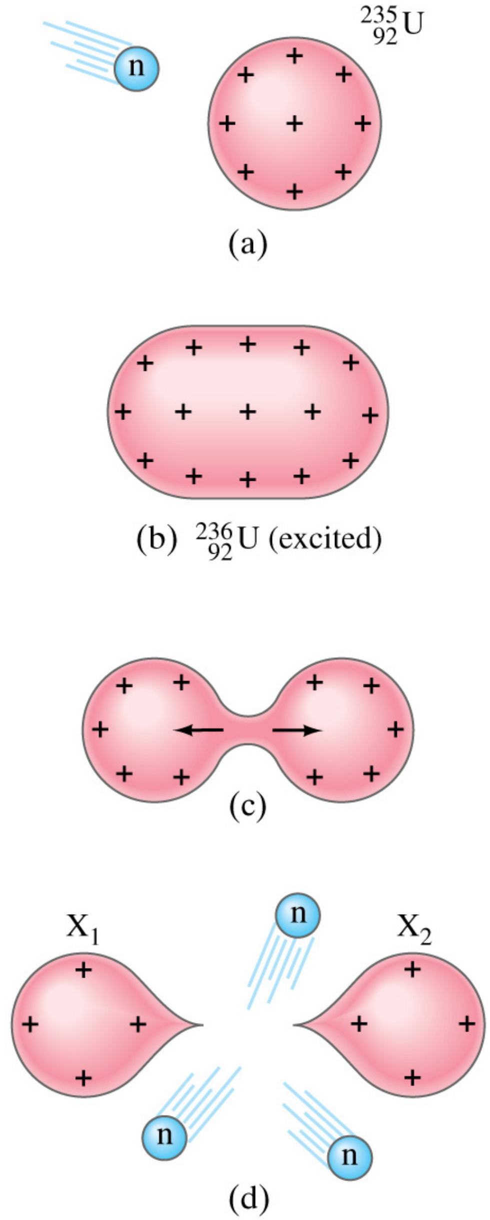
$^{239}_{93}Np$ itself decays by β decay to produce plutonium-239.

- Neutrons are very effective in starting nuclear reactions
- they nave no charge and therefore are not repelled by the nucleus.

31.2 Nuclear Fission; Nuclear Reactors

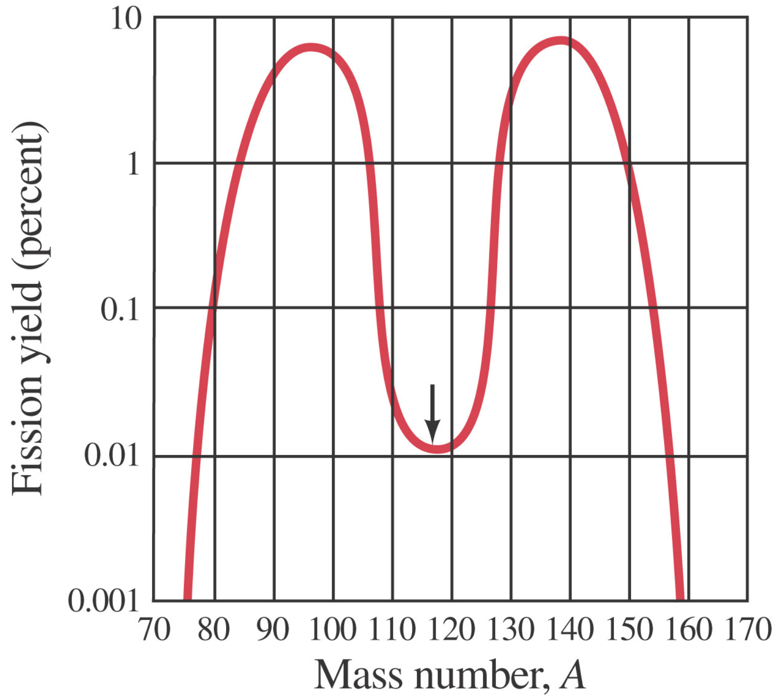
After absorbing a neutron, a uranium-235 nucleus will split into two roughly equal parts.

One way to visualize this is to view the nucleus as a kind of liquid drop.



31.2 Nuclear Fission; Nuclear Reactors

The mass distribution of the fragments shows that the two pieces are large, but usually unequal.

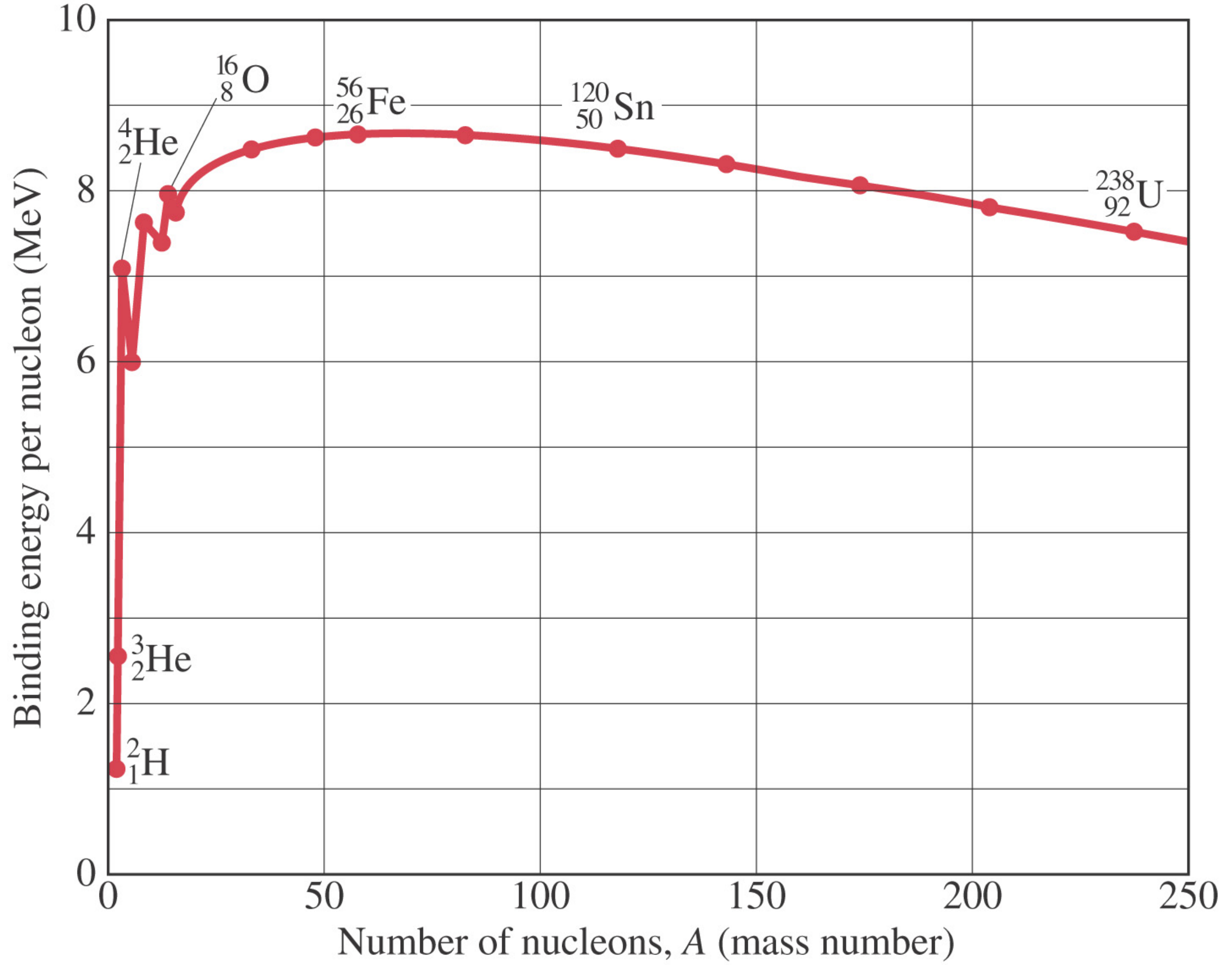


The total energy released by a single Uranium fission is ~ 200 MeV

Or 3.2×10^{-11} J

Weight-for-weight, this is about 2.5 million times the energy released by burning Coal. (see HW10 31.21)

How Much Energy is available from Fission?



After the Uranium atom splits, the daughters have higher binding energy per nucleon that the parent.

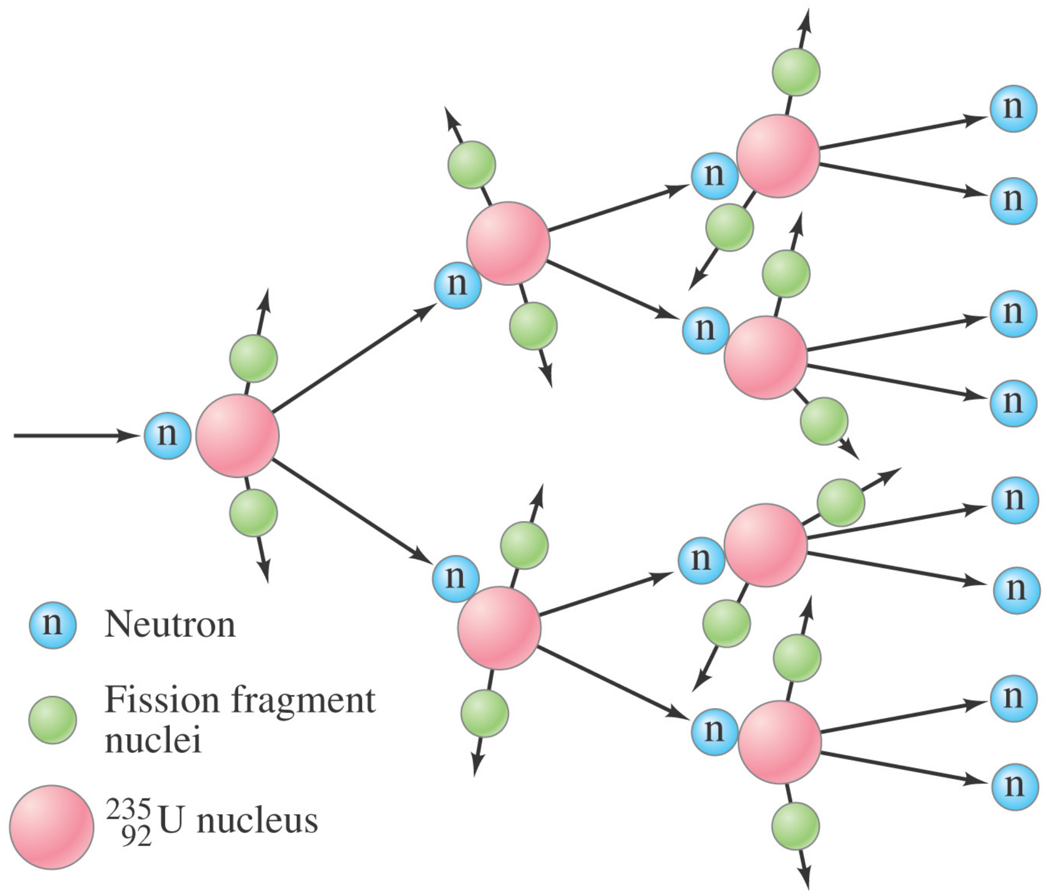
Thus energy is released (As gamma rays and kinetic energy)

$$n + {}^{235}U \rightarrow {}^{54}Xe + {}^{93}Sr + 2n$$

31.2 Nuclear Chain Reaction

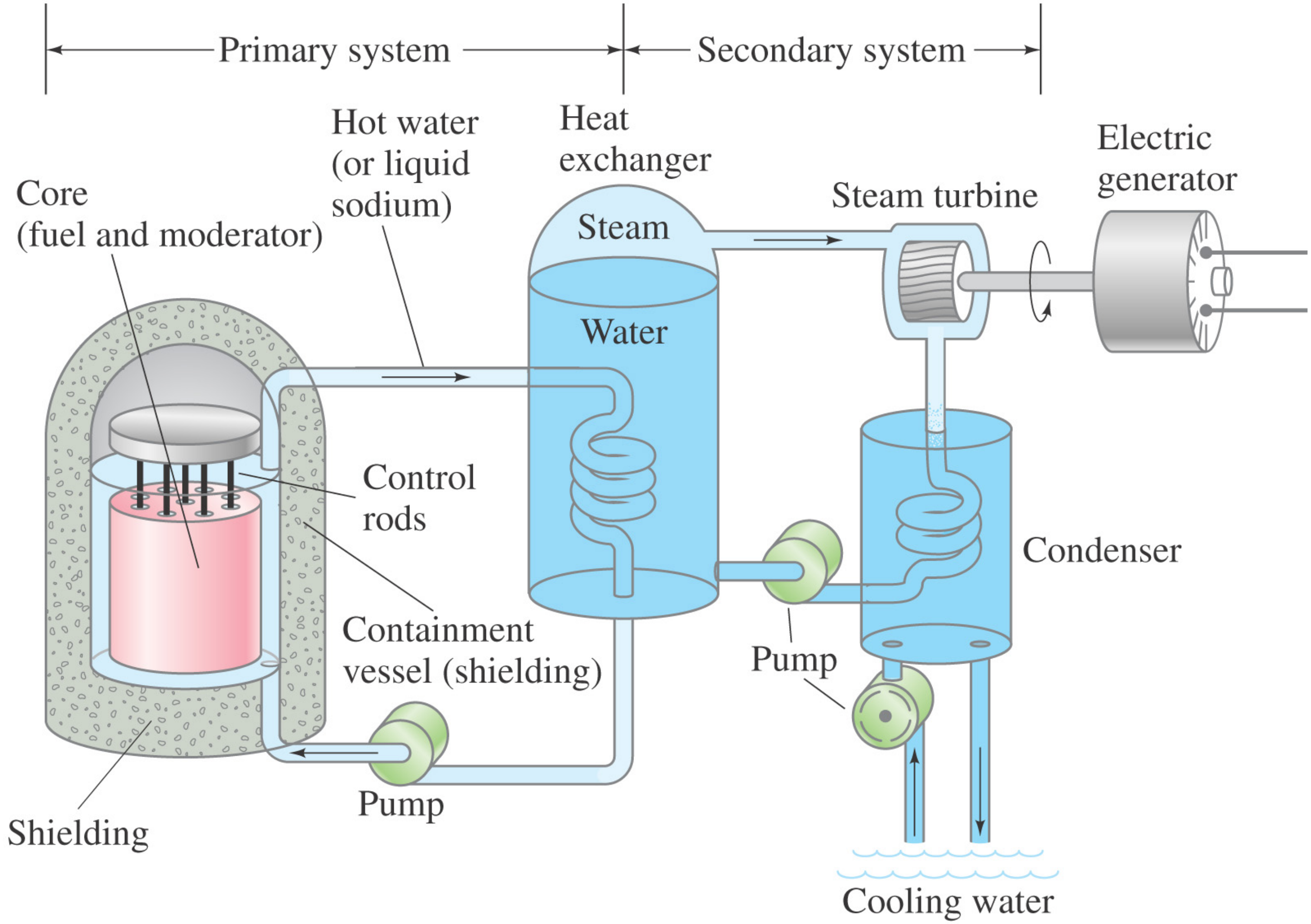
The energy release in a fission reaction is quite large (200 MeV). Also, since smaller nuclei are stable with fewer neutrons, several neutrons emerge from each fission as well.

These neutrons can be used to induce fission in other nuclei, causing a chain reaction.



31.2 Nuclear Fission; Nuclear Reactors

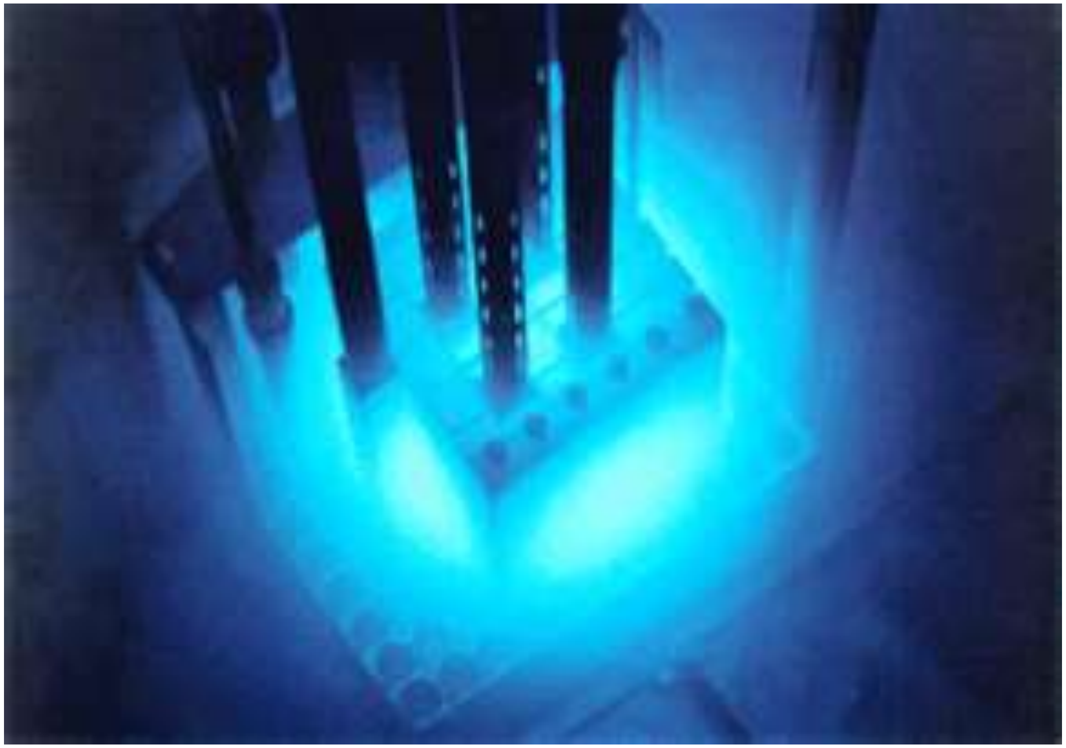
The reactor contains control rods, usually cadmium or boron, that absorb neutrons and can be used for fine control of the reaction, to keep it critical but just barely.



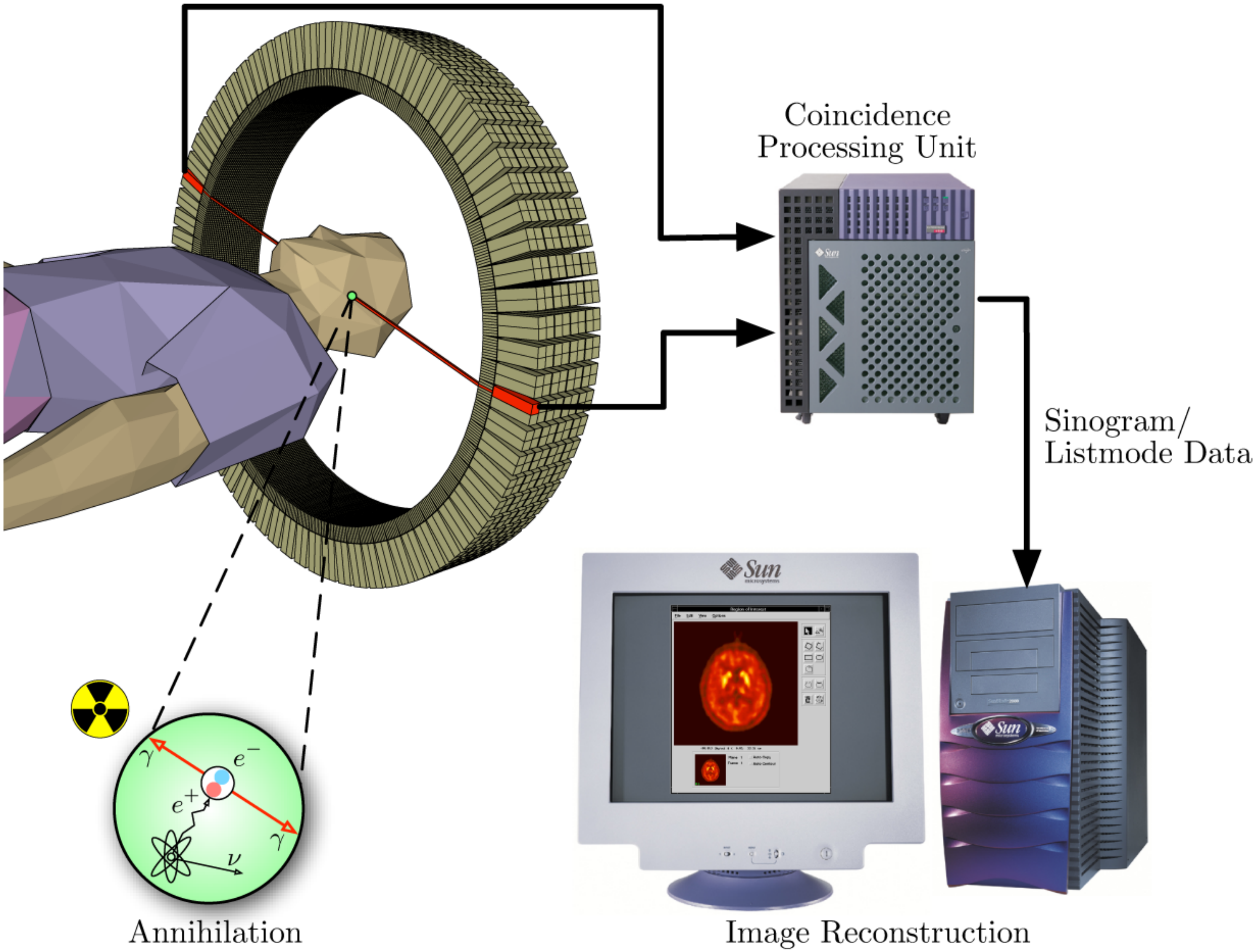
31.2 Nuclear Fission; Nuclear Reactors

A moderator is needed to slow the neutrons; otherwise their probability of interacting is too small. Common moderators are heavy water and graphite.

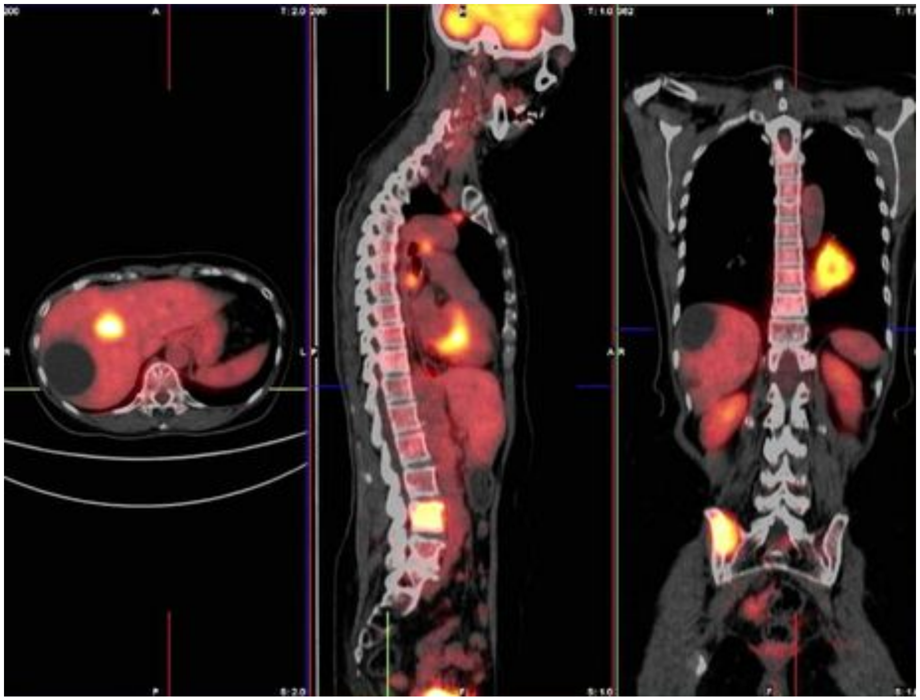
Unless the moderator is heavy water, the fraction of fissionable nuclei in natural uranium is too small to sustain a chain reaction, about 0.7%. It needs to be enriched to about 2-3%.

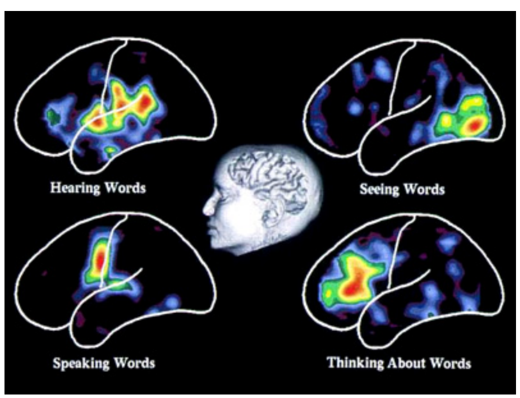


Positron Emission Tomography (PET)



PET: Positron Emission Tomography





- A radioactive element that decays by positron emission is incorporated into a chemical that will be taken up by certain types of cells in the body. This chemical (called the tracer) is injected into the patient.
- The tracer accumulates in that target cells
- The positrons annihilate with electrons, releasing a pair of 511 keV gamma ray photons in exactly opposite directions.
- A ring (or cylinder) of gamma-ray detectors surrounding the patient detects the pairs of photons, and their direction and hence locates the site of the tracer
- Computer processing (tomographic reconstruction) produces a 2D or 3D image, or a series of slices through the body.
- Different tracers can reveal the sites of different metabolic processes in the body.
- Glucose is most commonly used as it lights up cells that are “working hard.”

ConcepTest 31.6 Radiation Shielding

Which type of radiation goes farther in matter before losing all of its energy ?

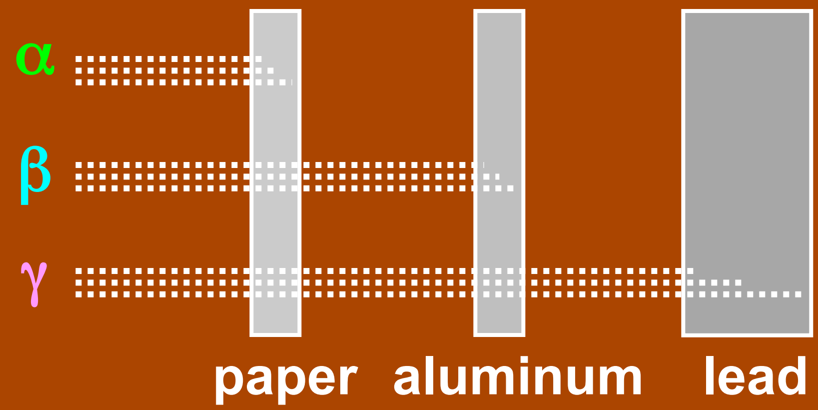
1) alpha radiation
2) beta radiation
3) gamma radiation
4) all about the same distance

ConcepTest 31.6 Radiation Shielding

Which type of radiation goes farther in matter before losing all of its energy ?

1) alpha radiation
2) beta radiation
3) gamma radiation
4) all about the same distance

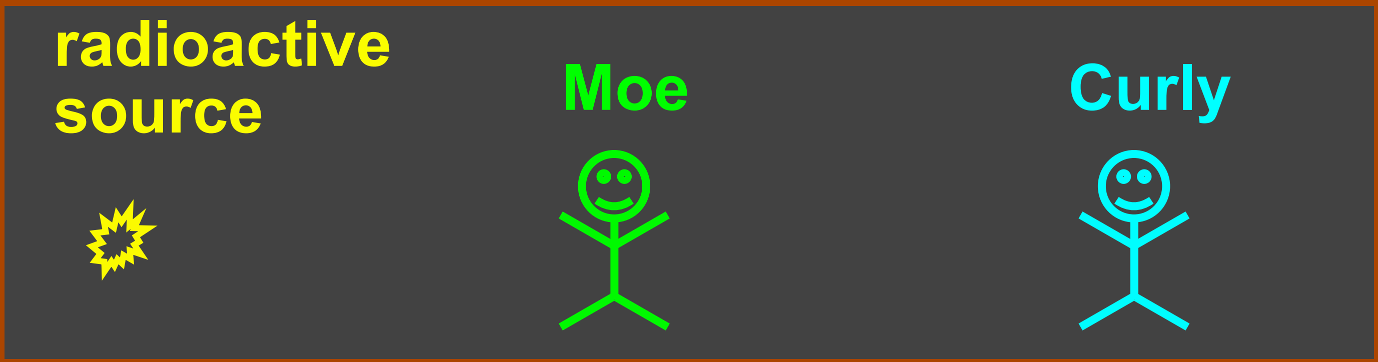
Alpha particles have such a large charge, they ionize many atoms in a short distance, and so lose their energy rapidly and stop. Gamma rays travel great distances before ionizing an atom.



ConcepTest 31.7a Radiation Exposure I

Curly is twice as far from a small radioactive source as Moe. Compared to Curly's position, the intensity of the radiation (and therefore exposure) at Moe's position is about:

1) one-quarter
2) one-half
3) the same
4) double
5) quadruple

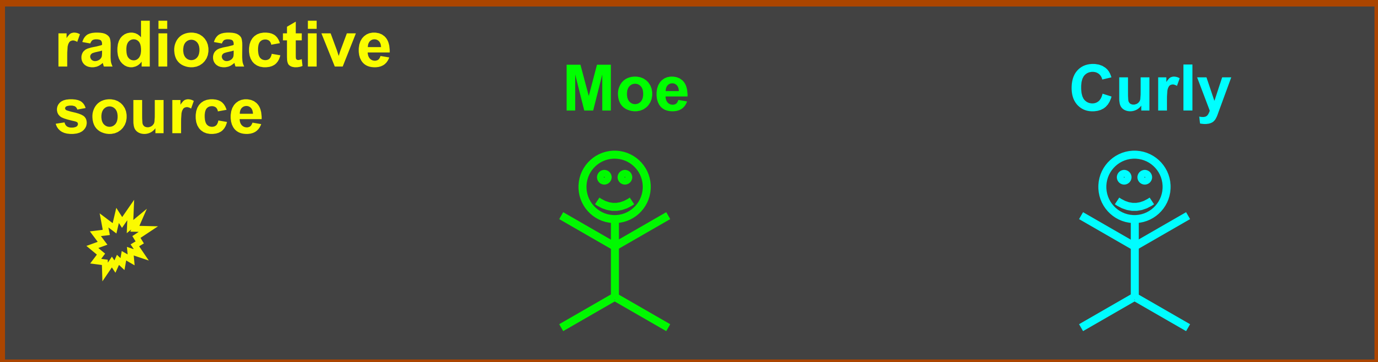


ConcepTest 31.7a Radiation Exposure I

Curly is twice as far from a small radioactive source as Moe. Compared to Curly's position, the intensity of the radiation (and therefore exposure) at Moe's position is about:

1) one-quarter
2) one-half
3) the same
4) double
5) quadruple

A small source can be treated as a point source and so it obeys the inverse square law of intensity. Twice as close means 4 times the intensity (and therefore exposure).



ConcepTest 31.8 Radiation Damage

Radiation can damage matter such as metals or biological tissue by:

1) heating up the material
2) causing cancer in the metal
3) producing fission reactions in the material
4) removing electrons from the atoms
5) producing fusion reactions in the material

ConcepTest 31.8 Radiation Damage

Radiation can damage matter such as metals or biological tissue by:

1) heating up the material
2) causing cancer in the metal
3) producing fission reactions in the material
4) removing electrons from the atoms
5) producing fusion reactions in the material

Radiation can ionize the atoms in matter, which means knocking out electrons. Metals become brittle and cell processes can be disrupted.

Follow-up: What type of radiation will tend to do the most damage?