This lecture will help you understand:

- Radioactivity
- The Atomic Nucleus and the Strong Nuclear Force
- Half-Life and Transmutation
- Radiometric Dating
- Nuclear Fission
- Nuclear Fusion
Radioactivity

Radioactivity:

• results from radioactive decay, which is the process whereby unstable atomic nuclei transform and emit radiation.

• has existed longer than the human race.
Radioactivity

Unstable atomic nuclei:
• have an imbalance of neutrons to protons.
• are radioactive.
Radioactivity

Most radiation we encounter is:

• natural background radiation that originates in Earth and space (cosmic rays from the Sun and stars).

• more intense at higher altitudes.
Radioactivity

Cosmic rays are of two types:

- high-energy particles.
- high-frequency electromagnetic radiation (gamma rays).

They affect us indirectly by transforming nitrogen atoms in the air to radioactive carbon-14, which ends up in plants we consume.
The origins of radioactivity go back to

A. military activities in the mid-20th century.
B. the industrial revolution two centuries ago.
C. the beginning of human error.
D. before humans emerged on Earth.
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When an atom undergoes radioactive decay, it

A. becomes an ion of the same element.
B. becomes an isotope of the same element.
C. turns into a completely different element.
D. may or may not turn into a completely different element.
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Radioactivity

Types of radiation:

- **alpha (α)** carries positive electrical charge
- **beta (β)** carries negative electrical charge
- **gamma (γ)** carries no charge
Radioactivity

Alpha particle:
- consists of two protons and two neutrons (a helium nucleus)
- loses energy quickly during interaction
- can be stopped easily by a few pieces of paper due to its large mass and double positive charge
- does not normally penetrate lightweight material (paper, clothing)
- causes significant damage to the surface of a material (living tissue) due to great kinetic energy
- picks up electrons and becomes harmless helium when traveling through air
- is deflected in the presence of magnetic or electric fields
Radioactivity

Beta particle:
- is an ejected electron from a neutron
- has both a smaller mass and electric charge than an alpha particle, and moves faster
- loses energy at a slower rate in air and travels farther before stopping
- can be stopped by several sheets of aluminum foil
- penetrates fairly deeply into skin (potential for harming or killing living cells)
- once stopped, becomes an ordinary electron
- is deflected in the opposite direction to an alpha particle in the presence of magnetic and electric fields
Radioactivity

Gamma rays:

- are high-frequency electromagnetic radiation
- are emitted when a nucleus in an excited state moves to a lower energy state
- are more harmful than alpha or beta particles
- are most penetrating because they have no mass or charge
- are pure energy, greater per photon than in visible or ultraviolet light and X-rays
- are unaffected by magnetic and electric fields, and therefore interact via direct hit with an atom
Radioactivity
CHECK YOUR NEIGHBOR

Which of these is the nucleus of the helium atom?

A. Alpha particle.
B. Beta particle.
C. Gamma ray.
D. All are different forms of helium.
Which of these is the nucleus of the helium atom?

A. Alpha particle.
B. Beta particle.
C. Gamma ray.
D. All are different forms of helium.

Comment:
A beta particle is a high-speed electron; a gamma ray is electromagnetic radiation.
The Atomic Nucleus and the Strong Nuclear Force

The strong nuclear force is a very distance sensitive attraction between nucleons.

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The strong force is a force in the

A. atom that holds electrons in orbit.
B. nucleus that holds nucleons together.
C. Both of the above.
D. None of the above.
The strong force is a force in the

A. atom that holds electrons in orbit.
B. nucleus that holds nucleons together.
C. Both of the above.
D. None of the above.

Comment:
The strong force is strong only between close-together nucleons. For far-apart protons, the electric force is greater.
The Atomic Nucleus and the Strong Nuclear Force

The presence of neutrons helps hold the nucleus together.

All nucleons, both protons and neutrons, attract one another by the strong nuclear force.

Only protons repel one another by the electric force.
The Atomic Nucleus and the Strong Nuclear Force

But in large nuclei, far-apart neutrons are less effective in holding a nucleus together.
Half-Life and Transmutation

Half-life:
• is the rate of decay for a radioactive isotope.
• is the time required for half of an original quantity of an element to decay.
• is constant and independent of any physical or chemical change the atom may undergo.
• can be calculated at any given moment by measuring the rate of decay of a known quantity using a radiation detector.
A certain isotope has a half-life of one day. This means the amount of that isotope remaining at the end of two days will be

A. zero.
B. one eighth.
C. one quarter.
D. half.
A certain isotope has a half-life of one day. This means the amount of that isotope remaining at the end of two days will be

A. zero.
B. one eighth.
C. one quarter.
D. half.

Comment:
And after three days, the amount remaining will be one eighth.
Half-Life and Transmutation

Radioactive isotopes decay at a rate characteristic of each isotope. Rates are described by half-life.

The shorter the half-life of a substance ⇒ the faster it disintegrates and the more active the substance.
Half-Life and Transmutation

Transmutation of elements:
the changing of one chemical element to another occurring in

- natural events—natural transmutation
- artificially in labs—artificial transmutation

\[ ^1_0 n + ^{14}_7 N \rightarrow ^{14}_6 C + ^1_1 H \]
Half-Life and Transmutation

Natural transmutation:

Alpha emission from a nucleus:

- mass number decreases by 4
- atomic number decreases by 2
- resulting atom belongs to an element two places back in periodic table

\[
\begin{align*}
238_{92}^1\text{U} &\rightarrow 234_{90}^1\text{Th} + \frac{4}{2}^2\text{He}
\end{align*}
\]
Half-Life and Transmutation

Beta emission from a nucleus:
- no change in mass number—no loss in nucleons
- atomic number increases by 1
- resulting atom belongs to an element one place forward in periodic table

Gamma emission from a nucleus:
- no change in mass number
- no change in atomic number
Half-Life and Transmutation

Artificial Transmutation

Ernest Rutherford’s cloud-chamber experiment in 1919 succeeded in transmuting a chemical element. After bombardment of nitrogen gas with alpha particles from a radioactive piece of ore, he found traces of oxygen and hydrogen.

Since then, synthetic elements have been produced from atomic numbers 93 to 115, all with short half-lives.

\[
\frac{4}{2}\text{He} + \frac{14}{7}\text{N} \rightarrow \frac{17}{8}\text{O} + \frac{1}{1}\text{H}
\]
When an element ejects an alpha particle, the atomic number of the resulting element

A. reduces by 2.
B. reduces by 4.
C. increases by 2.
D. increases by 4.
When an element ejects an alpha particle, the atomic number of the resulting element

A. reduces by 2.
B. reduces by 4.
C. increases by 2.
D. increases by 4.

Explanation:
An alpha particle (a helium nucleus) has atomic number 2. So, ejection of an alpha particle means a loss of two protons. Hence, the atomic number of the element is lowered by two.
When an element ejects a beta particle, the atomic number of that element

A. reduces by 1.
B. increases by 1.
C. reduces by 2.
D. increases by 2.
When an element ejects a beta particle, the atomic number of that element

A. reduces by 1.
**B. increases by 1.**
C. reduces by 2.
D. increases by 2.

*Explanation:*
A beta particle (an electron) has electric charge –1. So, ejecting a beta particle means a loss of one unit of charge and a gain of 1 in atomic number. In beta emission, a neutron ejects an electron and becomes a proton. So, the element adds a proton to its nucleus.
A certain element emits 1 alpha particle, and its products then emit 2 beta particles in succession. The atomic number of the resulting element is changed by

A. zero.
B. –1.
C. –2.
D. none of the above.
A certain element emits 1 alpha particle, and its products then emit 2 beta particles in succession. The atomic number of the resulting element is changed by

A. zero.
B. –1.
C. –2.
D. none of the above.

Explanation:
Removal of the alpha decreases atomic number by 2, but removal of two electrons increases it by 2, so there is no net change in atomic number.
Radiometric Dating

• Carbon dating used for plants and animals
• Based upon ratio of carbon-12 to carbon-14
• Half-life of carbon-14 is about 5760 years
• Method not exact due to fluctuations in Earth’s carbon-14 production
Radiometric Dating

• Nonliving things dated through uranium and lead isotopes
• Uranium-238 decays to lead-206
• Uranium-235 decays to lead-207
An archaeological dig uncovers an ancient spear whose wooden handle contains 1/8 the radioactive carbon of a fresh piece of wood. About how old is the spear?

A. 11,520 years old  
B. 17,280 years old  
C. 46,080 years old  
D. 23,040 years old
An archaeological dig uncovers an ancient spear whose wooden handle contains 1/8 the radioactive carbon of a fresh piece of wood. About how old is the spear?

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**Explanation:**

If 1 half-life reduces the C-14 by 1/2, then 2 reduces it by 1/4 and 3 reduces it by 1/8, so the answer is:

\[ 3 \times 5760 \text{ years} = 17,280 \text{ years} \]
Nuclear Fission:

A neutron hitting a U-235 nucleus may cause it to stretch and fly apart.

\[ _0^1 n + _{92}^{235} U \rightarrow _{91}^{91} Kr + _{56}^{142} Ba + 3(_0^1 n) \]
Nuclear Fission

Energy released is in the form of kinetic energy of fission fragments that fly apart from one another, with some energy given to ejected neutrons, and the remainder given to gamma radiation.

1. The greater force is the strong nuclear force.
2. Critical deformation occurs.
3. The greater force is the electric force, which results in a splitting of the nucleus.
Nuclear Fission

Chain reaction:

is a self-sustaining reaction in which the products of one reaction event stimulate further reaction events.
Nuclear Fission

Critical mass:
• the minimum mass of fissionable material in a reactor or nuclear bomb that will sustain a chain reaction
• a mass large enough to sustain fission

At or above critical mass, in a large quantity of atoms, an enormous explosion can occur.
Uranium-235, uranium-238, and uranium-239 are different

A. elements.
B. ions.
C. isotopes.
D. nucleons.
Uranium-235, uranium-238, and uranium-239 are different

A. elements.
B. ions.
C. isotopes.
D. nucleons.

Comment:
U-235 is the isotope that can undergo fission.
Mass–Energy Equivalence:

\[ E = mc^2 \]

Albert Einstein in the early 1900s:

- discovered that mass is congealed energy.
- formulated the famous equation, \( E = mc^2 \), which is the key to understanding why and how energy is released in nuclear reactions.
Mass–Energy Equivalence:

\[ E = mc^2 \]

Relationship of equation terms:

- The more energy associated with a particle, the greater is the mass of the particle.
- The mass of a nucleon outside the nucleus is greater than the mass of the same nucleon bound in the nucleus.
- The greater mass of the nucleon is evident by the energy required to pull the nucleons apart from one another.
Mass–Energy Equivalence: \[ E = mc^2 \]

Relationship of equation terms:

• When nucleons lose mass in a nuclear reaction, the loss of mass, \( \Delta m \), multiplied by the square of the speed of light is equal to the energy release: \( E = \Delta mc^2 \).

• Mass difference is related to the binding energy of the nucleus—how much is required to dissemble the nucleus.
Mass–Energy Equivalence: \[ E = mc^2 \]

A graph of nuclear masses versus atomic number of elements from hydrogen to uranium shows:

- an upward slope with increasing atomic number—elements are more massive as atomic numbers increase.
- a slightly curved slope because of disproportionally more neutrons in the more massive atoms.
Which of these nuclei has the greatest mass?

A. Hydrogen.
B. Iron.
C. Lead.
D. Uranium.
Which of these nuclei has the greatest mass?

A. Hydrogen.
B. Iron.
C. Lead.
D. Uranium.

*Comment:*
And the nucleus with the smallest mass is hydrogen. Be sure to distinguish between the mass of a nucleus and the mass-per-nucleon of a nucleus.
Mass–Energy Equivalence:

\[ E = mc^2 \]

Dividing the mass of a nucleus by the number of nucleons in the nucleus gives the mass per nucleon.

Graph of nuclear mass per nucleon inside each nucleus versus atomic number from hydrogen to uranium:

- greatest mass per nucleon occurs for hydrogen, because it has no binding energy to pull its mass down.
In which of these nuclei does the proton have the greatest mass?

A. Hydrogen.
B. Iron.
C. Lead.
D. Uranium.
In which of these nuclei does the proton have the greatest mass?

A. Hydrogen.
B. Iron.
C. Lead.
D. Uranium.

*Explanation:*
Although hydrogen is the lightest element, its lone proton has greater mass than the protons in all other atomic nuclei. Hydrogen has more “mass per nucleon.”
In which of these nuclei does the proton have the least mass?

A. Hydrogen.
B. Iron.
C. Lead.
D. Uranium.
In which of these nuclei does the proton have the least mass?

A. Hydrogen.

B. Iron.

C. Lead.

D. Uranium.

**Explanation:**
Iron has the least mass per nucleon but the strongest binding energy. (See the following three slides.)
A graph shows the relationship between the mass per nucleon and the atomic number. The graph indicates that nucleons in uranium fragments have less mass compared to nucleons in the uranium nucleus. The uranium nucleus fragments that are now nuclei of atoms such as barium and krypton are also shown. The uranium-235 nucleus is highlighted as having a point of interest on the graph.
Mass–Energy Equivalence:

\[ E = mc^2 \]

Graph of nuclear mass per nucleon versus atomic number for uranium:

- The nucleons in a uranium nucleus have more mass than the nucleons in uranium fragments.
Nuclear Fusion

Nuclear fusion:

- is the combination of nuclei of light atoms to form heavier nuclei with the release of much energy.

Any nuclear transformation that moves nuclei toward iron releases energy.

Iron is the “nuclear sink” for energy production.
Nuclear Fusion

A graph of mass per nucleon versus atomic number from hydrogen to iron

- shows how the average mass per nucleon decreases from hydrogen to iron.
Nuclear Fusion

Thermonuclear fusion:

• Nuclear fusion is produced by high temperature resulting in more tightly bound nuclei.
• Mass decreases as energy is released.
• This is analogous to chemical combustion requiring a high temperature, where the end result is energy release and a tightly bound molecule.
• A solution is still being sought for reactions to occur under controlled conditions to provide an enormous amount of sustained energy.
When energy is released by the process of fission or fusion, the total mass of the material after the event is

A. less.
B. the same.
C. more.
D. none of the above.
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A. less.
B. the same.
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D. none of the above.

*Explanation:*
The name of the game for energy release is to lose mass. All reactions, nuclear or chemical, lose mass when energy release is the outcome. For chemical reactions, which are much less energetic than nuclear reactions, the mass lost is so small that it is typically ignored.