Lecture 43
Introduction to Nuclear Physics

- **1896** – the birth of nuclear physics
  - Becquerel discovered radioactivity in uranium compounds
- **Rutherford showed the radiation had three types**
  - Alpha (He nucleus)
  - Beta (electrons)
  - Gamma (high-energy photons)
- **1911** Rutherford, Geiger and Marsden performed scattering experiments
  - Established the point mass nature of the nucleus
  - *Nuclear force* was a new type of force
- **1919** Rutherford and coworkers first observed nuclear reactions in which naturally occurring alpha particles bombarded nitrogen nuclei to produce oxygen
- **1932** Cockcroft and Walton first used artificially accelerated protons to produce nuclear reactions
- **1932** Chadwick discovered the neutron
- **1933** the Curies discovered artificial radioactivity
- **1938** Hahn and Strassman discovered nuclear fission
- **1942** Fermi achieved the first controlled nuclear fission reactor
\(\alpha\) particles: \(^4_2\text{He}\) nuclei
Barely penetrate a piece of paper

\(\beta^-\) particles: electrons
Can penetrate a few mm of aluminum

\(\gamma\) photons (more energetic than x-rays)
Can penetrate several cm of lead
Most alpha particles passed right through the gold foil with only small deflection. But some were deflected at large angles, even backward!
It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.

— Rutherford

(about 1 in 8000 were scattered backwards)
If the atom has a concentrated positive nucleus, some alpha particles will be able to come very close to the nucleus and thus feel a very strong repulsive force.
Backward Scattering estimates the nucleus size — the incoming alpha must be stopped by the Coulomb force, then flung back.

\[ PE_\alpha = KE_\alpha \]
\[
\frac{1}{2} m_\alpha v_\alpha^2 = \frac{2Zke^2}{R} 
\]
\[
R = \frac{4Zke^2}{m_\alpha v_\alpha^2} 
\]
\[
R \approx \frac{4(79)(9 \times 10^9 \text{Nm}^2/\text{C}^2)(1.6 \times 10^{-19}\text{C})^2}{(6.64 \times 10^{-27}\text{kg})(1.5 \times 10^7\text{m/s})^2} \approx 5 \times 10^{-14}\text{m} 
\]
In 1911 Rutherford proposed that the atom nucleus consists of protons plus some neutral particles.

In 1917, Rutherford discovered the first nuclear reaction.

In 1932 the neutral particle was discovered. It has almost the mass of the proton but no electric charge.
A doubly charged helium ion \((q = +2e)\) is released from rest at the positive electrode. What is its kinetic energy when it reaches the negative electrode?

A. 2 eV.
B. 10 eV.
C. 20 eV.
D. \(-10 \text{ eV}\).
E. It’s not possible for it to reach the negative electrode.
A doubly charged helium ion \((q = +2e)\) is released from rest at the positive electrode. What is its kinetic energy when it reaches the negative electrode?

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Lecture 44
Nuclear Physics after Rutherford

\[ \alpha + N \rightarrow p + O \]

\[ \frac{4}{2}He + \frac{14}{7}N \rightarrow \frac{1}{1}p + \frac{17}{8}O \]

or

\[ \frac{A}{Z}X \]

\[ A = N_p + N_n \]

\[ Z = N_p \]
\[ R = 1.3 \times 10^{-15} \text{ meters} \times A^{1/3} \]

No nucleus with p only (except Hydrogen)
No nucleus with n only (at all)
Balance n and p, but more n because of Coulomb repulsion of p

“Isotopes—same X and Z, different A”

\[ \begin{align*}
\frac{11}{6}C & \quad \text{Unstable} \\
\frac{12}{6}C & \quad \text{Stable} \\
\frac{13}{6}C & \quad \text{Stable} \\
\frac{14}{6}C & \quad \text{Unstable}
\end{align*} \]

“too many p”
“too many n”
Nuclear “Beta” Decays

Too many n? $n_{bound} \rightarrow p_{bound} + e^- + \nu$

Too many p? $p_{bound} \rightarrow n_{bound} + e^+ + \nu$

or

$^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + e^- + \nu$ “Beta$^-$ emitter”

$^{A}_{Z}X \rightarrow ^{A}_{Z-1}Y + e^+ + \nu$ “Beta$^+$ emitter”
Heavy Nuclei Decays (Besides “Beta Decay”)
(Heavy usually means heavier than lead $^{208}_{82} Pb$)

“Alpha Decay” $^A_Z X \rightarrow \alpha + ^{(A-4)}_{(Z-2)} Y^*$

Nucleus $Y$ is left with extra energy, $Y^* \rightarrow Y + \gamma$

“Alpha emitters” also emit gammas

Famous alpha decay found by the Curies
Why Alpha Emissions?

Helium 4 is very tightly bound — it can even exist inside heavy nuclei and escape by “quantum tunneling”
Example

The speed of an alpha particle

Alpha particles are usually characterized by their kinetic energy in MeV. What is the speed of an 8.3 MeV alpha particle?

**SOLVE**  Alpha particles are helium nuclei, having \( m = 4 \, u = 6.64 \times 10^{-27} \, \text{kg} \). The kinetic energy of this alpha particle is \( 8.3 \times 10^6 \, \text{eV} \). First, we convert the energy to joules:

\[
K = 8.3 \times 10^6 \, \text{eV} \times \frac{1.60 \times 10^{-19} \, \text{J}}{1.00 \, \text{eV}} = 1.33 \times 10^{-12} \, \text{J}
\]

Example

The speed of an alpha particle

Now we can find the speed:

\[
K = \frac{1}{2}mv^2 = 1.33 \times 10^{-12} \, \text{J}
\]

\[
v = \sqrt{\frac{2K}{m}} = 2.0 \times 10^7 \, \text{m/s}
\]

This is about 1/10 the speed of light. *Non-rel okay.*
Lecture 45

“Decay Chains” and Decay Energies

Decay Chain of U-238
(Chains typically end with Lead)
$E_b \approx 8 \text{ MeV}$ or about $\frac{E_b}{M_p c^2} \approx \frac{8 \text{ MeV}}{940 \text{MeV}} \approx 10^{-3}$

of the “rest energy” from $E = Mc^2$
Einstein’s famous equation \[ E = m \ c^2 \]

Proton: \[ mc^2 = 938.3 \text{MeV} \]

Neutron: \[ mc^2 = 939.5 \text{MeV} \]

Deuteron: \[ mc^2 = 1875.6 \text{MeV} \]

Adding these, get 1877.8 MeV

Difference is Binding energy, 2.2 MeV

\[ M_{\text{Deuteron}} = M_{\text{Proton}} + M_{\text{Neutron}} - |\text{Binding Energy}/c^2| \]
The kinetic energy of stuff after a decay is given by $Q$

$$Q = \left((\text{Rest mass})_{\text{before}} \times c^2\right) - \left((\text{Rest mass})_{\text{after}} \times c^2\right)$$

Alpha Decays 1 MeV - 10 MeV

Beta Decays 0.1 MeV - 2 MeV

Gamma Decays 0.1 MeV - 2 MeV

All of these are up to a million times more than atomic energies (1-10 eV)
Energy of electrons is lost to neutrinos in the decay

Sharp alpha energy

Sharp gamma energies
Cobalt 60
The number of particles that decay in a given time is proportional to the total number of particles in a radioactive sample.

\[ \Delta N = -\lambda N \Delta t \]

- \( \lambda \) is called the *decay constant* and determines the rate at which the material will decay.

- The *decay rate* or *activity*, \( R \), of a sample is defined as the number of decays per second.

\[ R = \left| \frac{\Delta N}{\Delta t} \right| = \lambda N \]
• The decay curve follows the equation

\[
    N = N_0 e^{-\lambda t}
\]

• The *half-life* is also a useful parameter

• The half-life is defined as the time it takes for half of any given number of radioactive nuclei to decay

\[
    T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}
\]
Energy Release in Decay

Chunk of Plutonium 238 (as ceramic) used in radioisotope electric generator
The half-life for beta-decay of $^{14}\text{C}$ is 5730 years. If you start with 1000 carbon-14 nuclei, how many will be around in 22920 years?

\[
N(t) = N_0 e^{-\lambda t} = N_0 e^{-\frac{\ln 2}{T} \frac{t}{T}}
\]

\[
T_{1/2} = \frac{\ln 2}{\lambda} \approx \frac{0.693}{\lambda}
\]

\[
\lambda = \frac{\ln 2}{5730 \text{ years}} = 1.209 \times 10^{-4} \text{ yr}^{-1}
\]

\[
N(t) = 1000 e^{-1.209 \times 10^{-4} (22920)} = 62.5
\]
The half-life for beta-decay of $^{14}\text{C}$ is $\sim6,000$ years. You test a fossil and find that only 25% of its $^{14}\text{C}$ is un-decayed. How old is the fossil?

- 3,000 years
- 6,000 years
- 12,000 years
The half-life for beta-decay of $^{14}\text{C}$ is $\sim6,000$ years. You test a fossil and find that only $25\%$ of its $^{14}\text{C}$ is un-decayed. How old is the fossil?

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Radioactivity is the spontaneous emission of radiation

Experiments suggested that radioactivity was the result of the decay, or disintegration, of unstable nuclei

Three types of radiation can be emitted

- **Alpha particles**
  - The particles are $^4\text{He}$ nuclei
- **Beta particles**
  - The particles are either electrons or positrons
    - A positron is the antiparticle of the electron
    - It is similar to the electron except its charge is $+e$
- **Gamma rays**
  - The “rays” are high energy photons
\( \alpha \) particles: \( ^4_2 \text{He} \) nuclei

\( \beta^- \) particles: electrons

\( \gamma \) photons (more energetic than x-rays)

B field into screen

Radioactive sources

detector

Barely penetrate a piece of paper

Can penetrate a few mm of aluminum

Can penetrate several cm of lead
Alpha Decay

\[ ^{226}_{88} Ra \rightarrow ^{222}_{86} Rn + ^{4}_2 He \]

- Half life for this decay is 1600 years
- Excess mass is converted into kinetic energy
- Momentum of the two particles is equal and opposite
During beta decay, the daughter nucleus has the same number of nucleons as the parent, but the atomic number is one less.

In addition, an electron (positron) was observed.

The emission of the electron is from the nucleus.

The nucleus contains protons and neutrons.

The process occurs when a neutron is transformed into a proton and an electron.

Energy must be conserved.
The energy released in the decay process should almost all go to kinetic energy of the electron.

Experiments showed that few electrons had this amount of kinetic energy.

To account for this “missing” energy, in 1930 Pauli proposed the existence of another particle.

Enrico Fermi later named this particle the neutrino.

Properties of the neutrino:
- Zero electrical charge
- Mass much smaller than the electron, probably not zero
- Spin of $\frac{1}{2}$
- Very weak interaction with matter
Gamma Decay

- Gamma rays are given off when an excited nucleus “falls” to a lower energy state.
  - Similar to the process of electron “jumps” to lower energy states and giving off photons.
- The excited nuclear states result from “jumps” made by:
  - A proton or neutron.
- The excited nuclear states may be the result of violent collision or more likely of an alpha or beta emission.
- Example of a decay sequence:
  - The first decay is a beta emission.
  - The second step is a gamma emission.

\[ ^{12}_5 B \rightarrow ^{12}_6 C^* + e^- + \bar{\nu} \]

\[ ^{12}_6 C^* \rightarrow ^{12}_6 C + \gamma \]

- The \( C^* \) indicates the Carbon nucleus is in an excited state.
- Gamma emission doesn’t change either \( A \) or \( Z \).
IONIZATION

- Ionization is a process by which a neutral atom acquires a positive or a negative charge.
- Ionizing radiation can strip electrons from atoms as they travel through media.
- An atom from which an electron has been removed is a positive ion.
- In some cases a stripped electron may subsequently combine with a neutral atom to form a negative ion, usually free electron is called an negative ion.

- **Directly ionizing radiation:**
- Charged particles produce large amount of ionization in its energy loss to the medium.
  - Eg., electrons, protons, α-particles

- **Indirectly ionizing radiation:**
- Neutral particles themselves produce very little ion pairs. Instead, they eject directly ionizing particles from the medium.
  - Eg., photons, neutrons
Charged particle
Summary

Interaction of ionizing radiation with matter

- Charged particles interact strongly and ionize directly.
- Neutral particles interact less, ionize indirectly and penetrate farther.

α

β

γ

n

bremsstrahlung

δ-electron

n capture photon

recoil proton
Which of the following decays is NOT allowed?

1. $^{238}_{92}U \rightarrow ^{234}_{90}Th + \alpha$

2. $^{214}_{84}Po \rightarrow ^{210}_{82}Pb + ^4_2He$

3. $^{14}_6C \rightarrow ^{14}_7N + \gamma$

4. $^{40}_{19}K \rightarrow ^{40}_{20}p + ^0_{-1}e^- + ^0_0\bar{\nu}$
Which of the following decays is NOT allowed?

1. $^{238}_{92}U \rightarrow ^{234}_{90}Th + \alpha$

2. $^{214}_{84}Po \rightarrow ^{210}_{82}Pb + ^{4}_{2}He$

3. $^{14}_{6}C \rightarrow ^{14}_{7}N + \gamma$

4. $^{40}_{19}K \rightarrow ^{40}_{20}p + ^{0}_{-1}e^- + ^{0}_{0}\bar{\nu}$
Which of these (induced fission) reactions are allowed?

(a) \( \_0^1 n + \_92^{235}U \rightarrow \_54^{140}Xe + \_38^94Sr + 2 \_0^1 n \)

(b) \( \_0^1 n + \_92^{235}U \rightarrow \_50^{132}Sn + \_42^{101}Mo + 3 \_0^1 n \)

(c) \( \_0^1 n + \_94^{239}Pu \rightarrow \_53^{127}I + \_41^{93}Nb + 3 \_0^1 n \)
(a) and (b). Reactions (a) and (b) both conserve total charge and total mass number as required. Reaction (c) violates conservation of mass number with the sum of the mass numbers being 240 before reaction and being only 223 after reaction.