Nuclear Physics

The Atom

First Model of the Atom
From Democritus to Dalton (1803)

Discovery of the Electron 1897
J.J. Thomson’s Experiment

Crooke’s Paddlewheel Tube

Plum Pudding Model of the Atom 1904
Discovery of the Nucleus 1911
(E. Rutherford, H. Geiger, H. Marsden)

Rutherford's Experiment

Rutherford's Model of the Atom

Discovery of Neutron 1932
J. Chadwick's Experiment

What keeps the nucleons together?
Residual Strong Nuclear Force

Model of the Atom
Structure and Properties of the Nucleus

Terminology

• Nucleus / Nuclei
• Nuclides
• Nucleons
• Isotopes
• Radionuclides

Shape and Size of Nuclei

\[ r = r_0 A^{1/3} \text{ where } r_0 = 1.2 \text{ fm} \]

Formative Quiz

For a nucleus of mass number \( A \), find:

(a) An approximate expression for the mass of the nucleus.
(b) An approximate expression for the volume of the nucleus.
(c) A numerical value for its density.
(d) If the Earth were compressed until it has the density of a nucleus, how large would it be?

Assume that \( m_n \approx m_p \).

Units

• Nuclear charges
• Nuclear masses
• Nuclear energy
• Nuclear distances

Binding Energy and Nuclear Forces
Nuclear Binding Energy

\[ E_b = (Z m_p + N m_n - M_X) c^2 \] where \( c^2 = 931.494 \text{ MeV/u} \)

Nuclear binding energy per nucleon

\[ E_b / A \]

Formative Quiz

1. What is the binding energy and the binding energy per nucleon for the most common stable isotope of iron?

2. What is the binding energy of the last neutron in \(^{13}\text{C}\)?

Radionuclides

The Nuclear Age

- X-Rays
- Radioactivity
- Decay Processes
X-Rays

- Discovery of X-Rays
- Production of X-Rays
- What are X-Rays?
- Applications

Discovery of X-Rays
W. Roentgen 1895

First x-ray picture
Roentgen's wife left hand

Production of X-Rays

What are X-Rays?

High energy photons

\[ E = hf = \frac{hc}{\lambda} \]

Crookes X-Ray Discharge Tube

Applications

X-ray pictures of patient bodies

Customers and baggage check at airports

What did he swallow?

What did she swallow?
Radioactivity

- Discovery of Radioactivity
- Types of Radiation
- Decay Rate and Half-Life

Discovery of Radioactivity
Henri Becquerel 1896

Discovery of Radioactivity
Pierre and Marie Curie 1898
Discovery of Polonium and Radium

Radioactivity
Spontaneous emission of nuclear radiation from radionuclides.
Applications and Commercial Products

- Neutron source for neutron triggers in nuclear reactors and weapons.
- Kept Russian Moon rovers internal components warm during lunar nights.
- Tobacco
- Anti Static Brushes

Polonium Poisoning Cases

- 2006 Alexander Litvinenko
- 2012 Yasser Arafat
- Irène Joliot-Curie 1956

Radium

Applications and Commercial Products
Types of Nuclear Radiation

- **Alpha**
  - Helium nuclei $^4\text{He}$
  - Charge: $+2e$
  - Penetrating Power: Low (paper)

- **Beta**
  - Electrons/Positrons
  - Charge: $-e$ / $+e$
  - Penetrating Power: Medium (few cm of Al)

- **Gamma**
  - Photons
  - Charge: 0
  - Penetrating Power: High (several cm of Pb)

Decay Rate and Half-Life

- $N(t) = N_0 e^{-\lambda t}$
- $R(t) = R_0 e^{-\lambda t}$
- $R = \lambda N$
- $T_{1/2} = (\ln 2) / \lambda$
- $N = m N_0 / \text{molar mass}$

### Formative Quiz

1. Consider a sample of a thousand $^{14}\text{C}$ nuclei. How many will still be undecayed in 22,920 years?

2. (a) What is the decay constant of $^{226}\text{Ra}$?
   (b) If a sample contains $3.00 \times 10^{16}$ $^{226}\text{Ra}$ nuclei at $t = 0$, what is its activity in Curies at that time?
   (c) What is the activity when the sample is 2.00 x 10^3 year old?

3. At time $t = 0$, a radioactive sample contains 3.50 mg of pure $^{11}\text{C}$.
   (a) What is the number of radioactive nuclei at $t = 0$?
   (b) What is the activity of the sample initially and after 8.00 h?

4. A sample of the isotope $^{131}\text{I}$, which has a half-life of 8.04 days, has an activity of 5.00 mCi at the time of shipment. Upon receipt in a medical laboratory, the activity is 4.20 mCi. How much time has elapsed between the two measurements?

### Disintegration Energy (Q value)

Energy released during a nuclear decay

$$Q = (M_i - M_f) c^2$$

### Nuclear Decays

- Energy, momentum and nucleon number are conserved
- Less massive particles carry most of the energy
- Particles emitted created during emission process

### Decay Processes

- Disintegration Energy
- Alpha Decay
- Beta Decay
- Electron Capture
- Gamma Decay
- Energy-Level Diagrams
- Decays and Nuclide Chart
- Decay Series

### Alpha Decay

A radioactive nucleus emits an alpha particle (loses two protons and two neutrons)

$$^{\alpha}X \rightarrow ^{\alpha}Z-2\text{Y} + ^4\text{He}$$

$$Q = (M_X - M_Y - M_\alpha) c^2$$

$x$: parent nucleus $Y$: daughter nucleus $Y$ and $\alpha$: products of the decay
Formative Quiz
Radium Alpha Decay
(a) What is the Q value?
(b) Demonstrate that $Q = K_a$
(c) What is $K_a$?

Formative Quiz
The Poisoning of Alexander Litvinenko
The Radioactive Death of a Russian Spy
1 μg of $^{210}$Po was injected in Litvinenko’s body.
(a) Calculate the activity of the sample.
(b) Compare (ratio) to activity of class sample (0.1 μCi).
(c) Write the equation of the $^{210}$Po alpha decay.

Alpha Decay Application: The Smoke Detector
A nucleus decays by emitting an electron or a positron and an antineutrino or neutrino

$$^{h}X \rightarrow ^{h+1}Y + e^- + \text{anti } \nu_e$$
$$Q = (M_X - M_Y) c^2$$

$$^{h}X \rightarrow ^{h+1}Y + e^+ + \nu_e$$
$$Q = (M_X - M_Y - 2 m_e) c^2$$

Neutrinos
One of world’s biggest neutrino detector is in Canada SNO (Sudbury Neutrino Observatory)

Beta Decay Application: Carbon Dating
$^{14}\text{N} + n \rightarrow ^{14}\text{C} + p$
$^{14}\text{C} \rightarrow ^{14}\text{N} + e^- + \text{anti } \nu_e$
For all living organisms, \( \frac{^{14}\text{C}}{^{12}\text{C}} \approx 1.3 \times 10^{-12} \)

A piece of charcoal containing 25.0 g of carbon is found in some ruins of an ancient city. The sample shows a \( ^{14}\text{C} \) activity of 250 decays/min. How long has the tree from which this charcoal came been dead?

**Electron Capture or K-Capture**

A nucleus captures one of its orbital electron (K-shell).

\[
A_Z X + e^- \rightarrow A_{Z-1} Y + \nu
\]

\[ Q = (M_X - M_Y) c^2 = E_\nu \]

**Gamma Decay**

\[ A_Z X \rightarrow A_Z X + \gamma \]

- A nucleus undergoes alpha or beta decay and is left in an excited state.
- The nucleus undergoes a second decay to a lower energy state by emitting gamma rays.

**Energy-Level Diagrams**

- Beta-minus decay
  \[ ^{12}\text{B} \rightarrow ^{12}\text{C}^+ + e^- + \text{antib} \]
- Gamma decay
  \[ ^{12}\text{C}^+ \rightarrow ^{12}\text{C} + \gamma \]

**Summary Decay Pathways**

<table>
<thead>
<tr>
<th>Decay Pathway</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha decay</td>
<td>( \frac{1}{2}X \rightarrow \frac{1}{2}Y + \frac{1}{2}\text{He} )</td>
</tr>
<tr>
<td>Beta decay (e^-)</td>
<td>( \frac{1}{2}X \rightarrow \frac{1}{2}\text{He} + e^- + \nu )</td>
</tr>
<tr>
<td>Beta decay (e^+)</td>
<td>( \frac{1}{2}X \rightarrow \frac{1}{2}\text{He} + e^+ + \nu )</td>
</tr>
<tr>
<td>Electron capture</td>
<td>( \frac{3}{2}X + e^- \rightarrow \frac{3}{2}\text{He} + \nu )</td>
</tr>
<tr>
<td>Gamma decay</td>
<td>( \frac{3}{2}X \rightarrow \frac{3}{2}X + \gamma )</td>
</tr>
</tbody>
</table>
Formative Quiz

Identify the missing particle(s) X

1) $^{45}\text{Ca} \rightarrow X + e^- + \text{anti}\nu$ 
2) $^{58}\text{Cu}^* \rightarrow X + \gamma$ 
3) $^{36}\text{Cr} \rightarrow \text{Y} + X$ 
4) $^{238}\text{Pu} \rightarrow X + \alpha$ 
5) $^{239}\text{Np} \rightarrow ^{239}\text{Pa} + X$ 
6) $X + ^4\text{He} \rightarrow ^{24}\text{Mg} + n$ 
7) $^{235}\text{U} + n \rightarrow ^{90}\text{Sr} + X + 2n$ 
8) $2\ ^1\text{H} \rightarrow ^3\text{H} + X$

Decay Series

Our environment is constantly replenished with radioactive elements produced by the three natural decay series.

Quiz Nuclear Energy

1. What type of vessel was the first to be powered by a nuclear reactor?
   (a) Submarine
   (b) Battleship
   (c) Aircraft carrier
   (d) Destroyer

2. Which nation does NOT get at least 50 percent of its electricity from nuclear power?
   (a) France
   (b) Belgium
   (c) Sweden
   (d) Lithuania

3. Which nation has the world’s largest uranium deposit?
   (a) Australia
   (b) United States
   (c) Russia
   (d) Canada

4. How many nuclear power plants are in Australia?
   (a) 19
   (b) 9
   (c) 3
   (d) 0

5. Which U.S. state has the most operating commercial nuclear reactors?
   (a) Illinois
   (b) Pennsylvania
   (c) New York
   (d) California

6. Which is not found in an atom?
   (a) Electron
   (b) Cyclotron
   (c) Neutron
   (d) Proton
5. Who licenses nuclear power plants in the United States?
(a) The Atomic Energy Commission
(b) The Department of Energy
(c) The Nuclear Regulatory Commission
(d) Sandia National Laboratory

6. What element created in nuclear reactors is used to make most nuclear weapons?
(a) Polonium
(b) Cesium
(c) Plutonium
(d) Deuterium

7. Which nation quadrupled its output of electricity from nuclear power between 2000 and 2010?
(a) Japan
(b) China
(c) South Korea
(d) Thailand

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Nuclear Energy

- Nuclear Reactions
- Neutrons
- Fission
- Nuclear Reactors
- Fusion
- Thermonuclear Fusion in Stars
- Fusion on Earth: The Tokamak

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Nuclear Reactions

\[ a + X \rightarrow Y + b \]

\[ Q = (M_a + M_X - M_Y - M_b) c^2 \]

Formative Quiz

Can the reaction \( p + {}^{13}\text{C} \rightarrow {}^{14}\text{N} + n \) occur when \( {}^{13}\text{C} \) is bombarded by 2.0 MeV protons?

Fission

Discovered in 1938 by Otto Hahn

A heavy nucleus captures a thermal neutron and splits into two smaller nuclei.

Fission of Uranium 235

\[ {}^{235}\text{U} + n \rightarrow {}^{236}\text{U} \rightarrow {}^{141}\text{Ba} + 3{}^{92}\text{Kr} + 3n \]

200 MeV/fission event
Neutrons and Chain Reaction

Control Rods
Absorb thermal neutrons so they cannot initiate further fission reactions.

Nuclear Reactor

Fusion
Two light nuclei combine to form a heavier nucleus

Thermonuclear Fusion in Stars

Proton - Proton Cycle
Energy released in the fusion reactions in the proton-proton cycle

$$Q = (4 m_H - m_{He}) c^2 = 26.7 \text{ MeV}$$
CNO Cycle

Fusion Reactions on Earth

\[ ^2_1H + ^3_1H \rightarrow ^1_1H + ^3_1H \]
\[ ^2_1H + ^3_1H \rightarrow ^4_2He + n \]

What is the energy released?

Fusion on Earth

- High density of interacting particle (high collision rate)
- High plasma temperature \( T \approx 10^8 \) K (to overcome Coulomb's barrier)
- Long confinement time (magnetic or inertial)

Magnetic Confinement

Current-carrying wires

Magnetic field lines

Plasma

Magnetic Bottle

Tokamak

Toroidal vacuum chamber

External current

Poloidal

Plasma current

Plasma

Interior view of a Tokamak

Tokamak
Inertial Confinement

Laser Fusion