The ABC’s of Atomic Nuclei: The Modern Alchemist

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- The nucleus
- Chart of the nuclides
- Nuclear force
- Nuclear structure and excitations
- Radioactivity and fission
- Nuclear reactions and accelerators
- Quark effects inside nucleus
- Phases of nuclear matter
- Origin of the elements
- Applications of nuclear science

http://www.lbl.gov/abc
**Nucleus:** Discovered by Ernest Rutherford in 1911 in alpha particles scattering from atoms. It is the core of the atom, where most of its mass and all of its positive charge is concentrated. Except for $^1$H, the nucleus consists of a combination of protons and neutrons.

**Proton:** Nucleus of the hydrogen atom; carries same amount of charge ($\sim 1.6 \times 10^{-19}$ C) as electron but opposite sign; weights ($\sim 1.67 \times 10^{-27}$ kg or 938 MeV/c²) about 2000 times heavier than the electron; has spin $= \frac{1}{2} \hbar$. (Planck constant $\hbar \sim 1 \times 10^{-34}$ J·sec)

**Neutron:** discovered by James Chadwick in 1933; does not have charge; spin=$\frac{1}{2} \hbar$; slightly heavier than proton; half-life $\sim 10$ min ($n \rightarrow p + e^- + \bar{\nu}_e$).

**Nucleon:** either proton or neutron
~ 300 in nature
~ 1000 artificially produced
~ 6000 to be found

**Magic numbers**: 2, 8, 20, 28, 50, 82, 126 are neutron and/or proton numbers in nuclei with greater binding energy and stability.
Nuclear force

Nucleus is bounded by strong short-range attractive force between nucleons resulting from the exchange of the pion (π), first proposed by Hideki Yukawa in 1935 but was not found until 1947 by Cecil Powell.

**Pion**: mass ~ 1/7 of proton mass; has three different charges (e,0,-e); zero spin.

**Coulomb potential**

\[ V(r) \propto \frac{1}{r} \]

**Nuclear potential**

\[ V(r) \propto \frac{e^{-(m_c c / h) r}}{r} \]

Nuclear potential is ~ 100 times stronger than the Coulomb potential between electrons due to photon (γ) exchange.
**Nuclear size** can be measured from electron scattering as shown by Robert Hofstadter in 1957.

\[ \rho(r) = \frac{c}{1 + e^{(r-R)/a}} \]

Woods-Saxon form

Central nuclear density \( \rho_0 \sim A c \sim A/Z \cdot Z c \sim 0.16 \text{ fm}^{-3} \)

Diffuseness \( a \sim 0.5 \text{ fm} \)

Surface thickness \( t = (4\ln3)a \sim 2.3 \text{ fm} \)

Radius \( R \sim 1.2 \text{ A}^{1/3} \text{ fm} \)

Nuclei behave like liquid drops!
Nuclear mass can be expressed by liquid drop formula as suggested by Weizsäcker (1935); Bethe & Bacher (1936).

**Binding energy**: Minimum energy required to dissociate a nucleus into its constituent protons and neutrons; ~ 8 MeV per nucleon.

\[
B \equiv [Zm_p + Nm_n - \frac{A}{Z} m]c^2 \\
\approx a_v A - a_s A^{2/3} - a_{sys} \frac{(N-Z)^2}{A} - a_c \frac{Z^2}{A^{1/3}}
\]

\[56_{\text{Fe}}\]

\[a_v \sim 16 \text{ MeV}, a_s \sim 17 \text{ MeV}, a_{sys} \sim 25 \text{ MeV}, a_c \sim 0.7 \text{ MeV}\]
**Collective model**: A large number of nucleons can execute collective motions; introduced by Bohr, Mottelson & Rainwater in ~1950 for understanding nuclear rotational and vibrational excitations.

Rotational excitations

<table>
<thead>
<tr>
<th>$E$(MeV)</th>
<th>$J^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.186</td>
<td>12$^+$</td>
</tr>
<tr>
<td>1.635</td>
<td>10$^+$</td>
</tr>
<tr>
<td>1.137</td>
<td>8$^+$</td>
</tr>
<tr>
<td>0.704</td>
<td>6$^+$</td>
</tr>
<tr>
<td>0.355</td>
<td>4$^+$</td>
</tr>
<tr>
<td>0.112</td>
<td>2$^+$</td>
</tr>
</tbody>
</table>

$^{174}$W

Quadrupole vibrational excitations

<table>
<thead>
<tr>
<th>$E$(MeV)</th>
<th>$J^\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.202</td>
<td>2$^+$</td>
</tr>
<tr>
<td>1.162</td>
<td>4$^+$</td>
</tr>
<tr>
<td>1.103</td>
<td>0$^+$</td>
</tr>
<tr>
<td>0.560</td>
<td>2$^+$</td>
</tr>
<tr>
<td>0</td>
<td>0$^+$</td>
</tr>
</tbody>
</table>

$^{120}$Te

$E_J = \frac{J(J+1)\hbar^2}{2I}$, $J=0, 2, 4, \ldots$

$\hbar$=angular momentum (h)

$\pi$=parity; $I$=moment of inertia
Shell model: Nucleons occupy shell-like orbits inside nucleus; proposed by Maria Meyer & Hans Jensen in ~1949 to explain the magic numbers and the single-particle excitations in nuclei.

Protons and neutrons are fermions which satisfy the Pauli exclusion principle (proposed by Wolfgang Pauli in 1933) that no two fermions can occupy same quantum state.
Radioactivity

- **Alpha decay**: the nucleus releases an alpha particle (\(^4\)He)

\[
\frac{235}{92} \text{U} \rightarrow \frac{231}{90} \text{Th} + \frac{4}{2} \text{He}, \quad \tau_{1/2} \approx 7 \times 10^8 \text{ yr}
\]

- **Beta decay**: the nucleus either emits an electron and antineutrino or a positron and neutrino

\[
\begin{align*}
\frac{14}{6} \text{C} &\rightarrow \frac{14}{7} \text{N} + e^- + \bar{\nu}_e, \quad \tau_{1/2} \approx 5730 \text{ yr} \\
\frac{18}{9} \text{F} &\rightarrow \frac{18}{8} \text{O} + e^+ + \nu_e, \quad \tau_{1/2} \approx 110 \text{ min}
\end{align*}
\]

- **Gamma decay**: the nucleus lowers its internal energy by emitting a photon

\[
\frac{174}{74} \text{W}^* \left(0.112 \text{ MeV}\right) \rightarrow \frac{174}{74} \text{W} + \gamma, \quad \tau_{1/2} \approx 1.14 \text{ ns}
\]
**Fission**: A nucleus can split into two large fragments; discovered by Hahn and Strassman in 1939; and explained by Meitner and Frisch as well as Bohr and Wheeler in same year.

\[
n + ^{235\text{U}}_{92} \rightarrow ^{134\text{Xe}}_{54} + ^{100\text{Sr}}_{38} + \text{n}
\]

Fission occurs as a result of quantum tunneling through the fission barrier. Normally, \(^{235}\text{U}\) decays by alpha emission with only \(~7\times10^{-9}\) probability for fission due to a high fission barrier. A thermal neutron is needed to induce the fission by exciting the nucleus, leading to a lower fission barrier thus a larger tunneling probability.
Nuclear reactions and accelerators

With energetic particles ($e^-, p, d, \pi, \cdots$) from Van de Graaff generator (~1931), cyclotrons (invented by Ernest Lawrence ~1939) and modern accelerators, we can study the properties of nuclei and create new isotopes, e.g.

- Continuous Electron Beam Accelerator Facility (CEBAF) @ Thomas Jefferson National Laboratory 6 GeV (upgrade to 12 GeV)
  - Excited states of $p$ & $n$
  - Quark effects in nuclei

- Relativistic Heavy Ion Collider (RHIC) @ Brookhaven National Laboratory
  - $p+p$, $Au+Au@100$ GeV/A
  - Quark-gluon plasma
  - Proton structure

- TAMU K500 Superconducting Cyclotron
  - Variety of beams <100 MeV/A
    - Nuclear collective motions
    - Exotic nuclei
    - Hot nuclei
    - Nuclear reactions relevant to nucleosynthesis
Quark effects inside nucleus
Phases of nuclear matter

As nuclei are heated, they transform from a liquid to a gas of nucleons. With further heating, nucleons are excited to their resonances (N and Δ) and emit pions (π) and kaons (K) as well as other meson resonances (ρ, ω, K*), forming a hadronic gas. At extreme high temperature, hadrons dissolve into a plasma of quarks and gluons. Under compressions, nucleons inside nuclei lose their identity and form a dense matter of quarks.

Heavy ion collisions make it possible to heat and compress the nuclear matter and thus study the properties of nuclear matter under extreme conditions.
Origin of the elements

History of the Universe

Big Bang
Quark-Gluon Plasma
$10^{13}$K, 10^-6s

Protons & Neutrons
$10^{12}$K, 10^-4s

Low-mass Nuclei
$10^9$K, 3 min

Neutral Atoms
4000K, 10^5y

Star Formation
10^9y

Heavy Elements
>10^9y

Today

Source: Nuclear Science Wall Chart
Nuclear reactions during the first three minutes

- \( kT > 800 \text{ keV} \): neutrons and protons were in chemical equilibrium

\[
\frac{\rho_n}{\rho_p} \approx 0.2 \quad \text{at} \quad kT \approx 800 \text{ keV}
\]

- \( 800 \text{ keV} > kT > 60 \text{ keV} \): neutrons decayed freely (\( n \rightarrow p + e^- + \bar{\nu}_e \))

\[
\frac{\rho_n}{\rho_p} \approx 0.1 \quad \text{at} \quad kT \approx 60 \text{ keV}
\]

- \( 60 \text{ keV} > kT > 30 \text{ keV} \): nucleosynthesis occurred

\[
\begin{align*}
\text{n+p} & \rightarrow ^2\text{H} + \gamma \\
^2\text{H} + \text{n} & \rightarrow ^3\text{H} + \gamma \quad \text{or} \quad ^2\text{H} + \text{p} \rightarrow ^3\text{He} + \gamma \\
^2\text{H} + ^2\text{H} & \rightarrow ^4\text{He} + \gamma \\
^3\text{He} + \text{n} & \rightarrow ^4\text{He} + \gamma \quad \text{or} \quad ^3\text{H} + \text{p} \rightarrow ^4\text{He} + \gamma
\end{align*}
\]

Premodial He/\(H\) ratio

\[
\frac{\rho_{\text{He}}}{\rho_H} \approx 0.25
\]

Absence of stable nuclei at \( A=5 \) or 8 prevents the production of heavy elements during big bang nucleosynthesis.
Nuclear reactions inside stars: proposed by Hans Bethe in 1939

**Hydrogen burning (7X10^6 y)**
- Common to all chains
  - \( p + p \rightarrow d + e^+ + \nu_e \)
  - \( d + p \rightarrow ^3\text{He} + \gamma \)

  PPI-chain
  - \( ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + p + p \)

  PPII-chain
  - \( ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \)
  - \( ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \gamma \)
  - \( ^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He} \)

  PPIII-chain
  - \( ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \)
  - \( ^8\text{B} \rightarrow ^4\text{He} + ^4\text{He} + e^+ + \nu_e \)

**Helium burning (5X10^5 y)**
- \( ^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be} \)
- \( ^4\text{He} + ^8\text{Be} \rightarrow ^{12}\text{C} + \gamma \)
- \( ^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{O} + \gamma \)

**CNO cycle**
- \( ^{12}\text{C} + p \rightarrow ^{13}\text{N} + \gamma \)
- \( ^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu_e \)
- \( ^{13}\text{C} + p \rightarrow ^{14}\text{N} + \gamma \)
- \( ^{14}\text{N} + p \rightarrow ^{15}\text{O} + \gamma \)
- \( ^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu_e \)
- \( ^{15}\text{N} + p \rightarrow ^{12}\text{C}^4 + ^4\text{He} \)

**Carbon burning (600 y)**
- \( ^{12}\text{C} + ^{12}\text{C} \rightarrow ^{24}\text{Mg} + \gamma \)
  - \( \rightarrow ^{23}\text{Na} + p \)
  - \( \rightarrow ^{23}\text{Mg} + n \)
  - \( \rightarrow ^{20}\text{Ne}^4 + ^4\text{He} \)
  - \( \rightarrow ^{16}\text{O}^4 + ^4\text{He}^4 + ^4\text{He} \)

**Neon burning (1 y)**
- \( ^{20}\text{Ne} + \gamma \rightarrow ^{16}\text{O} + ^4\text{He} \)
- \( ^{20}\text{Ne} + ^4\text{He} \rightarrow ^{24}\text{Mg} + \gamma \)

**Oxygen burning (6 mon)**
- \( ^{16}\text{O} + ^{16}\text{O} \rightarrow ^{32}\text{S} + \gamma \)
  - \( \rightarrow ^{31}\text{P} + p \)
  - \( \rightarrow ^{31}\text{S} + n \)
  - \( \rightarrow ^{28}\text{Si} + ^4\text{He} \)
  - \( \rightarrow ^{28}\text{Mg}^4 + ^4\text{He}^4 + ^4\text{He} \)

**Silicon burning (1 d)**
- \( ^{28}\text{Si} + ^{28}\text{Si} \rightarrow ^{56}\text{Ni} + \gamma \)
- \( ^{56}\text{Ni} \rightarrow ^{56}\text{Co} + e^+ + \nu_e \)
- \( ^{56}\text{Co} \rightarrow ^{56}\text{Fe} + e^+ + \nu_e^{16} \)

**Time scales for stars of 25 solar mass**
Precollapse structure of massive stars

Through neutron captures and beta decays in supernova or neutron-star collisions, nuclei heavier than Fe can be produced (Burbidge, Burbidge, Fowler, and Hoyle, 1957).

**Figure 10-6**: Schematic diagram showing the dominant nuclear components, temperature, and density in different layers of a massive star prior to supernova explosion [120].
Applications of nuclear science

- Medicine/Biology
  - Radioisotope Production
  - Imaging Detectors
  - Biophysical Modeling
  - Cancer Therapy
  - Positron Emission Tomography
  - Radiation Effects

- Art/Archaeology
  - radioactive Dating
  - Ion Beam Analysis

- Energy
  - Nuclear Power
  - Muon Catalyzed Fusion
  - Heavy Ion Fission
  - Transmutation of Waste from Nuclear Power Plants

- Environment
  - Climate
  - Groundwater
  - Waste Cleanup
  - Radon

- Materials
  - Ion Implantation
  - Micropore Filters
  - Wear Testing
  - Nanostructures
  - Radiation Damage

- Space Applications
  - Single Event Effects
  - Detector Calibrations
  - Radiation Damage
Radioactive dating
Use naturally occurring radioactive isotopes ($^{14}$C) for dating objects that were once living.

Smoke detectors
Use alpha emitter $^{241}$Am to ionize the air.

Nuclear medicine:
Use radioactive isotopes for diagnosing and treating disease ($^{99m}$Tc, $^{60}$Co, $^{131}$I) as well as for generating images of brain activity ($^{18}$F) via Positron Emission Tomography (PET).

Magnetic Resonance Imaging (MRI): Use nuclear magnetic transitions to produce 3-D images of the human body.

Space exploration
Use alpha particles for identifying chemical elements present in Martian rocks.

Nuclear reactors:
Use fission of $^{235}$U and $^{239}$Pu nuclei to produce electric power.