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19 The Nucleus

Protons
Neutrons } Nucleons

Total number of nucleons: mass number → 238
Number of protons: atomic number → 92

$^{238}_{92}\mathrm{U}$

Isotopes: identical atomic numbers
different mass numbers
same chemical properties
different nuclear properties

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※ Nuclear stability and radioactive decay

Radioactivity: reflects kinetic stability

◎ Types of radioactive decay

✓ Frequently accompanied by γ-ray emission
high energy electromagnetic radiation

✓ α-particle production

$$^{238}_{92}\mathrm{U} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{234}_{90}\mathrm{Th}$$

α particle

✓ β-particle production

$$^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e} \qquad ({}^{1}_{0}\mathrm{n} \rightarrow {}^{1}_{1}\mathrm{p} + {}^{0}_{-1}\mathrm{e})$$

β particle

✓ Positron production

positron

$^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + {}^{0}_{1}\mathrm{e}$

$({}^{1}_{1}\mathrm{p} \rightarrow {}^{1}_{0}\mathrm{n} + {}^{0}_{1}\mathrm{e})$

$({}^{0}_{-1}\mathrm{e} + {}^{0}_{1}\mathrm{e} \rightarrow 2\,{}^{0}_{0}\gamma)$

✓ Electron capture

$^{201}_{80}\mathrm{Hg} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{201}_{79}\mathrm{Au} + {}^{0}_{0}\gamma$

inner-orbital electron

✓ Spontaneous fission (usually slow)

$^{254}_{98}\mathrm{Cf} \rightarrow$ lighter nuclides + neutrons

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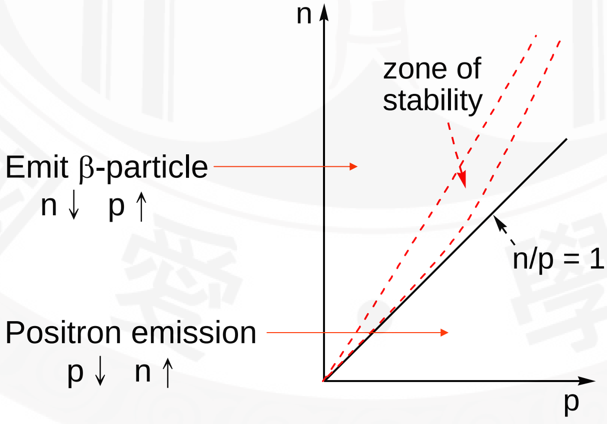
◎ Empirical rule of nuclear stability (prone to decay)

- With ≧ 84 protons: less stable

  lighter nuclides:
  n/p closer to 1 → more stable
  p ↑ → ratio ↑



- With even numbers of ps and ns → more stable

stable isotopes	p	n
168	even	even
57	even	odd
50	odd	even
4	odd	odd

- With magic numbers of ps or ns
  2, 8, 20, 50, 82, 126 → more stable

stable isotopes	p
3	18
2	19
5	20 (Ca)
1	21

◎ Decay series

emission in a series

$${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} \rightarrow \rightarrow {}^{206}_{82}\text{Pb}$$

※ The kinetics

Decay is an unimolecular process

$$\text{Rate} = -\frac{dN}{dt} = kN \quad (N \text{ for number of nuclides})$$

$$\Rightarrow \qquad \ln\left(\frac{N}{N_0}\right) = -kt \qquad\qquad t_{1/2} = \frac{0.693}{k}$$

A characteristic value

Unaffected by *T*, *P* or chemical form

No way to stop!!

Ex. $^{238}_{92}\text{U}$ half-life: 4.5×10^{9} yr

✓ Dating

C-14 method

$$^{14}_{7}\text{N} + {}^{1}_{0}\text{n} \rightarrow {}^{14}_{6}\text{C} + {}^{1}_{1}\text{H}$$

$$^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\text{e}$$

$t_{1/2}$ = 5730 yr

In atmosphere: reaching an equilibrium

$^{14}_{6}\text{C}/^{12}_{6}\text{C}$ remains constant

$^{*}CO_2$ → *Organic molecule in plants → *animals

↓

From $^{14}C/^{12}C$ to determine age ← decay ← died

(equilibrium stops)

Ex. If ratio is half that of atmosphere

→ 5370 yr old

Limitation: can not be older than 20000 yr

→ radioactivity too low to be accurate

Checked with tree growth: accurate within 10%

Oldest rock: 3×10^9 yr

Cooling time for earth surface: $1–1.5 \times 10^9$ yr

Age of earth at about: $4.0–4.5 \times 10^9$ yr

Ex. A rock with 0.115 mg ^{206}Pb/1.000 mg ^{238}U

Assuming ^{206}Pb is coming from ^{238}U

→ The original amount of ^{238}U was

$$\underbrace{(\frac{0.115}{206} \times 238)}_{\text{The amount decayed}} + 1.000 = 1.133\,\text{mg}$$

For ^{238}U $t_{1/2} = 4.5 \times 10^9$ yr $= 0.693/k$

→ $k = 0.693/4.5 \times 10^9\ \text{yr}^{-1}$

$$\ln\frac{N}{N_o} = -kt = \ln(\frac{1.000}{1.133}) = -(\frac{0.693}{4.5 \times 10^9\,\text{yr}})t$$

⇨ $t = 8.1 \times 10^8$ yr

※ Nuclear transformations

The change of one element into another

1919 Rutherford

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

From Ra with high velocity

Particle accelerator

cyclotron, synchrotron, linear accelerator
to accelerate charged particle in order to overcome electrostatic repulsion

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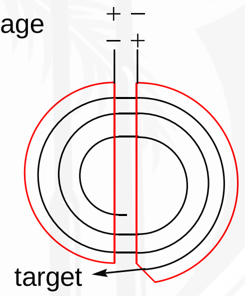
Cyclotron

High frequency alternating voltage in a vacuum chamber

With vertical magnetic field



✓ Neutron bombardment

no acceleration is necessary
more common for isotopes synthesis

neutral (generated from nuclear reactor)

$${}^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{239}_{92}\text{U} \rightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}\text{e}$$

$t_{1/2}$ = 23 min

Elements with atomic # > 92 are synthesized via artificial transmutations – transuranium elements

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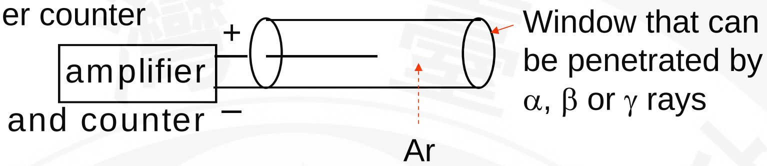
※ Detection of radioactivity

✓ Geiger counter



Detect ionization by radiation

✓ Scintillation counter (閃爍計數器)

$$\text{ZnS} \xrightarrow{\text{high-E radiation}} \text{flurorescence}$$

(caused by electronic excitation)

↓

measurement

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※ Thermodynamic stability

Ex. $8\,{}^{1}_{0}\text{n} + 8\,{}^{1}_{1}\text{H} \rightarrow {}^{16}_{8}\text{O}$

n　H

Mass of reactants = $8(1.67493 \times 10^{-24}) + 8(1.67262 \times 10^{-24})$ g
= 2.67804×10^{-23} g

Mass of product = 2.65535×10^{-23} g

Smaller by 0.1366 g/mol

Einstein: mass energy conversion

$E = mc^2$ (c: speed of light = 3.00×10^8 m/s)

$\Delta E = \Delta mc^2 = (-1.366 \times 10^{-4}\ \text{kg/mol})(3.00 \times 10^8\ \text{m/s})^2$
$= -1.23 \times 10^{13}$ J/mol or -2.04×10^{-11} J per nucleus
$= -1.28 \times 10^{-12}$ J per nucleon
$= -8.00$ MeV/nucleon (1 MeV = 1.60×10^{-13} J)

The reverse is the binding energy per nucleon

Ex. The binding E per nucleon for the ${}^{4}_{2}$He nucleus

AW(He) = 4.0026 amu AW(H) = 1.0078 amu

Mass including electrons

Mass of ${}^{4}_{2}$He nucleus = AW(He) – $2m_e$

Mass of e⁻

Mass of ${}^{1}_{1}$H nucleus = AW(H) $-m_e$

$\Delta m = (4.0026 - 2m_e) - [2(1.0078 - m_e) + 2m_n]$

Mass of neutron

$= 4.0026 - 2(1.0078) - 2(1.0087)$

$= -0.0304$ amu

$\Delta E = \Delta mc^2 = (-0.0304\ \text{amu})(1.66\times10^{-27}\ \text{Kg/amu})(3.00\times10^{8}\ \text{m/s})^2$

$= -4.54 \times 10^{-12}$ J/nucleus ⇨ 1.14×10^{-12} J/nucleon

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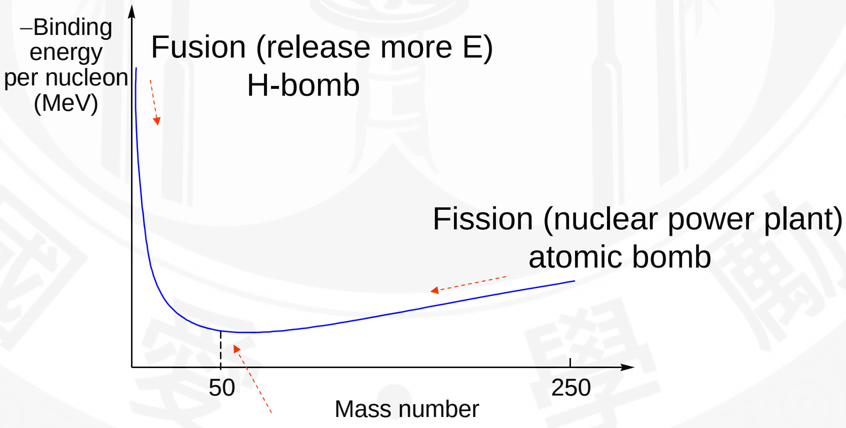
※ Nuclear fission and fusion



Fusion (release more E)
H-bomb

Fission (nuclear power plant)
atomic bomb

Most stable: ${}^{56}_{26}$Fe

◎ Fission

Ex. $^{1}_{0}n + ^{235}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$

$\downarrow$

Further fission

Cover 200 isotopes, 35 elements
Produce 2.4 neutron in average

More neutrons are produced – may be explosive

✓ Size of the sample

Too small: neutron escapes before striking a nucleus
– subcritical

Too large: neutrons are completely consumed
– super critical

In between: chain reactions keep at a constant rate
(one for one)
– critical

◎ Nuclear reactor

keep a self-sustaining chain reaction

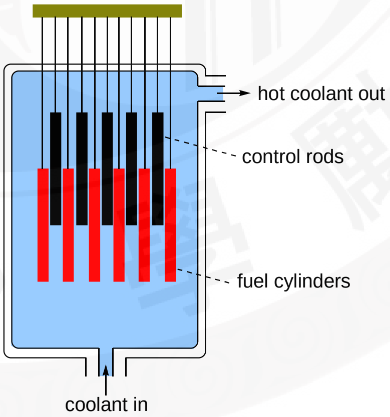
^{235}U enriched to 3% (natural abundance: 0.724)

→ UO_2 pellets in Zr or stainless steel tubes

Control rods: made of Cd or B to absorb neutrons

$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He$

Water used as moderator (slow down neutrons but not reacting)



Nuclear power → thermal E → steam → steam engine

Nuclear power ↓ biproducts → reprocess → reusable fuel

steam engine ↓ electricity generation

reprocess ↓ waste

such as ${}^{90}\mathrm{Sr}$ $t_{1/2} = 28.8$ yr

${}^{239}\mathrm{Pu}$ $t_{1/2} = 2400$ yr

◎ Fusion

In the sun

$${}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{1}\mathrm{e}$$

$${}^{1}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He}$$

$${}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2{}^{1}_{1}\mathrm{H}$$

$${}^{3}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{0}_{1}\mathrm{e}$$

Products are generally not radioactive

High E necessary : to overcome repulsions
occurs at high T

※ Effect of radiation

Somatic damage: damage to the organism itself
Genetic damage: damage to the genetic machinery

Biological effects

- The energy
  measured in rads (radiation absorbed dose)
  1 rad = 10^{-2} J/kg tissue
- The penetrating ability
  α – stops at skin
  β – down 1 cm
  γ – highly penetrating (the most dangerous)
- The ionizing ability
  α – very damaging
- The chemical property of the source

Overall effect: rem = rad × RBE