20 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

	Natural abundance
$^{233}_{92}\mathrm{U}$	Trace
$^{235}_{92}\mathrm{U}$	0.7%
$^{238}_{92}\mathrm{U}$	99.3%

※ 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

$$^{238}_{92}\mathrm{U} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{234}_{90}\mathrm{Th}\,(+\,2\,{}^{0}_{0}\gamma)$$

α particle

two different frequencies

✓ 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

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

Positron (anti-matter of electron)

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

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

annihilation

✓ 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

✓ Decay series

emission in a series

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

Half-life: 4.5×10^{9} years

◎ Empirical rule of nuclear stability (prone to decay)

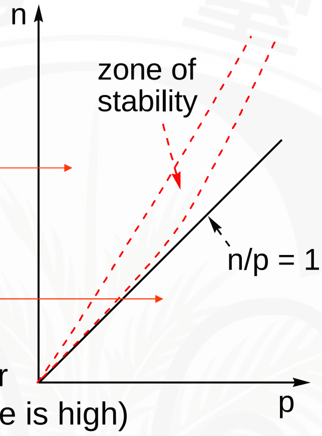
- With even numbers of ps and ns → more stable

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

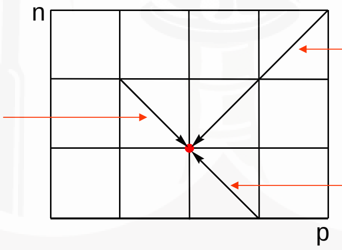
- With ≧ 84 protons: less stable
  lighter nuclides:
  n/p closer to 1 → more stable
  p ↑ → ratio ↑



Emit β-particle
n ↓ p ↑

Positron emission
p ↓ n ↑
or e⁻ capture (easier when nuclear charge is high)

α emission – with atomic number > 83
decreases n and p by 2



α emission

β emission

positron emission
electron capture

Ex. $^{20}_{11}Na$ n/p = 9/11

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

$^{97}_{40}Zr$ n/p = 57/40

$^{97}_{40}Zr \rightarrow {}^{97}_{41}Nb + {}^{0}_{-1}e$

$$^{235}_{92}\text{U} \rightarrow {}^{4}_{2}\text{He} + {}^{231}_{90}\text{Th}$$

Note: Empirical only

exceptions: $^{147}_{60}\text{Nd}$ radioactive (within the belt)

$^{233}_{90}\text{Th}$ → expect α decay
in fact → β decay

※ The kinetics

Decay is an unimolecular process

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

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

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

$^{60}_{27}\text{Co}$ half-life: 5.3 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 $^{14}\text{C}/^{12}\text{C}$ 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%

Mass spec. can be used to determine the ratio

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

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

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

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

⇨ $t = 8.1 \times 10^8$ yr

※ Nuclear transformations

The change of one element into another
a way to prepare new nuclei

1919 Rutherford

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

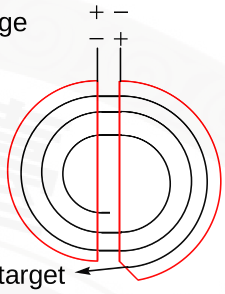
From Ra with high velocity

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

Cyclotron

High frequency alternating voltage
in a vacuum chamber

With vertical magnetic field



✓ Neutron bombardment

no acceleration is necessary (no repulsion)
more common for isotopes synthesis

neutral (generated from nuclear reactor)

$${}^{58}_{26}\mathrm{Fe} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{59}_{26}\mathrm{Fe}$$

$${}^{59}_{26}\mathrm{Fe} \rightarrow {}^{59}_{27}\mathrm{Co} + {}^{0}_{-1}\mathrm{e}$$

$${}^{59}_{27}\mathrm{Co} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{60}_{27}\mathrm{Co}$$

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

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

neptunium

$t_{1/2}$ = 23 min

$t_{1/2}$ = 2.35 days

$${}^{239}_{93}\mathrm{Np} \rightarrow {}^{239}_{94}\mathrm{Pu} + {}^{0}_{-1}\mathrm{e}$$

plutonium

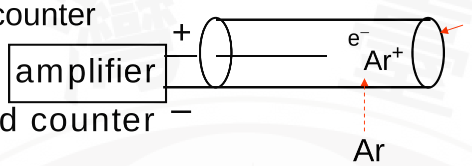
$${}^{239}_{94}\mathrm{Pu} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{242}_{96}\mathrm{Cm} + {}^{1}_{0}\mathrm{n}$$

$${}^{242}_{96}\mathrm{Cm} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{245}_{98}\mathrm{Cf} + {}^{1}_{0}\mathrm{n}$$

$t_{1/2}$ = 44 min

※ Detection of radioactivity

✓ Geiger counter



Window that can be penetrated by α, β or γ rays

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

※ Applications

✓ Radiotracers

$$6\ {}^*CO_2 + 6\ H_2O \xrightarrow[\text{chlorophyll}]{h\nu} {}^*C_6H_{12}O_6 + 6\ O_2$$

✓ Radiation therapy

I-131 concentrated in thyroid gland

✓ Positron emission tomography (PET)

C-11 in glucose – study brain metabolism

※ Thermodynamic stability

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

n H

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

Mass of product $= 2.65535 \times 10^{-23}$ g

Smaller by 0.1366 g/mol

Einstein: mass energy conversion
$E = mc^2$ (c: speed of light $= 3.00 \times 10^{8}$ m/s)

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

The reverse is the binding energy per nucleon

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

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

Mass including electrons

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

Mass of e$^-$

Mass of ${}^{1}_{1}\mathrm{H}$ 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

$\Delta E = \Delta mc^2 = (-0.0304\ \mathrm{amu})(1.66 \times 10^{-27}\ \mathrm{Kg/amu})(3.00 \times 10^{8}\ \mathrm{m/s})^2$
$= -4.54 \times 10^{-12}$ J/nucleus ⇨ 1.14×10^{-12} J/nucleon

Overall: $2.73 \times 10^{12}\ \mathrm{J/mol} + {}^{4}_{2}\mathrm{He} \rightarrow 2\,{}^{1}_{1}\mathrm{p} + 2\,{}^{1}_{0}\mathrm{n}$

Note: When dealing with a nuclear reaction:
number of electrons does not change

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + {}^{0}_{-1}\mathrm{e}$$

Atomic mass: $\underbrace{59.338}_{27\ e^-}$ $\underbrace{59.9308}_{28\ e^-}$ Mass: 0.000549

In fact a Ni^+ (27 e^-)

The difference of atomic mass is sufficient

$\Delta m = (m_{Ni} - 28m_e) + m_e - (m_{Co} - 27m_e)$
$= 59.9308 - 59.9338 = -0.0030$ amu

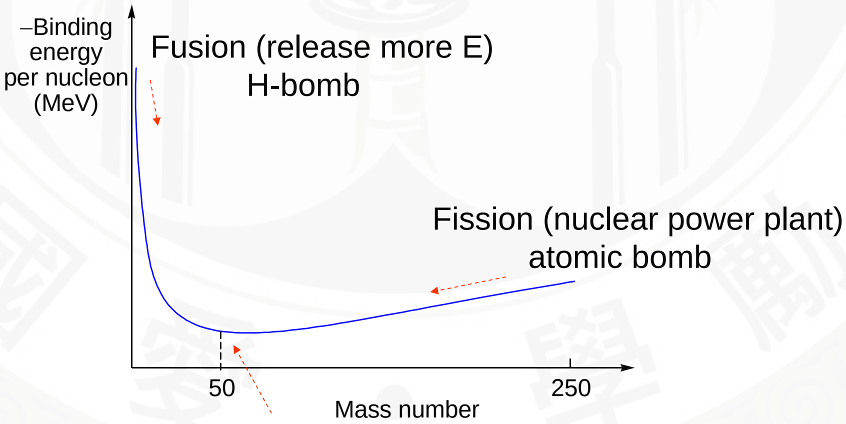
$\Delta E = \Delta mc^2 = -2.7 \times 10^{11}$ J/mol

✓ For reactions involving positron

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

$\Delta m = (m_D - 1m_e) + m_e - 2(m_H - 1m_e)$
$= m_D - 2m_H + 2m_e$ ← $1e^- + 1e^+$

※ Nuclear fission and fusion



Fusion (release more E)
H-bomb

Fission (nuclear power plant)
atomic bomb

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

◎ Fission

The first (in 1930s):

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

↓

Further fission

Covers 200 isotopes, 35 elements
Produces 2.4 neutron in average

More neutrons are produced – may be explosive

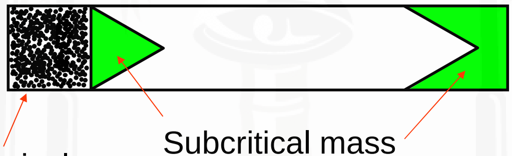
✓ Size of the sample

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

✓ Atomic bomb



Chemical explosives

Subcritical mass

⇩

When combined ⇨ supercritical mass

◎ Nuclear reactor

keep a self-sustaining chain reaction

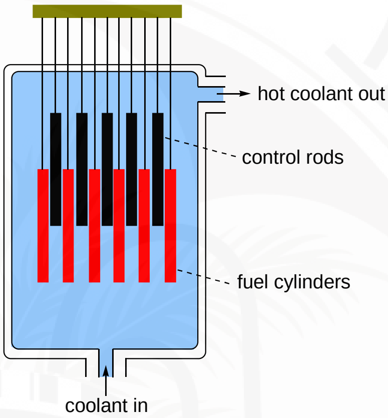
^{235}U enriched to 3% (natural abundance: 0.724)

→ UO_2 pellets in Zr or stainless steel tubes

Control rods: made of Cd or B to absorb neutrons

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

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



Nuclear power → thermal E → steam → steam engine

↓ biproducts → reprocess → reusable fuel

↓ waste

such as ^{90}Sr $t_{1/2} = 28.8$ yrs

^{239}Pu $t_{1/2} = 24400$ yrs

steam engine ↓ electricity generation

✓ Fuels other than ^{235}U

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

$t_{1/2} = 23$ min

$t_{1/2} = 2.35$ days

$$^{239}_{93}\text{Np} \rightarrow ^{239}_{94}\text{Pu} + ^{0}_{-1}\text{e}$$

Breeder (toxic and flammable)

◎ Fusion

In the sun $^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + {}^{0}_{1}e$

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

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

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

Products are generally not radioactive

High E necessary : to overcome repulsions
occurs at high T – thermonuclear rxns

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

At 40,000,000 K – lowest of its kind
↑
Initiated by an atomic bomb – hydrogen bomb

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※ Radiation dose

SI unit
becquerel – one nuclear disintegration/s
curie (Ci) – number of disintegration/s from 1 g of Ra
= 3.7×10^{10} disintegration/s

rad (radiation absorbed dose) – same as roentgen
deposits 1×10^{-2} J/kg tissue

RBE (relative biological effectiveness)

$\beta \sim 1$
$\gamma \sim 1$
$\alpha \sim 10$

rem (roentgen equivalent for man) = (# of rads) × RBE
命目

※ 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 (within body: most damaging)
  β – down 1 cm
  γ – highly penetrating (the most dangerous)

radiation	concrete	lead
β		1 mm
γ	2 m	10 cm

$$H_2O \xrightarrow{\gamma} H_2O\cdot^+ \xrightarrow{H_2O} H_3O^+ + HO\cdot$$

A free radical

- The ionizing ability
  α – very damaging
- The chemical property of the source

Overall effect: rem = rad × RBE

Short time exposure

0 – 25 rem	no detectable effect
25 – 50 rem	slight temp. decrease of white blood cell
100 – 200 rem	nausea, marked decrease of white blood cell
500 rem	death within 30 D for ½ exposed population

Typical radiation exposure per person

From nature	300 mrem/year
(from radon)	200
X-ray	~50
Power plant	~0.2
Total	~370 mrem/year

* ${}^{222}_{86}\mathrm{Rn}$ – decay product of ${}^{238}_{92}\mathrm{U}$ (earth's crust)

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Reinventing Chemistry

The person next to me says, "What do you do?" I answer "Im a chemist." S/he responds: "Chemistry was the one course in high school I flunked. What is it that chemists do, anyway?" I have tried two types of answers.

"Well, we make drugs. Like statins. Very useful. They are inhibitors of a protein called HMGA-CoA reductase, and they help to control cholesterol biosynthesis and limit cardiovascular disease."

"We change the way you live and die."