Chapter 18:

The Nucleus: A Chemist's View

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nucleons { (Composed of)

atomic number (Z)： # of protons

mass number (A)： (# of protons) + (# of neutrons)

isotopes：有相同之 but 不同之

nuclide：指一特定之原子 $^{A}_{Z}X$

Nucleus 的特點

- **Small size**

  radius of a typical nucleus: ~ cm

  radius of a typical atom: ~ cm

- **Very large density**

  density of the nucleus ~ 1.6 $\times 10^{14}$ g/cm^3

  一顆乒乓球大小之 nucleus material 質量 ~ 2.5 $\times 10^{9}$ tons

- **Huge energy that holds it together**

  nuclear process 牽涉之 energy 為一般化學反應之數百萬倍

18.1 Nuclear Stability & Radioactive Decay

thermodynamic stability vs. kinetic stability

- **輻射衰變** (radioactive decay) **之** **均需守恆**

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

- **已知約** 2000 nuclides，**僅** 279 **種為穩定** (with respective to radioactive decay)
- **元素具有最多之穩定同位素** – 10 **種**

- All nuclides with $Z \geq$ are unstable with respective to radioactive decay.
- Light nuclides are stable when neutron/proton ˜ 1.

  Heavy nuclides are stable when neutron/proton > 1 (which increases with Z).
- **某些質子數與中子數的組合似乎特別穩定，通常具偶數質數與偶數中子的組合較具奇數者為穩定**
- **某些質子數與中子數會形成特別穩定之** nuclides

  These magic numbers are 2, 8, 20, 28, 50, 82, & 126.

Fig. 18.1:
The zone of stability.

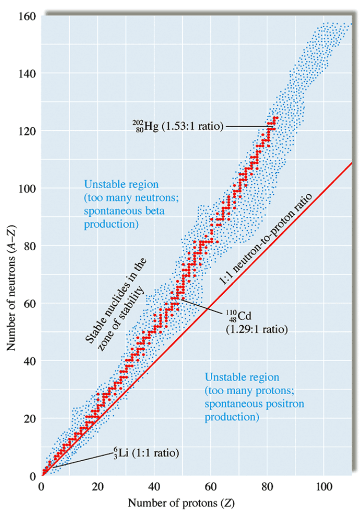


TABLE 18.1 Number of Stable Nuclides Related to Numbers of Protons and Neutrons

Number of Protons	Number of Neutrons	Number of Stable Nuclides	Examples
Even	Even	168	$^{12}_{6}C$, $^{16}_{8}O$
Even	Odd	57	$^{13}_{6}C$, $^{47}_{22}Ti$
Odd	Even	50	$^{19}_{9}F$, $^{23}_{11}Na$
Odd	Odd	4	$^{2}_{1}H$, $^{6}_{3}Li$

Types of Radioactive Decay

- *a*-particle production :

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

- *b*-particle production :

$$^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e$$

TABLE 18.2 Various Types of Radioactive Processes Showing the Changes That Take Place in the Nuclides

Process	Change in *A*	Change in *Z*	Change in Neutron/Proton Ratio	Example
β-particle (electron) production	0	+1	Decrease	$^{227}_{89}Ac \longrightarrow {}^{227}_{90}Th + {}^{0}_{-1}e$
Positron production	0	−1	Increase	$^{13}_{7}N \longrightarrow {}^{13}_{6}C + {}^{0}_{1}e$
Electron capture	0	−1	Increase	$^{73}_{33}As + {}^{0}_{-1}e \longrightarrow {}^{73}_{32}Ge$
α-particle production	−4	−2	Increase	$^{210}_{84}Po \longrightarrow {}^{206}_{82}Pb + {}^{4}_{2}He$
γ-ray production	0	0	—	Excited nucleus $\longrightarrow$ ground state nucleus + $^{0}_{0}g$
Spontaneous fission	—	—	—	$^{254}_{98}Cf \longrightarrow$ lighter nuclides + neutrons

- *g*-ray production:

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

- positron production:

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

- electron capture: (inner-orbital electron is captured by the nucleus)

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

Decay Series

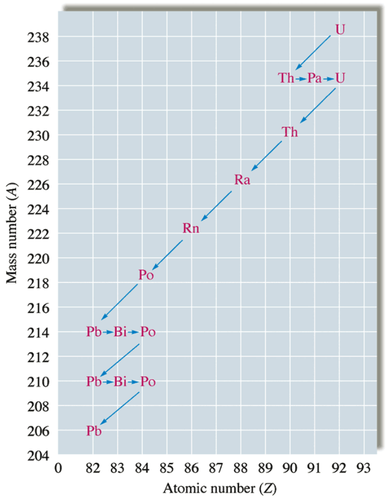
A radioactive nucleus reaches a stable state by a series of steps.

$$^{238}_{92}U \xrightarrow{\text{series of decay}} {}^{206}_{82}Pb$$

$$^{235}_{92}U \xrightarrow{\text{series of decay}} {}^{207}_{82}Pb$$

$$^{232}_{90}Th \xrightarrow{\text{series of decay}} {}^{208}_{82}Pb$$

Fig. 18.2: The decay series from ^{238}U to ^{206}Pb.



The rate of decay is proportional to the number of nuclides. This represents a ______ process.

$$\text{Rate} = -\frac{\Delta N}{\Delta t} = kN$$

$$\ln\left(\frac{N}{N_0}\right) = -kt$$

$$\text{half-life} \quad t_{1/2} = \frac{\ln(2)}{k} = \frac{0.693}{k}$$

18.2 The Kinetics of Radioactive Decay

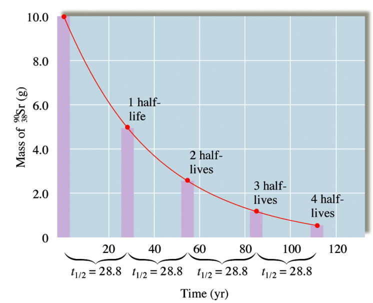


Fig. 18.3: The decay of a 10.0-g sample of strontium-90 over time. Note that the half-life is a constant 28.8 years.

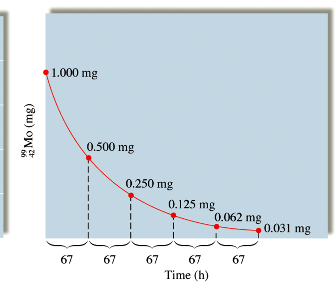


Fig. 18.4: The change in the amount of Mo-99 with time. ($t_{1/2}$ = 67 h)

TABLE 18.3 The Half-Lives of Nuclides in the $^{238}_{92}$U Decay Series

Nuclide	Particle Produced	Half-Life
Uranium-238 ($^{238}_{92}$U) ↓	α	4.51×10^9 years
Thorium-234 ($^{234}_{90}$Th) ↓	β	24.1 days
Protactinium-234 ($^{234}_{91}$Pa) ↓	β	6.75 hours
Uranium-234 ($^{234}_{92}$U) ↓	α	2.48×10^5 years
Thorium-230 ($^{230}_{90}$Th) ↓	α	8.0×10^4 years
Radium-226 ($^{226}_{88}$Ra) ↓	α	1.62×10^3 years
Radon-222 ($^{222}_{86}$Rn) ↓	α	3.82 days
Polonium-218 ($^{218}_{84}$Po) ↓	α	3.1 minutes
Lead-214 ($^{214}_{82}$Pb) ↓	β	26.8 minutes
Bismuth-214 ($^{214}_{83}$Bi) ↓	β	19.7 minutes
Polonium-214 ($^{214}_{84}$Po) ↓	α	1.6×10^{-4} second
Lead-210 ($^{210}_{82}$Pb) ↓	β	20.4 years
Bismuth-210 ($^{210}_{83}$Bi) ↓	β	5.0 days
Polonium-210 ($^{210}_{84}$Po) ↓	α	138.4 days
Lead-206 ($^{206}_{82}$Pb)	—	Stable

18.3 Nuclear Transformations

Nuclear Transformation

The change of one element into another.

In 1919, Lord Rutherford observed the first nuclear transformation:

Irene Curie and Frederick Joliot (1935 Nobel Laureate in Chemistry) :

$$^{27}_{13}\text{Al} + ^{4}_{2}\text{He} \longrightarrow ^{30}_{15}\text{P} + ^{1}_{0}\text{n}$$

- Over the years, many other nuclear transformations have been achieved, mostly using particle accelerators.
- By using neutron and positive-ion bombardment, scientists have been able to extend the period table.

西元1940**年之前，最重的已知元素為**

西元1940**年 ，利用中子與鈾**-238 **撞擊產生錼** (Np, Z = 93)

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

- **自西元**1940**年後，**Z = 93 ~112 **之超鈾元素** (transuranium elements) **已被合成出，其中許多之半衰期甚短。**

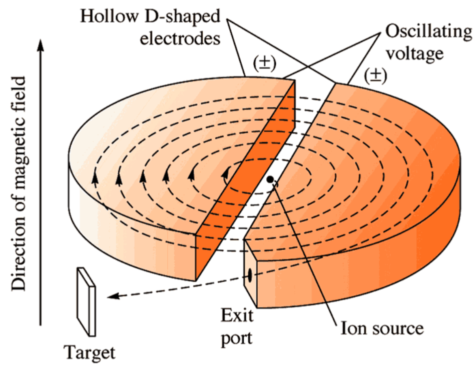


Fig. 18.5: A schematic diagram of a cyclotron.

TABLE 18.4 Syntheses of Some of the Transuranium Elements

Element	Neutron Bombardment	Half-Life
Neptunium (Z = 93)	${}^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{239}_{93}Np + {}^{0}_{-1}e$	2.35 days (${}^{239}_{93}Np$)
Plutonium (Z = 94)	${}^{239}_{93}Np \longrightarrow {}^{239}_{94}Pu + {}^{0}_{-1}e$	24,400 years (${}^{239}_{94}Pu$)
Americium (Z = 95)	${}^{239}_{94}Pu + 2\,{}^{1}_{0}n \longrightarrow {}^{241}_{94}Pu \longrightarrow {}^{241}_{95}Am + {}^{0}_{-1}e$	458 years (${}^{241}_{95}Am$)
Element	**Positive-Ion Bombardment**	**Half-Life**
Curium (Z = 96)	${}^{239}_{94}Pu + {}^{4}_{2}He \longrightarrow {}^{242}_{96}Cm + {}^{1}_{0}n$	163 days (${}^{242}_{96}Cm$)
Californium (Z = 98)	${}^{242}_{96}Cm + {}^{4}_{2}He \longrightarrow {}^{245}_{98}Cf + {}^{1}_{0}n$ or ${}^{238}_{92}U + {}^{12}_{6}C \longrightarrow {}^{246}_{98}Cf + 4\,{}^{1}_{0}n$	44 minutes (${}^{245}_{98}Cf$)
Rutherfordium (Z = 104)	${}^{249}_{98}Cf + {}^{12}_{6}C \longrightarrow {}^{257}_{104}Rf + 4\,{}^{1}_{0}n$	
Dubnium (Z = 105)	${}^{249}_{98}Cf + {}^{15}_{7}N \longrightarrow {}^{260}_{105}Db + 4\,{}^{1}_{0}n$	
Seaborgium (Z = 106)	${}^{249}_{98}Cf + {}^{18}_{8}O \longrightarrow {}^{263}_{106}Sg + 4\,{}^{1}_{0}n$	

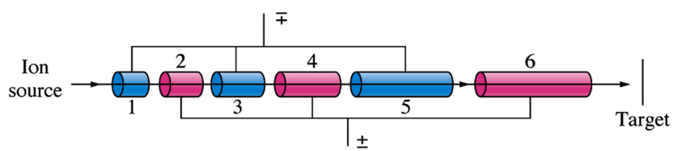


Fig. 18.6: Schematic diagram of a linear accelerator, which uses a changing electric field to accelerate a positive ion along a linear path.

18.4 Detection and Uses of Radioactivity

蓋格計數器 (Geiger-Müller counter, or Geiger counter):
測量放射性 (radioactivity) 最常見之儀器，利用幅射衰變放出之高能粒子通過物質會產生離子的原理。

$$Ar_{(g)} \xrightarrow{\text{High - energy particle}} Ar^{+}_{(g)} + e^{-}$$

閃爍計數器 (scintillation counter):另一常見測量放射性 (radioactivity) 的儀器，利用某些物質(如 ZnS) 受高能幅射撞擊後會放光的特性。

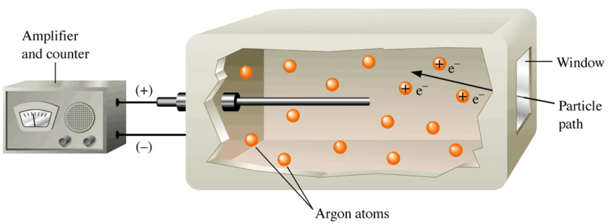


Fig. 18.7: A schematic representation of a Geiger-Müller counter. The high-energy radioactive particle enters the window and ionizes Ar atoms along its path. The resulting ions and electrons produce a momentary current pulse, which is amplified and counted.

Dating by Radioactivity

碳-14 定年法 (radiocarbon dating, or carbon-14 dating)

Originated in the 1940s by Willard Libby (Nobel laureate)

$${}^{14}_{6}C \rightarrow {}^{0}_{-1}e + {}^{14}_{7}N \qquad t_{1/2} = 5730 \text{ years}$$

大氣中， C-14 不斷地由來自外太空之高能中子粒子與 N-14 碰撞生成：

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

經漫長時間，C-14 之生成與衰變達到平衡，即大氣中之 C-14 量約維持恆定。

植物吸收大氣中的 CO_2 進行光合作用，只要植物還活著，其體內組成之 ${}^{14}_{6}C/{}^{12}_{6}C$ 比例與大氣中之比例相同；但當植物死後 (或用以製為物品布料)，${}^{14}_{6}C/{}^{12}_{6}C$ 比例便開始下降。

假設古代之大氣之 ${}^{14}_{6}C/{}^{12}_{6}C$ 比例與現今大氣相同，則可由化石/古物中的 ${}^{14}_{6}C/{}^{12}_{6}C$ 推得其年代。

例如: 某一挖出古木器之 ${}^{14}_{6}C/{}^{12}_{6}C$ 比例為現今活植物的一半，則可推斷此古木器的年齡約為 5730 年。

近代科學家發現，古代大氣中 ${}^{14}C$ 的含量與現在有顯著不同。碳-14 定年法對 1 萬年內之樣品可準確定年，但對於 2 ~3 萬年前的樣品則可能有3000年的誤差。

傳統碳-14 定年法一大缺點為須消耗相當大量的樣品(半克~數克)，以燃燒產生 CO_2 進行放射性測量。解決之道可利用質譜儀，僅須 ~10^{-3} g 之樣品即可精確量測 ${}^{14}_{6}C/{}^{12}_{6}C$ 比例。

Exercise 18.5 & 18.6

Brigham Young researcher Scott Woodward taking a bone sample for carbon-14 dating at an archeological site in Egypt.

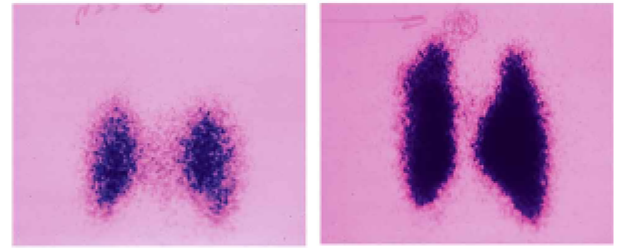


Fig. 18.8: After consumption of $Na^{131}I$, the patient's thyroid is scanned for radioactivity levels to determine the efficiency of iodine absorption. (left) A normal thyroid. (right) An enlarged thyroid.

Medical Applications of Radioactivity

provides sensitive and noninvasive methods for:

- learning about biological systems
- detection of disease
- monitoring the action and effectiveness of drugs
- early detection of pregnancy
- …. etc.

例如: I-131 可用以偵測治療甲狀腺疾病 (食入少量$Na^{131}I$)

Tl-201 及 Tc-99m 可用於評估心肌之破壞程度

TABLE 18.5 Some Radioactive Nuclides, with Half-Lives and Medical Applications as Radiotracers

Nuclide	Half-Life	Area of the Body Studied
^{131}I	8.1 days	Thyroid
^{59}Fe	45.1 days	Red blood cells
^{99}Mo	67 hours	Metabolism
^{32}P	14.3 days	Eyes, liver, tumors
^{51}Cr	27.8 days	Red blood cells
^{87}Sr	2.8 hours	Bones
^{99m}Tc	6.0 hours	Heart, bones, liver, and lungs
^{133}Xe	5.3 days	Lungs
^{24}Na	14.8 hours	Circulatory system

18.5 Thermodynamic Stability of the Nucleus

Energy and Mass

When a system gains or loses energy it also gains or loses a quantity of mass.

$\Delta E = \Delta mc^2$ $\qquad \dfrac{\Delta E}{c^2} = \Delta m$

If ΔE is negative, mass is lost from the system.

For **前例**: $8\ {}^{1}_{0}\text{n} + 8\ {}^{1}_{1}\text{H} \rightarrow {}^{16}_{8}\text{O}$

$\Delta E = -(1.366\times10^{-4}\ \text{kg/mol})(3.00\times10^{8}\ \text{m/s})^2 = -1.23\times10^{13}\ \text{J/mol}$

ΔE per ${}^{16}_{8}\text{O}$ nucleus $= -2.04\times10^{-11}$ J/nucleus

$= -1.28\times10^{2}$ MeV/nucleus

ΔE per nucleon for ${}^{16}_{8}\text{O} = -7.98$ MeV/nucleon

Thermodynamic stability of a nucleus: **計算此原子核若完全由質子及中子組合形成產生之位能變化**

Consider a hypothetical process:

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

Mass of $(8\ {}^{1}_{0}\text{n} + 8\ {}^{1}_{1}\text{H}) = 8(1.67493\times10^{-24}\ \text{g}) + 8(1.67262\times10^{-24}\ \text{g})$

$= 2.67804\times10^{-23}$ g

Mass of ${}^{16}_{8}\text{O}$ nucleus $= 2.65535\times10^{-23}$ g

$$\Delta m = -2.269\times10^{-25}\ \text{g/nucleus} = -0.1366\ \text{g/mol}$$

Binding Energy

Binding energy is the energy required to decompose the nucleus into its components.

has a binding energy per nucleon of 8.79 MeV

is the most stable nucleus.

Exercise 18.7 & 18.8

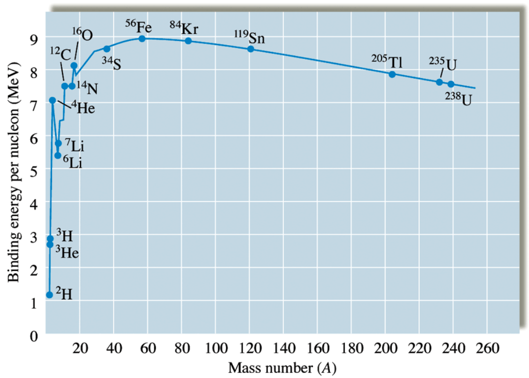


Fig. 18.9: The binding energy per nucleon as a function of mass number. The most stable nuclei are at the top of the curve. The most stable nucleus is ^{56}Fe.

18.6 Nuclear Fission and Nuclear Fusion

Nuclear Fission and Fusion

Fusion (核融合): Combining two light nuclei to form a heavier, more stable nucleus.

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

Fission (核分裂): Splitting a heavy nucleus into two nuclei with smaller mass numbers.

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{142}_{56}Ba + ^{91}_{36}Kr + 3^{1}_{0}n$$

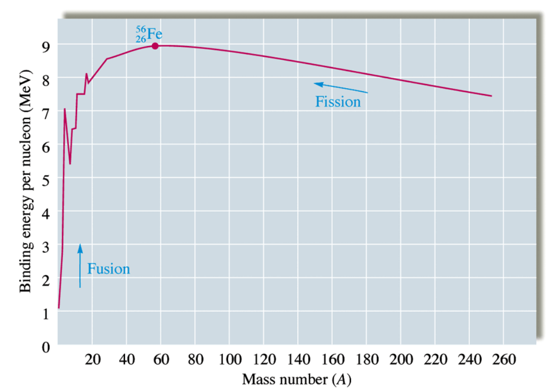


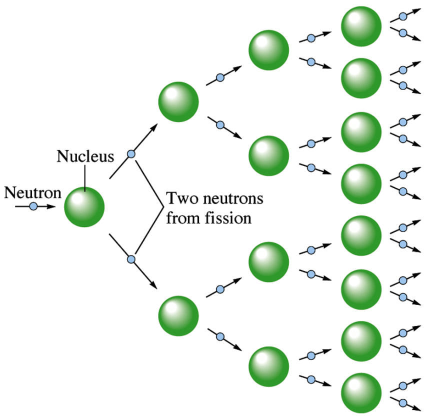
Fig. 18.10: Both fission and fusion produce more stable nuclides and are thus exothermic.

Fission Processes

A self-sustaining fission process is called a
.

Event	Neutrons Causing Fission	Result
subcritical	< 1	reaction stops
critical	= 1	sustained reaction
supercritical	> 1	violent explosion

Fig. 18.12: Representation of a fission process in which each event produces two neutrons, which can go on to split other nuclei, leading to a self-sustaining chain reaction.



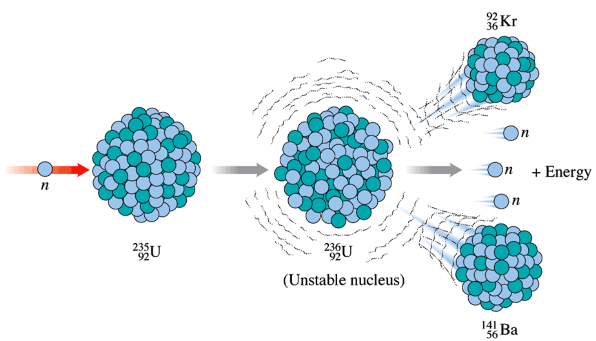


Fig. 18.11: On capturing a neutron, the nucleus undergoes fission to produce two lighter nuclides, free neutrons (typically three), and a large amount of energy.

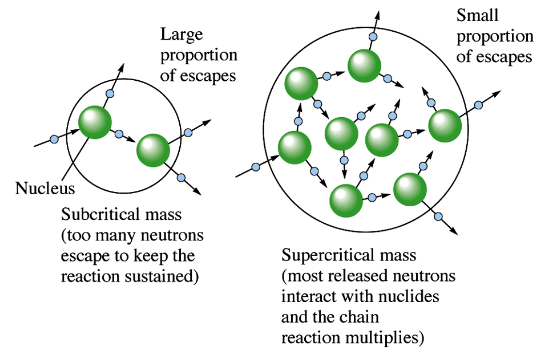


Fig. 18.13: If the mass of fissionable material is too small, most of the neutrons escape before causing another fission event, and the process dies out.

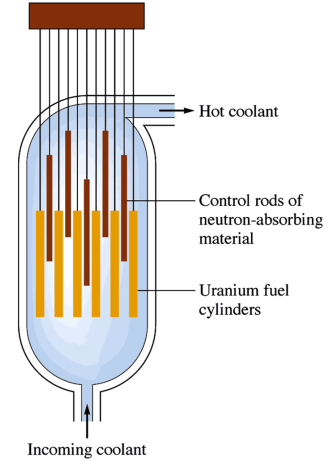
Key Parts of a Fission Reactor

Reactor Core: 3% $^{235}_{92}\text{U}$ + moderator and control rods.

- Uranium has been enriched (**天然鈾只含** ~0.7%) and is housed in cylinders.
- Moderator surrounds the cylinders to slow down the neutrons so that the uranium fuel can capture them more efficiently.
- Control rods, composed of substances that absorb neutrons, are used to regulate the power level of the reactor.

- Coolant
- Containment Shell

Fig. 18.15: A schematic of a reactor core. The position of the control rods determines the level of energy production by regulating the amount of fission taking place.



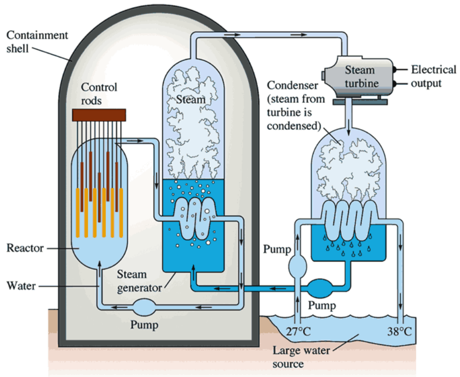


Fig. 18.14: A schematic diagram of a nuclear power plant.

Breeder Reactors

Fissionable fuel is produced while the reactor runs ($^{235}_{92}\text{U}$ is split, giving neutrons for the creation of $^{239}_{94}\text{Pu}$; change nonfissionable ^{238}U to fissionable ^{239}Pu):

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

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

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

One problem involves the hazards in handling Pu, which flames on contact with air and is very toxic.

Fusion

- Combining two light nuclei to form a heavier, more stable nucleus
- Producing large quantities of energy

太陽 (75% H + 26% He + 1% other elements) **由核融合過程釋出巨大能量：**

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

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

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

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

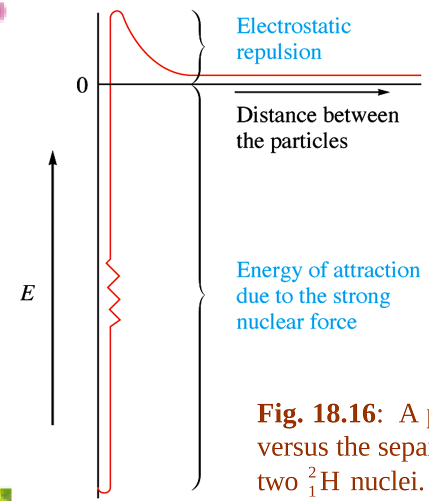


Fig. 18.16: A plot of energy versus the separation distance for two $^{2}_{1}H$ nuclei.

密集的研究欲開發例如以海水之氘($^{2}_{1}H$)為核融合反應燃料之可實行，主要障礙為引發核融合需要極高的溫度。

二個氘核間的靜電作用力大到需要高達4 ×10^{7} K **之溫度才可使其具足夠速度相互碰撞以至核作用力將之結合而放出巨大能量。**

目前有兩種系統可產生極高溫度：

-
-

At present, many technical problems remain to be solved.

18.7 Effects of Radiation

Biological Effects of Radiation

可分類為

- : damage to the organism itself
- : damage to the genetic machinery

Biological effects of radiation depend on:

1. Energy of the radiation
2. Penetration ability of the radiation
3. Ionizing ability of the radiation
4. Chemical properties of the radiation source

TABLE 18.7 Typical Radiation Exposures for a Person Living in the United States (1 millirem = 10^{-3} rem)

	Exposure (millirems/year)
Cosmic radiation	50
From the earth	47
From building materials	3
In human tissues	21
Inhalation of air	5
Total from natural sources	126
X-ray diagnosis	50
Radiotherapy	10
Internal diagnosis/therapy	1
Nuclear power industry	0.2
TV tubes, industrial wastes, etc.	2
Radioactive fallout	4
Total from human activities	67
Total	193

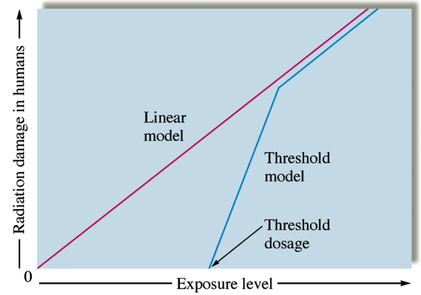


Fig. 18.17: The two models for radiation damage. In the linear model, even a small dosage causes a proportional risk. In the threshold model, risk begins only after a certain dosage.

TABLE 18.6 Effects of Short-Term Exposures to Radiation

Dose (rem)	Clinical Effect
0–25	Nondetectable
25–50	Temporary decrease in white blood cell counts
100–200	Strong decrease in white blood cell counts
500	Death of half the exposed population within 30 days after exposure

單位: **1 Röntgen (R)** = the quantity of X-ray or γ-ray radiation delivered to 0.001293 g of air, such that the ions produced in the air carry 3.34×10^{-10} C of charge.

1 rem (röntgen equivalent man) = a dose of any radiation that has the same effect of 1R

1 mrem = 10^{-3} rem

# of rems = (# of rads) × RBE

RBE: relative effectiveness of the radiation in causing biological damage

An aerial view of Fermilab, a high energy particle accelerator in Batavia, Illinois.