



## Chapter 22:

# Nuclear Reactions and Their Role in Chemistry

Reference: Chapter 18 in “Chemistry” 6/e  
by Steven S. Zumdahl & Susan A. Zumdahl



## 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<sup>3</sup>  
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



**nucleons**



(Composed of quarks)

atomic number (Z) : # of

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

isotopes : 有相同之 atomic # but 不同之 mass #

nuclide : 指一特定之原子



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**22.1 Mass and energy are  
conserved in *all* of their  
forms**

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- Isotopes with unstable atomic nuclei are and are called **radionuclides**.
- Radioactive isotopes undergo *nuclear reactions* as they emit high-energy particles and/or electromagnetic radiation.
- By the early 1900's physicist realized that the mass of a particle could not always be treated as constant.

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- The mass ( $m$ ) of a particle depends on its velocity ( $v$ ) relative to an observer

$$m = \frac{m_0}{\sqrt{1 - (v/c)^2}}$$

$c$  = speed of light =  $3.00 \times 10^8$  m/s

$v$  = speed of the particle in m/s

$m_0$  = particle's rest mass (mass at  $v = 0$ )

- The rest mass of the particle can be measured in the lab when the sample is at rest (from our viewpoint).

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## The Law of Conservation of Mass-Energy:

The sum of all the energy in the universe and the sum of all the mass (expressed as an equivalent in energy) is a constant.

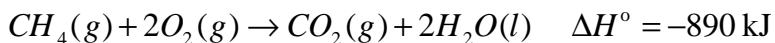
- The **Einstein equation** relates the change in rest mass to an energy change.

If  $\Delta E$  is negative, mass is lost from the system.

- Because  $c$  is so large, an enormous amount of energy accompanies even a small change in rest mass.



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- Consider the combustion of methane:





- Using the Einstein equation, the loss of 890 kJ of energy corresponds to the conversion of 9.89 ng of mass into energy.
  - This is about  $10^{-7}\%$  of the mass of 1 mol of  $\text{CH}_4$  and 2 mol of  $\text{O}_2$ .
  - Such tiny changes are not detectable by laboratory balances.
  - Thus, the Einstein equation has no practical application in chemistry.





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## 22.2 The energy required to break a nucleus into separate nucleons is called the nuclear binding energy



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- The mass of an atomic nucleus is always a little smaller than the sum of the rest masses of each of its *nucleons* (protons and neutrons).
  - The mass difference is called the *mass defect*.
  - The mass difference represents the amount of mass converted into energy, and released by the system, as the nucleons gathered to form the nucleus.
  - This energy is also called the *binding energy* because this amount of energy would need to be added to break the nucleus apart.
  - The *higher* the binding energy, the *more stable* the nucleus.
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### Consider the case of one He-4 nucleus:



rest mass of an isolated proton = 1.0072764669 u

rest mass of an isolated neutron = 1.0086649156 u

rest mass of one  ${}^4\text{He}$  nucleus = 4.0015061792 u

The mass defect is then

$$\Delta m_0 = 2(1.0072764669 \text{ u}) + 2(1.0086649156 \text{ u}) - 4.0015061792 \text{ u}$$

$$= 0.030375858 \text{ u}$$

Using the Einstein equation

$$\Delta E = 0.030375858 \text{ u} \times \frac{1.6605389 \times 10^{-27} \text{ kg}}{1 \text{ u}} \times (3.00 \times 10^8 \text{ m s}^{-1})^2$$

$$= 4.54 \times 10^{-12} \text{ J}$$

For the formation of 1 mol  ${}^4\text{He}$ :

$$\Delta E = \frac{4.54 \times 10^{-12} \text{ J}}{\text{nucleus}} \times \frac{6.02 \times 10^{23} \text{ nuclei}}{\text{mol}} = 2.73 \times 10^{12} \text{ J mol}^{-1}$$



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### Consider a hypothetical process:



$$\text{Mass of } (8 {}^1_0\text{n} + 8 {}^1_1\text{H}) = 8(1.67493 \times 10^{-24} \text{ g}) + 8(1.67262 \times 10^{-24} \text{ g})$$

$$= 2.67804 \times 10^{-23} \text{ g}$$

$$\text{Mass of } {}^{16}_8\text{O nucleus} = 2.65535 \times 10^{-23} \text{ g}$$

$$\Delta m = -2.269 \times 10^{-25} \text{ g/nucleus} = -0.1366 \text{ g/mol}$$

$$\Delta E = -(1.366 \times 10^{-4} \text{ kg/mol})(3.00 \times 10^8 \text{ m/s})^2 = -1.23 \times 10^{13} \text{ J/mol}$$

$$\Delta E \text{ per } {}^{16}_8\text{O nucleus} = -2.04 \times 10^{-11} \text{ J/nucleus}$$

$$= -1.28 \times 10^2 \text{ MeV/nucleus}$$





$$\Delta E \text{ per nucleon for } {}^{16}_8\text{O} = -7.98 \text{ MeV/nucleon}$$





$$1 \text{ eV} = \quad \text{J}$$





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- The energy from forming only 4 g of He (1 mol) could keep a 60 W light bulb burning for over 1440 years.
  - The formation of a nucleus from its nucleons is called **nuclear** (核融合).
    - No practical method for sustaining nuclear fusion currently exists on earth.
  - The binding energy per nucleon has a maximum (8.79 MeV) at  $^{56}\text{Fe}$ , meaning it is the most stable of all nuclei.
  - As the mass number increases, the binding energy per nucleon begins to drop.
  - One expects, and finds, that some of the heavier isotopes might breakup and form more stable isotopes.
  - **Nuclear** (核分裂) is the spontaneous breaking apart of a nucleus to form isotopes of intermediate mass number.
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## 22.3 Radioactivity is an emission of particles and/or electromagnetic radiation by unstable atomic nuclei



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- Except for H, all atomic nuclei have more than one proton, each bearing a positive charge.
- The force of attraction that keeps the protons, which repel, together is called the  $\alpha$ .
- The nuclear strong force overcomes the force of repulsion between protons and binds both the protons and neutrons together in the nucleus.
- Neutrons help “dilute” the electrostatic repulsions by intermingling with the protons in the nucleus.
  - Nuclei with “too few” neutrons and lots of protons are often unstable and occur among radionuclides.

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- Radionuclides undergo **radioactive decay** (輻射衰減), meaning they eject small nuclear fragments and sometimes high energy electromagnetic radiation as well.
- This is called **(輻射活性)**.
  - About 50 of the approximately 350 naturally occurring isotopes are radioactive.
- Radioactive decay 之 A & Z 均需守恆, 例如 :



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## Types of Radioactive Decay

### • **a-particle emission :**

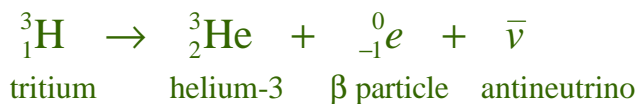


- \* The **a** particles bear a charge of  $+2$ , which is omitted from its symbol ( ${}^4_2\text{He}$ ).
- \* **a**-emitting radionuclides are common near the end of the periodic table.
- \* **a** particles are the most massive of any commonly emitted by radionuclides.
  - After traveling only a few centimeters in air, an **a** particle will lose kinetic energy, pick up electrons, and become a neutral He atom.
  - **a** particles cannot penetrate the skin, but can cause cancer in the soft tissues of the lungs or intestinal track if emitters are carried in air or on particles of food.



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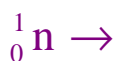
### • **b-particle emission :**



- \* Both the **b** particle and antineutrino are created when a neutron inside a nucleus decays to a proton.



Emission of a beta particle from a tritium nucleus. The net change can be represented as:



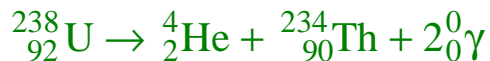
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- \* **a** particles are all emitted with the same discrete energy from a given radionuclide.
- \* **b** particles are emitted with a continuous spectrum of energies (with a characteristic upper limit) for a given radionuclide, which appears to violate the law of conservation energy.
- \* The  $\bar{\nu}$  (反微中子) was proposed to account for the “missing” energy. It is almost massless, has no charge, and was given the symbol  $\bar{\nu}$ .
- \* **b** particles are very small, so are less likely to collide with the molecules of anything it travels through.
- \* They can travel up to 300 cm in dry air.
- \* Only the highest energy **b** particles can penetrate the skin.



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### • **g-ray emission:**

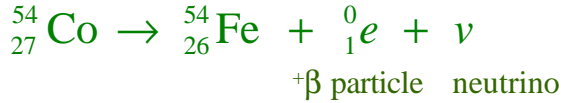


- \* **g radiation** consists of high energy photons and often accompanies either **a** or **b** radiation.
- \* **g** radiation is extremely penetrating and can only effectively be blocked by very dense materials like Pb.
- \* Emission of gamma radiation involves transition between energy levels *within* the nucleus.
- \* **X-rays**, like **g** rays, consist of high-energy electromagnetic radiation, but their energies are usually less than those of **g** radiation. (typically  $\leq 100$  keV)
- \* X-rays are emitted by some synthetic radionuclides, but are usually generated by special machines using a high-energy electron beam focused onto a metal target.

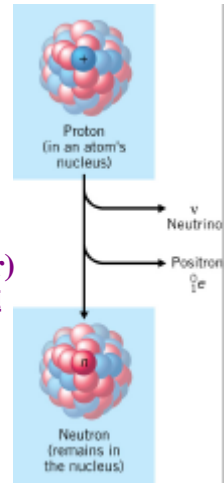
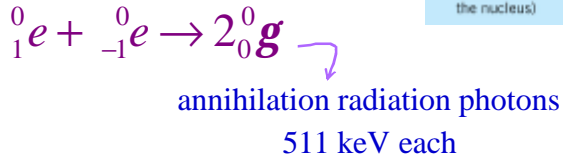
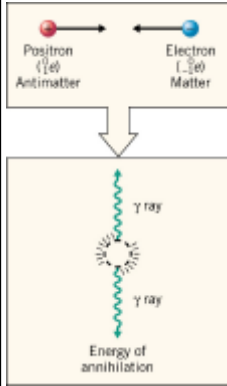


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• **positron emission:**



物質(matter)與其反物質(antimatter)相遇時，會發生完全的物質-能量轉換，產生如光子的能量形式，此一過程即為湮滅(annihilation)，又稱互毀、相消、對消滅。



<http://en.wikipedia.org/wiki/Annihilation>



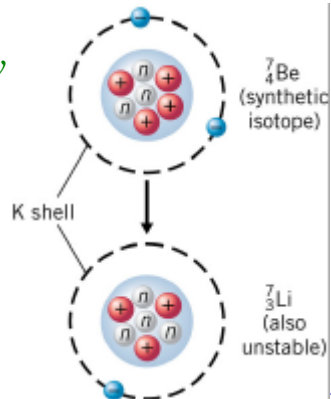
• **neutron emission:**



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



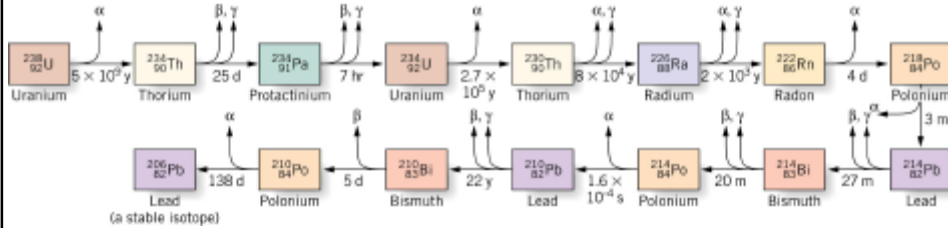
Net change:



Example 22.1

# Radioactive disintegration series

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

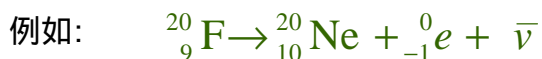


22.4 Stable isotopes fall within the “band of stability” on a plot based on numbers of protons and neutrons

- ◆ 已知約 2000 nuclides , 僅 279 種為穩定 (with respective to radioactive decay)
- ♣ All nuclides with  $Z \geq$  are unstable with respective to radioactive decay.
- ♣ Light nuclides are stable when neutron/proton  $\sim 1$ .  
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.



- Isotopes with  $Z > 83$  tend to be  $\alpha$  emitters.
  - Their nuclei have too many protons. The most efficient way to lose protons is by the loss of an alpha particle.
- Isotopes occurring above and to the left of the band of stability tend to be  $\beta^-$  emitters.
  - The  $n/p$  ratio is apparently too high. A nucleus that undergoes  $\beta^-$  decay loses a neutron and gains a proton which reduces the ratio.

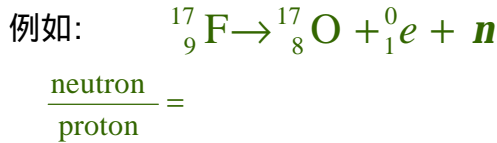


$$\frac{\text{neutron}}{\text{proton}} =$$



- Isotopes lying below and to the right of the band are positron emitters.

- These nuclei have too few neutrons to be stable.
- Positron emission increases the n/p ratio.



**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
$\beta$ -particle (electron) production	0	+1	Decrease	${}_{89}^{227}\text{Ac} \rightarrow {}_{90}^{227}\text{Th} + {}_{-1}^0e$
Positron production	0	-1	Increase	${}_{7}^{13}\text{N} \rightarrow {}_{6}^{13}\text{C} + {}_{1}^0e$
Electron capture	0	-1	Increase	${}_{33}^{73}\text{As} + {}_{-1}^0e \rightarrow {}_{32}^{73}\text{Ge}$
$\alpha$ -particle production	-4	-2	Increase	${}_{84}^{210}\text{Po} \rightarrow {}_{82}^{206}\text{Pb} + {}_{2}^4\text{He}$
$\gamma$ -ray production	0	0	—	Excited nucleus $\rightarrow$ ground state nucleus + ${}_{0}^0\gamma$
Spontaneous fission	—	—	—	${}_{98}^{254}\text{Cf} \rightarrow$ lighter nuclides + neutrons

- Nature favors even # for protons and neutrons.

**Odd-even rule:** When the numbers of neutrons and protons in a nucleus are both even, the isotope is far more likely to be stable than when both numbers are odd.

- The odd-even rule is related to the spins of nucleons.
- Of the 264 stable isotopes, only 5 have odd numbers of both protons and neutrons.
- 157 have even numbers of both protons and neutrons.
- Another rule for nuclear stability is based on *magic numbers* of nucleons.
  - Magic numbers supports the hypothesis that a nucleus has a shell structure with energy levels like those for electrons.

## 22.5 Transmutation is the change of one isotope into another

- Transmutation (核蛻變) can be caused by radioactive decay or by the bombardment of nuclei with high-energy particles such as:
  - Alpha particle (from natural emitters)
  - Neutrons from atomic reactors
  - Protons made by stripping electrons from hydrogen
- Beta particles (electrons) are not normally used because they are repelled by the electrons around the target nuclei.

In 1919, Lord Rutherford observed the first artificial transmutation:



In 1934, Irene Curie Joliot and Frédéric Joliot (1935 Nobel Laureate in Chemistry) produced the first artificial radioactive isotope:

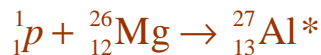


$\alpha$  particles can be produced from the bombardment of lithium-7 with protons:



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- A given compound nucleus can be made in a variety of ways.
- For example, aluminum-27 can be made by any of the following routes:



- The decay mode of the compound nucleus depends on its nuclear energy.



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- ◆ Over the years, many other transmutation 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 撞擊產生釷 (Np, Z = 93)



- ◆ 自西元1940年後，Z = 93 ~112 & 114 之超鈾元素 (transuranium elements) 已被合成出，其中許多之半衰期甚短。



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## 22.6 How is radiation measured?

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**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。



**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。

**薄膜劑量計 (film dosimeter):** 照相底片曝露於幅射下會隨時間而變暗，變暗程度與總幅射接受量成正比。於具幅射源環境下工作者常配戴此類偵測器以紀錄其總幅射曝受劑量。

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## 輻射活性與核分裂速率

**輻射活性 (activity):** 樣品於單位時間產生核分裂 (disintegrations) 之原子核數量; 決定於樣品中所含放射性同位素原子核的數目以及其衰變的速率。

- If a sample of matter is “highly radioactive”, many atoms are undergoing decay per unit of time.
- A small number of nuclei decaying at a rapid rate can produce the same activity as a larger number of atoms decaying at a slower rate.

單位:  $1 \text{ curie (Ci)} = 3.7 \times 10^{10} \text{ disintegrations/s}$   
= the activity of 1.0 g of Ra-226  
 $1 \mu\text{Ci} = 37,000 \text{ disintegrations/s}$   
 $1 \text{ becquerel (Bq)} = 1 \text{ disintegration/s}$

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The rate of decay is proportional to the number of nuclides. This represents a **first-order** process.

$$\text{activity} = -\frac{\Delta N}{\Delta t} = kN \quad k: \text{decay constant}$$

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

$$\text{half - life } t_{1/2} =$$

Example 22.2

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## 輻射劑量

- The energy equivalent to the quantity of radiation absorbed by some material is defined in units of **absorbed dose** or simply **dose**.
  - \* The SI unit of absorbed dose is the **gray (Gy)**
  - \* 1 Gy = 1 J of energy absorbed per kg of material
  - \* The Radiation Absorbed Dose (**rad**) is an older unit
  - \* 1 rad = 0.01 Gy

輻射物質的影響/傷害程度決定於:

- (1) 輻射活性 (activity, i.e. number of disintegrations per second)
- (2) 輻射\_\_\_\_\_及\_\_\_\_\_ (a or b or g)
- (3) 放射性物質的化學本質 (是否容易進入食物鏈或累積於生物體內)

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## 輻射之生物效應 – 劑量當量

- A different unit is used for measuring the biological effects of radiation:

$$H = DQN$$

$H$ : dose equivalent, SI unit = sievert 西弗 (Sv)

$D$ : absorbed dose

$Q$ : a factor that takes into account the biologically significant properties

for **a** radiation,  $Q \approx 1$ , for **b** or **g** radiation,  $Q \approx 20$

$N$ : any other factor bearing on the net effect

- Even small absorbed doses can be biologically harmful.
- The radiation can generate very reactive species with unpaired electrons called free radicals.
- Once the radicals are generated, they can start a chain of undesirable chemical events.

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The **rem** (倫目) is an older unit for dose equivalent:

$$1 \text{ rem} = 0.01 \text{ Sv}$$





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





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

$$1 \text{ mrem} = 10^{-3} \text{ rem}$$

A typical X-ray involves about 0.007 rem

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- A whole body dose of 25 rem (0.25 Sv) induces noticeable changes in blood.
  - A set of symptoms called **radiation sickness** develops at about 100 rem, and becomes severe at about 200 rems.
    - Symptoms include: nausea, vomiting, a drop in white blood count, diarrhea, dehydration, prostration, hemorrhaging, and loss of hair
  - If everyone in a large group received 400 rem, half would die in 60 days.
  - 600 rem would kill everyone within a week.
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- Natural and man made sources of radiation contribute to a combined **background radiation** total of about 360 mrem per person per year.
    - \* About 82% of the background radiation is from natural sources and the remaining 18% from medical sources (much in the form of X-rays).
  - Radiation sources should be avoided because the intensity of radiation diminishes as  $1/(\text{distance from a source})^2$ .
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## 22.7 Radionuclides have many medical and analytical applications

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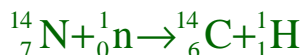
## Dating by Radioactivity

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

Originated in the 1940s by Willard Libby (Nobel laureate, 1960)



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：



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  $\text{CO}_2$  進行光合作用，只要植物還活著，其體內組成之  ${}^{14}_6\text{C}/{}^{12}_6\text{C}$  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)， ${}^{14}_6\text{C}/{}^{12}_6\text{C}$  比例便開始下降。

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假設古代之大氣之  $^{14}_6\text{C}/^{12}_6\text{C}$  比例與現今大氣相同，則可由化石/古物中的  $^{14}_6\text{C}/^{12}_6\text{C}$  推得其年代。

例如: 某一挖出古木器之  $^{14}_6\text{C}/^{12}_6\text{C}$  比例為現今活植物的一半，則可推斷此古木器的年齡約為 年。

近代科學家發現，古代大氣中 $^{14}\text{C}$  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 $\text{CO}_2$  進行放射性測量。解決之道可利用質譜儀，僅須 $\sim 10^{-3}$  g 之樣品即可精確量測  $^{14}_6\text{C}/^{12}_6\text{C}$  比例。

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## Medical Applications of Radioactivity

**Radiotracers** 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 $\text{Na}^{131}\text{I}$ )

Tl-201 及 Tc-99m 可用於評估心肌之破壞程度

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## 核能的其他用途



### ☆ 食物保存 (food irradiation)

利用適量輻射照射食物以消滅微生物，防止食物腐敗，常用之  $\gamma$  射線輻射源為 Co-60、Cs-137 等。目前爭議性考量為 radiolytic products



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### ☆ 材料檢驗 (Materials testing)



利用輻射可觀察材料的結構，例如使用鈷60 產生之  $\gamma$  射線穿透金屬材料，可觀察金屬結構是否有缺陷；或利用中子照相偵測飛機的渦輪葉片及蜂巢結構的腐蝕、瑕疵等，省時省力，提升飛航安全。

### ☆ 放射性同位素追蹤 (Radioactive tracers)

使用微量放射性同位素，可追蹤化學反應、機動設備流程監測、元素於植物成長過程的動向 (e.g. P uptake with Phosphorus-32) 或生態系統累積的狀況等。

### ☆ 昆蟲控制 (Pest control)

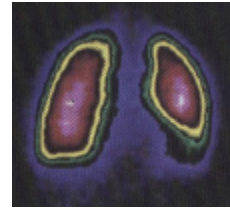
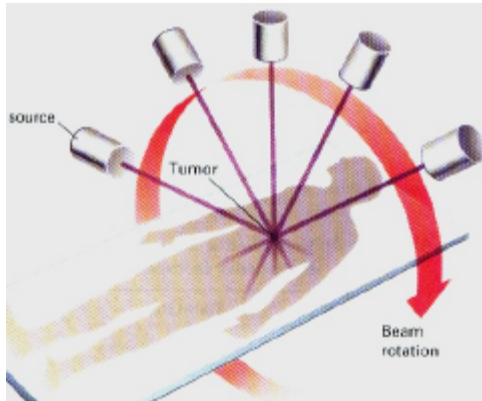
利用輻射照射昆蟲，使其不孕，在釋放於該類昆蟲出沒的地區，使之不能繁衍後代，造成昆蟲減少或甚至滅絕。



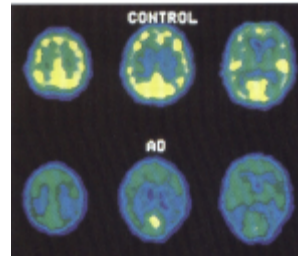
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☆ 醫療應用 (Medical applications)

癌症治療與醫學診斷



A gamma-ray scan of healthy lungs, produced by technetium (Tc)-99m



Study of Alzheimer's disease with positron emission tomography (PET) scans



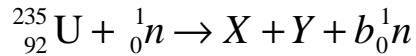
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**22.8 Nuclear fission is the breakup of a nucleus into two fragments of comparable size after capture of a slow neutron**

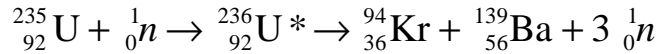


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- Neutrons are electrically neutral and so can penetrate an atom's electron cloud and enter the nucleus relatively easily.
- When they enter U-235 the nucleus breaks apart:



This is called **nuclear fission** (核分裂), for example:



- Uranium-235 is called a fissile isotope because it is capable of fission after neutron capture.
- The neutrons produced are called secondary neutrons and can be absorbed by other nuclei, leading to a **nuclear** (核連鎖反應).

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## Fission Processes

A self-sustaining fission process is called a **chain reaction**.

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

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## Energy yield from fission

Binding energy in  $^{94}\text{Kr}$  :

$$(8.5 \text{ MeV/nucleon}) \times 94 \text{ nucleons} = 800 \text{ MeV}$$

Binding energy in  $^{139}\text{Ba}$  :

$$(8.5 \text{ MeV/nucleon}) \times 139 \text{ nucleons} = 1200 \text{ MeV}$$

Total binding energy of products : 2000 MeV

Binding energy in  $^{235}\text{U}$  :

$$(7.6 \text{ MeV/nucleon}) \times 235 \text{ nucleons} = 1800 \text{ MeV}$$

$\Delta\text{BE}$  is  $\sim 200 \text{ MeV}$  ( J ) – energy released by each fission event

$\Rightarrow$  Energy produced by fission of 1 kg (4.25 mol)  $^{235}\text{U}$  is  $\sim 8 \times 10^{13} \text{ J}$  -- enough to keep a 100 W lightbulb work for 3000 years.

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## Key Parts of a Fission Reactor

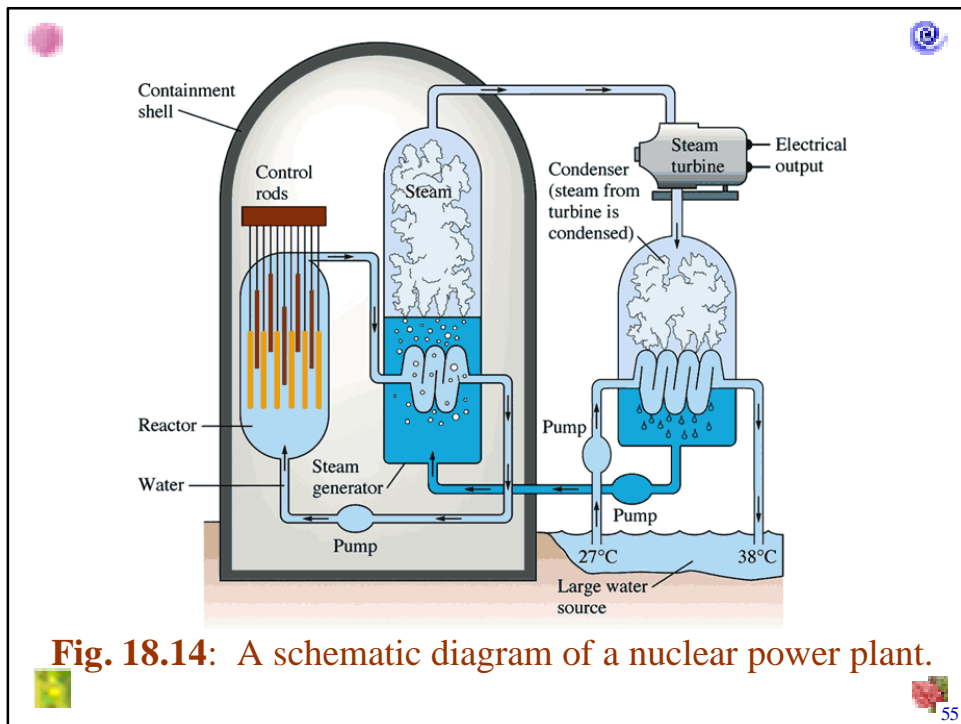
Reactor Core: 3%  $^{235}_{92}\text{U}$  + moderator and control rods.

- Uranium has been enriched (天然鈾只含  $\sim 0.7\%$   $^{235}\text{U}$  , 一般提昇至2~4%) 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

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

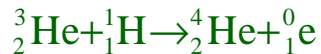
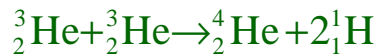
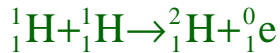
## Radioactive waste from nuclear power plants occur as solids, liquids, and gases

- \* The gases are mostly isotopes of krypton and xenon. With the exception of xenon-85 ( $t_{1/2} = 10.2$  years), the gases have short half-lives and decay quickly.
- \* Iodine-131 must be contained because iodine is concentrated in the human thyroid and it could cause cancer.
- \* Cesium-137 and strontium-90 can be absorbed by the body and possibly cause leukemia.
- \* Some wastes are so long-lived that the solid waste from reactors must be kept away from humans for many centuries.
- Perhaps the most intensely studied procedure for making solid radioactive waste secure is to convert them to glasslike or rocklike solids, which could then be “safely” buried deep within a rock stratum or in a mountain believed to be geologically stable with respect to earthquakes and volcanoes

## Fusion (核融合)

- 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：



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密集的研究欲開發例如以海水之氘( ${}^2_1\text{H}$ )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  $4 \times 10^7$  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：

- high-powered lasers
- heating by electric currents

At present, many technical problems remain to be solved.

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