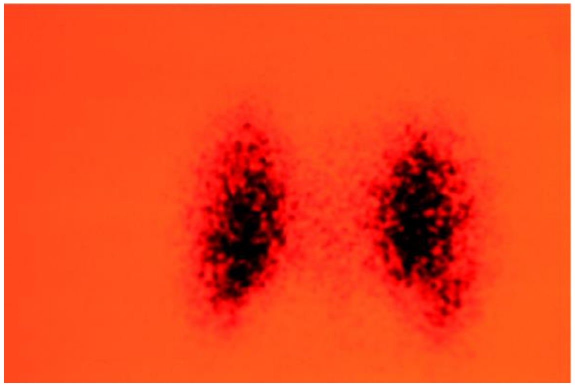
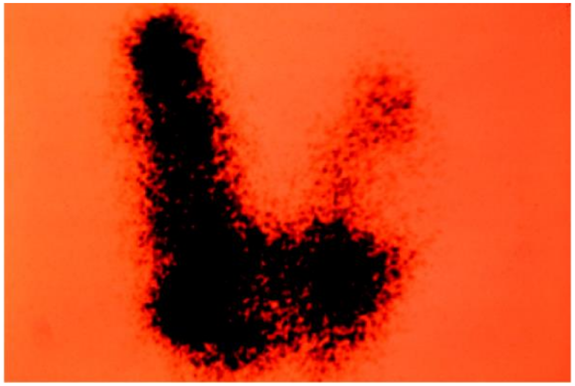
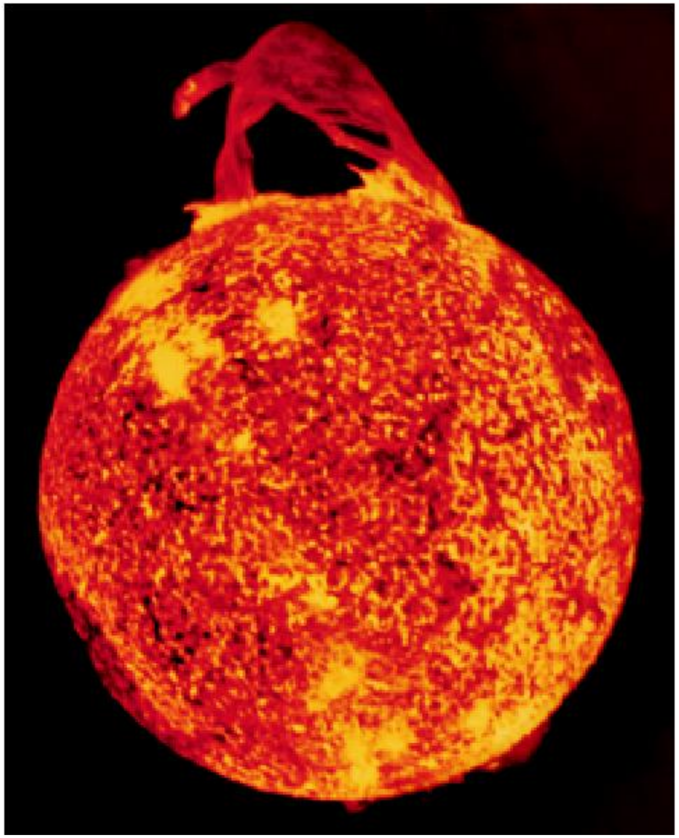



Nuclear Chemistry

Chapter 23



Review

Atomic number (Z) = number of protons in nucleus

Mass number (A) = number of protons + number of neutrons

= atomic number (Z) + number of neutrons

Mass Number → A

Atomic Number → Z

$^{A}_{Z}X$ ← Element Symbol

	proton	neutron	electron	positron	α particle
	$^{1}_{1}p$ or $^{1}_{1}H$	$^{1}_{0}n$	$^{0}_{-1}e$ or $^{0}_{-1}\beta$	$^{0}_{+1}e$ or $^{0}_{+1}\beta$	$^{4}_{2}He$ or $^{4}_{2}\alpha$
A	1	1	0	0	4
Z	1	0	-1	+1	2

Balancing Nuclear Equations

1. Conserve mass number (A).

The sum of protons plus neutrons in the products must equal the sum of protons plus neutrons in the reactants.

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{138}_{55}Cs + ^{96}_{37}Rb + 2\,^{1}_{0}n$$

235 + 1 = 138 + 96 + 2x1

2. Conserve atomic number (Z) or nuclear charge.

The sum of nuclear charges in the products must equal the sum of nuclear charges in the reactants.

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{138}_{55}Cs + ^{96}_{37}Rb + 2\,^{1}_{0}n$$

92 + 0 = 55 + 37 + 2x0

^{212}Po decays by alpha emission. Write the balanced nuclear equation for the decay of ^{212}Po.

alpha particle - $^{4}_{2}He$ or $^{4}_{2}\alpha$

$$^{212}_{84}Po \longrightarrow {}^{4}_{2}He + {}^{A}_{Z}X$$

$212 = 4 + A$ $\qquad$ $A = 208$

$84 = 2 + Z$ $\qquad$ $Z = 82$

$$^{212}_{84}Po \longrightarrow {}^{4}_{2}He + {}^{208}_{82}Pb$$

TABLE 23.1	Comparison of Chemical Reactions and Nuclear Reactions
Chemical Reactions	**Nuclear Reactions**
1. Atoms are rearranged by the breaking and forming of chemical bonds.	1. Elements (or isotopes of the same elements) are converted from one to another.
2. Only electrons in atomic or molecular orbitals are involved in the breaking and forming of bonds.	2. Protons, neutrons, electrons, and other elementary particles may be involved.
3. Reactions are accompanied by absorption or release of relatively small amounts of energy.	3. Reactions are accompanied by absorption or release of tremendous amounts of energy.
4. Rates of reaction are influenced by temperature, pressure, concentration, and catalysts.	4. Rates of reaction normally are not affected by temperature, pressure, and catalysts.

Nuclear Stability and Radioactive Decay

Beta decay

$^{14}_{6}C \longrightarrow ^{14}_{7}N + ^{0}_{-1}\beta$

$^{40}_{19}K \longrightarrow ^{40}_{20}Ca + ^{0}_{-1}\beta$

Decrease # of neutrons by 1

Increase # of protons by 1

$^{1}_{0}n \longrightarrow ^{1}_{1}p + ^{0}_{-1}\beta$

Positron decay

$^{11}_{6}C \longrightarrow ^{11}_{5}B + ^{0}_{+1}\beta$

$^{38}_{19}K \longrightarrow ^{38}_{18}Ar + ^{0}_{+1}\beta$

Increase # of neutrons by 1

Decrease # of protons by 1

$^{1}_{1}p \longrightarrow ^{1}_{0}n + ^{0}_{+1}\beta$

Nuclear Stability and Radioactive Decay

Electron capture decay

$^{37}_{18}Ar + ^{0}_{-1}e \longrightarrow ^{37}_{17}Cl$

$^{55}_{26}Fe + ^{0}_{-1}e \longrightarrow ^{55}_{25}Mn$

Increase number of neutrons by 1

Decrease number of protons by 1

$$^{1}_{1}p + ^{0}_{-1}e \longrightarrow ^{1}_{0}n$$

Alpha decay

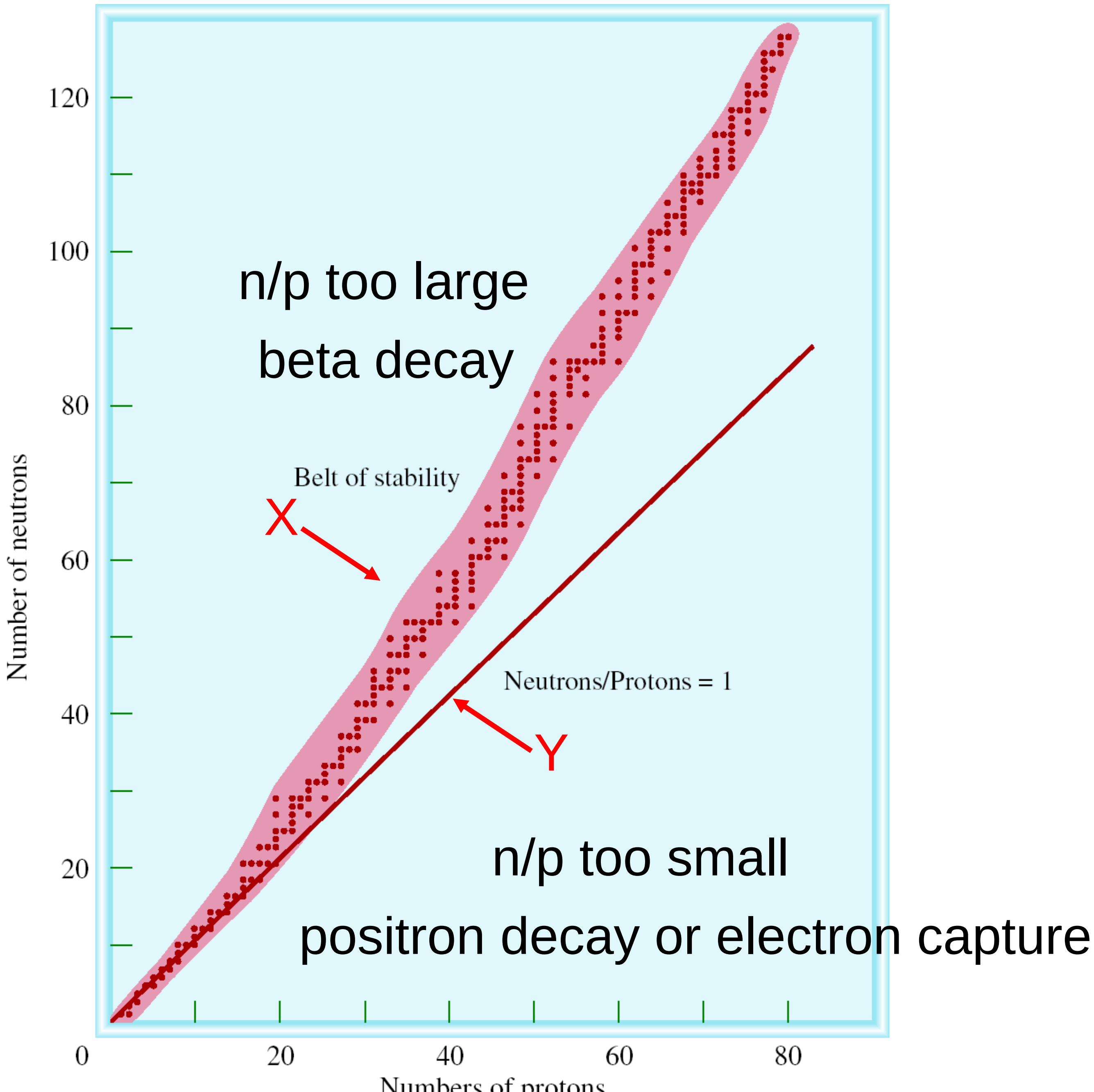
Decrease number of neutrons by 2

$^{212}_{84}Po \longrightarrow ^{4}_{2}He + ^{208}_{82}Pb$

Decrease number of protons by 2

Spontaneous fission

$^{252}_{98}Cf \longrightarrow 2\,^{125}_{49}In + 2\,^{1}_{0}n$



n/p too large
beta decay
Belt of stability
X
Neutrons/Protons = 1
Y
n/p too small
positron decay or electron capture
Number of neutrons
120
100
80
60
40
20
0
20
40
60
80
Numbers of protons

Nuclear Stability

- Certain numbers of neutrons and protons are ***extra*** stable
  - n or p = 2, 8, 20, 50, 82 and 126
  - Like extra stable numbers of electrons in noble gases (e^- = 2, 10, 18, 36, 54 and 86)
- Nuclei with even numbers of both protons and neutrons are more stable than those with odd numbers of neutron and protons
- All isotopes of the elements with atomic numbers higher than 83 are radioactive
- All isotopes of Tc and Pm are radioactive

TABLE 23.2 Number of Stable Isotopes with Even and Odd Numbers of Protons and Neutrons

Protons	Neutrons	Number of Stable Isotopes
Odd	Odd	4
Odd	Even	50
Even	Odd	53
Even	Even	164

Nuclear binding energy is the energy required to break up a nucleus into its component protons and neutrons.

$$\text{Nuclear binding energy} + {}^{19}_{9}\text{F} \longrightarrow 9\,{}^{1}_{1}\text{p} + 10\,{}^{1}_{0}\text{n}$$

$\Delta E = (\Delta m)c^2$

Δm = 9 x (p mass) + 10 x (n mass) – ^{19}F mass

Δm= 9 x 1.007825 + 10 x 1.008665 – 18.9984

Δm = 0.1587 amu

ΔE = 0.1587 amu x (3.00 x 10^8 m/s)^2 = -1.43 x 10^{16} amu m^2/s^2

Using conversion factors:

1 kg = 6.022 x 10^{26} amu   1 J = kg m^2/s^2

ΔE = 2.37 x 10^{-11} J

$$\Delta E = (2.37 \times 10^{-11} J) \times (6.022 \times 10^{23}/mol)$$

$$\Delta E = -1.43 \times 10^{13} J/mol$$

$$\Delta E = -1.43 \times 10^{10} kJ/mol$$

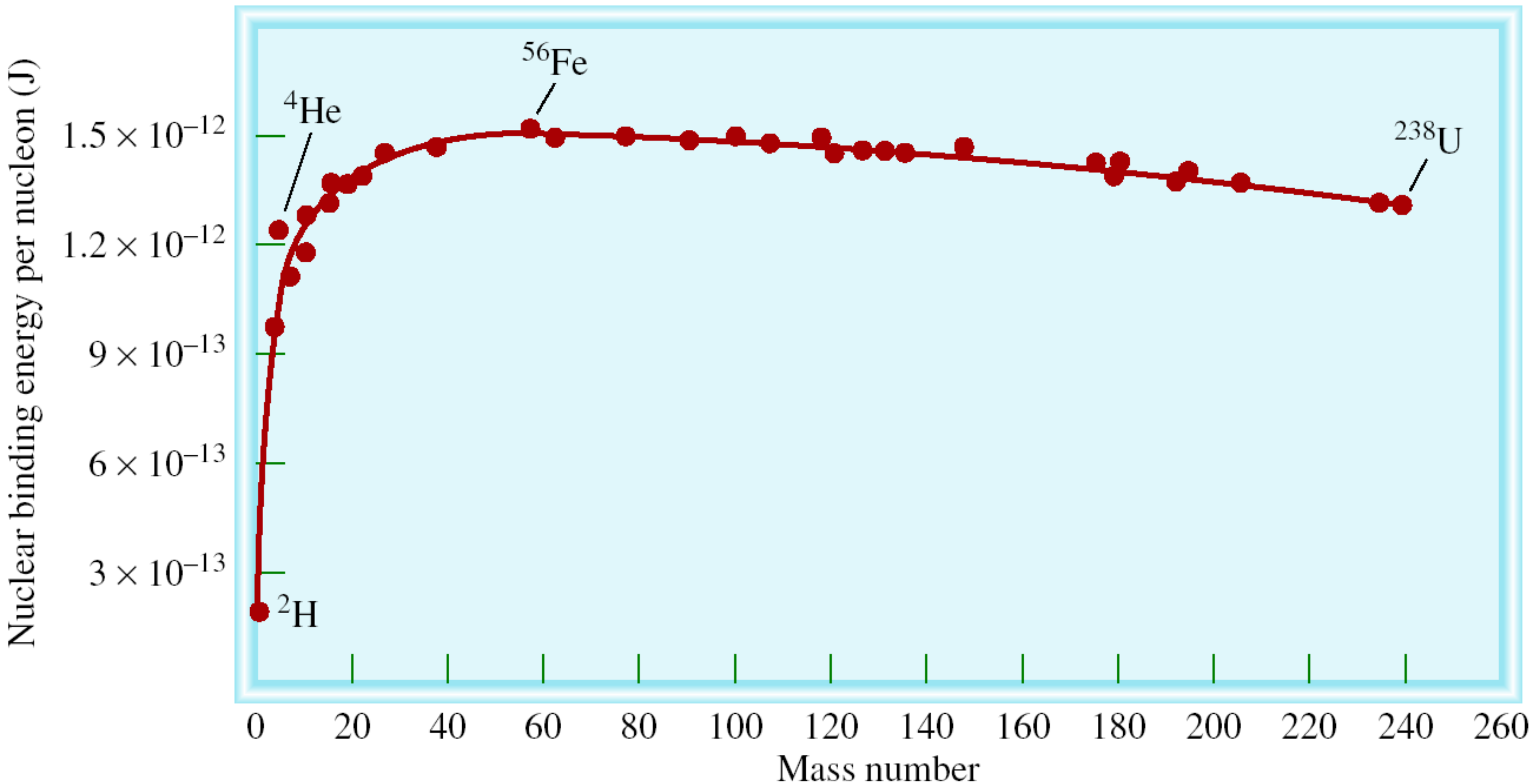
Nuclear binding energy = 1.43×10^{10} kJ/mol

$$\text{binding energy per nucleon} = \frac{\text{binding energy}}{\text{number of nucleons}}$$

$$= \frac{2.37 \times 10^{-11} \text{ J}}{19 \text{ nucleons}}$$

$$= 1.25 \times 10^{-12} \text{ J/nucleon}$$

Nuclear binding energy per nucleon vs mass number



$\frac{\text{nuclear binding energy}}{\text{nucleon}} \uparrow$ nuclear stability $\uparrow$

Kinetics of Radioactive Decay

$$N \longrightarrow \text{daughter}$$

$$\text{rate} = \lambda N$$

$$\ln \frac{N_t}{N_0} = -\lambda t$$

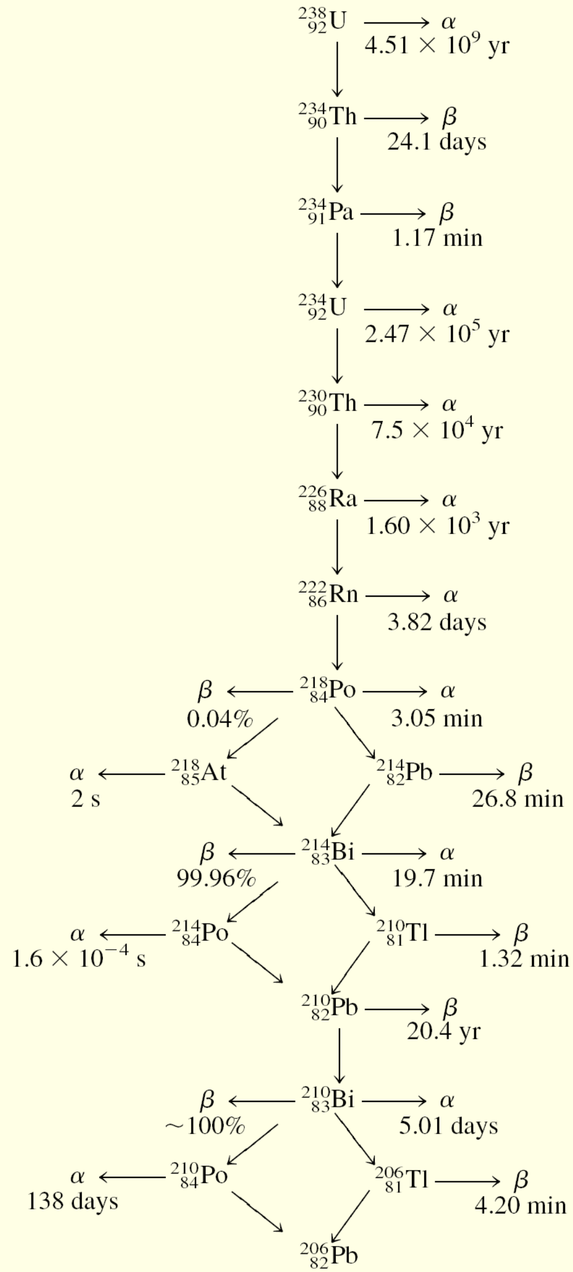
N = the number of atoms at time t

N_0 = the number of atoms at time $t = 0$

λ is the decay constant

$$t_{½} = \frac{0.693}{\lambda}$$

TABLE 23.3 **The Uranium Decay Series***



*The times denote the half-lives.

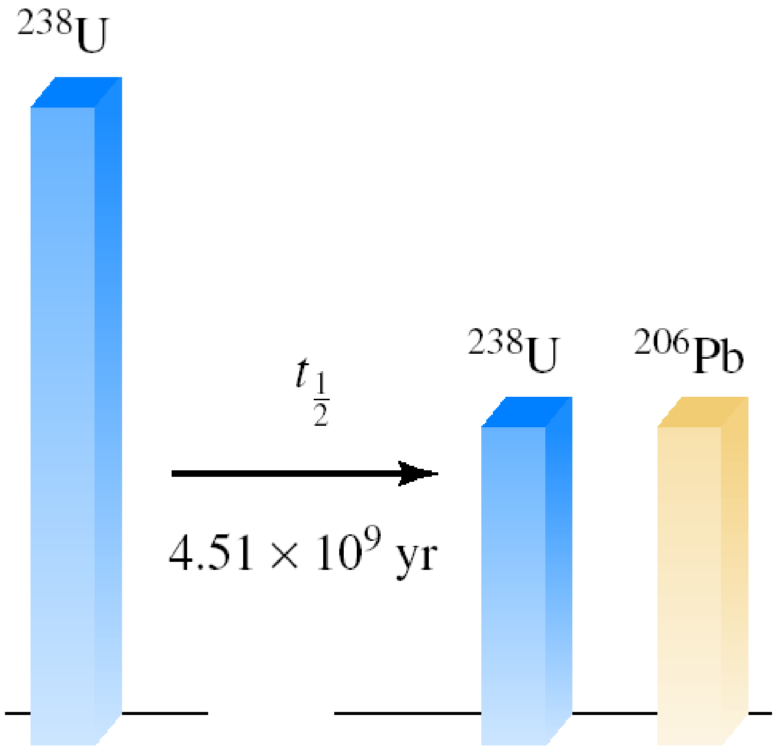
Radiocarbon Dating

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

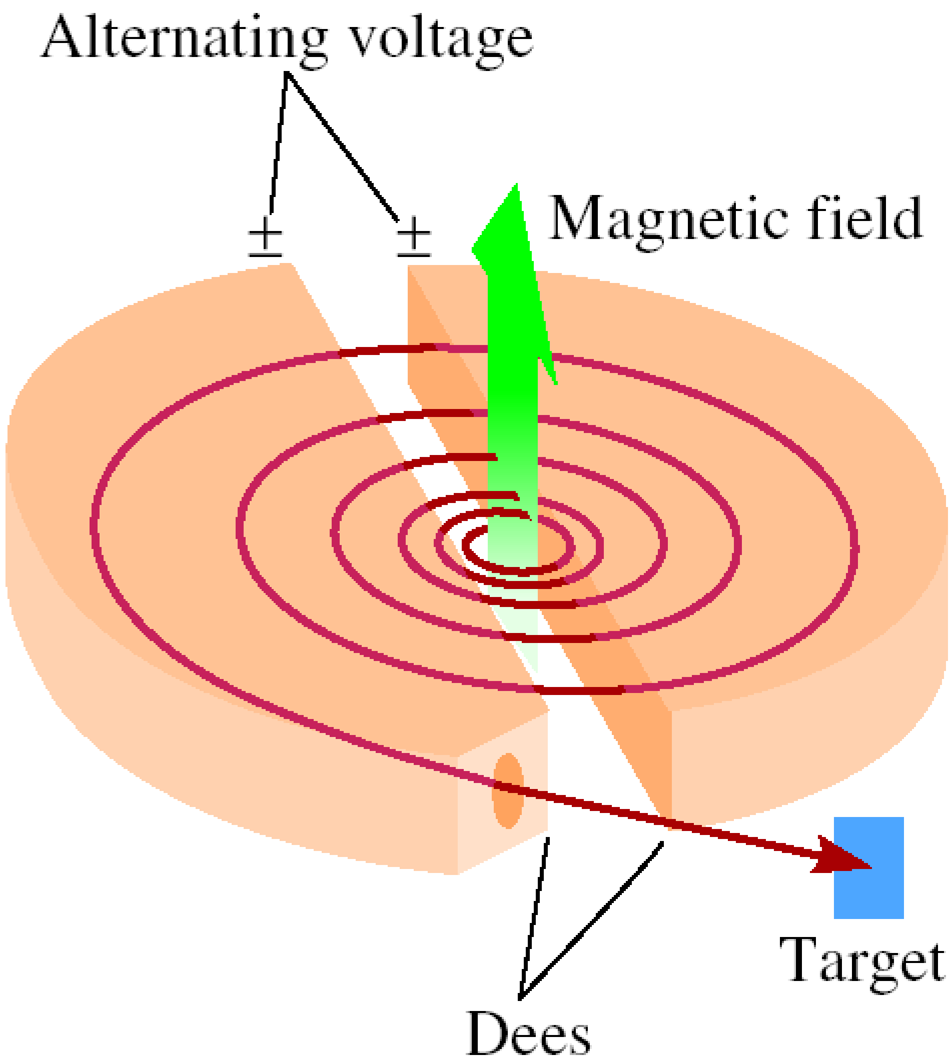
$$^{14}_{6}C \longrightarrow ^{14}_{7}N + ^{0}_{-1}\beta + \bar{\nu} \qquad t_{½} = 5730 \text{ years}$$

Uranium-238 Dating

$$^{238}_{92}U \longrightarrow ^{206}_{82}Pb + 8\,^{4}_{2}\alpha + 6\,^{0}_{-1}\beta \qquad t_{½} = 4.51 \times 10^{9} \text{ years}$$



Nuclear Transmutation



$$^{14}_{7}N + ^{4}_{2}\alpha \longrightarrow ^{17}_{8}O + ^{1}_{1}p$$

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

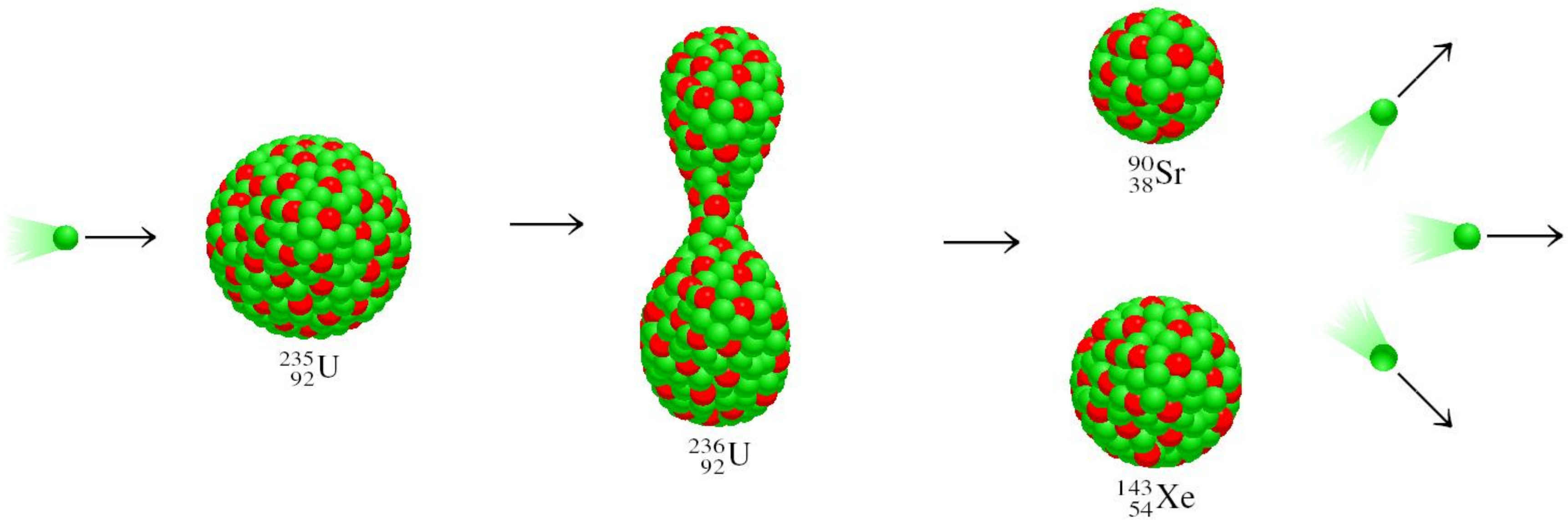
$$^{14}_{7}N + ^{1}_{1}p \longrightarrow ^{11}_{6}C + ^{4}_{2}\alpha$$

Nuclear Transmutation

TABLE 23.4 The Transuranium Elements

Atomic Number	Name	Symbol	Preparation
93	Neptunium	Np	$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{93}Np + ^{0}_{-1}\beta$
94	Plutonium	Pu	$^{239}_{93}Np \longrightarrow ^{239}_{94}Pu + ^{0}_{-1}\beta$
95	Americium	Am	$^{239}_{94}Pu + ^{1}_{0}n \longrightarrow ^{240}_{95}Am + ^{0}_{-1}\beta$
96	Curium	Cm	$^{239}_{94}Pu + ^{4}_{2}\alpha \longrightarrow ^{242}_{96}Cm + ^{1}_{0}n$
97	Berkelium	Bk	$^{241}_{95}Am + ^{4}_{2}\alpha \longrightarrow ^{243}_{97}Bk + 2^{1}_{0}n$
98	Californium	Cf	$^{242}_{96}Cm + ^{4}_{2}\alpha \longrightarrow ^{245}_{98}Cf + ^{1}_{0}n$
99	Einsteinium	Es	$^{238}_{92}U + 15^{1}_{0}n \longrightarrow ^{253}_{99}Es + 7^{0}_{-1}\beta$
100	Fermium	Fm	$^{238}_{92}U + 17^{1}_{0}n \longrightarrow ^{255}_{100}Fm + 8^{0}_{-1}\beta$
101	Mendelevium	Md	$^{253}_{99}Es + ^{4}_{2}\alpha \longrightarrow ^{256}_{101}Md + ^{1}_{0}n$
102	Nobelium	No	$^{246}_{96}Cm + ^{12}_{6}C \longrightarrow ^{254}_{102}No + 4^{1}_{0}n$
103	Lawrencium	Lr	$^{252}_{98}Cf + ^{10}_{5}B \longrightarrow ^{257}_{103}Lr + 5^{1}_{0}n$
104	Rutherfordium	Rf	$^{249}_{98}Cf + ^{12}_{6}C \longrightarrow ^{257}_{104}Rf + 4^{1}_{0}n$
105	Dubnium	Db	$^{249}_{98}Cf + ^{15}_{7}N \longrightarrow ^{260}_{105}Db + 4^{1}_{0}n$
106	Seaborgium	Sg	$^{249}_{98}Cf + ^{18}_{8}O \longrightarrow ^{263}_{106}Sg + 4^{1}_{0}n$
107	Bohrium	Bh	$^{209}_{83}Bi + ^{54}_{24}Cr \longrightarrow ^{262}_{107}Bh + ^{1}_{0}n$
108	Hassium	Hs	$^{208}_{82}Pb + ^{58}_{26}Fe \longrightarrow ^{265}_{108}Hs + ^{1}_{0}n$
109	Meitnerium	Mt	$^{209}_{83}Bi + ^{58}_{26}Fe \longrightarrow ^{266}_{109}Mt + ^{1}_{0}n$
110	Darmstadtium	Ds	$^{208}_{82}Pb + ^{62}_{28}Ni \longrightarrow ^{269}_{110}Ds + ^{1}_{0}n$
111	Roentgenium	Rg	$^{209}_{83}Bi + ^{64}_{28}Ni \longrightarrow ^{272}_{111}Rg + ^{1}_{0}n$

Nuclear Fission



$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{90}_{38}Sr + ^{143}_{54}Xe + 3^{1}_{0}n + \text{Energy}$$

Energy = [mass ^{235}U + mass n – (mass ^{90}Sr + mass ^{143}Xe + 3 x mass n)] x c^2

Energy = 3.3×10^{-11} J per ^{235}U

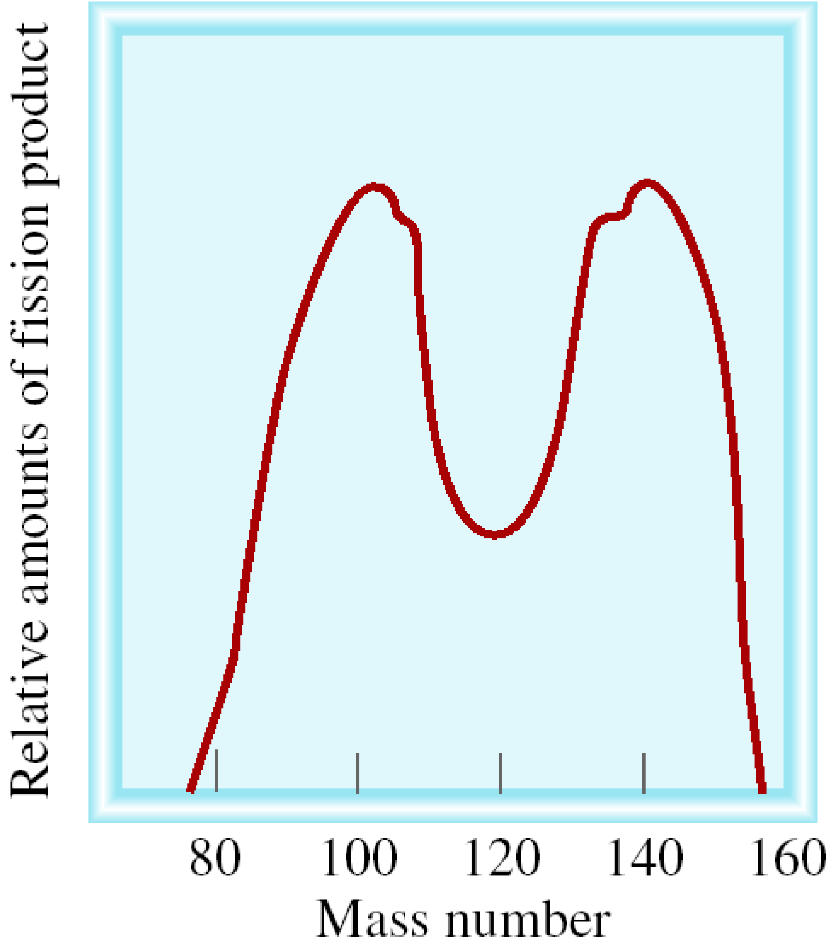
= 2.0×10^{13} J per mole ^{235}U

Combustion of 1 ton of coal = 5×10^{7} J

Nuclear Fission

Representative fission reaction

$${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{90}_{38}Sr + {}^{143}_{54}Xe + 3\,{}^{1}_{0}n + \text{Energy}$$



Nuclear Fission

Nuclear chain reaction is a self-sustaining sequence of nuclear fission reactions.

The minimum mass of fissionable material required to generate a self-sustaining nuclear chain reaction is the ***critical mass***.

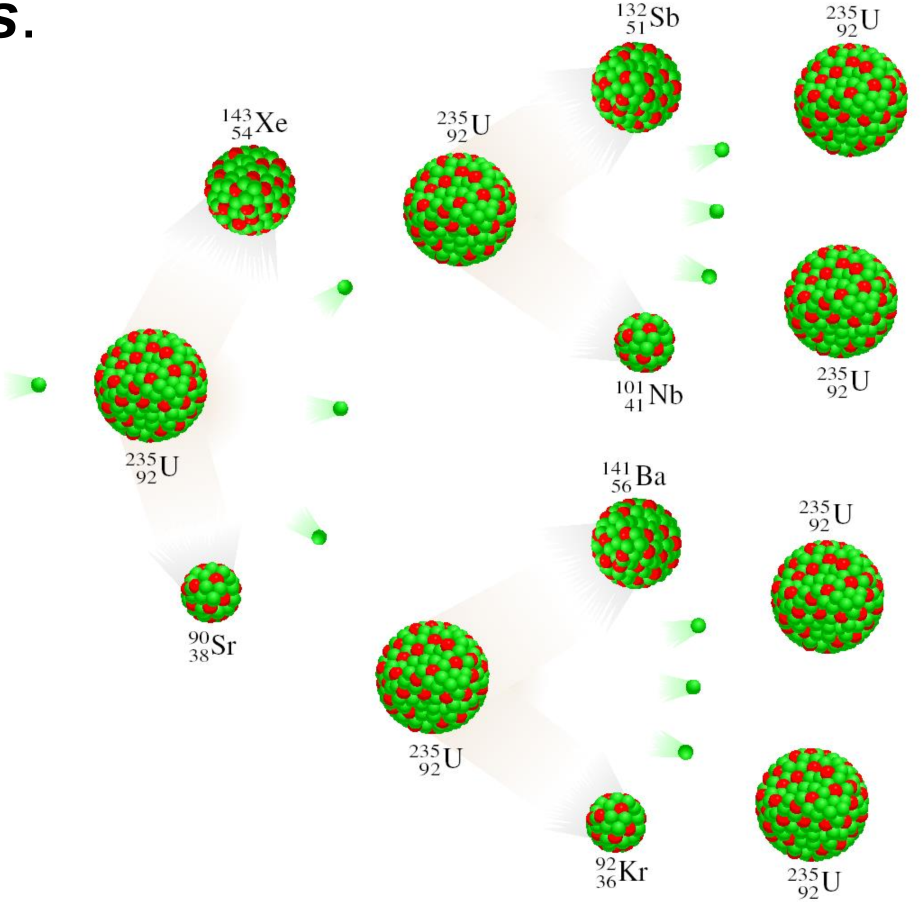
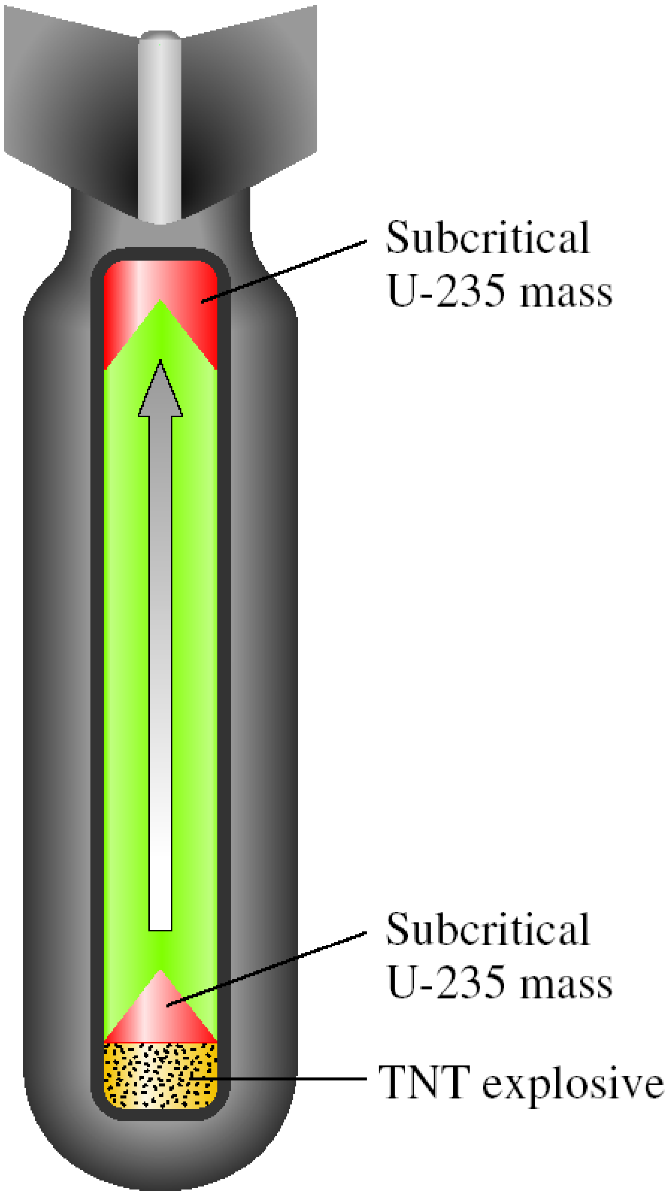


TABLE 23.5

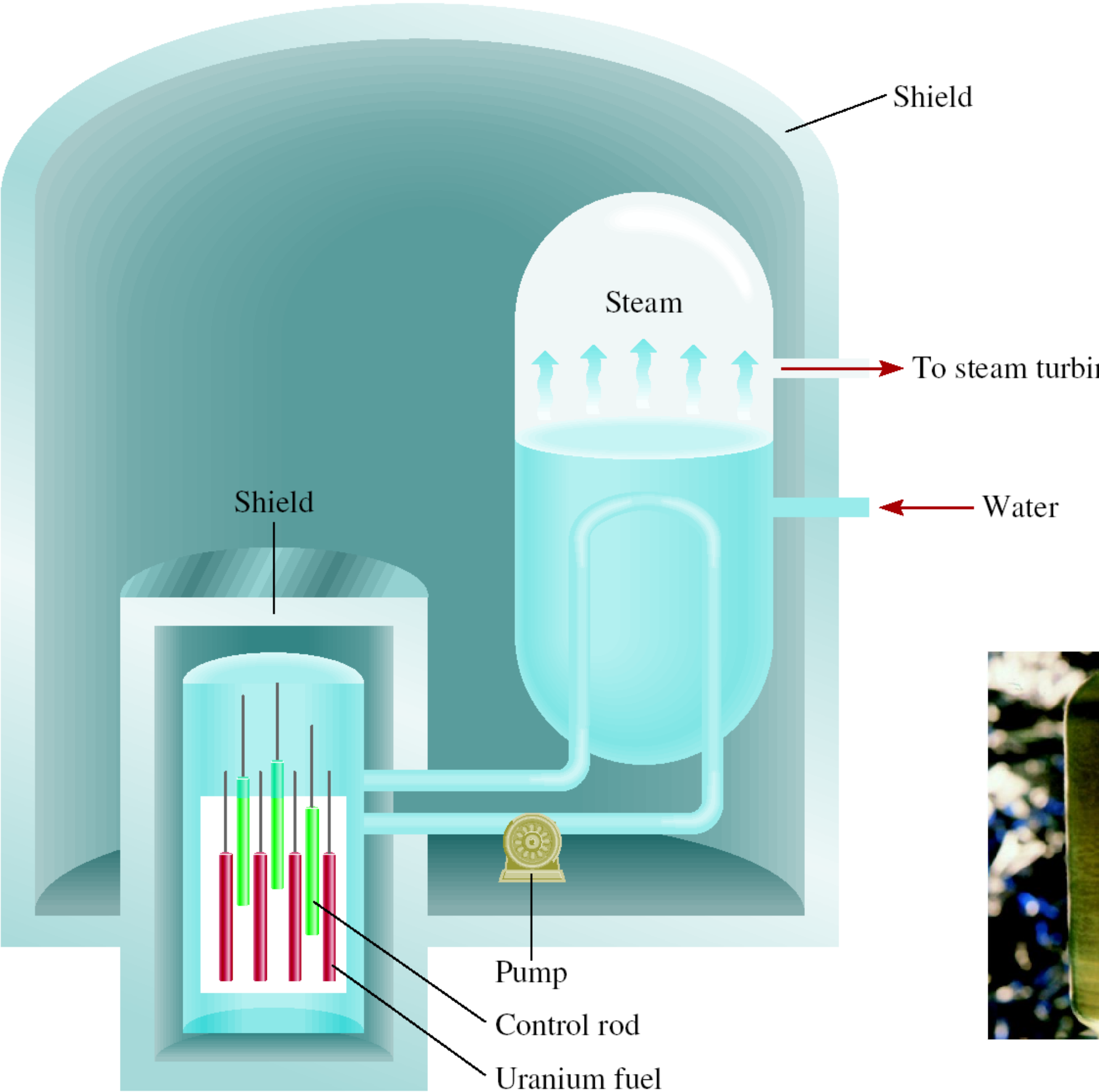
Nuclear Binding Energies of ^{235}U and Its Fission Products

	Nuclear Binding Energy
^{235}U	2.82×10^{-10} J
^{90}Sr	1.23×10^{-10} J
^{143}Xe	1.92×10^{-10} J

Schematic of an Atomic Bomb



Schematic Diagram of a Nuclear Reactor



refueling

U_3O_8

Chemistry In Action: Nature's Own Fission Reactor

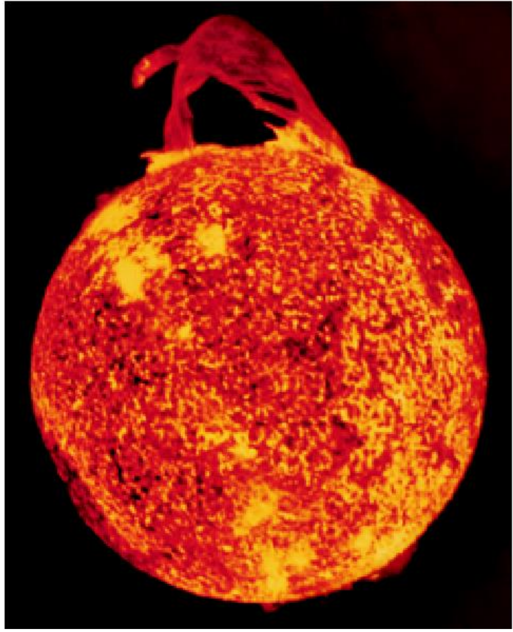
Natural Uranium

0.7202 % U-235 99.2798% U-238

Measured at Oklo

0.7171 % U-235

Nuclear Fusion



solar fusion

Fusion Reaction	Energy Released
${}^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{1}H + {}^{1}_{1}H$	6.3×10^{-13} J
${}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n$	2.8×10^{-12} J
${}^{6}_{3}Li + {}^{2}_{1}H \longrightarrow 2\ {}^{4}_{2}He$	3.6×10^{-12} J

Tokamak magnetic plasma confinement

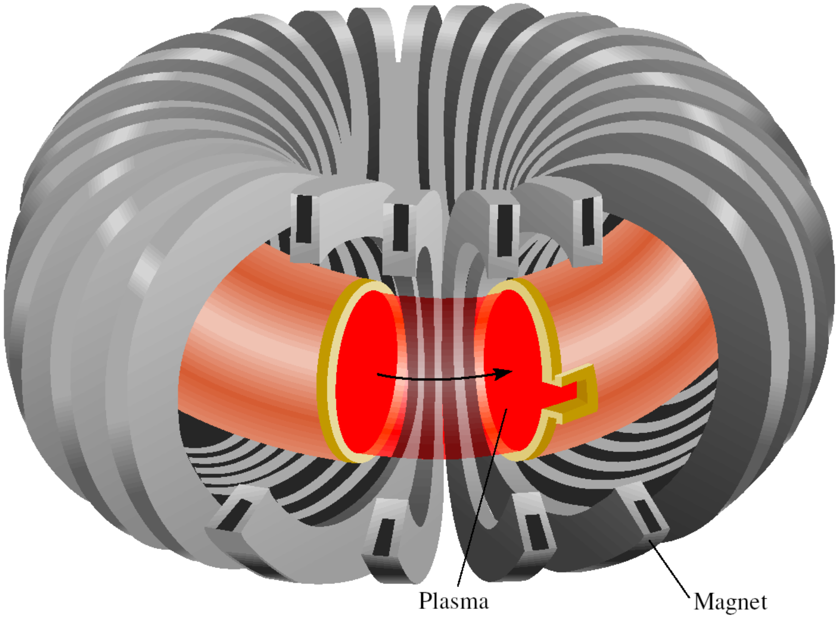
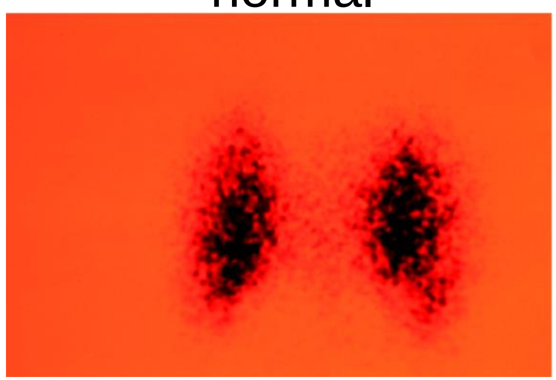


TABLE 23.6 Some Radioactive Isotopes Used in Medicine

Isotope	Half-Life	Uses
^{18}F	1.8 h	Brain imaging, bone scan
^{24}Na	15 h	Monitoring blood circulation
^{32}P	14.3 d	Location of ocular, brain, and skin tumors
^{43}K	22.4 h	Myocardial scan
^{47}Ca	4.5 d	Study of calcium metabolism
^{51}Cr	27.8 d	Determination of red blood cell volume, spleen imaging, placenta localization
^{60}Co	5.3 yr	Sterilization of medical equipment, cancer treatment
^{99m}Tc	6 h	Imaging of various organs, bones, placenta location
^{125}I	60 d	Study of pancreatic function, thyroid imaging, liver function
^{131}I	8 d	Brain imaging, liver function, thyroid activity

Thyroid images with ^{125}I-labeled compound

normal



enlarged

Radioisotopes in Medicine

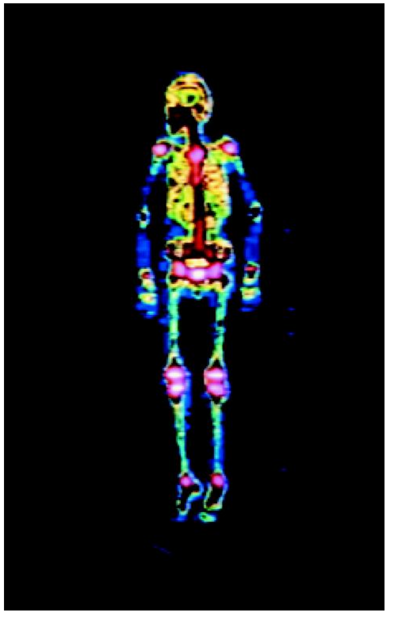
Research production of ^{99}Mo

$$^{98}_{42}\mathrm{Mo} + ^{1}_{0}\mathrm{n} \longrightarrow ^{99}_{42}\mathrm{Mo}$$

Commercial production of ^{99}Mo

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \longrightarrow ^{99}_{42}\mathrm{Mo} + \text{other fission products}$$

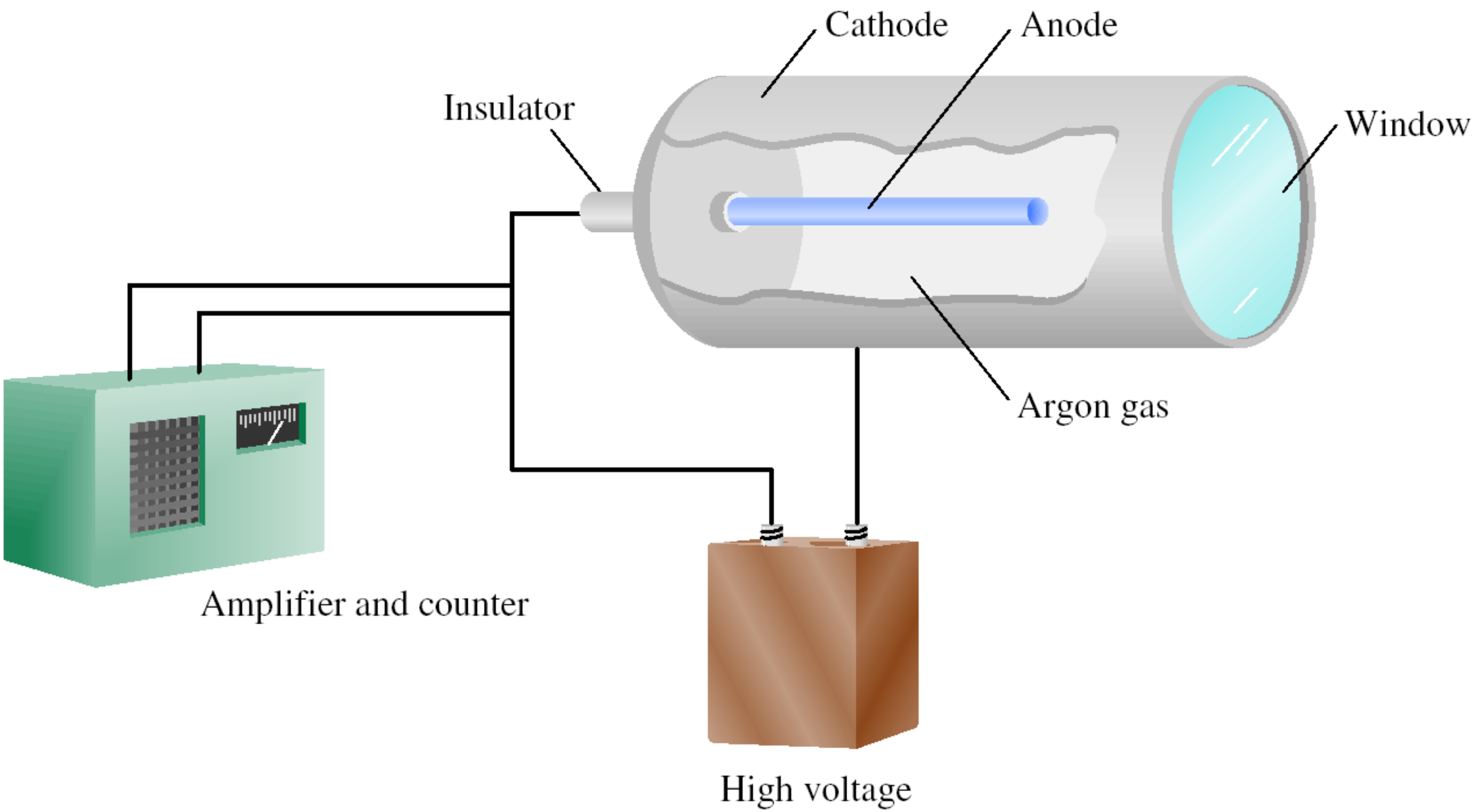
Bone Scan with ^{99m}Tc



$$^{99}_{42}\mathrm{Mo} \longrightarrow ^{99m}_{43}\mathrm{Tc} + ^{0}_{-1}\beta \qquad t_{½} = 66 \text{ hours}$$

$$^{99m}_{43}\mathrm{Tc} \longrightarrow ^{99}_{43}\mathrm{Tc} + \gamma\text{-ray} \qquad t_{½} = 6 \text{ hours}$$

Geiger-Müller Counter



Biological Effects of Radiation

***R**adiation **a**bsorbed **d**ose (**rad**)*

1 rad = 1 x 10^{-5} J/g of material

***R**oentgen **e**quivalent for **m**an (**rem**)*

1 rem = 1 rad x Q

<u>***Q**uality Factor*</u>

γ-ray = 1

β = 1

α = 20

TABLE 23.7 Average Yearly Radiation Doses for Americans

Source	Dose (mrem/yr)*
Cosmic rays	20–50
Ground and surroundings	25
Human body†	26
Medical and dental X rays	50–75
Air travel	5
Fallout from weapons tests	5
Nuclear waste	2
Total	133–188

*1 mrem = 1 millirem = 1 × 10^{-3} rem.

†The radioactivity in the body comes from food and air.

Chemistry In Action: Food Irradiation

Food Irradiation Dosages and Their Effects*

Dosage	Effect
Low dose (Up to 100 kilorad)	Inhibits sprouting of potatoes, onions, garlics.
	Inactivates trichinae in pork.
	Kills or prevents insects from reproducing in grains, fruits, and vegetables after harvest.
Medium dose (100 to 1000 kilorads)	Delays spoilage of meat, poultry, and fish by killing spoilage microorganism.
	Reduces salmonella and other food-borne pathogens in meat, fish, and poultry.
	Extends shelf life by delaying mold growth on strawberries and some other fruits.
High dose (1000 to 10,000 kilorads)	Sterilizes meat, poultry, fish, and some other foods.
	Kills microorganisms and insects in spices and seasoning.

*Source: *Chemical & Engineering News,* May 5 (1986).