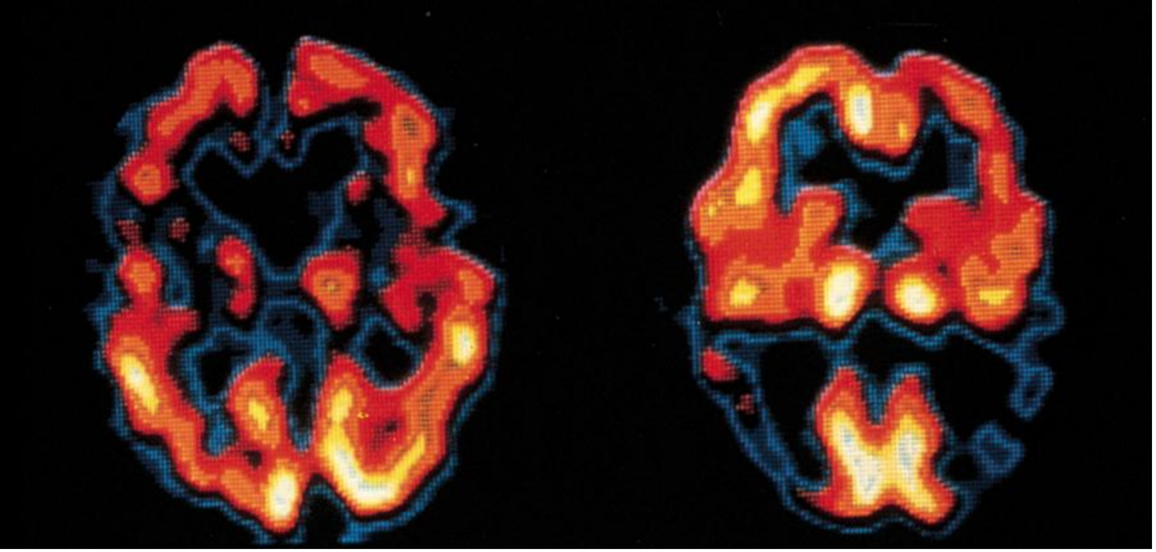
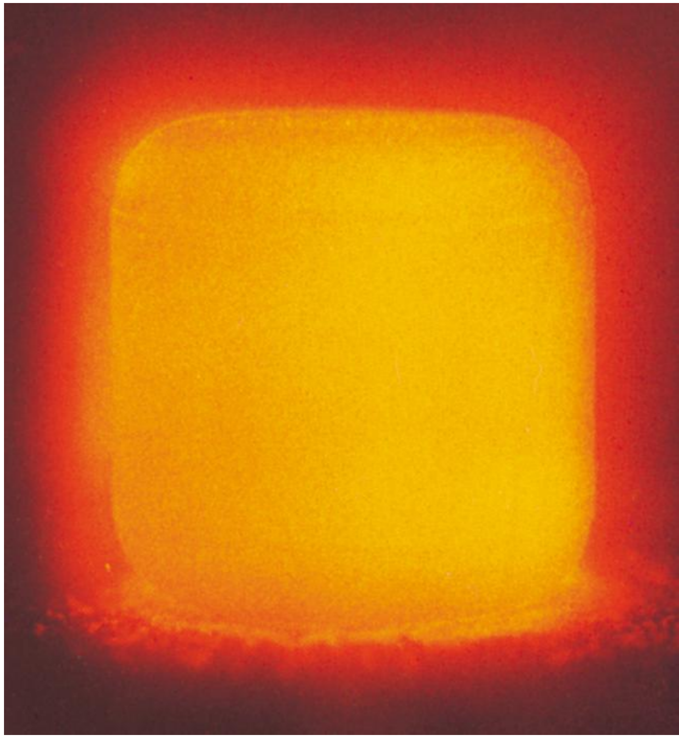




Nuclear Chemistry

Chapter 23

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

$^{A}_{Z}\mathrm{X}$ ← Element Symbol

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

Isotopes

Different forms of the same atom, having the same Atomic number (protons) and different mass number (different number of neutrons)

proton $^{1}_{1}H$

Deutron $^{2}_{1}H$

tritium $^{3}_{1}H$

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.

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

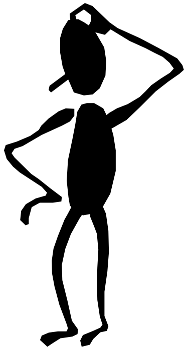
$$235 + 1 = 138 + 96 + 2x1$$

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

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

$212 = 4 + A$ $A = 208$

$84 = 2 + Z$ $Z = 82$

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

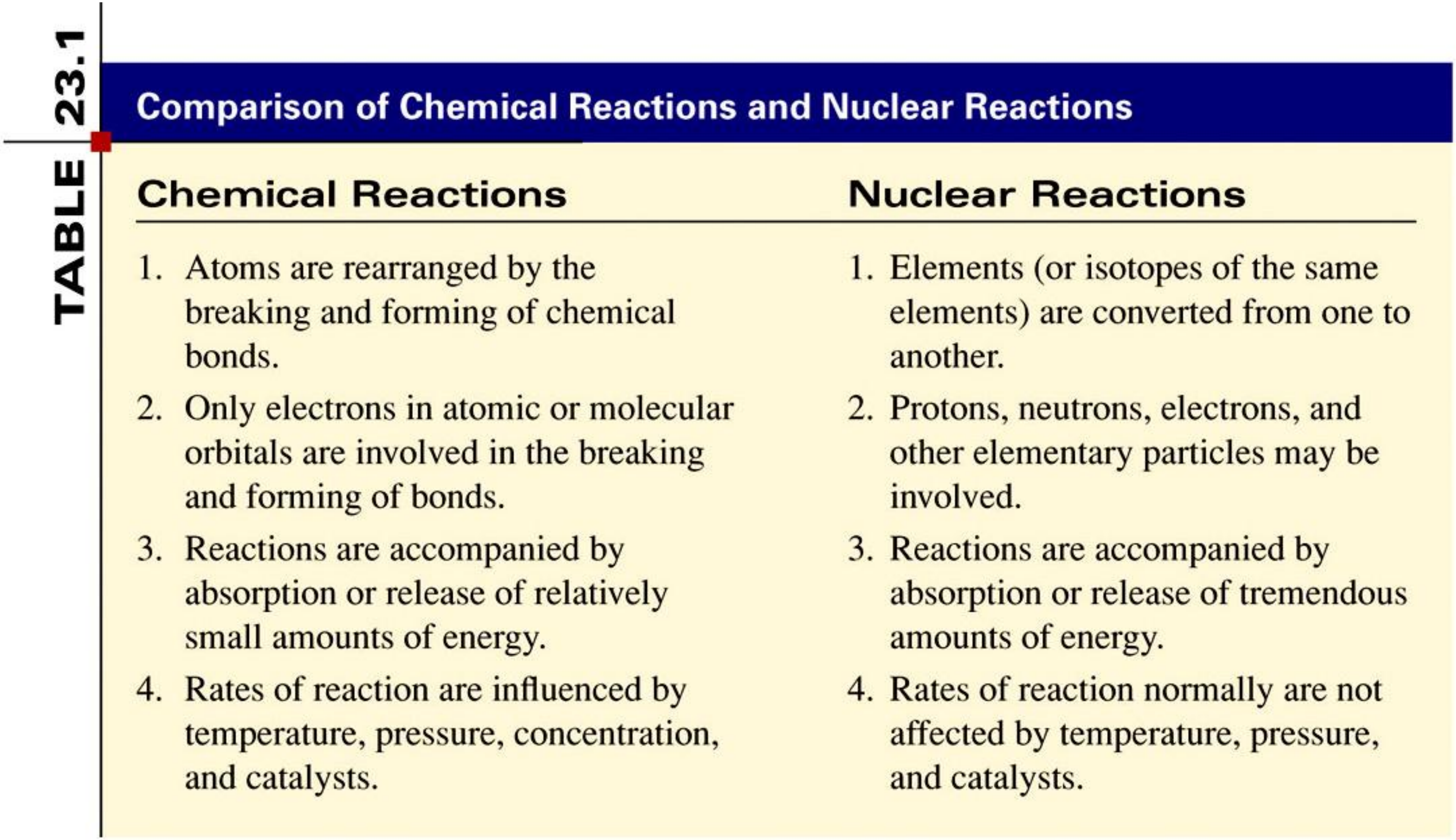


TABLE 23.1

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

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

Decrease # of neutrons by 1

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

Increase # of protons by 1

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

Positron decay

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

Increase # of neutrons by 1

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

Decrease # of protons by 1

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

ν and $\bar{\nu}$ have $A = 0$ and $Z = 0$

Nuclear Stability and Radioactive Decay

Electron capture decay

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

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

Increase # of neutrons by 1

Decrease # of protons by 1

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

Alpha decay

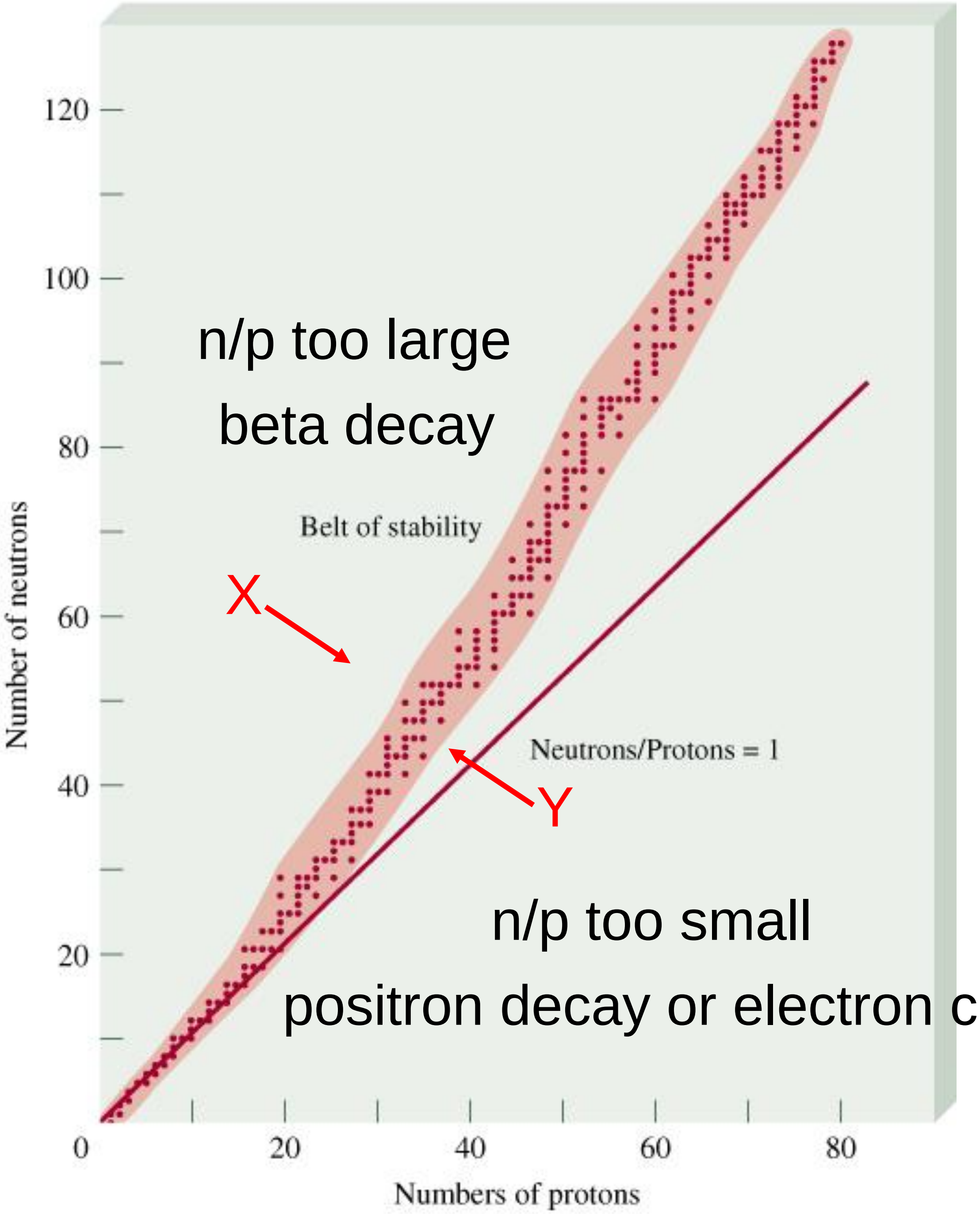
$$^{212}_{84}\text{Po} \longrightarrow {}^{4}_{2}\text{He} + {}^{208}_{82}\text{Pb}$$

Decrease # of neutrons by 2

Decrease # of protons by 2

Spontaneous fission

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



n/p too large

beta decay

n/p too small

positron decay or electron capture

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

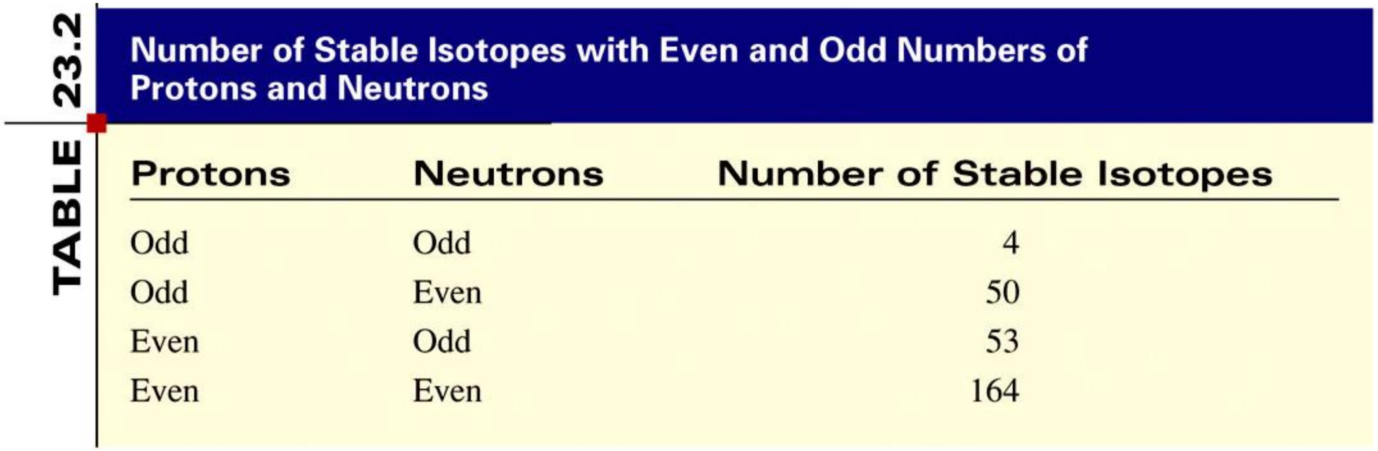


TABLE 23.2

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 (BE) is the energy required to break up a nucleus into its component protons and neutrons.

$$\mathrm{BE} + {}^{19}_{9}\mathrm{F} \longrightarrow 9\,{}^{1}_{1}\mathrm{p} + 10\,{}^{1}_{0}\mathrm{n}$$

$$E = mc^2$$

$$\mathrm{BE} = 9 \times (\text{p mass}) + 10 \times (\text{n mass}) - {}^{19}\mathrm{F}\ \text{mass}$$

$$\mathrm{BE}\ (\text{amu}) = 9 \times 1.007825 + 10 \times 1.008665 - 18.9984$$

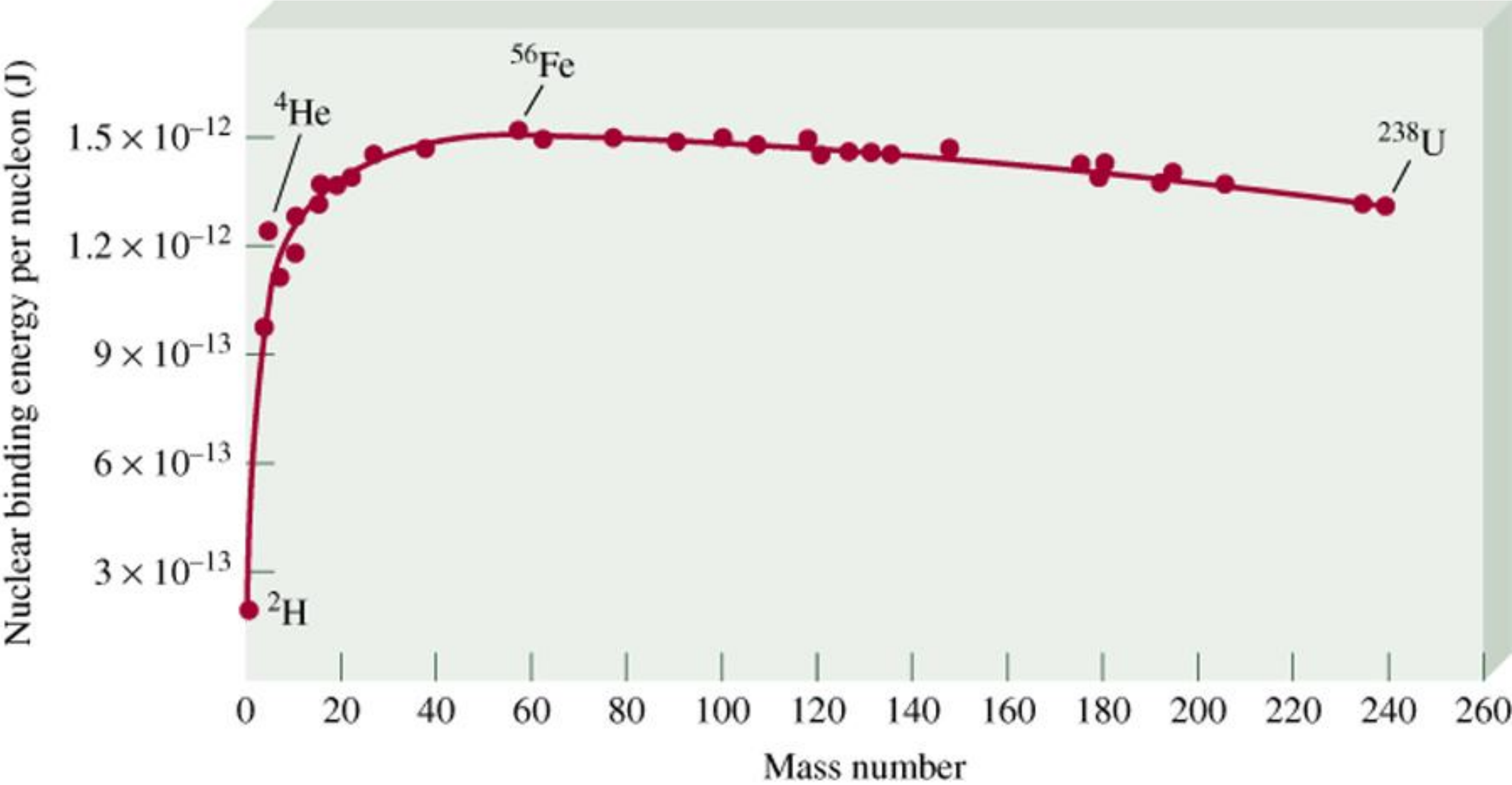
$$\mathrm{BE} = 0.1587\ \text{amu} \qquad 1\ \text{amu} = 1.49 \times 10^{-10}\ \mathrm{J}$$

$$\mathrm{BE} = 2.37 \times 10^{-11}\ \mathrm{J}$$

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

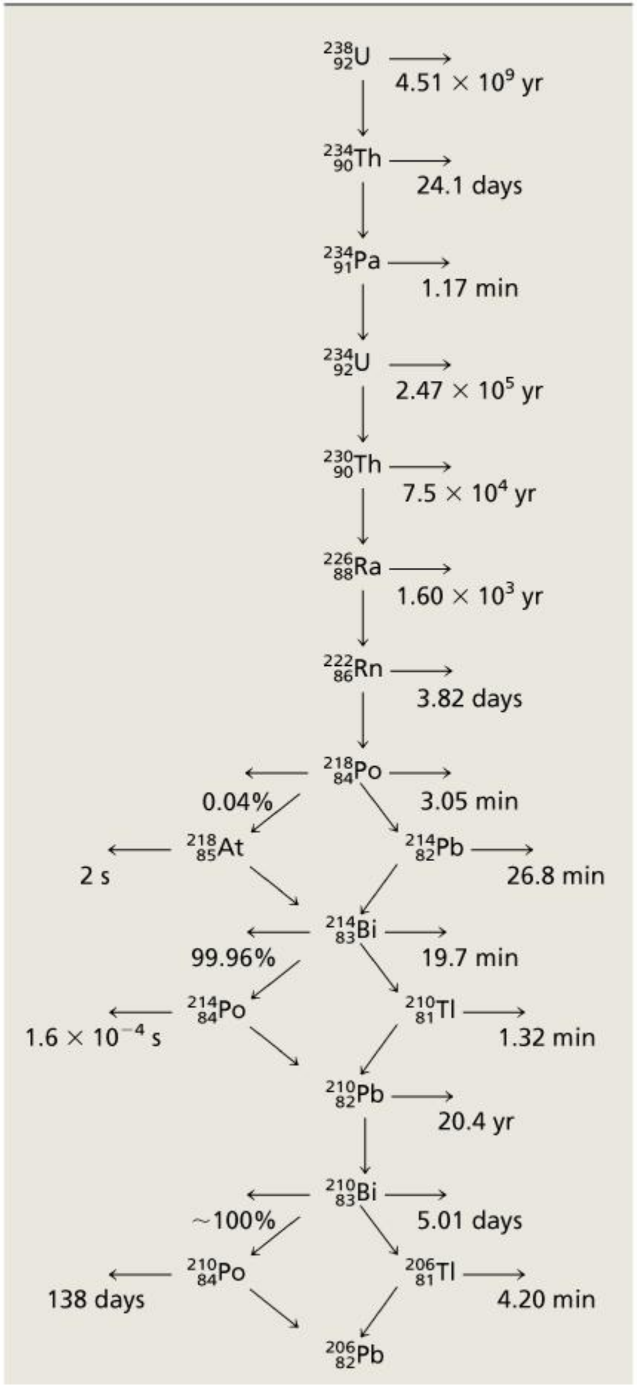
$$= \frac{2.37 \times 10^{-11}\ \mathrm{J}}{19\ \text{nucleons}} = 1.25 \times 10^{-12}\ \mathrm{J}$$

Nuclear binding energy per nucleon vs Mass number



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

Table 22.3 The Uranium Decay Series



Kinetics of Radioactive Decay

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

$$\text{rate} = -\frac{\Delta N}{\Delta t} \qquad \text{rate} = \lambda N$$

$$-\frac{\Delta N}{\Delta t} = \lambda N$$

$$N = N_0 \exp(-\lambda t) \qquad \ln N = \ln N_0 - \lambda t$$

N = the number of atoms at time t

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

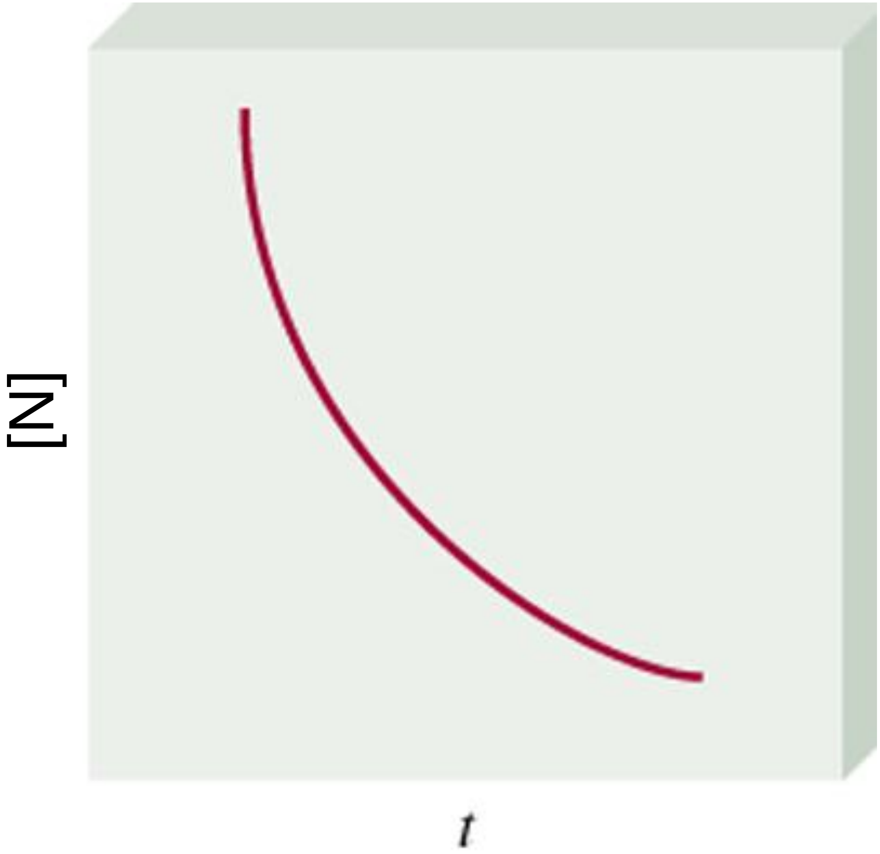
λ is the decay constant

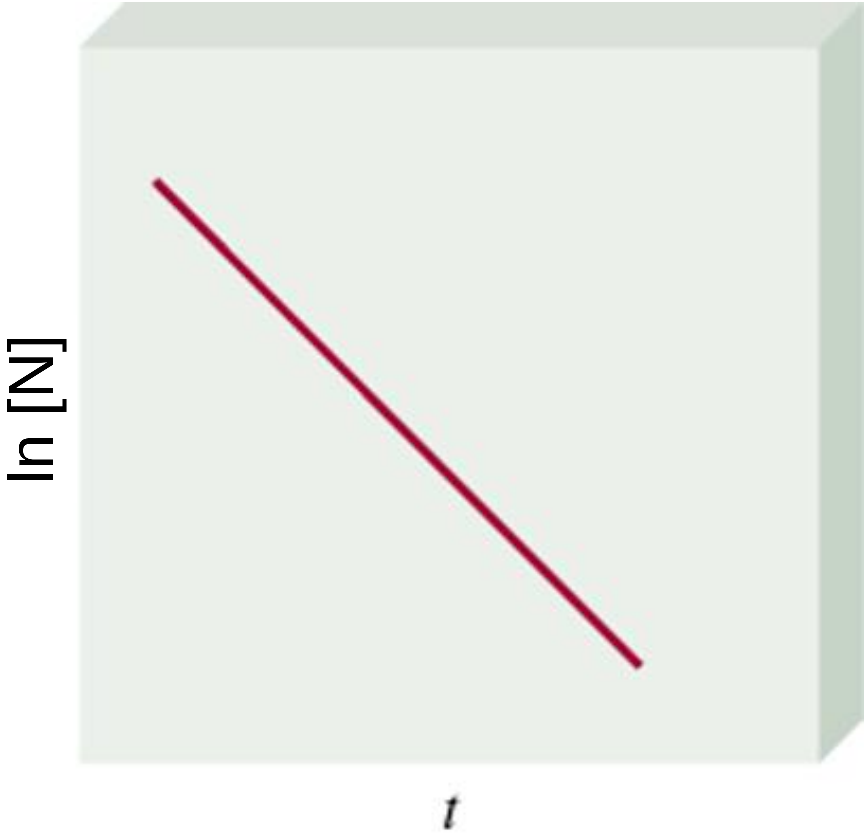
$$\lambda = \frac{\ln 2}{t_{1/2}}$$

Kinetics of Radioactive Decay

$[N] = [N]_0 \exp(-\lambda t)$

$\ln[N] = \ln[N]_0 - \lambda t$





EXAMPLE:

The half-life of ^{90}Sr is 29 years. What fraction of the atoms in sample of ^{90}Sr would remain 175 years later?

a) 0.166 b) 0.125 c) 0.015 d) 0.50

Total time / $t_{1/2}$

175/29 = 6.03 periods

1 -→ ½ --→ ¼ ----→ 1/8 ----→ 1/16 ----→ 1/32 -----→ 1/ 64

Another solution

$K = \ln 2/ t_{1/2} = 0.693/29 = 0.0239\ y^{-1}$

$\ln No/N = kt = 0.0239\ y^{-1} \times 175\ y$

$= 4.18$

$No/N = e^{4.18} = 65.36$

$N= 1/65.36 = 0.015$

Radiocarbon Dating

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

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

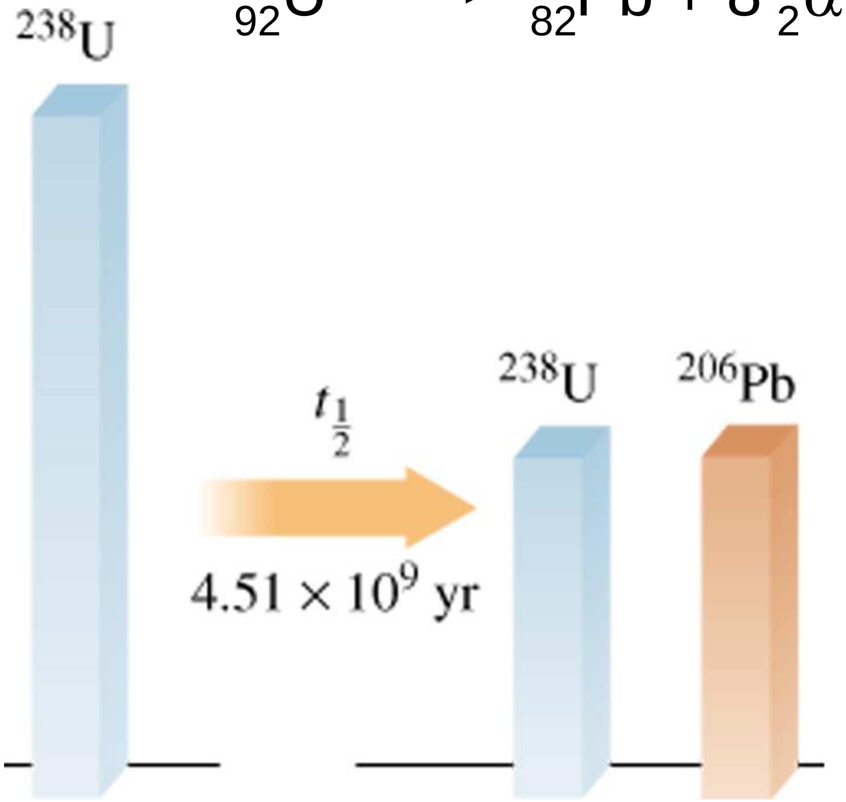
$t_{1/2}$ = 5730 years

$k = 0.693/5730 = 1.2 \times 10^{-4}\ \mathrm{y}^{-1}$

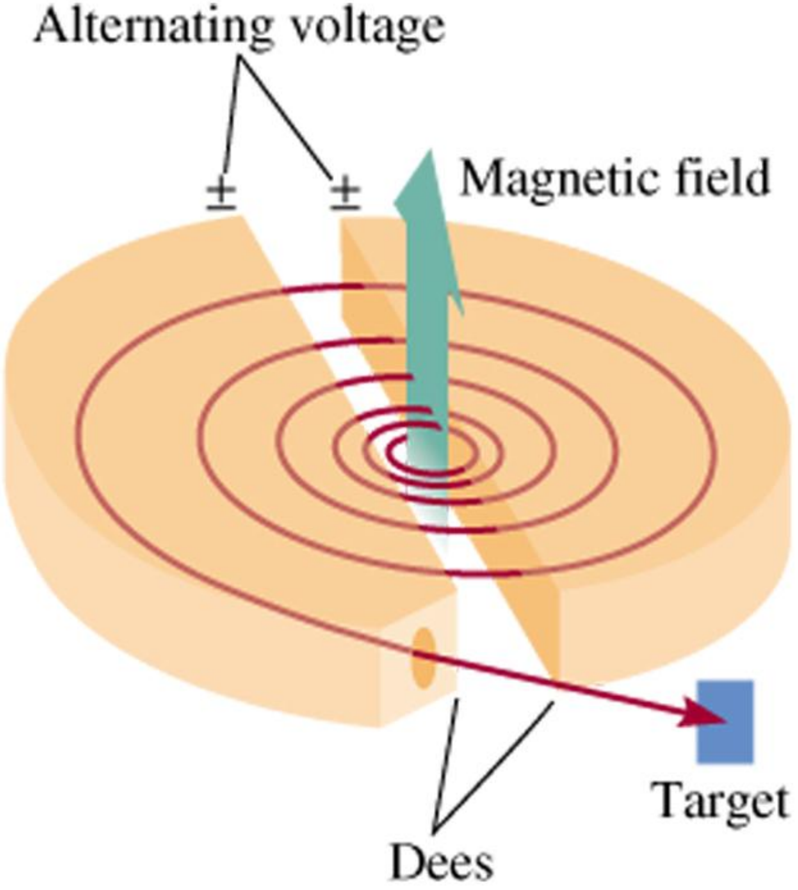
Uranium-238 Dating

$$^{238}_{92}\mathrm{U} \longrightarrow ^{206}_{82}\mathrm{Pb} + 8\,^{4}_{2}\alpha + 6\,^{0}_{-1}\beta$$

$t_{1/2}$ = 4.51 x 10^9 years



Nuclear Transmutation



Cyclotron Particle Accelerator

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

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

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

Nuclear Transmutation

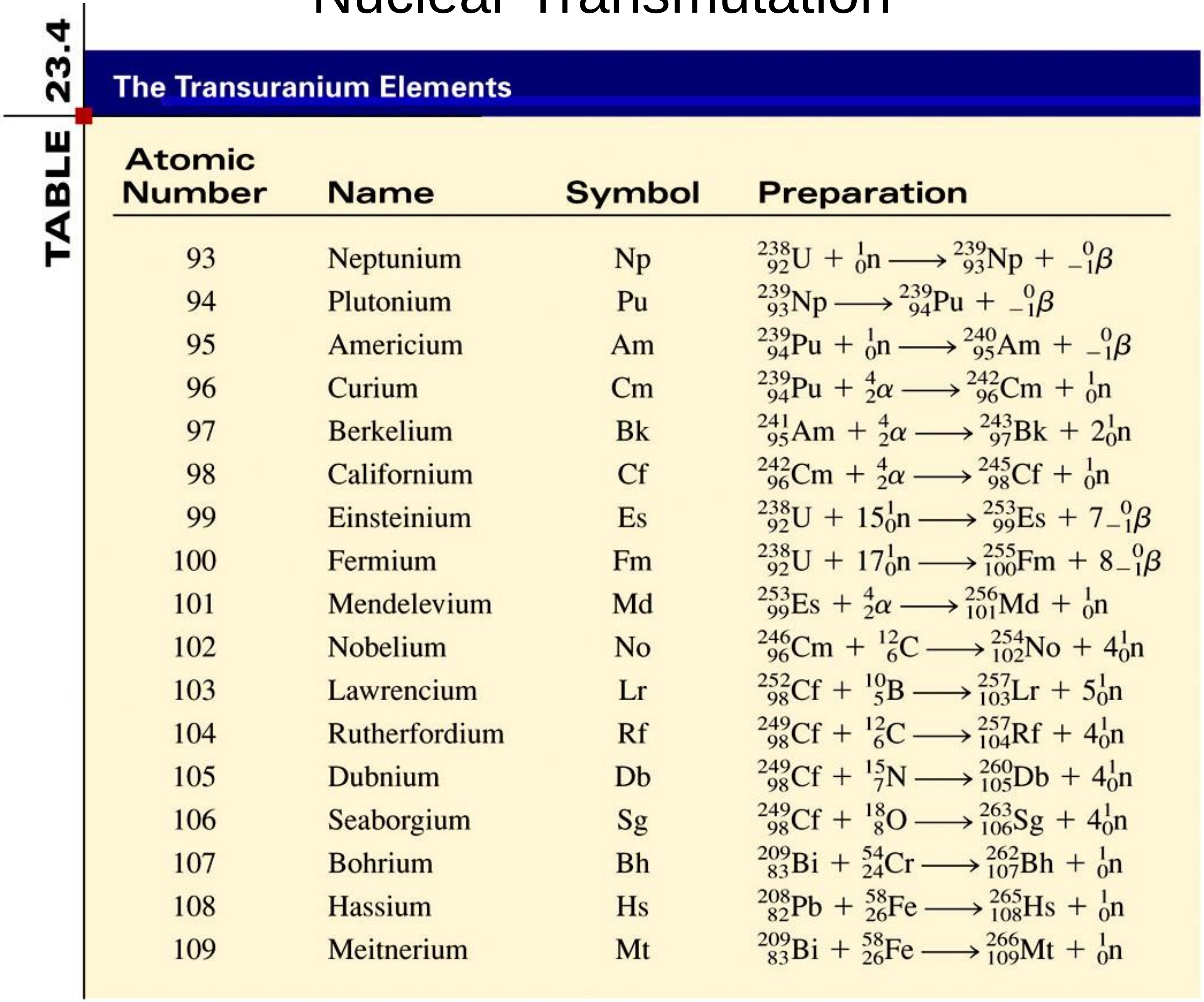
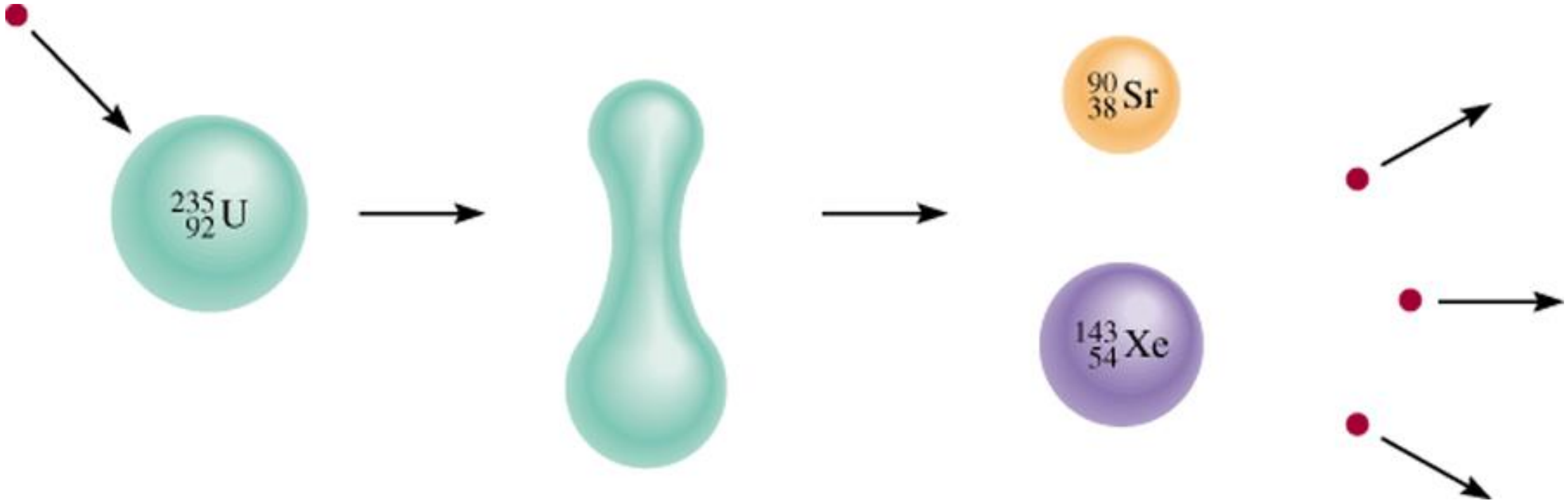


TABLE 23.4 **The Transuranium Elements**

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

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

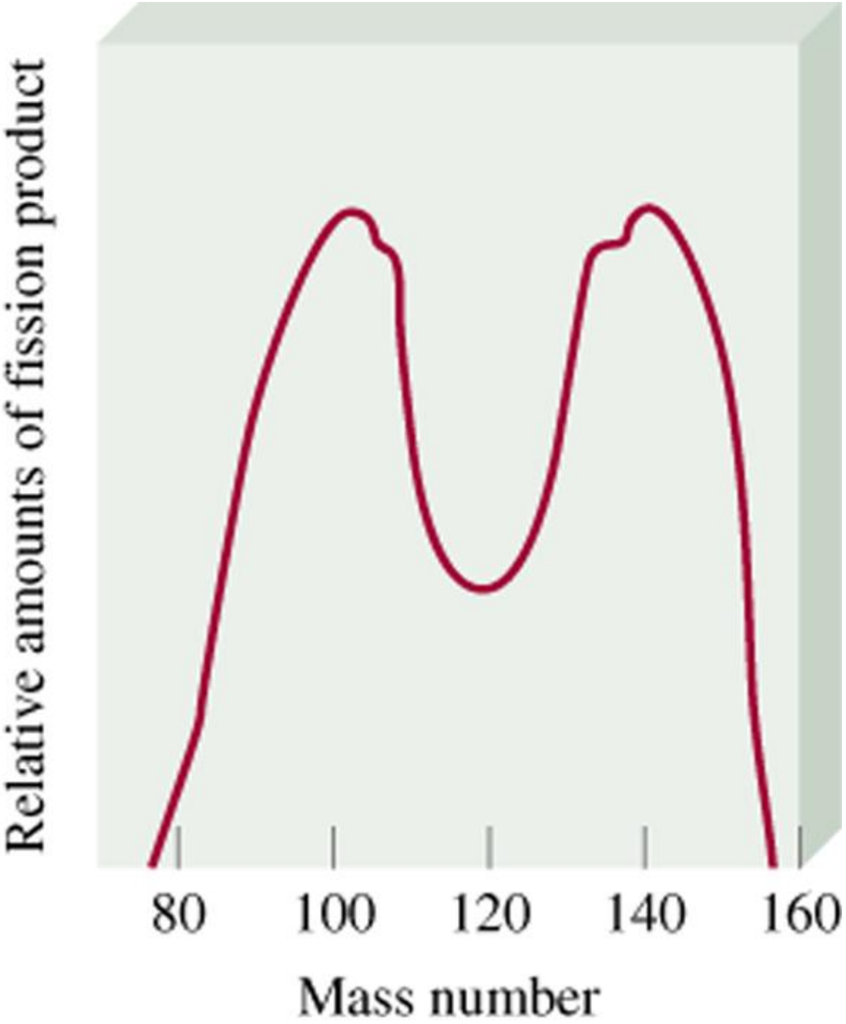
= 2.0×10^{13} J per mole ^{235}U

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

Nuclear Fission

Representative fission reaction

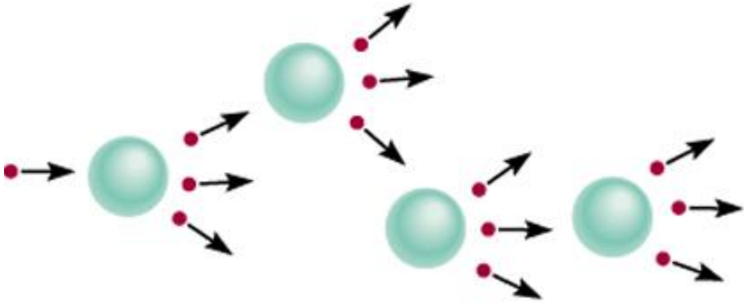
$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{90}_{38}\mathrm{Sr} + {}^{143}_{54}\mathrm{Xe} + 3\,{}^{1}_{0}\mathrm{n} + \mathrm{Energy} $$



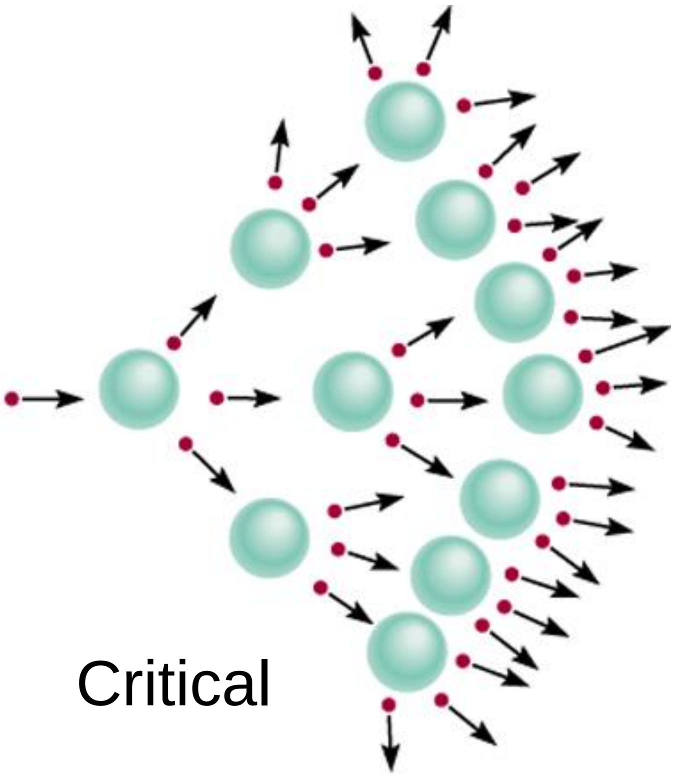
Nuclear Fission

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***.

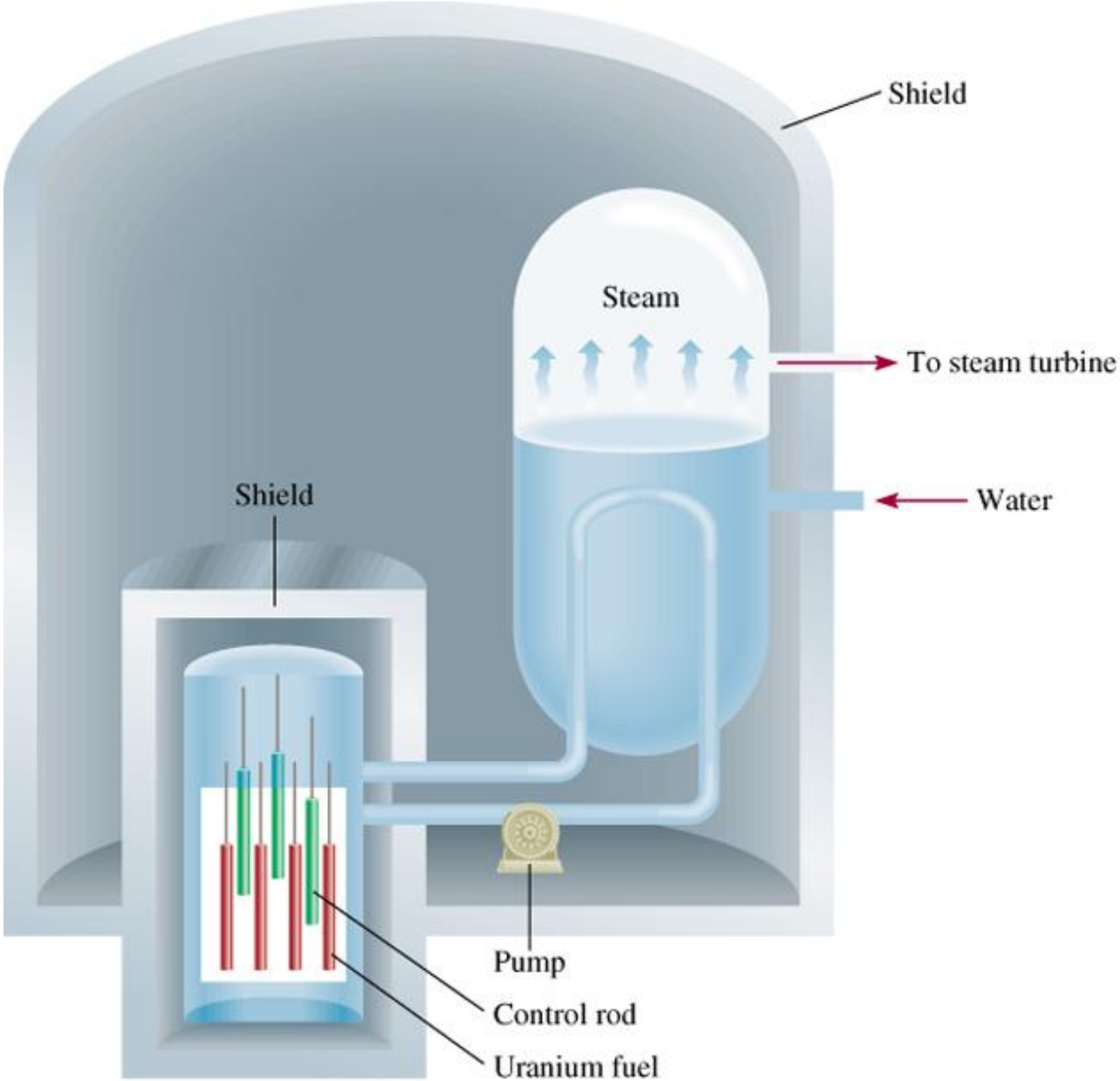


Non-critical



Critical

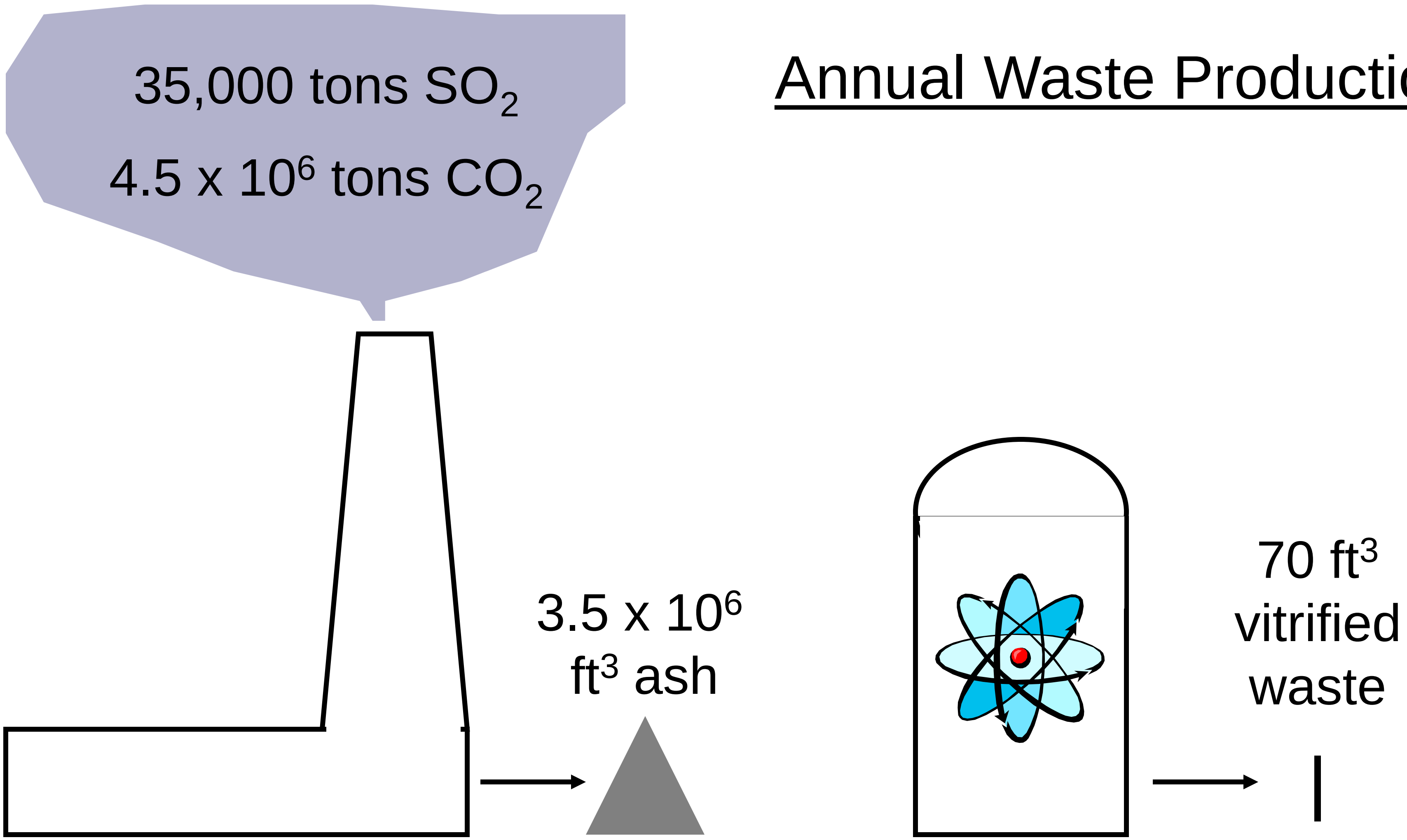
Nuclear Fission



Schematic diagram of a nuclear fission reactor

Nuclear Fission

Annual Waste Production



35,000 tons SO_2

4.5×10^6 tons CO_2

3.5×10^6 ft^3 ash

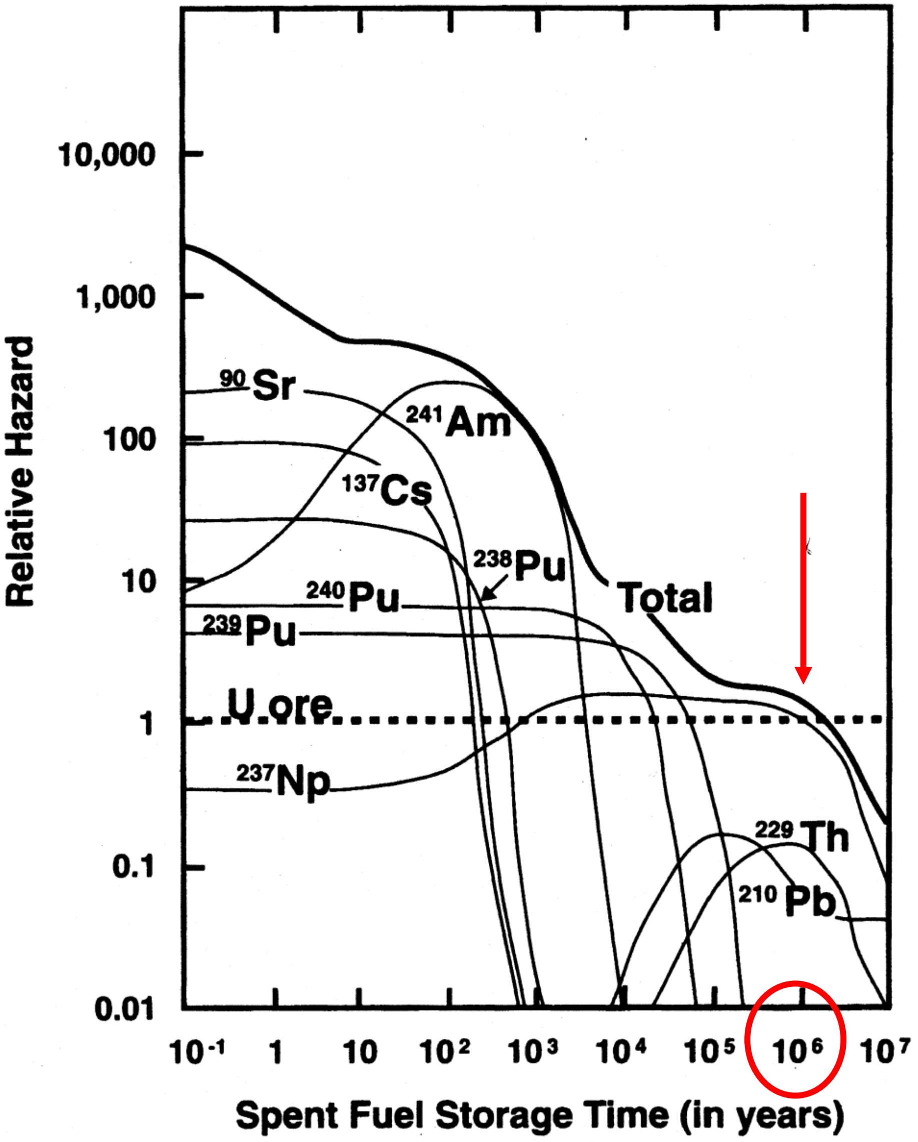
1,000 MW coal-fired
power plant

70 ft^3
vitrified
waste

1,000 MW nuclear
power plant

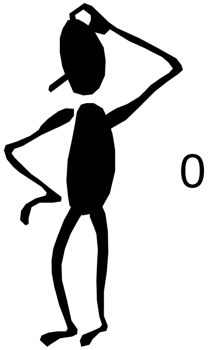
Nuclear Fission

Hazards of the radioactivities in spent fuel compared to uranium ore



From "Science, Society and America's Nuclear Waste," DOE/RW-0361 TG

Chemistry In Action: Nature's Own Fission Reactor



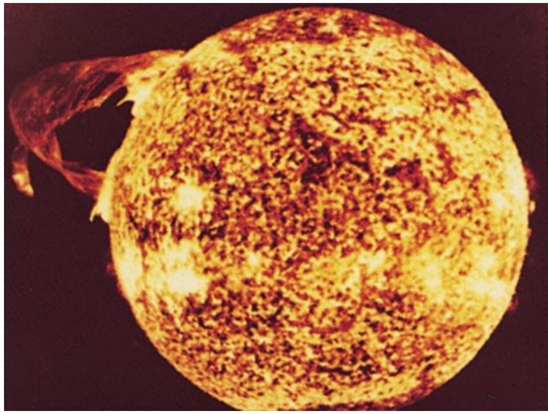
Natural Uranium

0.7202 % U-235 99.2798% U-238

Measured at Oklo

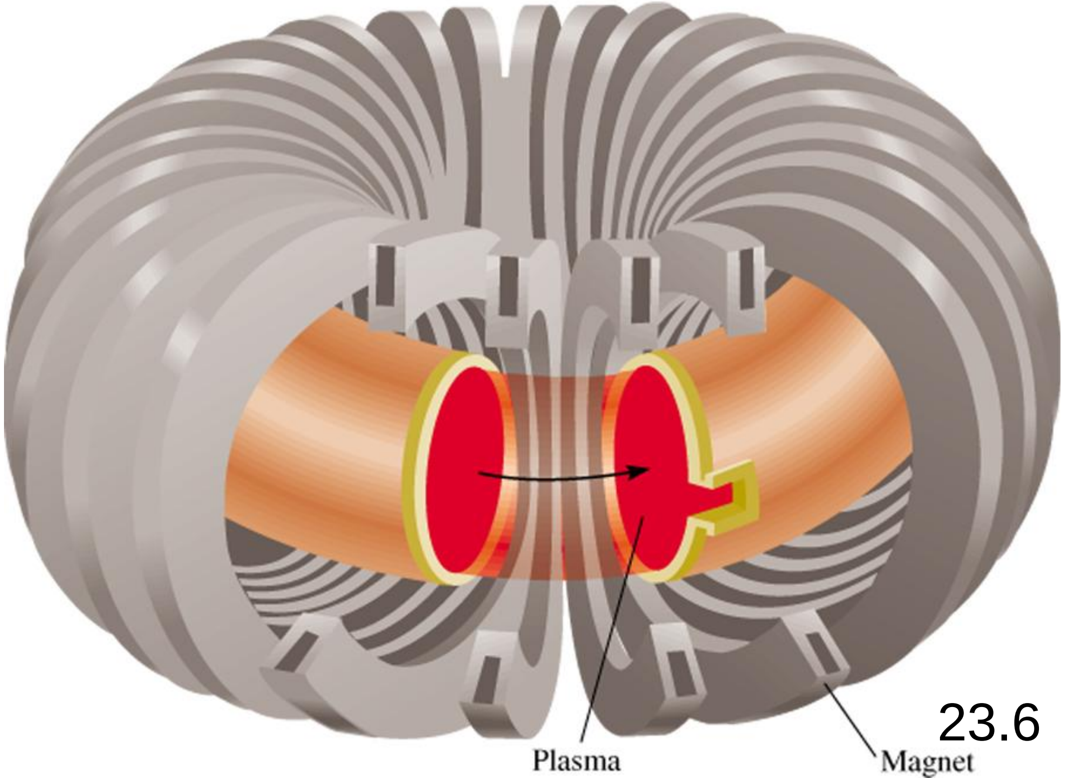
0.7171 % U-235

Nuclear Fusion



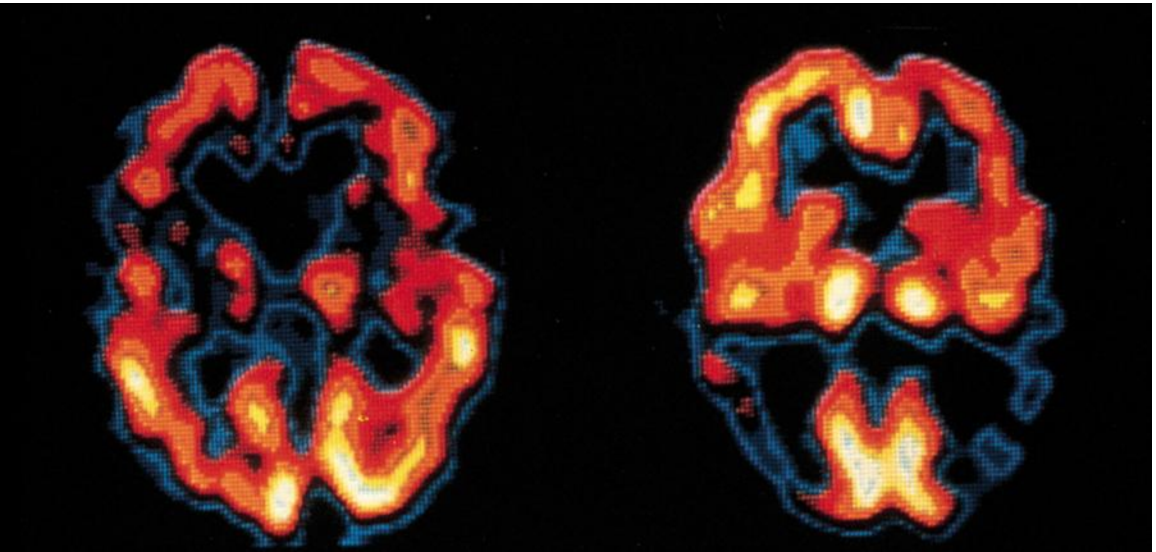
Fusion Reaction	Energy Released
${}^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{1}H + {}^{1}_{1}H$	6.3×10^{-13} J
${}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n$	2.8×10^{-12} J
${}^{6}_{3}Li + {}^{2}_{1}H \longrightarrow 2\,{}^{4}_{2}He$	3.6×10^{-12} J

Tokamak magnetic plasma confinement



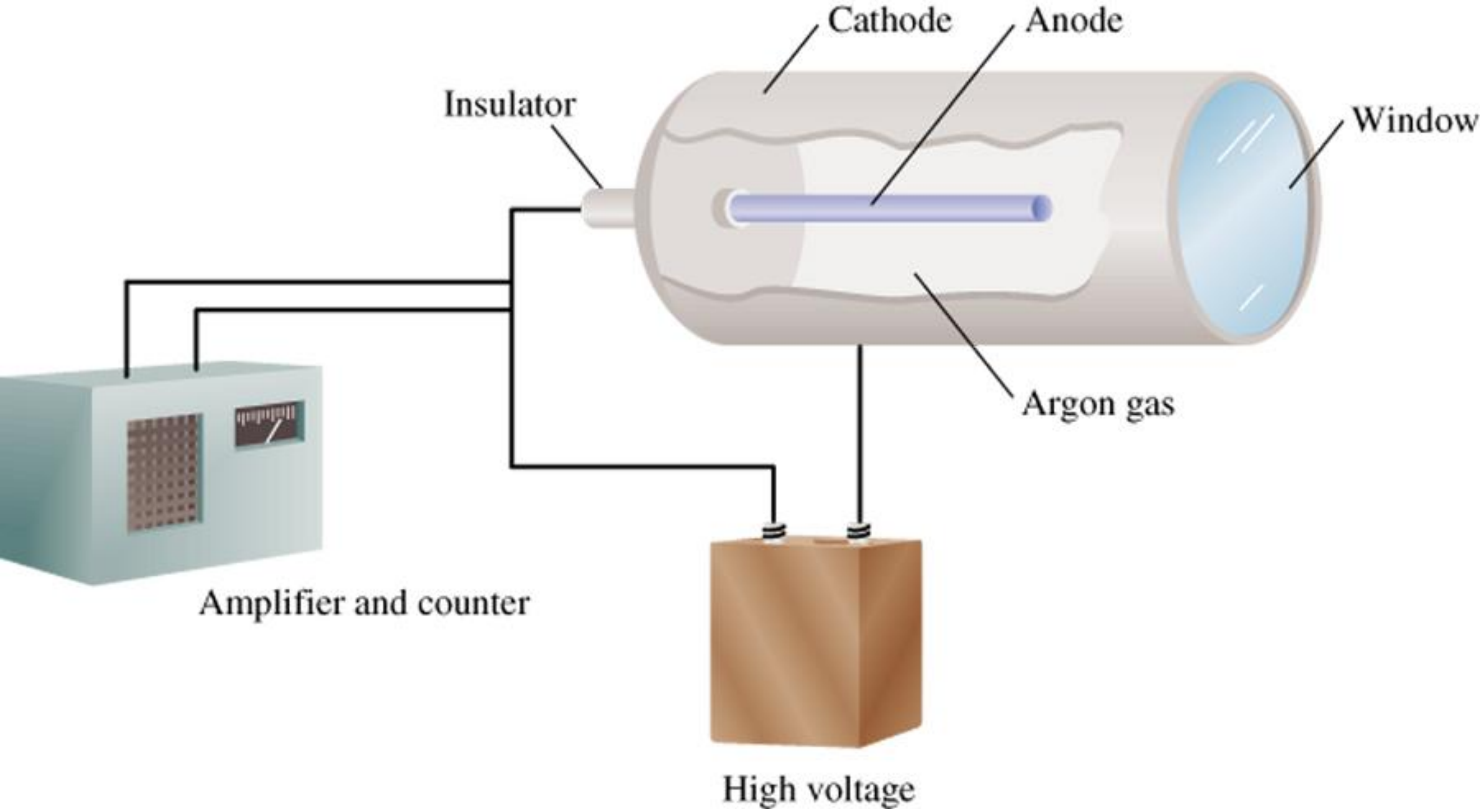
Radioisotopes in Medicine

- 1 out of every 3 hospital patients will undergo a nuclear medicine procedure
- ^{24}Na, $t_{½}$ = 14.8 hr, β emitter, blood-flow tracer
- ^{131}I, $t_{½}$ = 14.8 hr, β emitter, thyroid gland activity
- ^{123}I, $t_{½}$ = 13.3 hr, γ–ray emitter, brain imaging
- ^{18}F, $t_{½}$ = 1.8 hr, β^{+} emitter, positron emission tomography
- ^{99m}Tc, $t_{½}$ = 6 hr, γ–ray emitter, imaging agent



Brain images with ^{123}I-labeled compound

Geiger-Müller Counter



Biological Effects of Radiation

Radiation ***a***bsorbed ***d***ose (***rad***)

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

Roentgen ***e***quivalent for ***m***an (***rem***)

1 rem = 1 rad x Q

Quality Factor

γ-ray = 1

β = 1

α = 20

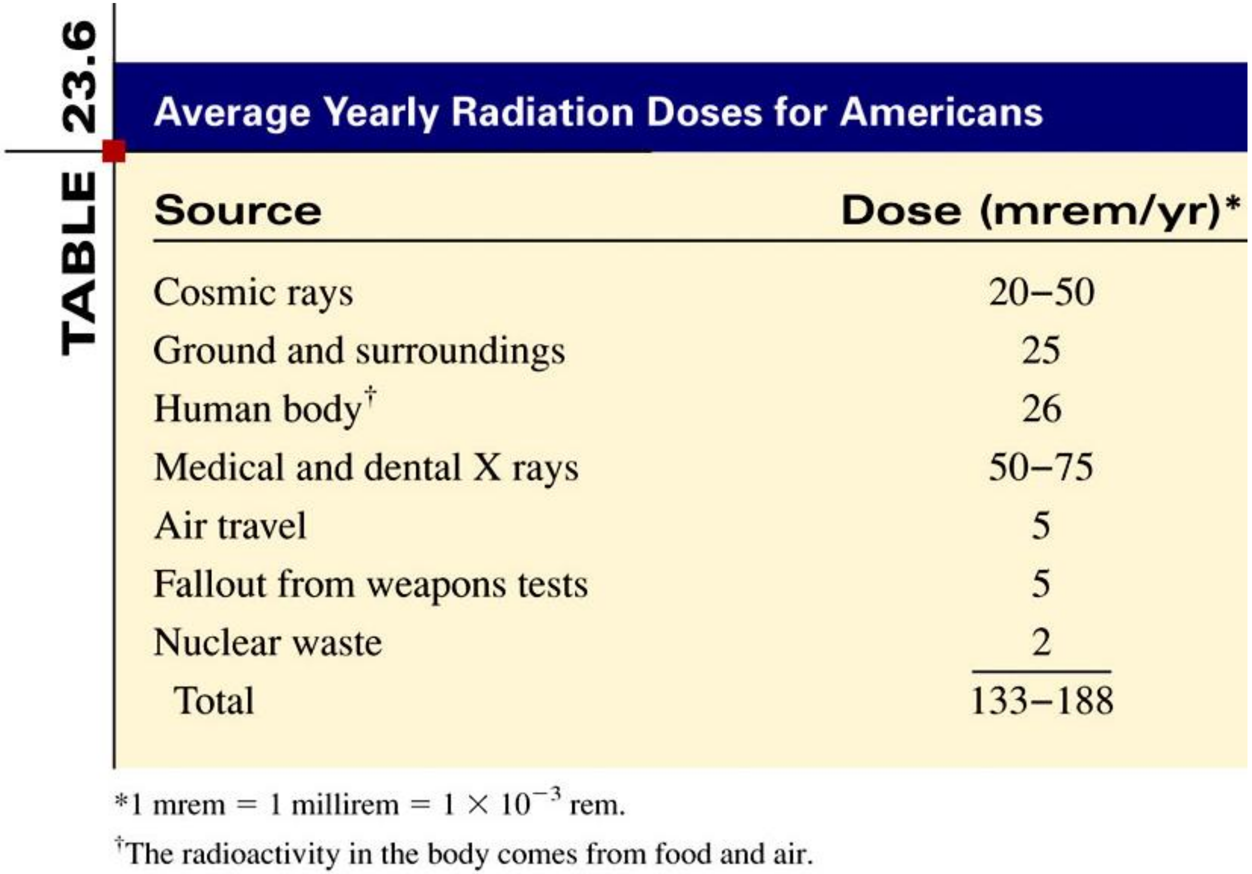


TABLE 23.6

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

Dosage	Effect
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.
100 – 1000 kilorads	Delays spoilage of meat poultry and fish. Reduces salmonella. Extends shelf life of some fruit.
1000 to 10,000 kilorads	Sterilizes meat, poultry and fish. Kills insects and microorganisms in spices and seasoning.