(20-1)

Ch. 20 Nuclear Chem

- nuclei change! ($C \rightarrow N$, $U \rightarrow Ba$ etc.)
  - (compare to chem reactions)
- mass changes slightly ⇒ large energy changes

$e = mc^2$

Applications (20.9)

17% world-wide

① Energy source ~20% of US electricity

current: all waste for one reactor in one barrel of "glass"

- cheap, efficient - no greenhouse gases "clean", acid rain, etc.

② Medicinal

a) diagnostic tracers, "imaging" — brain imaging

PET positron emission tomography

- thyroid, heart, tumors, bone studies — blood fl. track

b) therapy: anti-cancer radiation therapy

③ Radioactive tracers

~~[illegible]~~

- unravel biological pathways
- photosynthesis

④ Age dating

^{14}C for archeological dates

K/Ar dating for geological

⑤ Food irradiation: kill/retard bacteria, molds, yeast (ala pasteurization)

⑥ Bombs!!

- fission (original)
- fusion (H-bomb)

20.1 Radioactivity: Spontaneous Disintegration of Nucleus ("but may be slow")

A. Nuclear Review: Symbols for "Nuclide"

$^{A}_{Z}E$ ← mass # (A)

↑ atomic number (Z)

Z = # of protons (redundant, given element symbol)

A = protons + neutrons sum

[illegible] "nucleons"

$n's = A - Z$

"isotopes" ~~or "nuclides"~~ differ in # of neutrons (^{12}C, ^{13}C, C

"radioisotopes" – release radiation

shorthands: $^{12}_{6}C$ = ^{12}C = C-12 = 12-C

B. Common "Particles" involved in Radioactivity & Nucleus

- memorize names, symbols, constitution
- different types have different penetrating power, biological impact (20.8)
  - complex between # rays, (roentgen, R)

discuss
absorbed rays (rad: radiation absorbed dose)
and rem (bio effectiveness)
effective rem = quality factor × dosage

20.2 Nuclear Reactions: Equations + Balancing

① balance mass sum (top)
② charge (bottom)

5 types of Radioactive Decay (Spontaneous)

	Isotope Change		Effect on n/p ratio
① alpha emission	$^{A}_{Z} \longrightarrow {}^{4}_{2}\text{He} + $	A-4 change Z-2 change	little impact;
② beta emission	$^{A}_{Z} \longrightarrow {}^{0}_{-1}e + {}^{A}_{Z+1}$	same increase	lower
③ positron emission	$^{A}_{Z} \longrightarrow {}^{0}_{+1}e + {}^{A}_{Z-1}$	same decrease	higher
④ electron capture	$^{A}_{Z} + {}^{0}_{-1}e \longrightarrow {}^{A}_{Z-1}$	same decrease	higher
⑤ gamma emission	$^{A}_{Z} \longrightarrow {}^{0}_{0}\gamma + {}^{A}_{Z}$	} same	no impact

Radioactive Series: many decays give unstable daughters, which then undergo serial decays

Brown Fig 21.4 – α, β, β (any sequence common series to oust 4 n's)

$$^{4}_{2}\text{He} + {}^{0}_{-1}e + {}^{0}_{-1}e = {}^{4}_{0} \equiv 4\,{}^{1}_{0}n$$

Fill in the Holes, Name the Processes

① ${}^{234}Pu \longrightarrow {}^{4}_{2}He + \boxed{\quad}$

② ${}^{14}C \longrightarrow {}^{14}N + \boxed{\quad}$

③ ${}^{230}U \longrightarrow {}^{226}Th + \boxed{\quad}$

④ ${}^{99}_{43}Tc^{*} \longrightarrow {}^{99}_{43}Tc + \boxed{\quad}$

⑤ ${}^{0}_{-1}e + {}^{81}_{37}Rb \longrightarrow \boxed{\quad}$

⑥ ${}^{210}Pb \longrightarrow {}^{0}_{+1}e + \boxed{\quad}$

⑦ ${}^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + \boxed{\quad = \quad}$ neutron bombardment

⑧ ${}^{35}_{17}Cl + {}^{1}_{1}H \longrightarrow {}^{32}_{16}S + \boxed{\quad}$ Proton bombardment

⑨ ${}^{239}_{92}U + {}^{4}_{2}He \longrightarrow {}^{1}_{0}n + \boxed{\quad}$ Alpha bombardment

(20-4)

Fill in the Holes, Name the Processes

① $^{234}_{94}Pu \longrightarrow {}^{4}_{2}He + \boxed{^{230}_{92}U}$ alpha emission

② $^{14}_{6}C \longrightarrow {}^{14}_{7}N + \boxed{^{0}_{-1}e}$ beta emission

③ $^{230}_{92}U \longrightarrow {}^{226}_{90}Th + \boxed{^{4}_{2}He}$ alpha emission

④ $^{99}_{43}Tc^{*} \longrightarrow {}^{99}_{43}Tc + \boxed{^{0}_{0}\gamma}$ gamma emission

⑤ $^{0}_{-1}e + {}^{81}_{37}Rb \longrightarrow \boxed{^{81}_{36}Kr}$ electron capture

⑥ $^{210}_{82}Pb \longrightarrow {}^{0}_{+1}e + \boxed{^{210}_{81}Tl}$ positron emission

⑦ $\overset{239}{^{238}_{92}U} + {}^{1}_{0}n \longrightarrow \overset{233}{\overbrace{^{141}_{56}Ba + {}^{92}_{36}Kr}} + \boxed{^{6}_{0} = 6\,^{1}_{0}n}$ neutron bombardment

⑧ $^{35}_{17}Cl + {}^{1}_{1}H \longrightarrow {}^{32}_{16}S + \boxed{^{4}_{2}He}$ Proton bombardment

⑨ $\overset{243}{^{239}_{92}U} + {}^{4}_{2}He \longrightarrow {}^{1}_{0}n + \boxed{^{242}_{94}Pu}$ Alpha bombardment

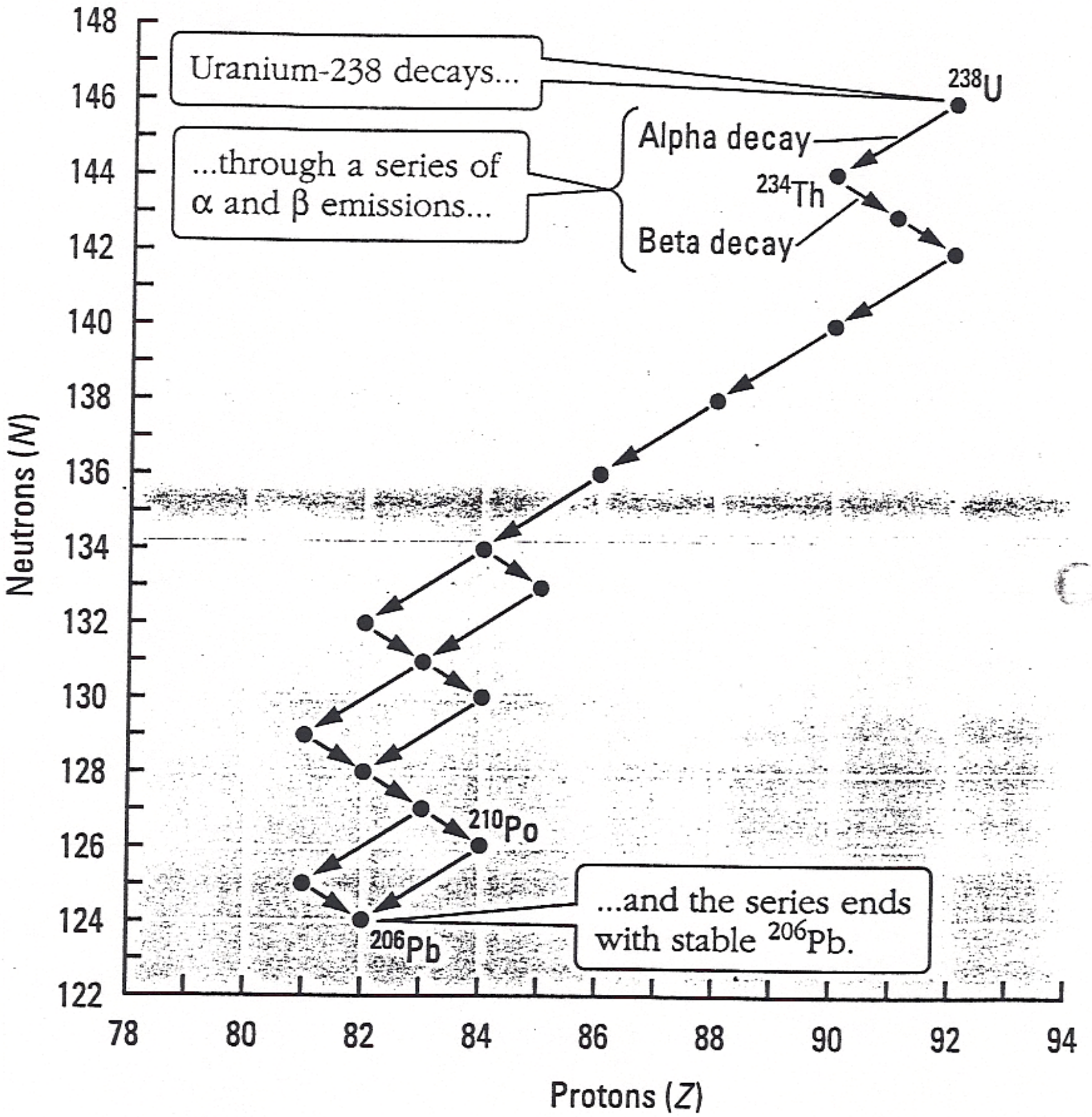

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Figure 20.1

20.5 Artificial Transmutation: By Bombardment with ^1_0n or Other Nuclei

① Key: must balance in same way
② often accompanied by production of side particles, often multiple neutrons
③ Few radioactive nuclei still found in nature – most for research or medicine are made by bombardment

Handout 20.4 7-9

20.3 Stability of Atomic Nuclei

A. Physics background

a. 3 Fundamental Forces

① gravity

② electrostatic (opposite charges attract)

③ "Strong nuclear force"

b. p/p repulsion destabilizes (nuclei > H) bad

- increases sharply with # of p's
- why do any atoms beyond H survive?

c. "Strong nuclear force" good

- attracts nucleides, holds nucleus together
- unknown how: deduction!
- increasing n's needed so nuclear force can balance electrostatic repulsion

Fig 20.2, 21.2 Brown

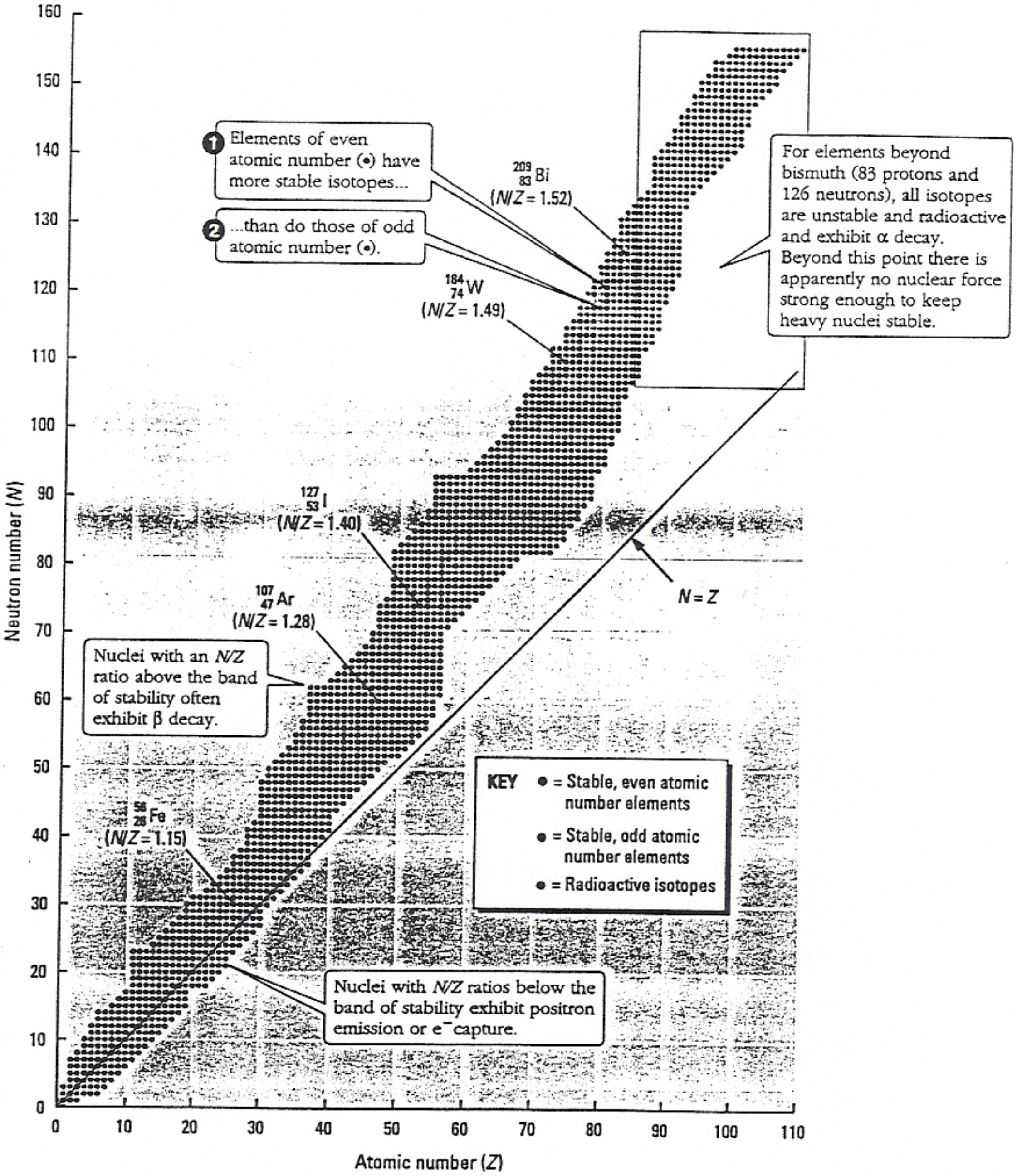
B. Decay Patterns: Band of Stability Target (n/p ratio)

① Rule of 83: Z > 83 radioactive

- nuclear force can't keep up!
- most elements @ Z < 83 have at least one stable isotope ($_{43}$Tc, $_{61}$Pm)

techicium promethium

- $\boxed{Z > 83 \text{ emit } \alpha}$ to reduce Z



① Elements of even atomic number (•) have more stable isotopes...

② ...than do those of odd atomic number (•).

For elements beyond bismuth (83 protons and 126 neutrons), all isotopes are unstable and radioactive and exhibit α decay. Beyond this point there is apparently no nuclear force strong enough to keep heavy nuclei stable.

Nuclei with an N/Z ratio above the band of stability often exhibit β decay.

Nuclei with N/Z ratios below the band of stability exhibit positron emission or e^- capture.

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Figure 20.2

For $Z < 83$:

② Above band of stability: $\frac{n}{p}$ too high

$\Rightarrow \boxed{\beta \text{ emission } (n \to p)}$ $\quad {}^1_0n \to {}^0_{-1}e + {}^1_1p$

$- \boxed{{}^A_Z \longrightarrow {}^A_{Z+1} + {}^0_{-1}e}$

③ Below band of stability: $\frac{n}{p}$ too low

so convert a $p \to n$

2 ways

$\boxed{\text{a. electron capture}}$

$${}^0_{-1}e + {}^1_1p \to {}^1_0n$$

or

$\boxed{\text{b. positron emission}}$

$${}^1_1p \to {}^1_0n + {}^0_{+1}e$$

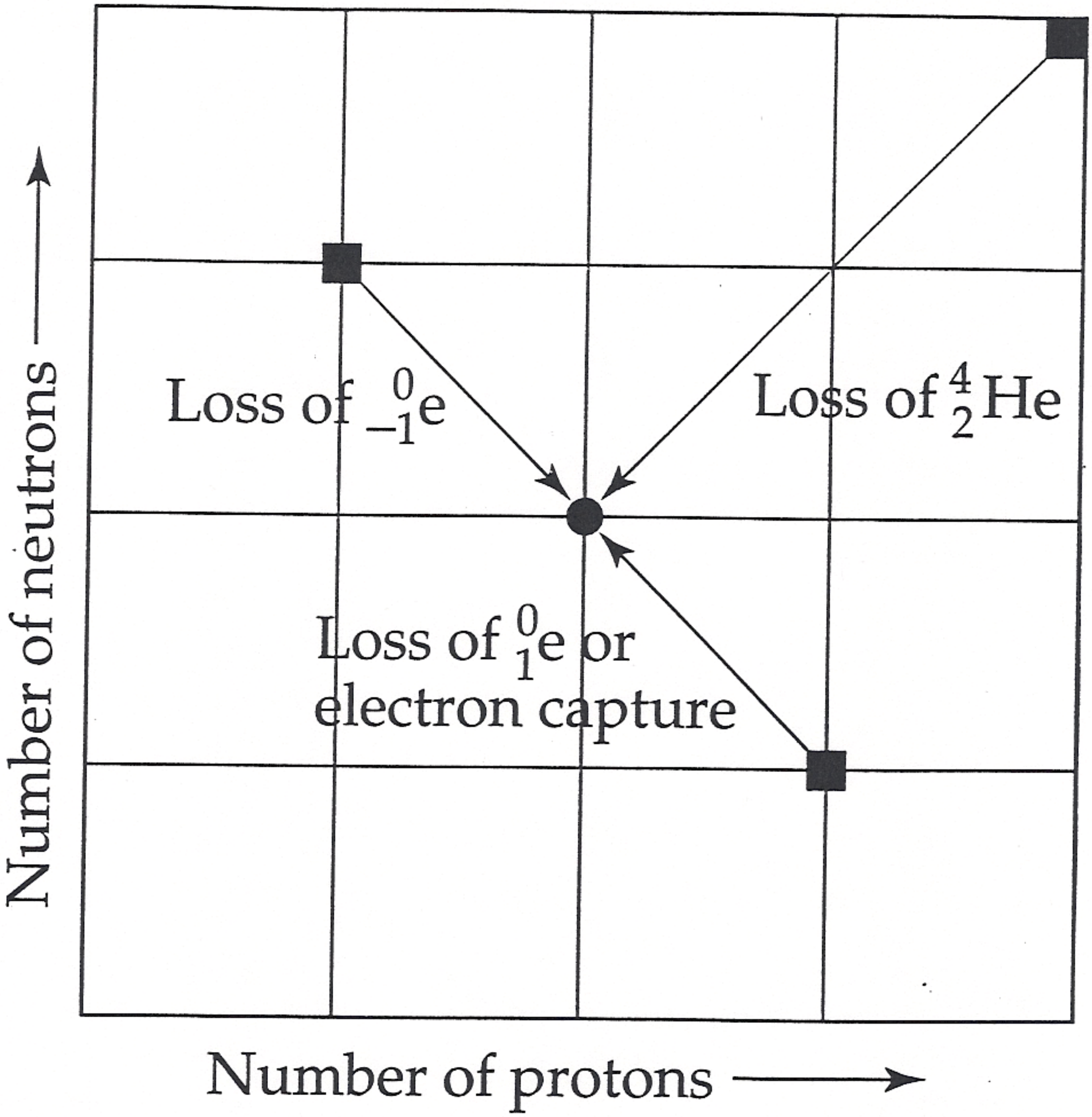
– electron capture more likely for high Z

$\boxed{\text{★ Practical: compare } n/p \text{ ratio to ratio in periodic table!!}}$

Note: some kind of stability pattern, pairing

– even #'s of p's, n's is preferred

Fig. 21.3 Effects of Radioactive Emissions



CHEMISTRY: The Central Science 7/e
by Brown/Lemay/Bursten

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(20-8)

Predict how the following would decay, by α, β, or positron emission, or by electron capture. Then draw the nuclide produced.

① ^{40}Cl

② ^{134}Ba

③ $^{237}_{93}\text{Np}$

④ What is the binding energy in kJ/mol for $^{16}_{8}\text{O}$?

Given

$^{16}_{8}\text{O}$	15,978
$^{1}_{1}\text{p}$	1,00783
$^{1}_{0}\text{n}$	1,00867

⑤ For the above, what is the binding energy in kJ/mol <u>nucleons</u>?

20-8

Predict how the following would decay, by α, β, or positron emission, or by electron capture. Then draw the nuclide produced.

① $^{40}_{17}Cl$ normal $^{36}_{17}Cl$ $\boxed{n/p \text{ too high}}$ $\boxed{\beta\text{-emission}}$

$\longrightarrow {}^{0}_{-1}e + \boxed{{}^{40}_{18}Ar}$ (better!)

② $^{134}_{56}Ba$ normal $^{137}_{56}Ba$ $\boxed{n/p \text{ too low}}$ positron emission or electron capture

$\longrightarrow {}^{0}_{+1}e + \boxed{{}^{134}_{55}Cs}$ or ${}^{0}_{-1}e + {}^{134}_{56}Ba \longrightarrow \boxed{{}^{134}_{55}Cs}$

③ $^{237}_{93}Np$ $\to Z = 83$ $\boxed{\text{Alpha}}$

$\longrightarrow {}^{4}_{2}He + \boxed{{}^{233}_{91}Pa}$

④ What is the binding energy in kJ/mol for $^{16}_{8}O$?

Given $^{16}_{8}O$ 15.978 amu $= (8 \times 1.00783) + (8 \times 1.00867) - 15.978$

$^{1}_{1}p$ 1.00783 $= 16.132 - 15.978 = 0.154$ g/mol

$^{1}_{0}n$ 1.00867 $E = mc^2 = \left(1.54 \times 10^{-5}\,\frac{kg}{mol}\right)\left(3.0 \times 10^{8}\,m/s\right)^2\left(\frac{1\,kJ}{1000\,J}\right)$

$= \boxed{1.386 \times 10^{10}\,kJ/mol}$

⑤ For the above, what is the binding energy in kJ/mol nucleons? 16 nucleons/1 mol ^{16}O

so $\frac{x\ kJ}{nucleon} = \frac{1.386 \times 10^{10}\,kJ}{\cancel{mol\ O}} \cdot \frac{1\,\cancel{mol\ O}}{16\ nucleons} = \boxed{8.46 \times 10^{8}\,\frac{kJ}{mol\ nucleon}}$

C. Binding Energy

– the mass of a nuclide is less then the sum of its component n's + p's

Missing mass (Δm) equals energy, the "nuclear binding energy" ≡ "strong nuclear force"

↓

"mass deficit"

$$\boxed{\Delta m = (\text{sum of } p\text{'s} + n\text{'s}) - \text{actual}}$$

$$\boxed{E = \Delta m c^2}$$

Δm in kg (convert from g)

E in J (convert to kJ)

Handout 208

Get answers in either kJ/mol (of nuclide)
or kJ/"mole nucleon"

– Fe-56 is most stable

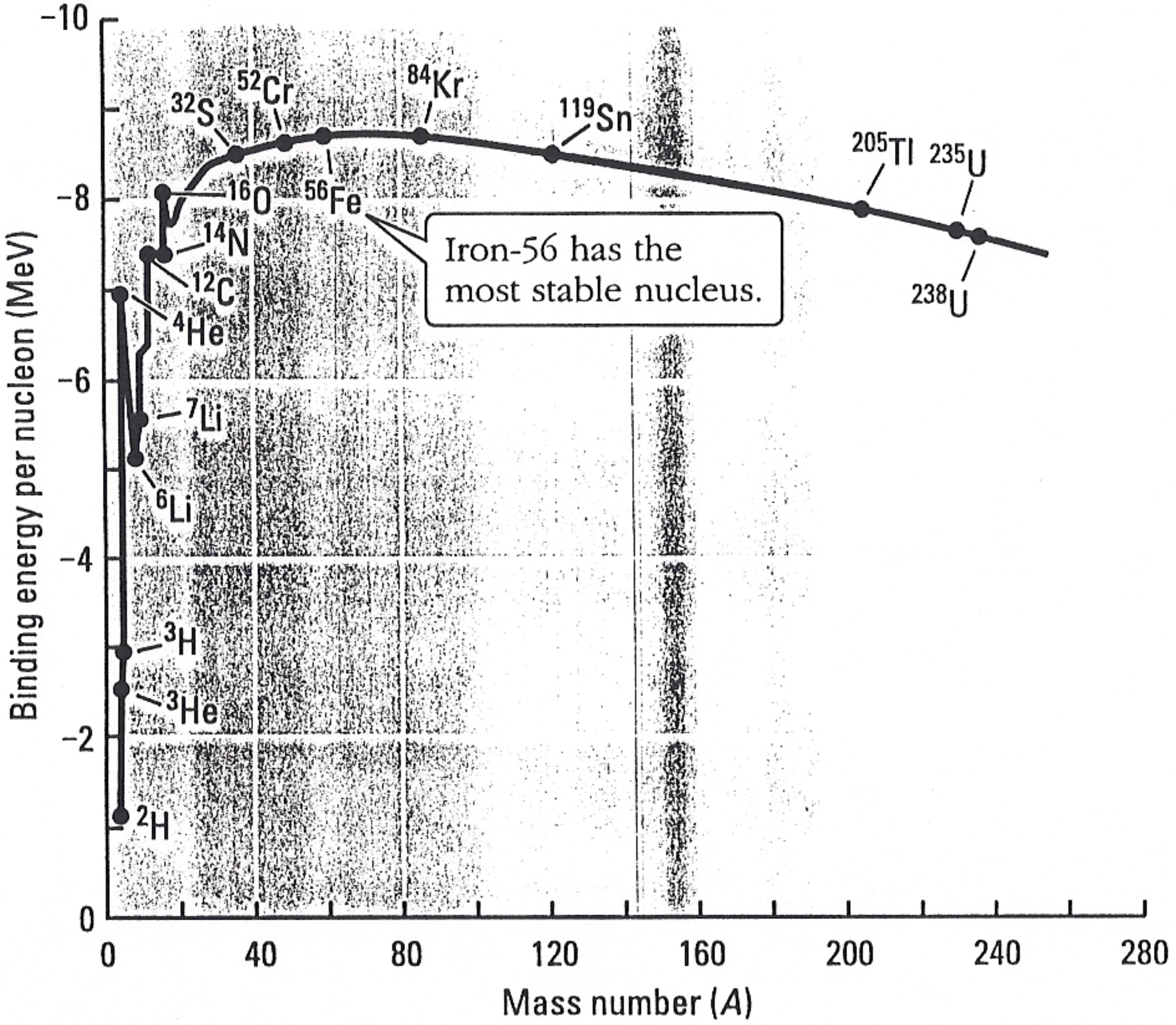
– the great energy of nuclear reactions is because "binding energy" is released

Fig 20.3

Fission (20.6): large nuclei fragment into smaller nuclides

Fusion (20.7): small combine to give bigger

Both occur to approach Fe-56.



Iron-56 has the most stable nucleus.

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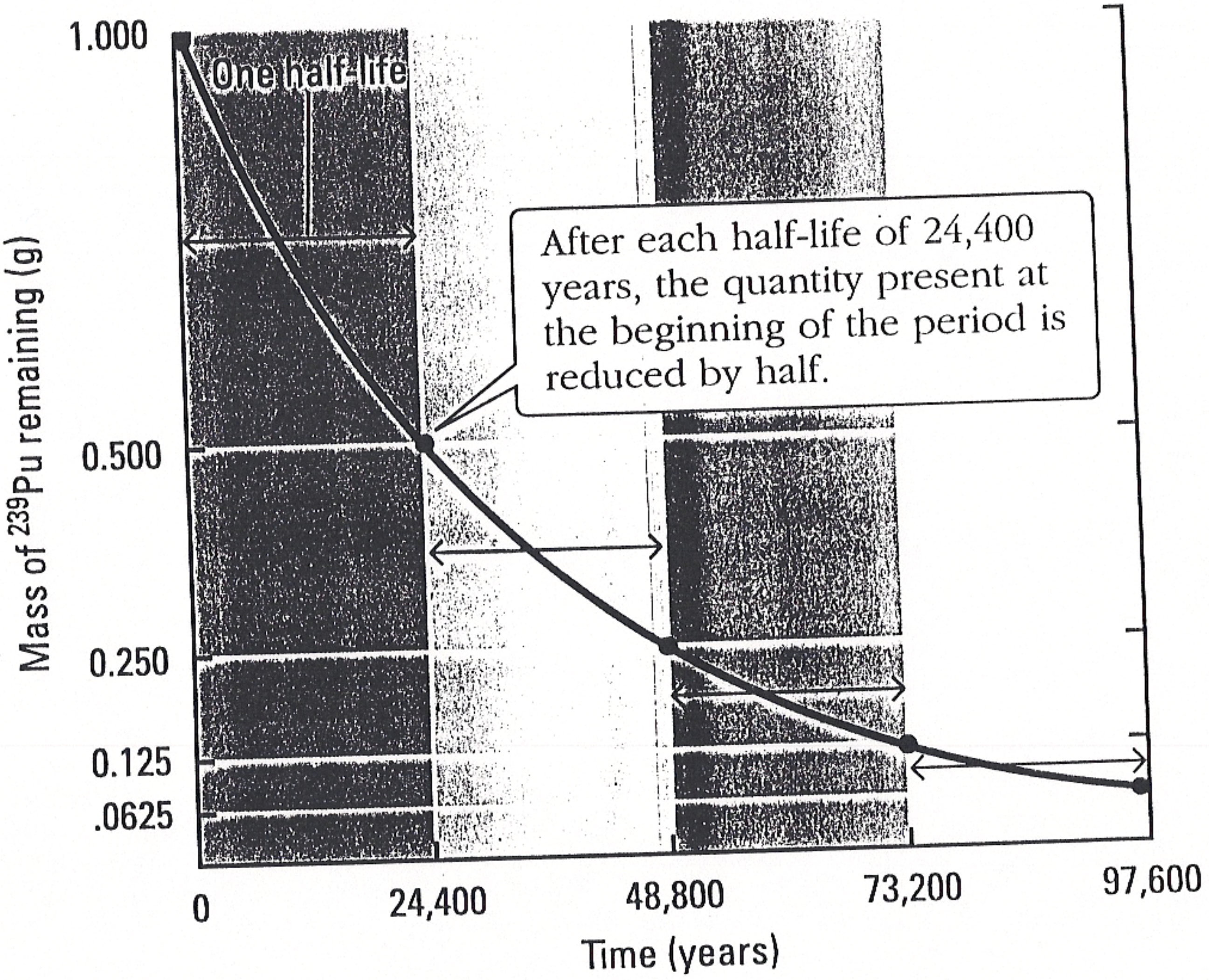
Figure 20.3

20.4 Rates of Radioactive Decay

A. Nuclear half-life: radioisotopes decay with 1st order rate laws, have characteristic $t_{1/2}$

Isotope	$t_{1/2}$	
$^{238}_{92}U$	5×10^9 years	-slow enough so plenty left
^{40}K	1×10^9 years	-used to date old rocks (daughter is ^{40}Ar)
^{14}C	5730 years	-medium, used to date human artifacts
^{131}I	8 days	Short, used in medical imaging
^{24}Na	15 hr	
^{99}Tc	6 hr	



After each half-life of 24,400 years, the quantity present at the beginning of the period is reduced by half.

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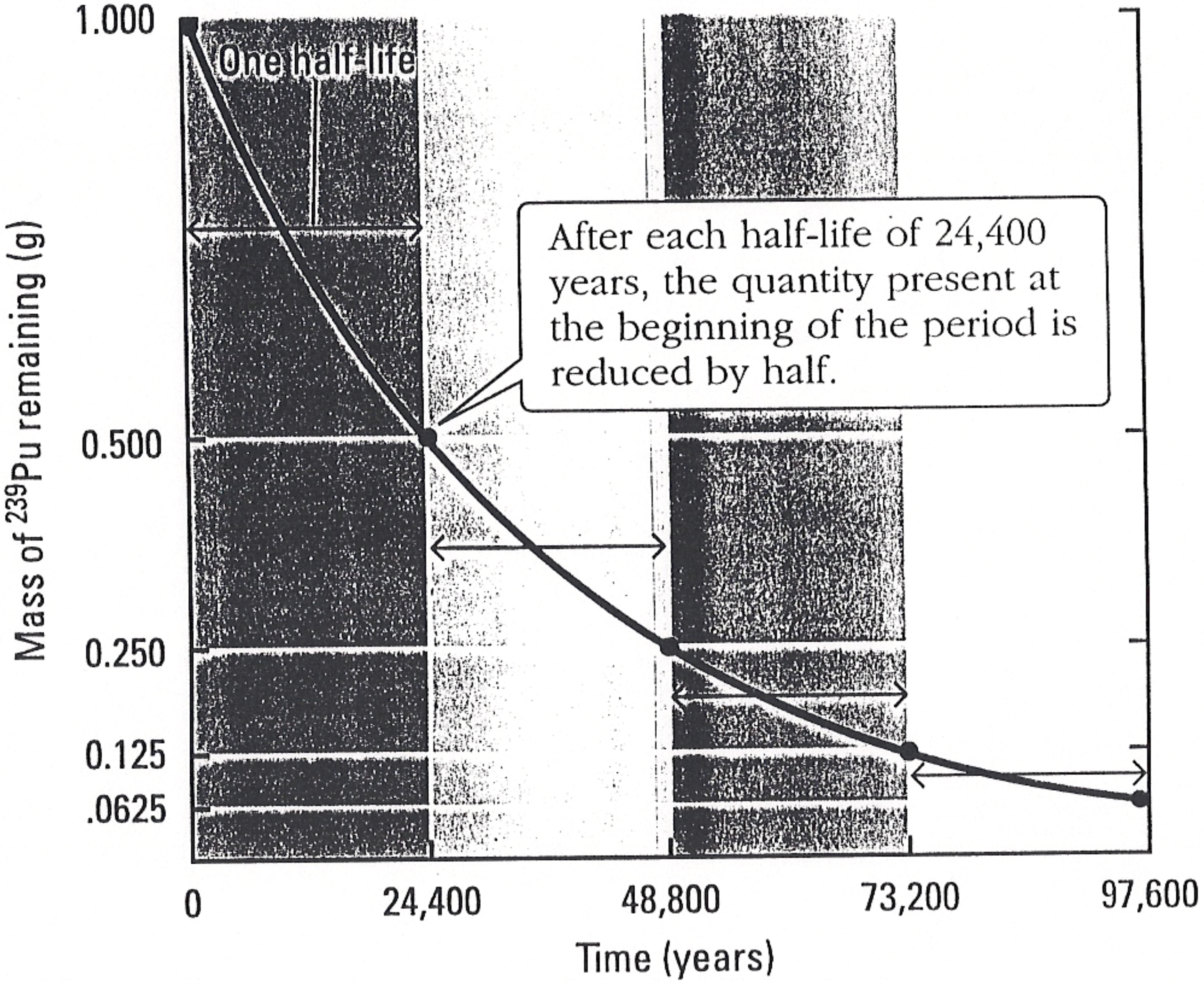
Figure 20.4



After each half-life of 24,400 years, the quantity present at the beginning of the period is reduced by half.

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Figure 20.4

Rock dating similar:

$^{40}K \rightarrow {}^{40}Ar \quad t_{1/2} = 1\times10^{9}$ y

$^{238}U \rightarrow {}^{206}Pb \quad t_{1/2} = 4.51\times10^{9}$ y

- ratio of ^{238}U ~~to~~ ^{206}Pb enables dates ($m_0 = {}^{238}U + {}^{206}Pb$, $m_t = {}^{238}U$)

- assumes that all ^{40}Ar, all ^{206}Pb came by decay: safe, because otherwise multiple isotopes of ^{206}Pb present

20.6 Nuclear Fission

$$^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n + \text{Energy!!}$$

$$\Delta E = -2\times10^{10}\ \text{kJ/mol}$$

$\boxed{\text{Fig 20.6}}$

Keys

① humongous energy released!!

② fact: neutron bombardment doesn't always result in same fission: sometimes other daughter nuclei produced $\boxed{\text{Fig 20.7}}$

★★ ③ neutron: both a reactant and a product!!
- more produced than used!!

⇒ ④ branching "chain reaction" $\boxed{\text{Fig 20.7}}$
- more n's ⇒ more fissions ⇒ more n's ⇒ more fissions, etc..
energy energy

⑤ "Critical Mass": enough ^{235}U to support chain
- "subcritical" - most n's escape, <1 following rxn, rxn slows and quits

2012

① ^{99}Tc $t_{1/2} = 6.0$ hours. What percentage of a dose of ^{99}Tc (used for a brain imaging scan) is left after 24h?

② ^{131}I $t_{1/2} = 8.0$ days. How long to decay to 10% of original?

③ ^{14}C $t_{1/2} = 5730$ years. "Live" carbon has activity of 15.3
A shirt is claimed to be Jesus's, but is found to have carbon activity of 14.0. How old is the shirt, and can the claim be true?

④ ^{90}Sr $t_{1/2} = 28.8$ y If 42 g of ^{90}Sr is buried, how much is left after 120 years?

2012

① ^{99}Tc $t_{1/2} = 6.0$ hours. What percentage of a dose of ^{99}Tc (used for a brain imaging scan) is left after 24 h?

$\boxed{\ln\left(\frac{r'c}{int}\right) = .693\left(\frac{t}{t_{1/2}}\right)}$

Qual: 24 h = 4 half lives

100% → 50% → 25% → 12.5% → $\boxed{6.25\%}$

or $\ln \frac{100\%}{x} = .693\frac{(24)}{(6)} = 2.772$ $\frac{100\%}{x} = e^{2.772} = 15.99$ $\boxed{x = 6.25\%}$

② ^{131}I $t_{1/2} = 8.0$ days. How long to decay to 10% of original?

$\ln\left(\frac{100\%}{10\%}\right) = .693\left(\frac{t}{8}\right)$ $\boxed{t = 26.6 \text{ days}}$

③ ^{14}C $t_{1/2} = 5730$ years. "Live" carbon has activity of 15.3. A shirt is claimed to be Jesus's, but is found to have carbon activity of 14.0. How old is the shirt, and can the claim be true?

$\ln\left(\frac{15.3}{14.0}\right) = .693\frac{t}{(5730)}$ $\boxed{t = 734 \text{ years}}$ Too new to be true!!

$8.88e^{-2} = \left(\frac{.693}{5730}\right)t$

④ ^{90}Sr $t_{1/2} = 28.8$ y If 42 g of ^{90}Sr is buried, how much is left after 120 years?

$\ln \frac{42}{x} = .693\left(\frac{120}{28.8}\right) = 2.89$

$\frac{42}{x} = e^{2.89} = 17.95$ $\boxed{x = 2.34 g}$

B. Decay Math

$kt_{1/2} = .693$ and $\ln\left(\frac{m_o}{m_t}\right) = kt$

$\boxed{\ln\left(\frac{m_o}{m_t}\right) = .693\left(\frac{t}{t_{1/2}}\right)}$ or $\boxed{t = \left(\frac{t_{1/2}}{.693}\right)\ln\left(\frac{m_o}{m_t}\right)}$

solving for remaining material after time

solving for time

m_o = original amount
m_t = amount after time t

Can be in mass, or emission rate, or activity, or 100% → percent.

C. C-14 and Age Dating

^{14}C $t_{1/2}$ = 5730 year   Human History Dates

- steady state concentration of $^{14}CO_2$ in air, formed via cosmic rays
- all living things incorporate $^{14}CO_2$ (via photosynthesis, eating ...)

* the % ^{14}C (relative to total carbon) is constant for all living things! (m_0 is known!!)

- at death, ^{14}C decays at $t_{1/2}$ rates
- comparing ^{14}C activity enables age dating for anything formerly "alive" (wood, cloth, anything ex-biological)

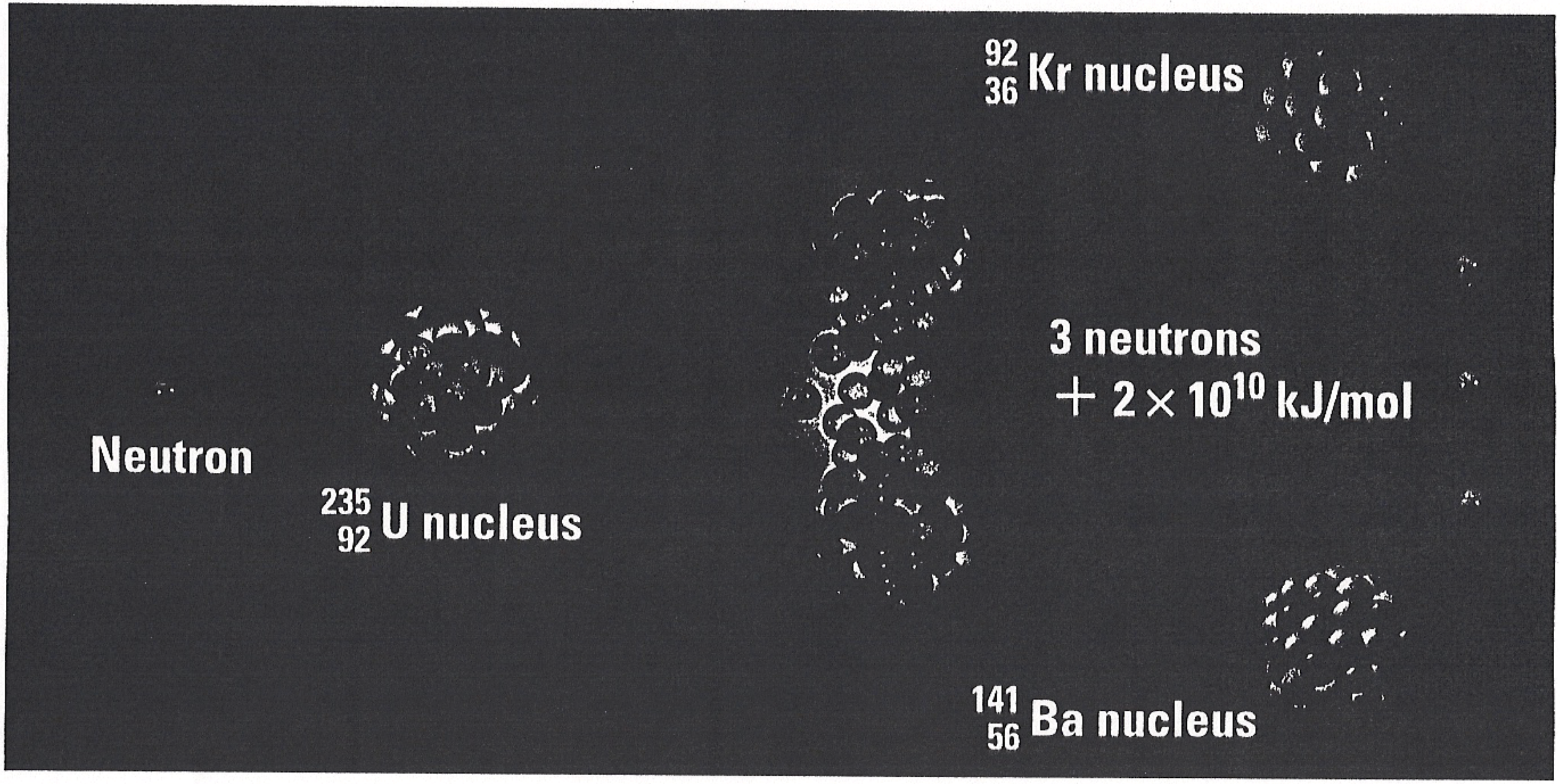

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Figure 2

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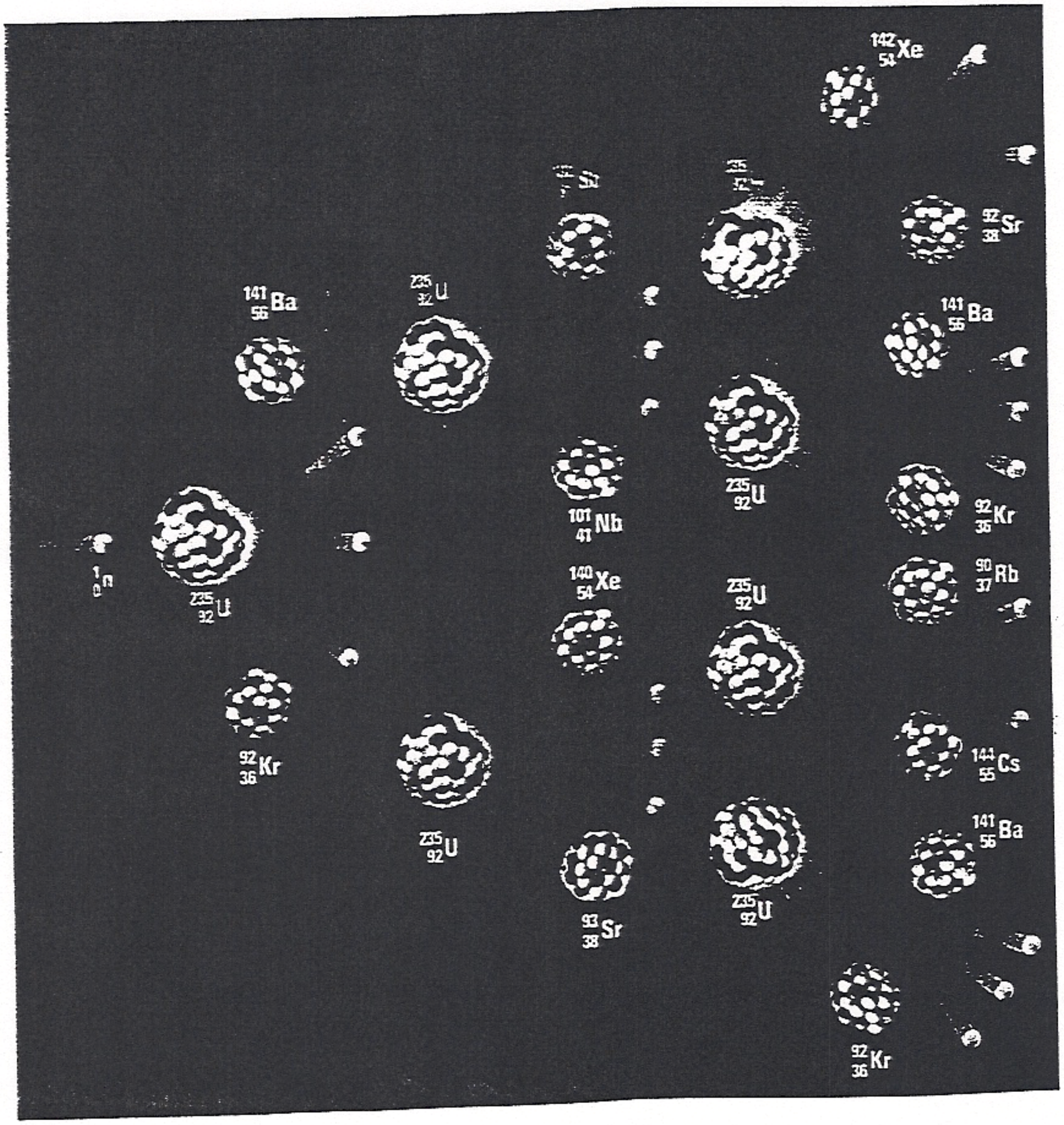
Figure 20.7



"Breeder Reactors": $^{238}U + ^{1}_{0}n \Rightarrow ^{234}Pu$ Plutonium is "bred" from ^{238}U

nonfissile ↗ highspeed fissile

- "supercritical", ≥1 neutron per fission gets captured by another ^{235}U, etc., proliferation

Atom bomb: 2 subcritical masses are combined to make supercritical! (chemical bomb propels one mass, smashes into other!)

Nuclear Reactors (Brown 21.2C)

① ^{235}U fuel rods (last for years)
- subcritical: can't explode!!

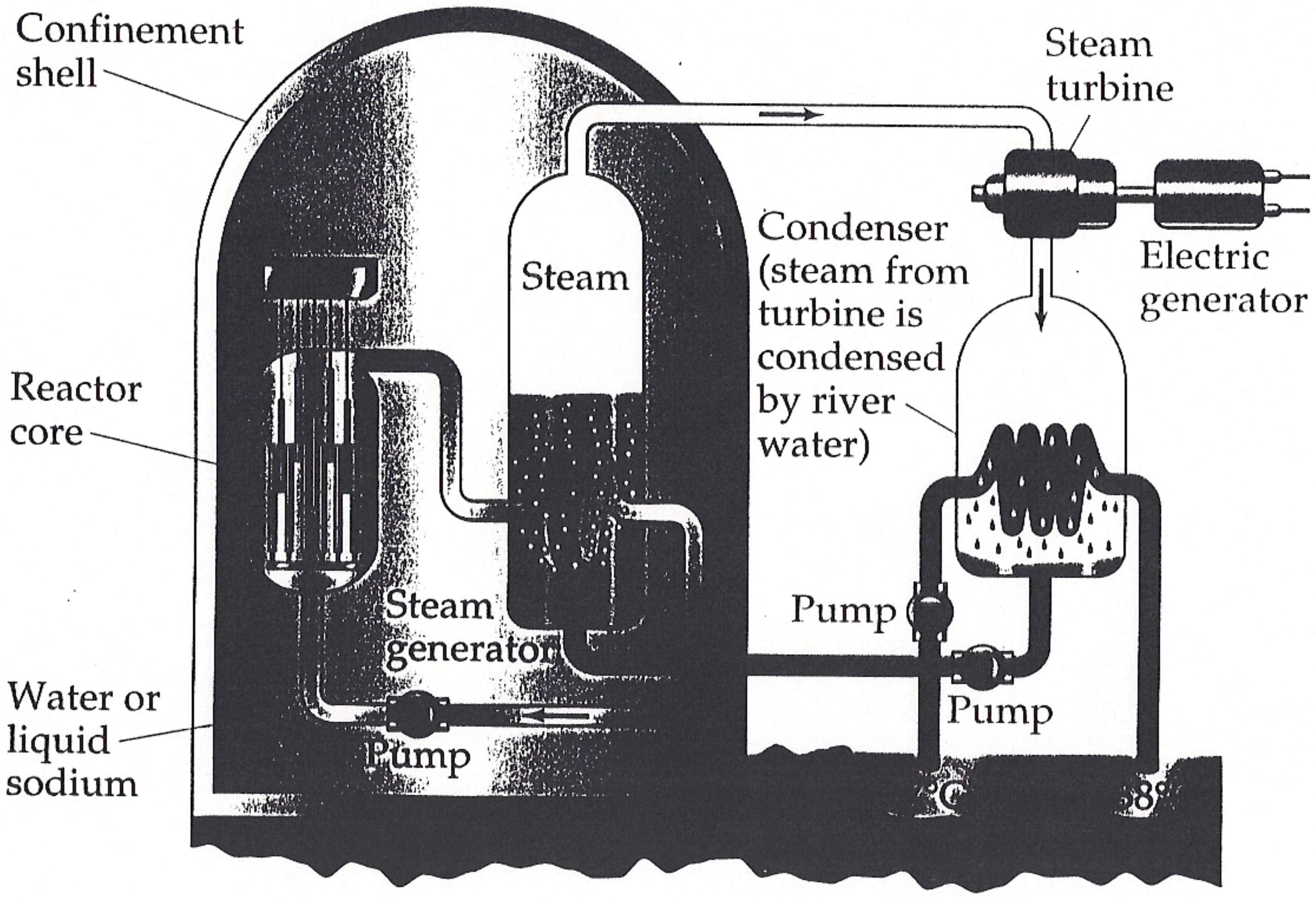
only 0.7% of U, need 3 for useful

② Cd control rods: separate fuel rods, absorb n's
- rate of chain reaction is adjusted by raising/lowering control rods (to control the rate of n's hitting a given fuel rod; as rod ages, needs more neutron hits to sustain rxn as ^{235}U gets less & less)

③ coolant (water) absorbs energy, produces steam that drives turbine ⇒ electricity

Concern: what do with spent fuel rods, still with radioactive content? Current: "vitrification", rods get "melted" and dissolved in liquid glass; poured in a steel can, cooled, and glasses over. For one year plant: one barrel only!!

Fig. 21.20(a) Nuclear Reactor



20.7 Nuclear Fusion

$$4\,{}^{1}_{1}H \longrightarrow {}^{4}_{2}He + 2\,{}^{0}_{+1}e \qquad \Delta E = -2.5\times10^{9}\ kJ$$

$$2\,{}^{2}_{1}H \longrightarrow {}^{4}_{2}He$$

- solar process, sun's energy!

Ideal: no radioactive byproducts, huge energy, cheap H_2O fuel!!

Problem: huge temps needed (to overcome nuclear repulsion) to push H's together, materials to contain

H-bomb: fission bomb used to provide heat needed to support fusion!

20.8 Radiation: Effects + Units

20.8 Radiation: Effects & Units

rad energy absorbed / body mass (dosage)

(1 food cal = 1/2 million rads)

rem biological damage

effective dose = rads × impact factor

(dose) (quality)

Key: "rems" measures risk

a) not all rays equal

b) dosage doesn't consider variance in penetratio

Typical: < 0.4 rems/year (cosmic, x rays, radon...)

>25 rems to cause trace damage

>500 rems 50% chance of death within 30 years

Rays & damage (depends on whether internal or external)

α: little penetration, only irritates outer skin (bad if generated internally)

β: penetrates a few mm

★ γ: high energy, deep penetration

- can generate DNA mutation
- not bad internally, because largely escape!