1412 - E3
CH 21 - Nuclear Chemistry
Notes

21

CHAPTER 21: NUCLEAR CHEMISTRY

Introduction

Problem: not all nuclei are stable

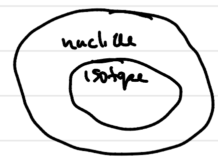
Remedy: change less stable element into a more stable one.

(a) Fusion — combine smaller nuclei

(b) Fission — split larger nuclei

Nuclear Structure and Stability [21.1]

Terminology



atomic mass A

atomic number Z $\,{}^{A}_{Z}X$

n

ISOTOPE — Same Z, different A

NUCLIDE — Any isotope with a set number of Z & A

NUCLEON — a proton or a neutron

(proton, neutron)

- DENSITY of a nucleus is 1.8×10^{14} g/cc.
  - ↪ if earth had same mass as it now does, but a density of 1.8×10^{14} g/cc, the radius of the earth would only be about 200 yards (not 4,000 miles)!

(remove all empty space)

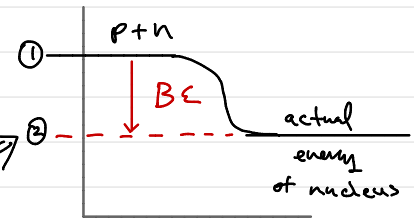
¿What holds atoms together?

4 Types of Forces

① electronagnetic
② gravitational
③ weak nuclear force (binding)
④ strong nuclear force

whatever it is, it must be stronger than the repulsion between like-charged protons

Nuclear Binding Energy



Energy of nucleus must be more stable than energy of its parts (given it stays together)

$$E = mc^2$$

often measured in eV

($1 eV / 1.603\times10^{-19} J$)

nuclear binding energy

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

$$\boxed{BE = (\Delta m)\, c^2}$$

mass defect

Mass is converted into energy ... once assembled, the weight of the atom is less than the sum of its parts!

(EX) Calculate Nuclear Binding

¿What is the binding energy, BE, for the nuclide, ^4_2He, in MeV/nucleus, given the Mass Defect is 0.0305 amu. Recall 1 J = 1 Kg•m²/s².

Monday, Nov 18

(a) $BE = (\Delta m) c^2$

$= \frac{0.0305\ g}{mol} \Big| \frac{2.998E8^2\ m^2}{s^2} = 2.74E12 \frac{kg\ m^2}{s^2\ mol} = \frac{2.74E12\ J}{mol}$

($\frac{kg\ m^2}{s^2} = J$)

$\frac{0.0305\ amu}{atom} = \frac{0.0305\ g}{mol}$

(b) $\frac{\square\ MeV}{nuclei} = \frac{2.74E12\ J}{mol} \Big| \frac{1\ eV}{1.603E-19\ J} \Big| \frac{MeV}{1E6\ eV} \Big| \frac{1\ mol}{6.02E23\ nuclei}$

$= 0.284 \frac{\times 10^{31}}{\times 10^{29}} \frac{MeV}{nuclei} = 0.284 \times 10^2 \frac{MeV}{nuclei} = \boxed{28.4 \frac{MeV}{nuclei}}$

Nuclear Stability (Z/n ratio)

- Of the 1000's of nuclides, only ~250 are stable
- UNSTABLE: $\frac{n}{p}$ strays from blue line
- ESPECIALLY STABLE:

  Magic Numbers "Double Magic": if both 'p' & 'n'

  p, n, (p+n) = 2, 8, 28, 50, 82, 126
- TO GET STABLE

  usually, there is a gain/loss of one of the following:

electron — beta $^{0}_{-1}\beta$ ← # nucleons ← charge

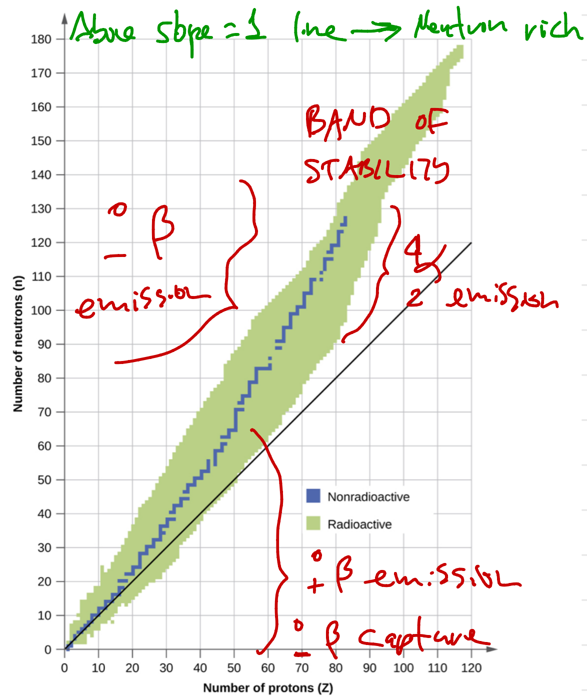
positron $^{0}_{+1}\beta$

He nucleus — alpha $^{4}_{2}\alpha$

proton $^{1}_{1}p$ (or $^{1}_{1}H$)

neutron $^{1}_{0}n$

gamma $^{0}_{0}\gamma$ (raw energy)



Sample Reaction Scenarios

(a) n/p too large (conv. n → p)

$^{216}_{88}Ra \longrightarrow ^{228}_{89}Ac + ^{0}_{-1}\beta$

(b) n/p too small (conv p → n)

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

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

$^{226}_{88}Ra \longrightarrow ^{222}_{86}Rn + ^{4}_{2}\alpha$

(c) A > 84 (often α decay)

(EX) Relative Stability of Nuclides

¿Which is more stable: K-39 or K-40?

$^{39}_{19}K$ $\quad$ $^{40}_{19}K$

20 $\quad$ 21

Magic Number of neutrons

(EX) Nuclear Reactions

¿Complete the following reactions . . .

both Mass & Charge must each balance across equation

(a) $^{26}Mg + \square \rightarrow {}^{26}Al + {}^{1}_{0}n$

$^{26}_{12}Mg + {}^{1}_{1}p \rightarrow {}^{26}_{13}Al + {}^{1}_{0}n$ $\quad$ $27 \rightarrow 27$, $13 \rightarrow 13$

(b) $^{40}_{18}Ar + \square \rightarrow {}^{43}K + {}^{1}_{1}H$

$^{40}_{18}Ar + {}^{4}_{2}\alpha \rightarrow {}^{43}_{19}K + {}^{1}_{1}H$ $\quad$ $40 \rightarrow 40$, $20 \rightarrow 20$

(EX) Binding Energy per Nucleon

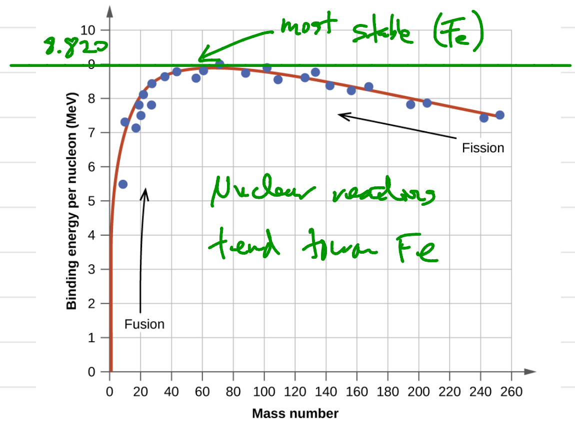
¿What is the BE for ^4_2He?

Earlier, we calculated BE = 28.4 MeV/nuclei

$$\therefore \frac{\square \text{ MeV}}{\text{nucleon}} = \frac{28.4 \text{ MeV}}{\text{nuclei}} \cdot \frac{1 \text{ nucleus}}{4 \text{ nucleons}} = \boxed{7.10 \text{ MeV/nucleon}}$$

(EX) Calculate Binding Energy

¿What is the binding energy per nucleon, in MeV, for $^{56}_{26}Fe$, given it has an atomic mass of 55.9349 amu?



$^{56}_{26}Fe$ (56 − 26 = 30)

ⓐ Calc AW = $(26 \times 1.0073) + (30 \times 1.0087) + (26 \times 0.00055 \text{ amu})$ = **56.4651 amu**

ⓑ Mass defect = 56.4651 (theo) − 55.9349 (actual) = **0.5302 amu**

ⓒ $E = mc^2 = \frac{0.5302 \text{ amu}}{} \left| \frac{1.6605 \times 10^{-27} \text{ kg}}{\text{amu}} \right| \frac{(2.998 \times 10^8)^2 \text{ m}^2}{s^2}$

$= 7.913 \times 10^{(16-27)} \frac{\text{kg m}^2}{s^2} = 7.913 \times 10^{-11}$ J for atom

ⓓ $\frac{\square \text{ MeV}}{\text{nucleon}} = \frac{7.913 \times 10^{-11} \text{ J}}{\text{atom}} \left| \frac{1 \text{ MeV}}{1.602 \times 10^{-13} \text{ J}} \right| \frac{1 \text{ atom}}{56 \text{ nucleon}} = $ **8.820 MeV/nucleon**

Nuclear Equations [21.2]

Examples

Madam Curie first to isolate unstable element, polonium

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

James Chadwick discovered the neutron

$$^{9}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + ^{1}_{0}n$$

Ernst Rutherford was the first to prepare radioisotope by artificial means

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

First controlled chain nuclear reactin started with . . .

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{87}_{35}Br + ^{146}_{57}La + 3\,^{1}_{0}n$$

Radioactive Decay [12.3]

Key Terms

RADIOACTIVE DECAY – change of unstable nuclide to another

PARENT NUCLIDE – unstable nuclide

DAUGHTER NUCLIDE – resulting nuclide

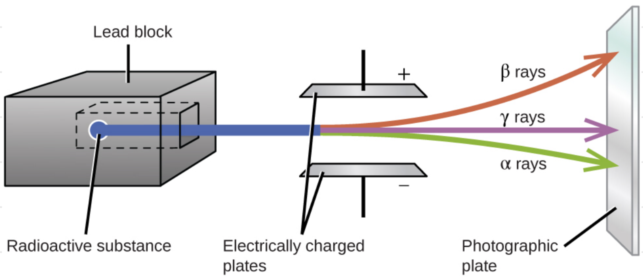


Figure 21.6 Alpha particles, which are attracted to the negative plate and deflected by a relatively small amount, must be positively charged and relatively massive. Beta particles, which are attracted to the positive plate and deflected a relatively large amount, must be negatively charged and relatively light. Gamma rays, which are unaffected by the electric field, must be uncharged.

Types of Radioactive Decay

Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	$^A_ZX \quad ^4_2He + ^{A-4}_{Z-2}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	$^A_ZX \quad ^0_{-1}e + _{Z+1}^{A}Y$		A: unchanged Z: increase by 1
Gamma decay	$^A_ZX \quad ^0_0\gamma + ^A_ZY$	Excited nuclear state; γ	A: unchanged Z: unchanged
Positron emission	$^A_ZX \quad ^0_{+1}e + _{Y-1}^{A}Y$		A: unchanged Z: decrease by 1
Electron capture	$^A_ZX \quad ^0_{-1}e + _{Y-1}^{A}Y$	X-ray	A: unchanged Z: decrease by 1

ALPHA DECAY — gives off $^4_2\alpha$ ($^4_2He^{2+}$)

↳ typical for large (A > 200, Z > 83)

↳ daughter will have larger n/p ratio than parent

GAMMA EMISSION – quantum of high-every EMR

↳ occurs when a daughter nuclide is formed in an excited ground state

eg: $^{60}_{27}Co^* \rightarrow ^{60}_{27}Co + ^0_0\gamma$

BETA DECAY — emission of electron

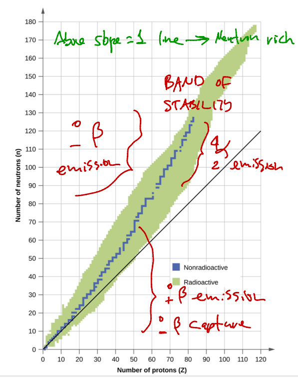
↳ essentially, neutron —> proton + electron

↳ daughter will have smaller n/p ratio than parent

POSITRON EMISSION — emission of a "positive" electron

↳ convert element fo next lower on PC; e.g. . . $^{15}_8O \rightarrow ^0_{+1}e + ^{15}_7N$ (or $^0_{+1}\beta$)

↳ occurs in low n/p parents [n/p_daughter > n/p_parent]



ELECTRON CAPTURE

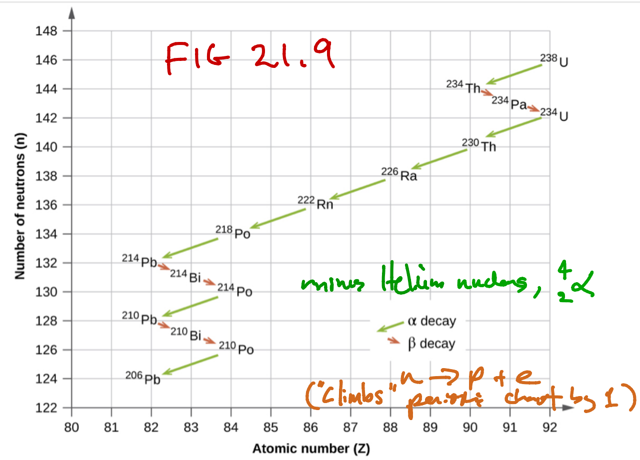
↳ essentially, proton + electron —> neutron (opposite beta-decay)

↳ same net result as positron emission (choice is kinetically driven)

Radioactive Decay Series

For heavier elements, there are three main decay series, allof which terminate at a stable isotope of lead, Pb-82.

Figure 21.9 Uranium-238 undergoes a radioactive decay series consisting of 14 separate steps before producing stable lead-206. This series consists of eight α decays and six β decays.



Radioactive Half-Lives

Follows 1st order kinetics

$$
\begin{aligned}
rate &= k[A] \\
lnA &= -kat + lnA_o \\
lnN_t &= -\lambda t + lnN_o \\
ln\frac{N_o}{N} &= \lambda t \\
ln2 &= \lambda t_{1/2} \quad (at\, t_{1/2}, \frac{N_o}{N} = \frac{2}{1}) \\
t_{1/2} &= \frac{0.693}{\lambda}
\end{aligned}
$$

Also → $N_t = N_0 e^{-\lambda t}$

FIG 21.10

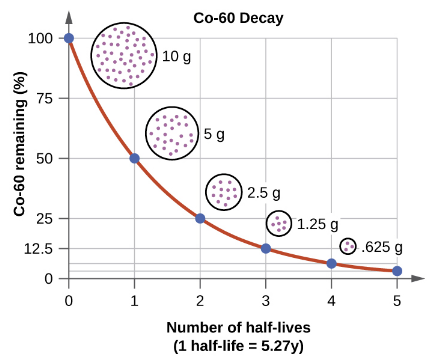


Figure 21.10 For cobalt-60, which has a half-life of 5.27 years, 50% remains after 5.27 years (one half-life), 25% remains after 10.54 years (two half-lives), 12.5% remains after 15.81 years (three half-lives), and so on.

(EX) Calculate Time to Decay [21.6 check]
¿Radon-222 has a half-life of 3.823 days. How long will it take 0.750 g of 86Ra-222 to decay to the point that only 0.100 g remains?

¿ Radon-222 has a half-life of 3.823 days. How long will it take 0.750 g of $^{222}_{86}Ra$ to decay to the point only 0.100 g remains?

Analysis: 3-possible equations: ⓐ $t_{1/2} = \frac{0.693}{\lambda}$

ⓑ $N_t = N_0 e^{-\lambda t}$ ⓒ $\ln\left(\frac{N_0}{N}\right) = \lambda t$

Strategy ⓐ, then ⓒ

(i) $t_{1/2} = \frac{0.693}{\lambda}$ → $\lambda = \frac{0.693}{t_{1/2}} = \frac{0.693}{3.823 \text{ days}} = 0.181 \text{ days}$

(ii) $\ln\left(\frac{N_0}{N}\right) = \lambda t$ → $t = \ln\left(\frac{N_0}{N}\right) \times \frac{1}{\lambda} = \ln\left(\frac{0.750}{0.100}\right) \times$

$= 2.01 \times \frac{1 \text{ days}}{0.181} = 11.1 \text{ days}$

(EX) Calculate of an item ('rate proportional to N' assumption) [21.6b]
¿Samples of seeds and plant matter from King Tutankhamun's tomb have a C-14 decay rate of 9.07 disintegrations/min/g of C. How long ago did King Tut's reign come to an end?

EXTRACT: $N_t \propto Rate_t = 9.07$ disintegrations·g/min
$N_0 \propto Rate_0 = 13.6$ disintegrations·g/min (std. info)
$t_{1/2} = 5730$ yr (std. info)

• Know/Can Calc all information needed to use eq ...

$\frac{N_t}{N_0} \propto \frac{Rate_t}{Rate_0}$

$t = -\frac{1}{\lambda}\ln\left(\frac{N_t}{N_0}\right)$

$\frac{\lambda}{1} = \frac{0.693}{5730y}$

⇓

$t = -\frac{5730y}{0.693}\ln\left(\frac{9.07}{13.6}\right) = -(8270y)(-0.405) = \boxed{3350 yr}$

So, King Tut's reign ended about
+2017
−3350
−1333
+2 (there is no yr. zero) −1BC → +1AD
−1335 ⟸ $\boxed{1340 BC}$

Wed. Nov 29th

Nuclear Fission

FISSION – decomposition of unstable, large nuclie

CHAIN REACTION – decompositon of fewer nuclei provide enough mass and energy to cause greater number of nuclei to decompose

FISSILE (or FISSIONALBE) – material that can sustain a nuclear fission chain reaction

CRITICAL MASS – amount of material needed to sustain chain reaction

SUBCRITICAL MASS – amount of material that can NOT sustain chain reaction

SUPERCRITICAL MASS – amount of material that causes an increase in the rate of fission

FIG. 21.16

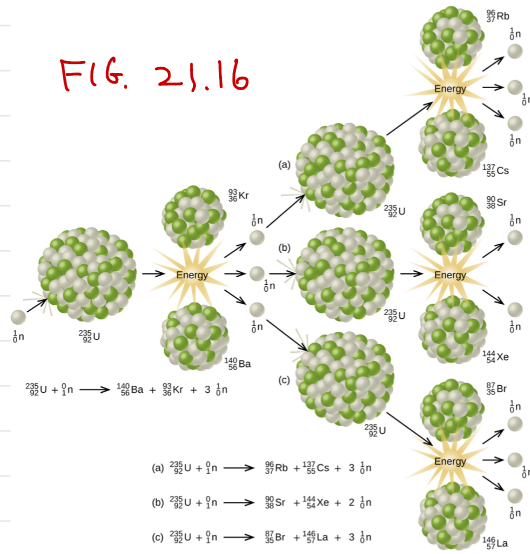
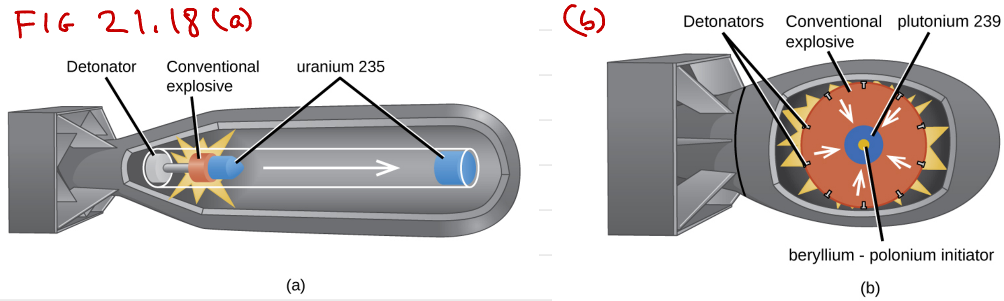


FIG 21.18 (a) (b)



(a) Hiroshima 6 Aug 1945 "Little Boy"

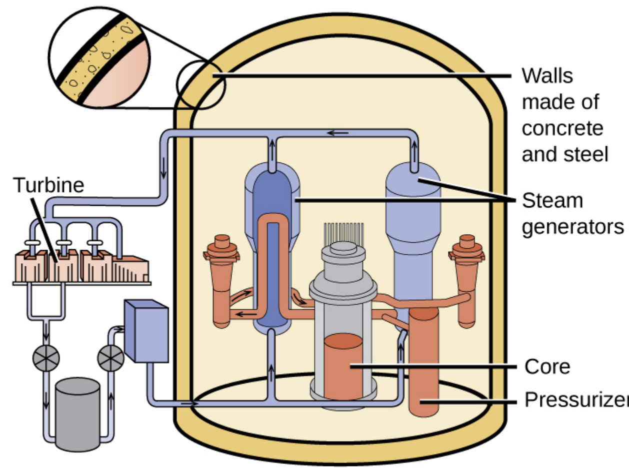
(b) Nagasaki 12 Aug 1945 "Fat Man"

Factoid

$$\frac{\text{Energy of fission } (1 \text{ kg } ^{235}U)}{\text{Energy of combustion } (1 \text{ kg Coal})} = \frac{2{,}500{,}000}{1}$$

- Rxn rates controlled by adjusting # neutrons in chain reaction.

Fission Reactors



(b)

NUCLEAR FUEL
↳ fissionalbe isotope
↳ U-235 (U-238 not fissionable)

MODERATOR
↳ slows neutrons to a speed low enough to cause fission
↳ ex: graphite, heavy water (D2O, ^2H20)

FIG 21.19

COOLANT
↳ carried heat to boiler
↳ ex: water, molten salt, lead

CONTROL RODS
↳ controls reaction by adjusting # slow neutrons
↳ material = boron, cadmium

$$^{10}_{5}B + ^{1}_{0}n \longrightarrow ^{7}_{3}Li + ^{4}_{2}He$$

Nuclear Fusion and Fusion Reactors

- Convert light nuclei into heavier ones (the sun)

$$4\,{}^{1}_{1}H \longrightarrow {}^{4}_{2}He + 2\,{}^{0}_{+1}(\text{positron})$$

- He has 0.7% less mass than 4 H ⟶ mass loss ~ energy $E = mc^2$

Thermofusion

Induced by high temperatures

$${}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + 2\,{}^{1}_{0}n$$

deuterium tritoh