Nuclear Chemistry Notes

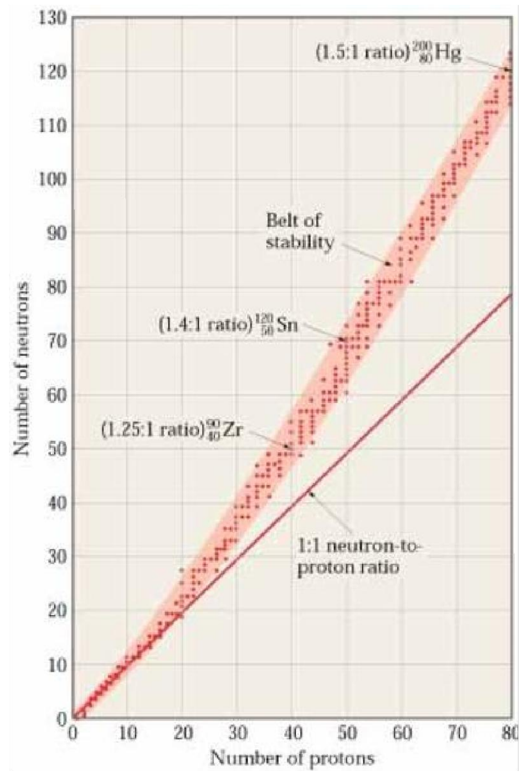
I. Nuclear chemistry

- involves changes with the nucleus, which changes the identity of the atom

A. Nuclear Stability

Whether or not a nucleus is stable depends on the ratio of protons to neutrons in the nucleus.

- The belt of stability diagram is used to determine if the ratio is stable or unstable



- If the ratio is unstable, the nucleus will decay to become more stable
  - Radiation will be emitted from nucleus in attempt to make nucleus more stable

* Use the ratio of protons to neutrons on belt of stability to determine if atoms under atomic number 83 are stable or unstable

- if too many neutrons or too few neutrons compared to protons, the nucleus will be unstable

* All atoms with an atomic number of 83 and greater are naturally unstable

* For any element that is considered unstable, it is then radioactive and is called a **radioisotope**.

B. Types of Radiation (Reference Table O)

An unstable nucleus will decay to eventually produce a more stable nucleus. When the nucleus decays, it emits radiation as one of four particles.

1) **Alpha** Decay

Heavy atoms tend to emit alpha particles from the nucleus in an attempt to become more stable

Alpha particle = mass of 4, charge of 2

Symbol = $^{4}\alpha_{2}$ or $^{4}He_{2}$

2) **Beta** Decay

Conversion of a neutron to a proton in a nucleus in an attempt to become more stable

beta particle = mass of 0, charge of -1

Symbol = $^{0}\beta_{-1}$ or $^{0}e_{-1}$

3) **Positron** Emission

Conversion of a proton to a neutron in a nucleus in an attempt to become more stable

positron particle = mass of 0, charge of +1

Symbol = $^{0}\beta_{+1}$ or $^{0}e_{+1}$

4) **Gamma** Emission

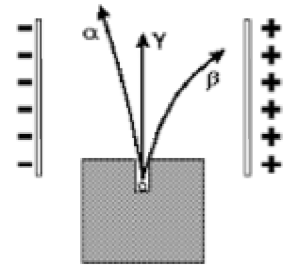
Very high frequency radiation emitted from a nucleus when undergoing changes to become more stable

gamma particle = mass of 0, charge of 0

Symbol = $^{0}\gamma_{0}$

Table O
Symbols Used in Nuclear Chemistry

Name	Notation	Symbol
alpha particle	$^{4}_{2}He$ or $^{4}_{2}\alpha$	α
beta particle	$^{0}_{-1}e$ or $^{0}_{-1}\beta$	β^-
gamma radiation	$^{0}_{0}\gamma$	γ
neutron	$^{1}_{0}n$	n
proton	$^{1}_{1}H$ or $^{1}_{1}p$	p
positron	$^{0}_{+1}e$ or $^{0}_{+1}\beta$	β^+



C. Natural decay (transmutation) equations

Alpha, beta and positron decay are natural transmutations that occur as a result of unstable neutron-to-proton ratios. Reference Table N will tell you what the decay mode is for a given unstable nucleus

Table N
Selected Radioisotopes

Nuclide	Half-Life	Decay Mode	Nuclide Name
^{198}Au	2.695 d	β^-	gold-198
^{14}C	5715 y	β^-	carbon-14
^{37}Ca	182 ms	β^+	calcium-37
^{60}Co	5.271 y	β^-	cobalt-60
^{137}Cs	30.2 y	β^-	cesium-137
^{53}Fe	8.51 min	β^+	iron-53
^{220}Fr	27.4 s	α	francium-220
^{3}H	12.31 y	β^-	hydrogen-3
^{131}I	8.021 d	β^-	iodine-131
^{37}K	1.23 s	β^+	potassium-37
^{42}K	12.36 h	β^-	potassium-42
^{85}Kr	10.73 y	β^-	krypton-85
^{16}N	7.13 s	β^-	nitrogen-16
^{19}Ne	17.22 s	β^+	neon-19
^{32}P	14.28 d	β^-	phosphorus-32
^{239}Pu	2.410×10^4 y	α	plutonium-239
^{226}Ra	1599 y	α	radium-226
^{222}Rn	3.823 d	α	radon-222
^{90}Sr	29.1 y	β^-	strontium-90
^{99}Tc	2.13×10^5 y	β^-	technetium-99
^{232}Th	1.40×10^{10} y	α	thorium-232
^{233}U	1.592×10^5 y	α	uranium-233
^{235}U	7.04×10^8 y	α	uranium-235
^{238}U	4.47×10^9 y	α	uranium-238

Source: *CRC Handbook of Chemistry and Physics*, 91st ed., 2010–2011, CRC Press

1) Alpha decay

When a nucleus emits an alpha particle, the overall mass decreases by 4 and the overall charge decreases by 2

ex) $^{226}Ra_{88} \rightarrow {}^{4}\alpha_{2} + {}^{222}Rn_{86}$

ex) $^{239}Pu_{94} \rightarrow {}^{4}\alpha_{2} + {}^{235}U_{92}$

* alpha particle is always a product along with the new, more stable element

2) Beta decay

When a nucleus emits a beta particle, the overall mass does not decrease but and the overall charge increases by 1

ex) $^{131}I_{53} \rightarrow {}^{0}\beta_{-1} + {}^{131}Xe_{54}$

ex) $^{3}H_{1} \rightarrow {}^{0}\beta_{-1} + {}^{3}He_{2}$

* beta particle is always a product along with the new, more stable element

3) Positron emission

When a nucleus emits a positron particle, the overall mass does not decrease but and the overall charge decreases by 1

ex) $^{53}Fe_{26} \rightarrow {}^{0}\beta_{+1} + {}^{53}Mn_{25}$

ex) $^{19}Ne_{10} \rightarrow {}^{0}\beta_{+1} + {}^{19}F_{9}$

* positron particle is always a product along with the new, more stable element

D. Half Life

Radioactive substances decay at a constant rate that is NOT dependent on temperature, pressure or concentration. It is also a random event.

- Impossible to predict when a given unstable nucleus will decay
- CAN predict the number of unstable nuclei that will decay in a given amount of time

<u>Half-life</u> = the time it takes for HALF of the atoms in a given sample of an element to decay

a) Each isotope has its own half life
b) ****Reference Table N**** lists the isotopes together with their half-lives and mode of decay
c) Use a chart like the one below to answer half-life questions

Half Lives	0	1	2	3	4	5	6
Time Passed	0						
Amount remaining							

Examples:

1) What fraction of a sample of Co-60 will remain after 26.5 years?
Reference table N = Co-60 half life is 5.3 years. So every 5.3 years half of the sample will decay

Half Lives	0	1	2	3	4	5	6
Time Passed	0	5.3	10.6	15.9	21.2	26.5	
Amount remaining	1	1/2	1/4	1/8	1/16	1/32	

Answer: 1/32 of Co-60 will remain

2) How many grams of a starting amount of 100. grams of Fe-53 will remain after 25.5 minutes?
Reference table N = Fe-53 half life is 8.51 minutes. So every 8.51 minutes half of the sample will decay

Half Lives	0	1	2	3	4	5	6
Time Passed	0	8.51	17.02	25.53			
Amount remaining	100g	50g	25g	12.5g			

Answer: 12.5 grams of Fe-53 will remain

3) A 50.0 gram sample of N-13 decays to 12.5 grams in 19.94 seconds. What is its half-life?

Half Lives	0	1	2	3	4	5	6
Time Passed	0						
Amount remaining	50g	25g	**12.5g**				

It took 2 half-life periods to decay from 50 grams to 12.5 grams.

19.94/2 = 9.97 seconds **Answer: the half-life = 9.97 seconds**

4) There are 5.0 grams of I-131 left after 40.1 days. How many grams were in the original sample?

Reference table N = I-131 half life is 8.021 days. So every 8.021 days half of the sample will decay

Half Lives	0	1	2	3	4	5	6
Time Passed	0	8.021	16.04	24.06	32.08	**40.1**	
Amount remaining	160g	80.g	40.g	20.g	10.g	**5.0g**	

It took 5 half-life periods to decay over 40.1 days. So you would work backwards (double the amount for each half-life) and determine amount remaining at time 0.

Answer: original amount had 160. grams

5) How many years passed if only 25.0 grams of an original 100.0 gram sample of C-14 is left?

Reference table N = C-14 half life is 5715 years. So every 5715 years half of the sample will decay

Half Lives	0	1	2	3	4	5	6
Time Passed	0	5715	11430				
Amount remaining	100 g	50.g	25.g				

Answer: 11,430 years has passed

6) What is the total percent of Rn-222 remaining in an original sample after 19.1 days?

Reference table N = Rn-222 half life is 3.823 days. So every 3.823 days half of the sample will decay

Half Lives	0	1	2	3	4	5	6
Time Passed	0	3.823	7.65	11.47	15.3	19.1	
Amount remaining	100%	50%	25%	12.5%	6.25%	3.125%	

Answer: 3.125% will be left

E. Artificial transmutation

Artificial transmutation: when bombarding the nucleus with high-energy particles brings about a change to the nucleus

To tell the difference between natural and artificial transmutation:

Natural decay has a single nucleus undergoing decay = $^{19}\text{Ne}_{10} \rightarrow {}^{0}\beta_{+1} + {}^{19}\text{F}_{9}$

single reactant

Artificial transmutation has two reactants producing the decay = $^{9}\text{Be}_{4} + {}^{1}\text{H}_{1} \rightarrow {}^{6}\text{Li}_{3} + {}^{4}\text{He}_{2}$

two reactants

For artificial transmutation, you will need to be able to determine the missing particle given the reaction. Law of conservation of mass and change states that the total mass and charge of both sides of the equation must be equal.

Examples:

total mass = 236 total mass = 236

1) Given $^{1}\text{n}_{0} + {}^{235}\text{U}_{92} \rightarrow {}^{141}\text{Ba}_{56} + \text{X}$ What particle is X?

total charge is 92 total charge is 92

141 + x = 236 mass is 95

56 + x = 92 charge is 36

X = $^{95}\text{Kr}_{36}$

total mass = 18 total mass = 18

2) Given $^{14}\text{N}_{7} + {}^{4}\text{He}_{2} \rightarrow {}^{1}\text{He}_{1} + \text{X}$ What particle is X?

total charge is 9 total charge is 9

1 + x = 18 mass is 17

1 + x = 9 charge is 8

X = $^{17}\text{O}_{8}$

total mass = 13 total mass = 13

3) Given $^{9}\text{Be}_{4} + \text{X} \rightarrow {}^{12}\text{C}_{6} + {}^{1}\text{n}_{0}$ What particle is X?

total charge is 6 total charge is 6

9 + x = 13 mass is 4

4 + x = 6 charge is 2

X = $^{4}\text{He}_{2}$

F. Applications of radioisotopes

Radioactive elements (radioisotopes) have many practical applications in industry, medicine and research.

1) Dating

Carbon-14 (C-14) is best used for dating previously living materials. When an organism is alive, it takes in carbon-14 from the atmosphere. When the organism dies, it no longer takes in any carbon, and we can measure the decay of C-14 to N-14. With a half-life of 5730 years, it can be used for up to four half-lives for dating organic materials.

Uranium-238 (U-238) can be used to date geological materials such as rocks and other geological formations. As U-238 decays, it turns into Pb-206, and the ratio of U-238/Pb-206 can help to determine how old the non-living material is.

2) Chemical Tracers

A radioisotope used to follow the path of a material in a system is called a tracer.

Phosphorus-31 (P-31) is mixed in with fertilizer, which when taken up by plants, can be traced and help to determine proper amounts and timing of fertilizer applications.

3) Medical Applications

Certain radioisotopes that are quickly eliminated from the body and halve short half-lives are important as tracers in medical diagnosis. Many are also used in treatments of various disorders and diseases.

Iodine-131 (I-131) is used in both detection and treatment of thyroid conditions because it will naturally accumulate and be used in the thyroid gland.

Cobalt-60 (Co-60) emits large amounts of gamma radiation when it decays. These rays can be aimed at cancerous tumors. It can also be used to irradiate certain types of foods to kill bacteria present. This way the food lasts longer and is less likely to spoil.

Technetium-99m ($Tc\text{-}99_m$) is given to patients with cancerous tumors, and it will accumulate in the tumor and be easily detected by a scan. This will help physicians to map out a tumor for treatment or removal. It is commonly used for brain tumors in this way.

When radioisotopes are used for diagnostic purposes, it is helpful if they have a short half-life and are quickly eliminated by the body do they do not damage healthy tissue.

G. Fission and fusion

These are a type of artificial transmutation in which changes are done to the nucleus of an atom. However, these two types of nuclear reactions involve converting some of the mass into large amounts of energy.

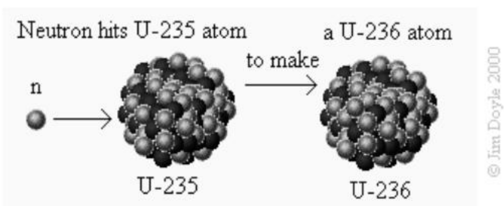
1. Nuclear Fission

Takes place when a heavy atomic nucleus, such as U-233, U-235 or Pu-239, breaks apart into two or more smaller pieces with the release of some energy.

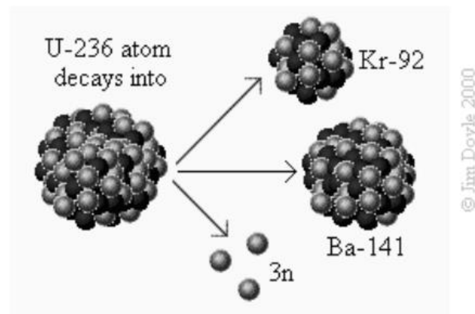
Reaction: $^{1}n_{0} + {}^{235}U_{92} \rightarrow {}^{142}Ba_{56} + {}^{91}Kr_{36} + 3\ {}^{1}n_{0} + \text{energy}$

** During this process some of the mass of the original atom is converted into energy in accordance with the equation $E = mc^2$.

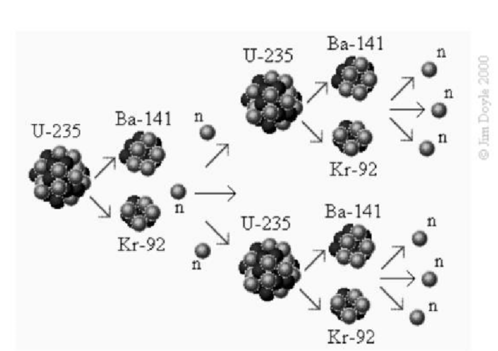
STEP 1



STEP 2

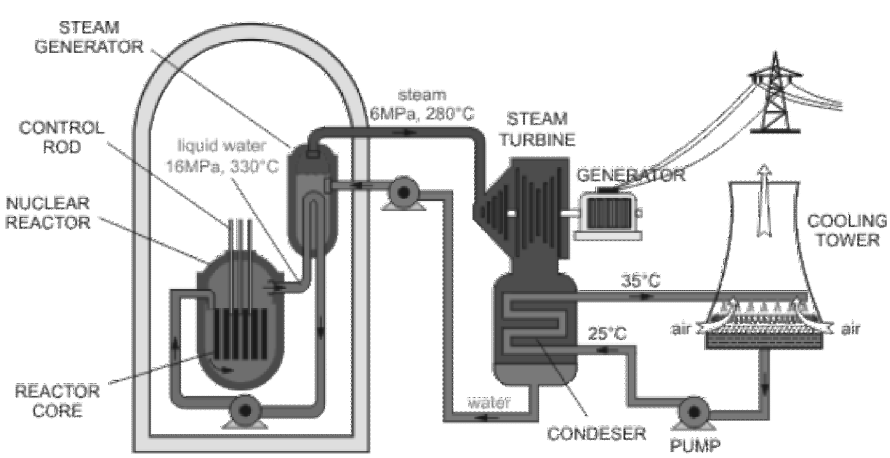


The initial NEUTRON that bombarded the U-235 nucleus creates what's called a chain reaction.



Applications:

CONTROLLED REACTION: A Nuclear Power Plant



In a controlled fission reaction within a nuclear reactor, much of the energy generated is in the form of heat. A coolant fluid, usually liquid sodium or water, removes the heat from the reactor core. The heat is used to generate steam, which drives a turbine that in turn generates electricity.

The control of fission in a nuclear reactor involves two steps: neutron moderation and neutron absorption.

Neutron Moderation: a process that slows down neutrons so the reactor fuel captures them to continue the chain reaction. Moderation is necessary because most of the neutrons produced move so fast they will pass right through a nucleus without being absorbed.

Neutron Absorption: to prevent the chain reaction from going to fast (or too slow), a power plant uses control rods to absorb neutrons. When the control rods extend all the way into the reactor core, the fission reaction proceeds slowly or doesn't go at all. As the rods are pulled out, they absorb fewer neutrons and the process speeds up. If the chain reaction were to go too fast, heat might be produced before the coolant (water) can remove it, which could lead to mechanical failure and a meltdown of the reactor core.

UNCONTROLLED REACTION: Nuclear Fission Bomb

The design is nearly identical to a fission reactor, except there are NO control rods

PROBLEMS WITH FISSION: 1) Produce lots of radioactive wastes which are difficult to store and have long half-lives
2) Costly to build safe and effective power plants

2) Nuclear Fusion
Takes place when nuclei combine together to produce a nucleus of greater mass.

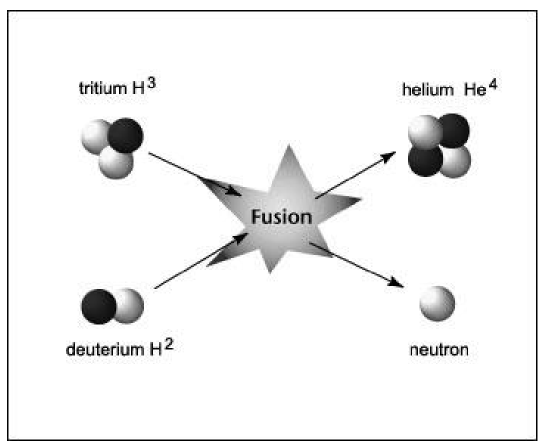
Nuclear Fusion as an energy source

Reaction: $\mathbf{{}^{2}H_{1} + {}^{2}H_{1} \rightarrow {}^{4}He_{2}}$

Or

$\mathbf{{}^{2}H_{1} + {}^{3}H_{1} \rightarrow {}^{4}He_{2} + {}^{1}n_{0}}$

**Ultimately, fusion is the combining (fusing) of two Hydrogen atoms to form Helium



#1 PROBLEM WITH FUSION: Need to overcome the need for extreme heat, need to develop materials strong enough to withstand heat, difficult to contain the nuclei into a small enough area/hard to "control" the reaction