Chapter 2

Atomic Structure and Nuclear Chemistry

Atoms & Elements Part 0: Atomic Structure – An Introduction

Electrostatics – an underlying force throughout chemistry

The word ATOM is derived from
the Greek *ATMOS* meaning "uncut" or "indivisible."

460 – 370 B.C. Democritus uses the term "**atmos**" as a proponent of the discontinuous matter concept

1808 Dalton's Atomic Theory

1. Elements are made of tiny particles called atoms.
2. All atoms of a given element are identical.
3. The atoms of a given element are different from those of any other element.
4. Atoms of one element can combine with atoms of other elements to form compounds. A given compound always has the same relative numbers and types of atoms.
5. Atoms are indivisible in chemical processes. That is, atoms are not created or destroyed in chemical reactions. A chemical reaction simply changes the way the atoms are grouped together.

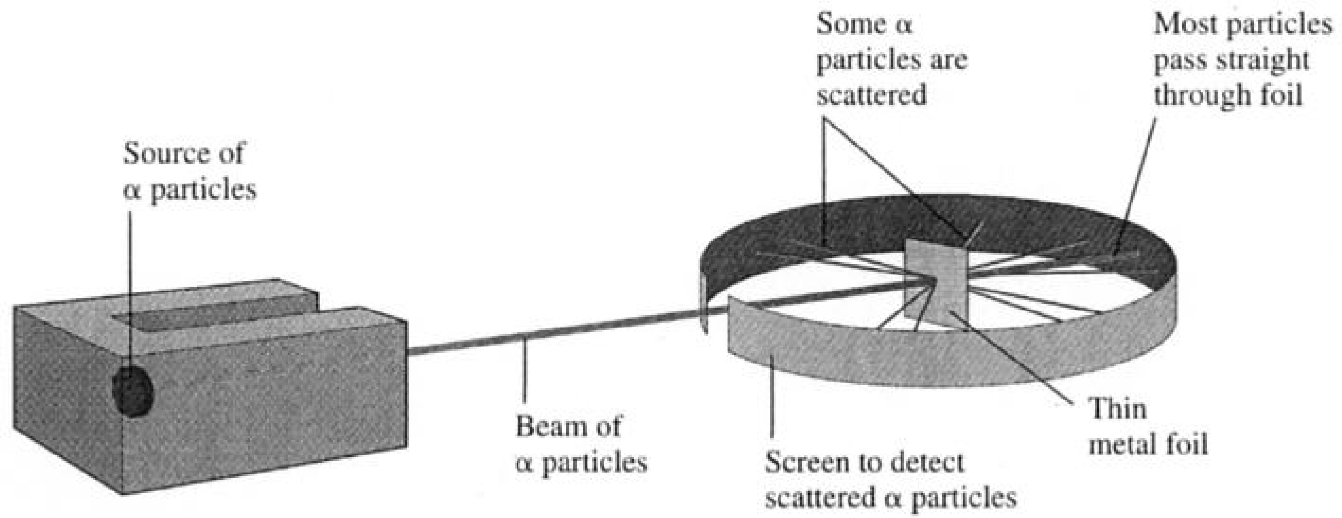
Late 1890's JJ Thomson shows atoms contain negative particles - **electrons**

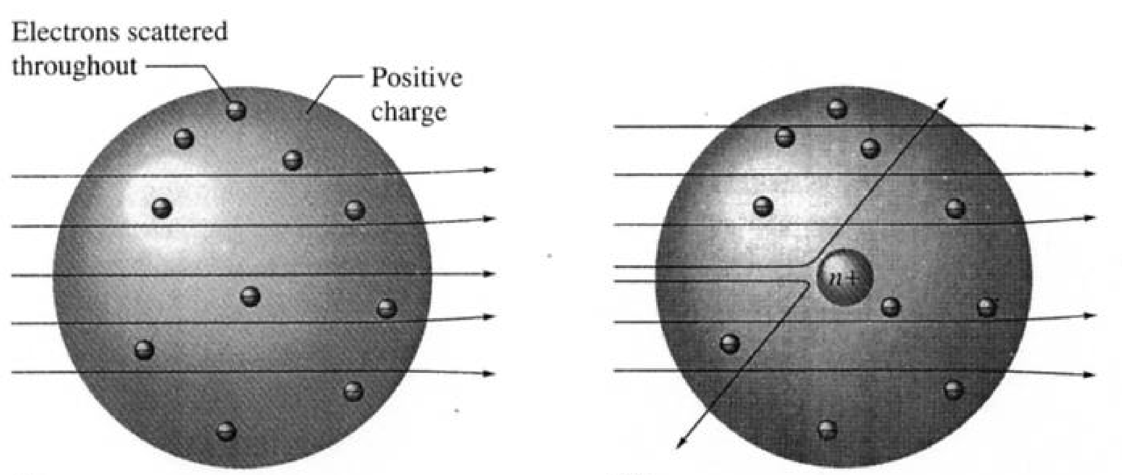
JJ Thomson proposes that atoms must also contain positive particles to give the atom an overall zero charge – **protons**

Late 1890's Lord Kelvin proposes the "plum pudding" model for the atom

1911 Rutherford proposes the "**nuclear atom**" – an atom with a dense center of positive charge (the **nucleus**) surrounded by tiny electrons in an otherwise empty space (grape / mile)

Rutherford's Gold Foil Experiment





1919 Rutherford determined that a proton had the same magnitude of charge as an electron **(proton = +1 and electron = -1)**

1932 Rutherford demonstrated the existence of **neutrons** in most nuclei. The neutron has no charge (neutral) and is slightly more massive than a proton.

1932 Chadwick determined the existence of **isotopes** - atoms with the same number of protons, but with different numbers of neutrons
(only major change to Dalton's original atomic theory)

What have we learned since 1932?

subatomic particle	relative charge	relative mass

Atomic number:

Mass number:

Isotopes:

Let's put it all together.

Atoms are the basic building blocks of matter.
Matter is defined as anything with MASS & VOLUME.
What is the relationship between atomic structure and matter?

Periodic Table of the Elements

1 Group IA	2 Group IIA	3 Group IIIB	4 Group IVB	5 Group VB	6 Group VIB	7 Group VIIB	8 Group	9 Group VIIIB	10 Group	11 Group IB	12 Group IIB	13 Group IIIA	14 Group IVA	15 Group VA	16 Group VIA	17 Group VIIA	18 Group VIIIA
1 **H** 1.01																	2 **He** 4.00
3 **Li** 6.94	4 **Be** 9.01											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
11 **Na** 22.99	12 **Mg** 24.30											13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.06	17 **Cl** 35.45	18 **Ar** 39.95
19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.87	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.84	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.39	31 **Ga** 69.72	32 **Ge** 72.64	33 **As** 74.92	34 **Se** 78.96	35 **Br** 79.90	36 **Kr** 83.80
37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.94	43 **Tc** (98)	44 **Ru** 101.07	45 **Rh** 102.91	46 **Pd** 106.42	47 **Ag** 107.87	48 **Cd** 112.41	49 **In** 114.82	50 **Sn** 118.71	51 **Sb** 121.76	52 **Te** 127.60	53 **I** 126.90	54 **Xe** 131.29
55 **Cs** 132.91	56 **Ba** 137.33	57 **La** 138.91	72 **Hf** 178.49	73 **Ta** 180.95	74 **W** 183,84	75 **Re** 186.21	76 **Os** 190.23	77 **Ir** 192.22	78 **Pt** 195.08	79 **Au** 196.97	80 **Hg** 200.59	81 **Tl** 204.38	82 **Pb** 207.2	83 **Bi** 208.98	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** (226)	89 **Ac** (227)	104 **Rf** (261)	105 **Db** (262)	106 **Sg** (266)	107 **Bh** (264)	108 **Hs** (269)	109 **Mt** (268)	110 – (271)	111 – (272)	112 – (277)		114 – (289)		116 – (289)		118 – (293)
				58 **Ce** 140.12	59 **Pr** 140.91	60 **Nd** 144.24	61 **Pm** (145)	62 **Sm** 150.36	63 **Eu** 151.96	64 **Gd** 157.25	65 **Tb** 158.93	66 **Dy** 162.50	67 **Ho** 164.93	68 **Er** 167.26	69 **Tm** 168.93	70 **Yb** 173.04	71 **Lu** 174.97
				90 **Th** 232.04	91 **Pa** 231.04	92 **U** 238.03	93 **Np** (237)	94 **Pu** (242)	95 **Am** (243)	96 **Cm** (248)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (260)	102 **No** (259)	103 **Lr** (262)

Keeping the terms straight – the path to Mastery!

Atoms vs Elements vs Compounds

Atom: the smallest component of an element

Element: substance composed of only 1 type of atom

Compound: substance composed of a fixed ratio of atoms

H_2O

$C_6H_{12}O_6$

Video Error Correction: The ratio of C:H:O is 6:12:6

One formula unit of $Ca_3(PO_4)_2$ contains ___________ elements and ___________atoms.

A = 9; 13
B = 3; 9
C = 3; 13
D = 3; 5

Atoms & Elements Part 1:

Atomic Structure: Isotopes and the Nucleus

Atoms are the building blocks of matter.

What is the definition of matter?

There are 3 subatomic particles that are the building block of atoms.

What are the 3 subatomic particles and their charges?

Which subatomic particle(s) create the mass of an atom?

Which subatomic particle(s) create the volume of an atom?

What is the atomic number of an atom? What is its symbol?

What is the mass number of an atom? What is its symbol?

Is every atom of an element identical? Why or why not?

What are isotopes?

Distinguishing between Isotopes

What is the mass number of an atom containing 42 protons, 42 electrons, and 47 neutrons?

Write the elemental symbol for the isotope above using the ${}_{Z}^{A}E$ format.

Iodine has an atomic number of 53. I-131 is used in the medical treatment of thyroid conditions. How many neutrons and protons are contained in the nucleus of this isotope?

The Average Atomic Mass of an element is a weighted average of the mass of its isotopes based on their natural abundance.

Do all elements have the same distribution of isotopes?

The isotopic distribution for chromium is shown below.
The atomic number for chromium is 24.

Isotope	% Abundance
^{50}Cr	4.345
^{52}Cr	83.79
^{53}Cr	9.50
^{54}Cr	2.365

Which isotope is the lightest?

Which isotope is the most abundant?

Which isotope has the largest number of neutrons?

The Atomic Number and Average Atomic Mass are listed with each element on the periodic table.

24
Cr
51.996

Nuclear Chemistry Part 1:

Nuclear Structure Review & Introduction to Nuclear Chemistry

Symbols for 3 isotopes of carbon:

$^{12}_{6}C$	$^{13}_{6}C$	$^{14}_{6}C$
carbon-12	carbon-13	carbon-14

How many protons are in carbon-12?

How many neutrons are in carbon-12?

How many protons are in carbon-13?

How many neutrons are in carbon-13?

How many protons are in carbon-14?

How many neutrons are in carbon-14?

What is the same about the isotopes of carbon?

What is different about the isotopes of carbon?

What does the subscripted 6 represent?

What is the name and symbol for the subscripted 6?

What do the superscripted 12, 13, & 14 represent?

What is the name and symbol for the superscripted 12, 13, & 14?

Radioisotopes: unstable isotopes

Radioactive decay: the nucleus of a radioactive isotope undergoes a natural process to become a more stable nucleus

Background Radiation: radiation from natural sources

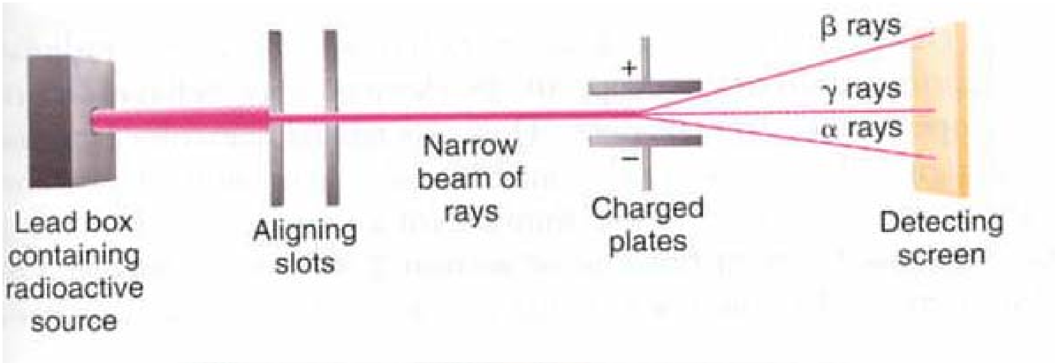
Artificial Radioisotopes: man-made isotopes

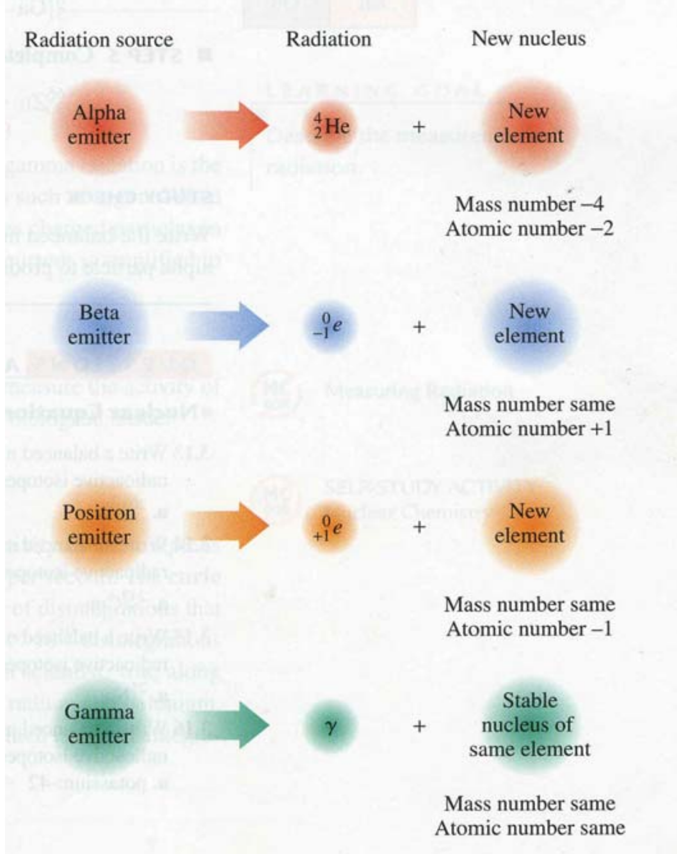
Average Exposure to Radiation from Common Sources

Source: National Council on Radiation Protection and Measurements, NCRP Report No. 93 (1993)

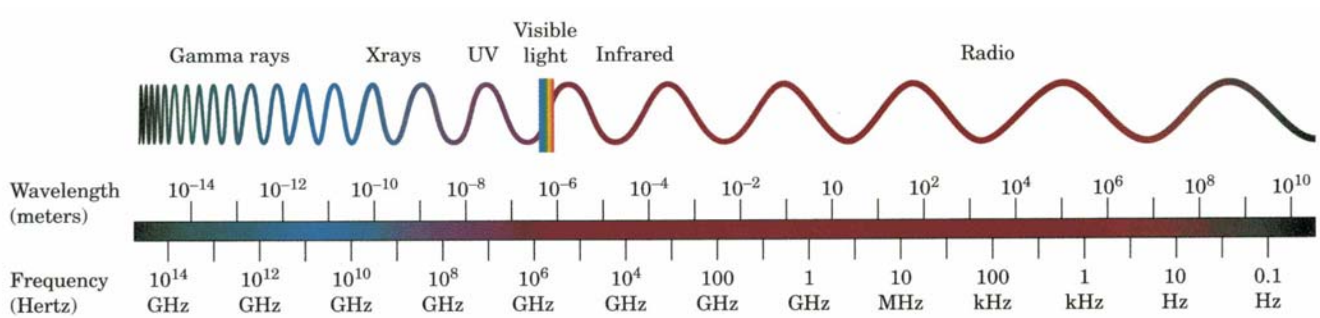
Source	Dose (mrem/year)
Natural Sources	
Cosmic rays	27
Terrestrial radiation (rock, buildings)	28
Inside the body (K-40 and Ra-226)	39
Radon in the air	200
Total	294
Artificial Sources	
Medial x-rays	39
Nuclear medicine	14
Consumer products	10
Nuclear power plants	0.5
All others	1.5
Total	65
Grand Total	359

The major types of radiation





Electromagnetic Radiation



Nuclear Chemistry Part 2: Nuclear Reactions

Nuclear Reaction: a change in the composition of the nucleus of an atom

3 Types

1) radioactive decay

Unstable nuclei eject subatomic particles &/or high energy photons of light to stabilize

2) fusion

Combining nuclei into larger nuclei – stars & the sun

3) fission

Splitting the nuclei of atoms – power plants & bombs

Type of Radiation	Symbol	Mass # (A)	Charge	Relative penetrating ability	Shielding required	Biological hazard
Alpha particle	α, ${}^{4}_{2}He$	4	2+	Very low	Clothing	None unless inhaled
Beta particle	β, ${}^{0}_{-1}e$	0	1–	Low	Heavy cloth, plastic	Mainly to eyes, skin
Gamma ray	γ, ${}^{0}_{0}\gamma$	0	0	Very high	Lead or concrete	Whole body
Neutron	${}^{1}_{0}n$	1	0	Very high	Water, lead	Whole body
Positron	β^{+}, ${}^{0}_{+1}e$	0	1+	Low	Heavy cloth, plastic	Mainly to eyes, skin

Nuclear decay does NOT depend on the environment of the atom.

Temperature, pressure, or type of compound do NOT change radioactive decay.

ALL nuclear reactions are exothermic – releasing a HUGE amount of energy from the nucleus.

α-Decay & Balancing Nuclear Reactions

$$^{238}_{92}U \rightarrow {}^{234}_{90}Th + \alpha + \gamma$$

Type of radioactivity released?

How does the total number of protons in the reactant compare with the total number of protons in the products?

How does the mass number of the reactant compare with the mass number of the products?

Does the γ-ray effect the mass balance of the reaction above?

Is the nuclear reaction above balanced?

Predict the product of the following nuclear reaction.

$$^{222}_{86}Rn \rightarrow \boxed{} + \alpha + \gamma$$

β-Decay of Neutron-rich Isotopes

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

β particles are produced from an unstable nucleus when a neutron is transformed into a proton releasing a high energy electron.

Practice – complete the nuclear reaction below.

$$^{133}_{54}Xe \rightarrow \boxed{} +\ ^{0}_{-1}e$$

Positron Decay of Proton-rich Isotopes

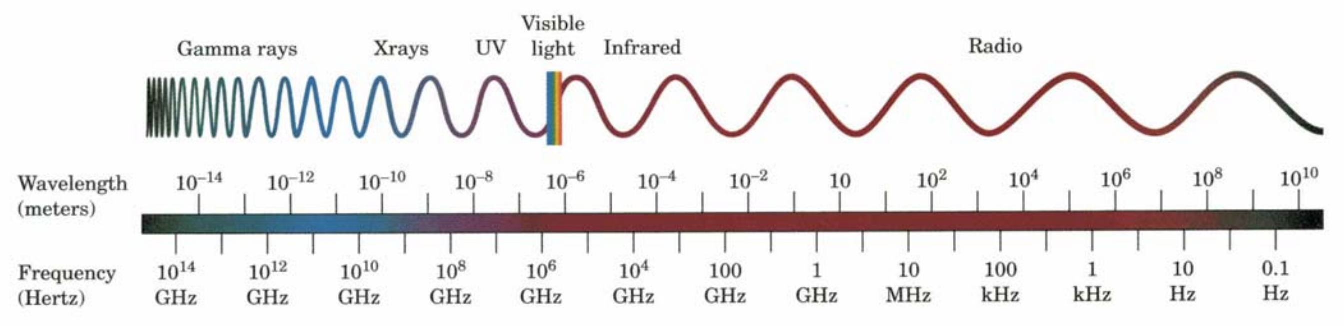
$$^{1}_{1}p \rightarrow\ ^{1}_{0}n +\ ^{0}_{+1}e$$

A positron is produced from an unstable nucleus when a proton is transformed into a neutron releasing a high energy positron.

Practice – complete the nuclear reaction below.

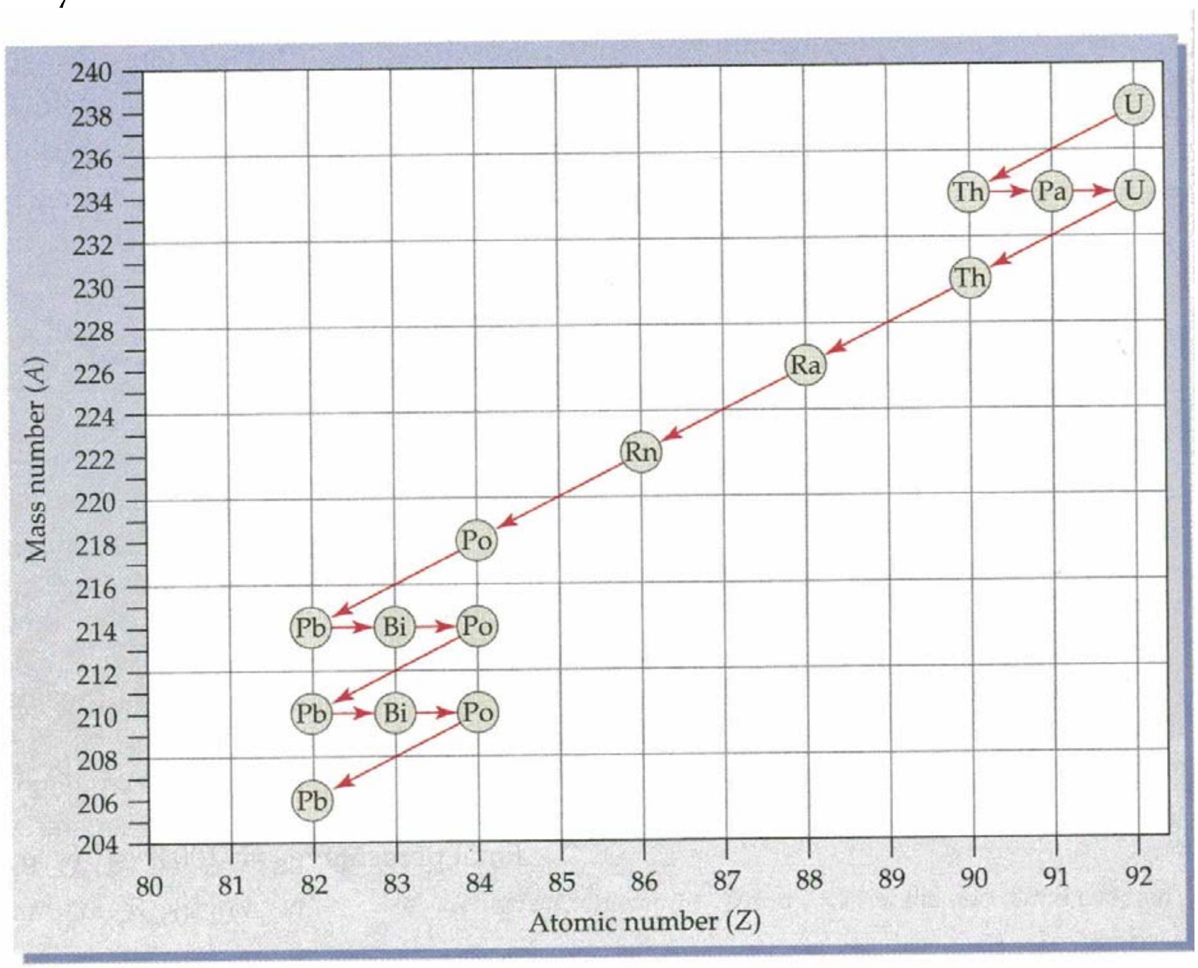
$$\boxed{} \rightarrow\ ^{79}_{36}Kr +\ ^{0}_{+1}e$$

X rays and Gamma Radiation



Nuclear decays often occur in a series before reaching a stable isotope. Identify the types of radioactive decay in the series shown above.

Decay series for $^{238}U \rightarrow {}^{206}Pb$



Balance the following nuclear reactions and identify the type(s) of radioactivity given off.

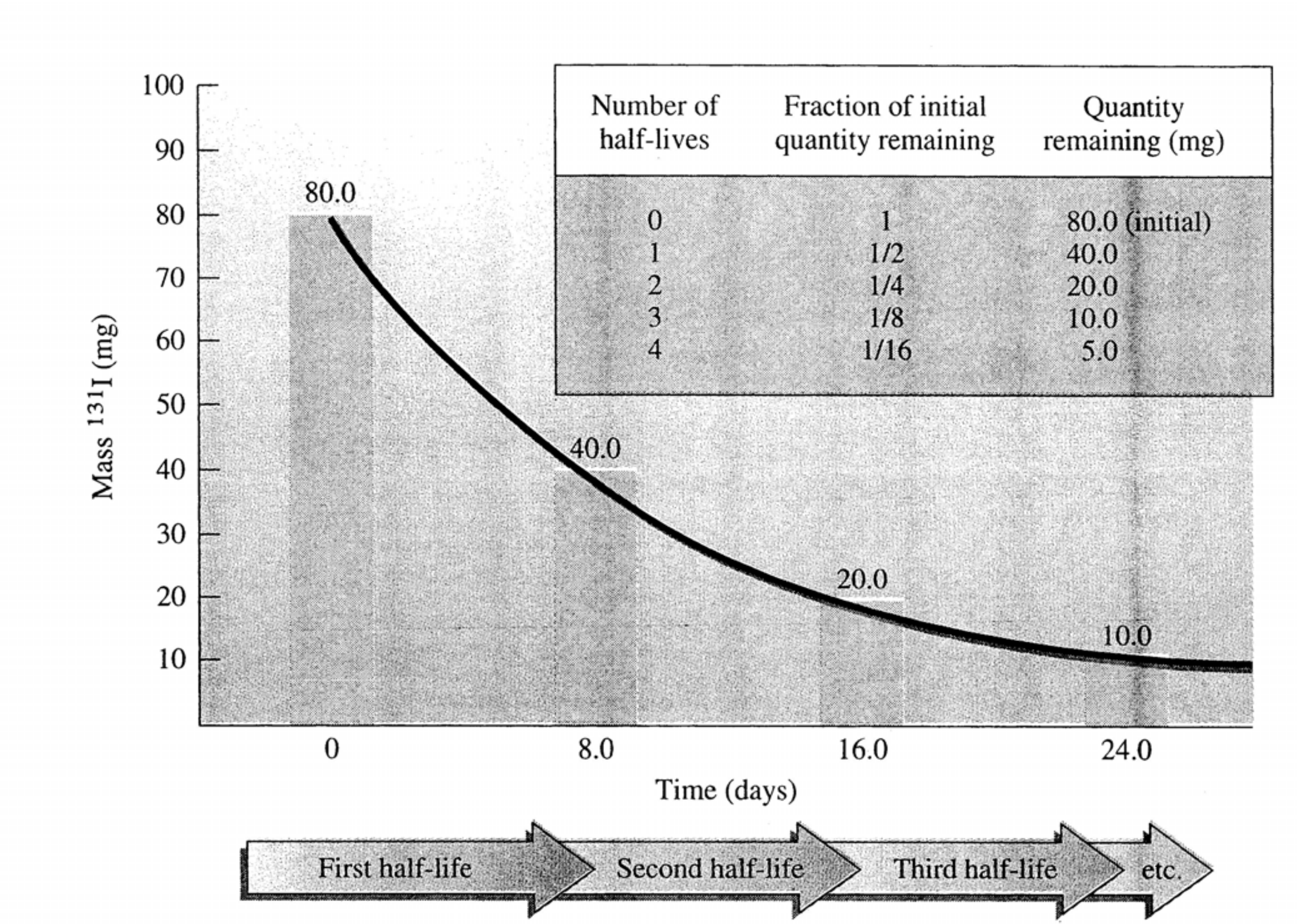
a) $^{118}_{54}Xe \rightarrow \boxed{} + \beta^+$

b) $^{210}_{84}Po \rightarrow \boxed{} + \alpha + \gamma$

c) $^{40}_{19}K \rightarrow {}^{40}_{20}Ca + \boxed{} + \gamma$

Nuclear Chemistry Part 3: Radioactivity & Half-Lives

$t_{1/2}$ = half-life



Number of half-lives	Fraction of initial quantity remaining	Quantity remaining (mg)
0	1	80.0 (initial)
1	1/2	40.0
2	1/4	20.0
3	1/8	10.0
4	1/16	5.0

Use the following table to answer the questions below.

Radioisotope	Radiation type	Half-life
barium-131	γ	11.6 days
carbon-14	β	5730 yr
chromiuim-51	γ, x-rays	27.8 days
iodine-131	β	8.1 days
cobalt-60	β, γ	5.3 yr
uranium-238	α, β, γ	4.5×10^9 yr

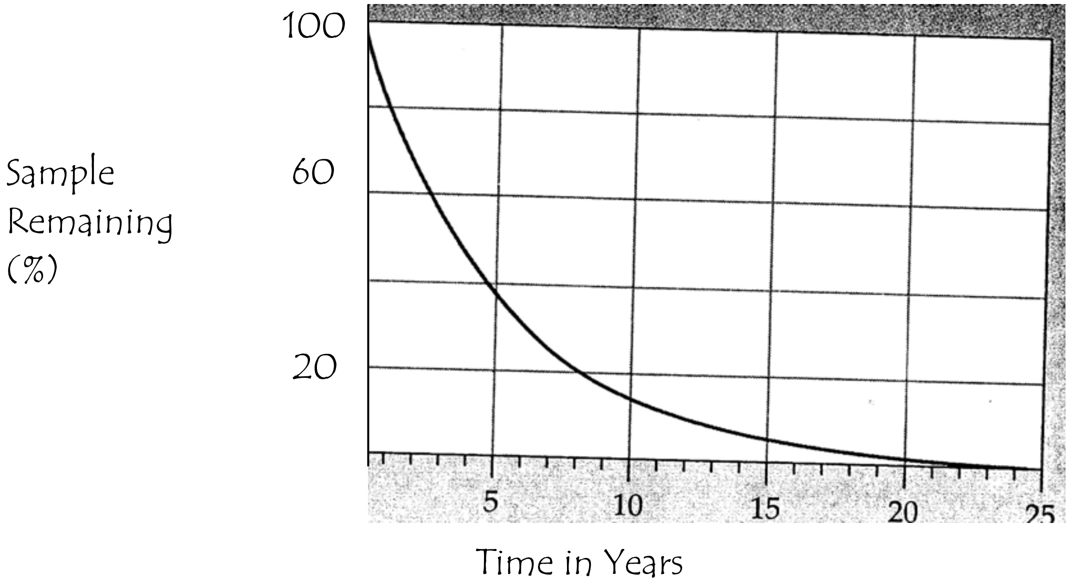
Consider a 100. g sample of ^{51}Cr.

a) How long will it take ½ of the sample to decay?

b) How many grams of ^{51}Cr will remain after 83.4 days?

How old is a fossil if only 6.25% of the original ^{14}C remains?

What is the half-life of the radionuclide with the following decay curve?



We have a 100 g sample of the radionuclide above. How long do we need to wait for the radioactivity to decrease to 1/8 of its original value?

Nuclear Chemistry Part 5: Nuclear Medicine

1) Medical Imaging

General procedure:
a) radioactive isotope is administered
b) radioactive isotope is allowed to metabolize
c) radiation is measured for location and intensity
d) computer processing translates data into images

2) Radiation Therapy
Selective destruction of pathological cells and tissues

Medical Applications of Radioisotopes

Isotope	Half-life	Medical Application
Ce-141	32.5 days	Gastrointestinal tract diagnosis; measuring blood flow to the heart
Ga-67	78 hour	Abdominal imaging; tumor detection
Ga-68	68 min	Detect pancreatic cancer
P-32	4.3 days	Treatment of leukemia, excess red blood cells, pancreatic cancer
I-125	60 days	Treatment of brain cancer
I-131	8 days	Imaging thyroid; treatment of Graves' disease, goiter, and hyperthyroidism; treatment of thyroid and prostate cancer
Sr-85	65 days	Detection of bone lesions; brain scans
F-18	109 min	PET scans for brain activity & tumor detection
Tc-99m	6 hours	Imaging of skeleton and heart muscle, brain, liver, heart, lungs, bone, spleen, kidney and thyroid; most widely used radioisotope in nuclear medicine

Nuclear Chemistry Part 4: Biological Effects of Ionizing Radiation (optional)

Radiation can damage DNA causing genetic mutations by breaking phosphoester bonds close to each other on opposing strands of DNA

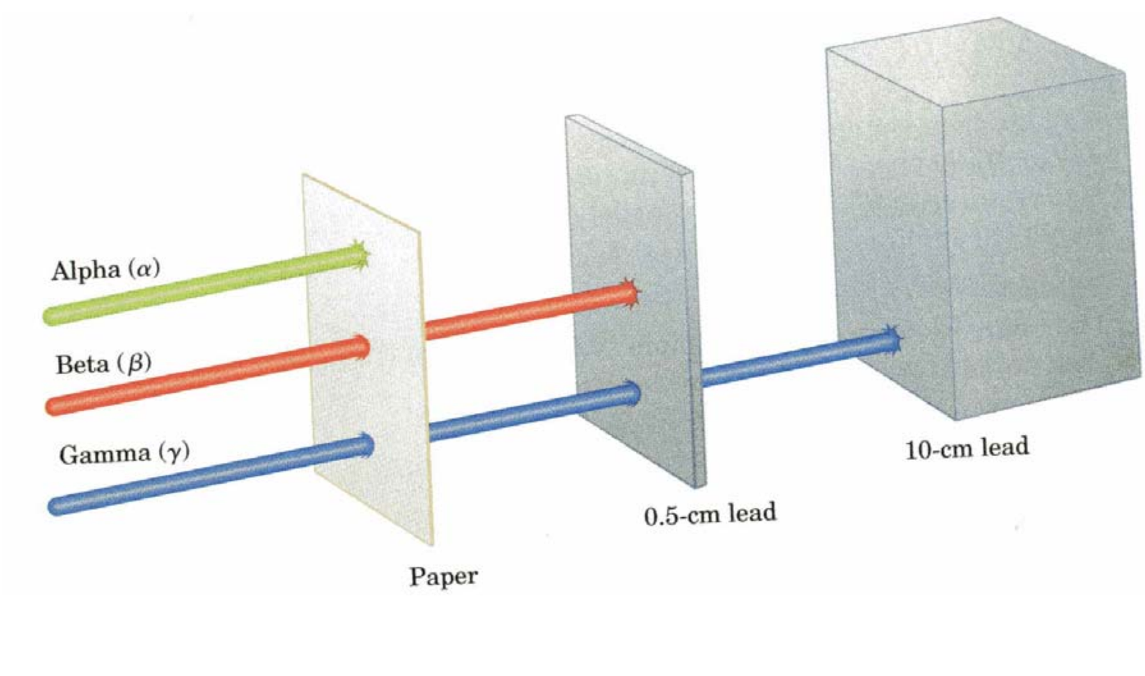
α, β, β^+, γ and x-rays interact with matter causing ion formation.

The biological effects of radiation depend on

1) energy of the radiation

Type of Radiation	Energy of Radiation	Penetrating distance into water
α	3 – 9 MeV	0.02 – 0.04 mm
β, β^+	0 -3 MeV	0 – 4 mm
x-rays	100 eV – 10 keV	0.01 – 1 cm
γ-rays	10 keV – 10 MeV	1 – 20 cm

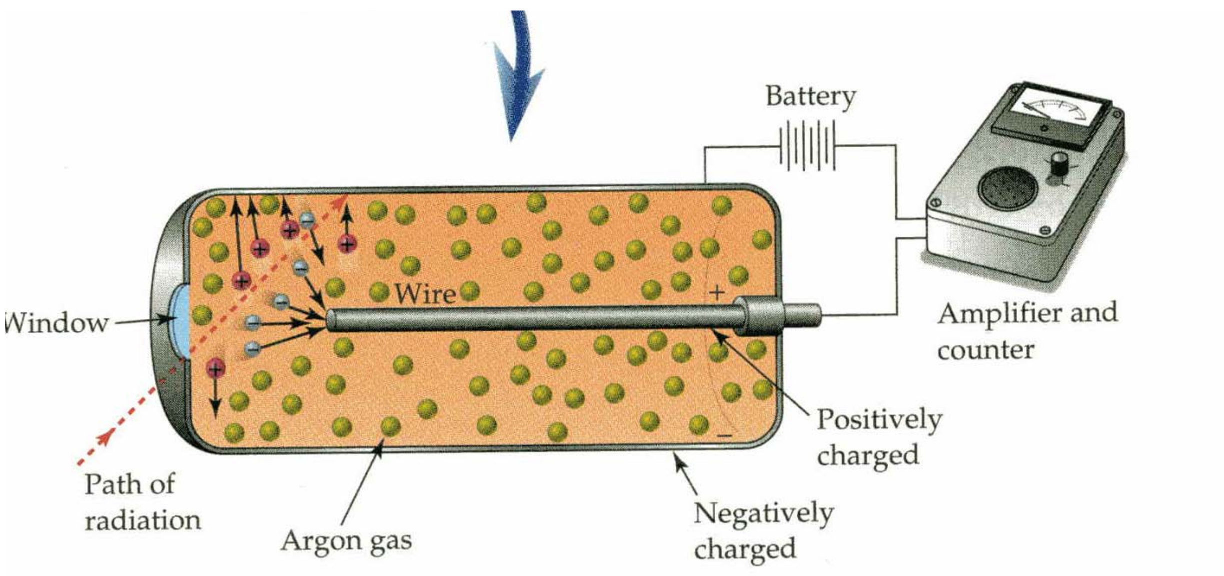
2) penetrating power of the radiation



Measurement of Radiation

Geiger-Muller Counter

Electricity is conducted through gas that contains charged particles.



Film Badges – dosimeters

Units of Radiation Intensity

1) Number of radioactive emissions

2) Absorbed Dose

3) Effective Dose

Absorbed Dose vs Effective Dose

1 Rad of α causes 20x the damage of 1 Rad of γ-rays

1 rem of α causes the same damage as 1 rem of γ-rays

Radiation Units and their Abbreviations

Aspect being Described	Unit	Symbol
Amount of Radioactive Decay	Bequerel	Bq
	Curie	Ci
Absorbed Dose	Gray	Gy
	Radiation absorbed dose	Rad
Effective Dose	Sievert	Sv
	Roentgen equiv man	rem

Health Effects of Ionizing Radiation depend on the following:

1) intensity of the energy of the radiation

2) length of exposure to the radiation

3) whether the radioactive source is inside or outside the body

2 types of effects

1) Acute

Effective Dose (Sv)	Symptoms
0.05–0.2	None
0.2–0.5	Temporary decrease in white blood cell count.
0.5–1.0	*Headache and increased risk of infection.* Possible temporary male sterility.
1.0–2.0	LD_{10}; nausea, hair loss, fatigue. Loss of white blood cells; temporary male sterility.
2–3	LD_{35}; loss of hair all over the body, fatigue and general illness. High risk of infection.
3–4	LD_{50}; uncontrollable bleeding in the mouth. Permanent sterility in women.
4–6	LD_{60}; death resulting from internal bleeding and infection. Permanent female sterility.
6–10	LD_{100}; death after 14 days.

2) Chronic

To minimize exposure

1) Shielding

2) Distance –Intensity is inversely proportional to the square of the distance.

Nuclear Chemistry Part 6: Fusion versus Fission (optional)

Fusion

$$^{2}_{1}H \quad + \quad ^{3}_{1}H \quad \rightarrow \quad ^{4}_{2}He \quad + \quad ^{1}_{0}n \quad + \quad 5.3 \times 10^{8} \text{ kcal/mol of He}$$

Compare with the energy released from chemical bonds:

$$CH_4(g) \quad + \quad 2\ O_2(g) \quad \rightarrow \quad CO_2(g) \quad + \quad H_2O(l) + 213 \text{ kcal}$$

Trans-uranium elements are produced by fusion reactions.

$$^{252}_{98}Cf \quad + \quad ^{10}_{5}B \quad \rightarrow \quad ^{257}_{103}Lr \quad + \quad 5\ ^{1}_{0}n$$

Fission – the source of bombs and energy

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n + \gamma + \text{energy}$$

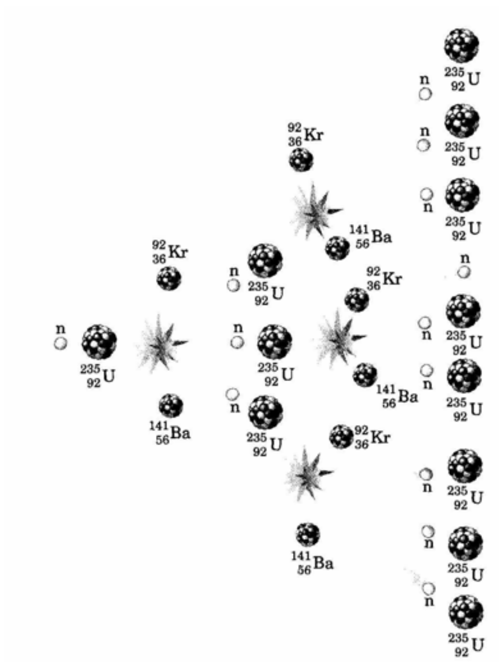
For every $^{235}_{92}U$ nucleus, more than 1 neutron is generated.

Chain Reaction: only 1 of the neutrons produced reacts with another nucleus

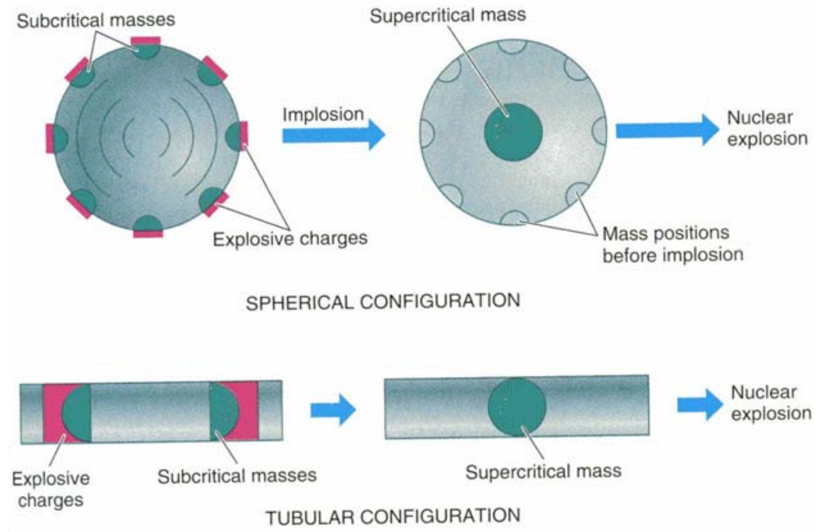
Expanding or Branching Reaction: more than 1 of the neutrons produces additional fission reactions

Critical: a constant-rate chain reaction

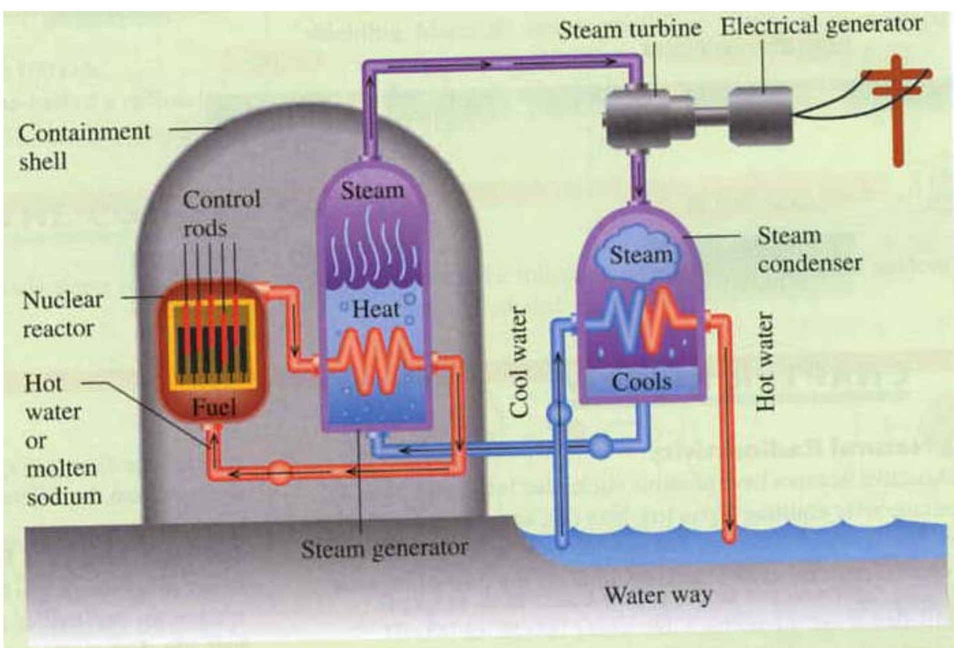
Supercritical: a branching chain reaction that will lead to an explosion



Nuclear bombs



Nuclear Power



Remember: ALL forms of energy have negative consequences.