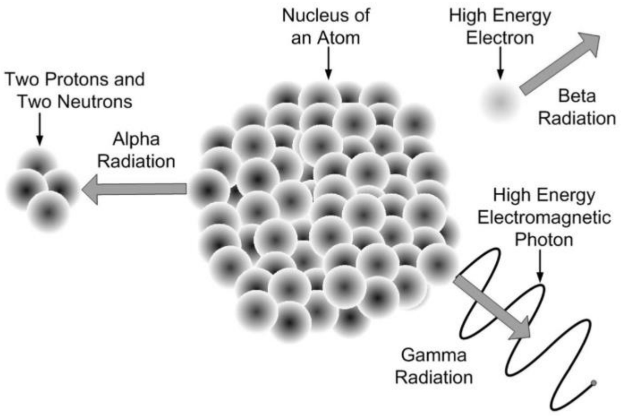
WASHINGTON LATIN PUBLIC CHARTER SCHOOL

HONORS CHEMISTRY 2019-20

UNIT 6

RADIOACTIVITY AND NUCLEAR CHEMISTRY



Contents

1) Review of Atomic Symbols
2) Types of Radiation
3) Properties of Radiation
4) Rate of radioactive decay and half-life
5) Uses of radiation
6) Binding Energy and Mass Defect
7) Nuclear Energy: Fission and Fusion

Key words: atomic number, mass number, isotopes, radioactive, radioactivity, radioactive decay, alpha particle, beta particle, gamma ray, nuclear reaction, nuclear equation, ionizing power, penetrating power, half-life, tracer, carbon dating, binding energy, mass defect, nuclear fission, nuclear fusion, atom bomb, hydrogen bomb

Lesson 1 – What is radioactivity?

1) Review of atomic symbols

- The nucleus of an atom contains protons and neutrons

- The number of protons in the nucleus of an atom is called the **atomic number**

- Every atom with the same atomic number has the same name and chemical symbol
  - eg every atom with 6 protons is a carbon atom (symbol C)
  - eg every atom with 8 protons is an oxygen atom (symbol O)

- The atomic number of an atom can be included in the chemical symbol of an atom by writing it as a subscript before the atomic symbol, eg $_{6}C$ or $_{8}O$; but given that the symbol itself tells you the number of protons in an atom, the subscript is redundant and is usually omitted

- It is not possible to predict the number of neutrons in an atom from the atomic number alone; this is because atoms with the same number of protons (ie the same atomic number) can have different numbers of neutrons; the sum of the number of protons and neutrons in the nucleus of an atom is called its **mass number**; the mass number is written as a superscript before the atomic symbol
  - eg an atom with 4 protons and 5 neutrons will have a mass number of 9 (symbol ^{9}Be or $^{9}_{4}Be$)
  - eg an atom with 8 protons and 8 neutrons will have a mass number of 16 (symbol ^{16}O or $^{16}_{8}O$)

- the mass number of the atom can be included in the name by writing it after the name, separated by a hyphen:
  - eg the name of ^{9}Be or $^{9}_{4}Be$ is **beryllium-9**
  - **eg** the name of ^{16}O or $^{16}_{8}O$ is **oxygen-16**
  - **eg** the name of ^{12}C or $^{12}_{6}C$ is **oxygen-16**
  - **eg** the name of ^{13}C or $^{13}_{6}C$ is **carbon-13**

- Atoms such as carbon-12 and carbon-13 which have the same number of protons (ie the same atomic number) but different numbers of neutrons (ie different mass numbers) are called **isotopes**

- The average mass of the different isotopes of an atom is called the **relative atomic mass** and is given in the Periodic Table

- Isotopes of the same element all have the same chemical properties; chemical reactions are therefore not specific to particular isotopes and so most chemical equations do not include any mass numbers; atomic numbers are also usually omitted Eg $CuSO_4 + Zn \rightarrow ZnSO_4 + Cu$

2) Types of Radiation

(a) Principles of nuclear stability

- The nucleus of an atom contains protons and neutrons

- Protons have a positive charge and so repel each other; the purpose of the neutrons is to hold the protons together; the force of attraction between protons and neutrons must therefore be stronger than the repulsion between the protons, or the nucleus would not be stable

- The stability of a nucleus depends on the balance between the number of protons and neutrons in the nucleus; nuclei with too many protons (more than 82) or too many neutrons are unstable; these nuclei will emit particles from their nucleus in order to become more stable; the spontaneous emission of particles from the nucleus of an atom is known as **radioactivity or radioactive decay**; atoms which emit particles from their nucleus are said to be **radioactive**

- Most elements have isotopes; in many cases one or more of these isotopes is radioactive, whilst others are not radioactive; for this reason, it is usual to refer to individual isotopes when describing radioactivity (eg cobalt-60 is radioactive but cobalt-59 is not)

- Generally, radioactive atoms will emit one of two different types of particle; these are known as **alpha particles** and **beta particles**

(b) Alpha and beta particles

- **alpha-particles (α-particles)** consist of two protons and two neutrons
    - α-particles therefore have a mass number of 4 and a charge of +2
    - they are identical to the nucleus of a typical He atom
    - they are therefore given the symbol ${}^{4}_{2}\text{He}$ or ${}^{4}_{2}\alpha$; the superscript 4 denotes the mass number of the particle and the subscript 2 indicates the charge on the particle
    - α-particles are emitted when a nucleus has too many protons to be stable; after an α-particle has been emitted, the new nucleus has two protons and two neutrons fewer than it did before; it is therefore an atom of a different element
    - this change can be written in the form of a **nuclear equation:**

      eg: ${}^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} + {}^{4}_{2}\alpha$ (^{232}Th emits an α-particle and becomes ^{228}Ra)

      eg ${}^{224}_{88}\text{Ra} \rightarrow {}^{220}_{86}\text{Rn} + {}^{4}_{2}\alpha$ (^{224}Ra emits an α-particle and becomes ^{220}Rn)

- **beta-particles (β-particles)** consist of a high-energy electron
  - β-particles have a mass number of 0 and a charge of -1
  - they are therefore given the symbol $^{0}_{-1}e$ or $^{0}_{-1}\beta$
  - an electron is emitted when a neutron changes into a proton and an electron; the proton remains in the nucleus but the electron is emitted: $^{1}_{0}n \rightarrow ^{1}_{1}p + ^{0}_{-1}e$
  - β-particles are emitted when a nucleus has too many neutrons to be stable; after a β-particle has been emitted, the new nucleus has one proton more and one neutron fewer than it did before; it is therefore an atom of a different element; this change can also be written in the form of a nuclear equation:

    eg: $^{60}_{27}Co \rightarrow ^{60}_{28}Ni + ^{0}_{-1}\beta$ ^{60}Co emits a β-particle and becomes ^{60}Ni

    eg $^{214}_{82}Pb \rightarrow ^{214}_{83}Bi + ^{0}_{-1}\beta$ ^{214}Pb emits a β-particle and becomes ^{214}Bi

(c) Nuclear equations vs chemical equations

- The emission of an α-particle or a β-particle from a nucleus is an example of a **nuclear reaction**; a nuclear reaction results in the change in the composition of a nucleus and therefore results in the formation of new atoms with different atomic numbers; **chemical reactions**, by contrast, do not change the composition of a nucleus – they only involve the rearrangement of the electrons in orbitals and therefore do not result in the formation of new atoms

- For this reason, nuclear equations always include atomic numbers and mass numbers of every particle, as these change during the reaction; chemical reactions do not usually include atomic numbers and mass numbers as these do not change during chemical reactions

- Nuclear equations are not concerned with the electrons in orbitals; for this reason the overall charges on atoms are usually omitted from nuclear equations (ie $^{4}_{2}\alpha$ is actually $^{4}_{2}\alpha^{2+}$ but the charge is usually omitted from the nuclear equation); chemical equations must include charges

- In nuclear equations, the sum of the mass numbers of the reactants must equal the sum of the mass numbers of the products, and the sum of the atomic numbers of the reactants must equal the sum of the atomic numbers of the products:

  Eg $^{232}_{90}Th \rightarrow ^{228}_{88}Ra + ^{4}_{2}\alpha$ (sum of mass numbers = 232; sum of atomic numbers = 90)

(d) Gamma rays

- The emission of an α or β-particle often results in a much more stable nucleus with a much lower potential energy (ie radioactive decay is exothermic); this potential energy is converted into a high-energy photon of electromagnetic radiation known as a **gamma ray** (γ-ray); γ-rays are only emitted at the same time as α or β-particles; they have no charge and no mass and they do not themselves change the composition of the nucleus

- α-particles, β-particles and γ-rays are collectively known as "nuclear radiation"; many radioactive isotopes occur naturally; radiation emitted from naturally occurring isotopes is known as "natural radiation"

Lesson 2 – What are the main features of radiation?

3) Properties of Radiation

- α-particles collide easily with other particles, pulling electrons away from them until the α-particle has gained two electrons and become a stable helium atom; as a result α-particles are very strongly ionising – any particles they hit are likely to lose electrons and become ionised; because of this, α-particles are very quickly destroyed; they generally travel no further than 4 cm in air and are easily stopped by a thin piece of paper

- β-particles are much smaller and so collide less easily with other particles; but when they do, they transfer energy to the particles they collide with and these particles may lose electrons as a result; so β-particles are also ionising, although much less so than α-particles; eventually the β-particle will slow down and be absorbed into the electron shells of another atom; β-particles have more penetrating power than α-particles; they can travel a long distance through air and can pass through paper but can be stopped by a thin sheet of metal

- γ-rays have no charge and no mass; they therefore do not cause ionisation in other particles and often pass through them completely without being absorbed; as a result γ-rays have a very low ionising power but a very high penetrating power; they cannot be completely stopped and a few centimetres of lead or several metres of concrete is needed to significantly reduce their intensity

Type of radiation	Α	Β	Γ
penetrating power	Low – stopped by 4 cm of air or a piece of paper	Medium – stopped by a thin sheet of metal	High – intensity reduced by a few centimetres of lead or a few metres of concrete
Ionising power	High	Medium	Low

- All three types of radiation are high in energy and if living cells are exposed to significant quantities of radiation they can be seriously damaged; sometimes the cells are killed (they are effectively burned); sometimes the cells will mutate and become cancerous; either way, high levels of exposure to radiation can be fatal

- Exposure to low levels of radiation is not harmful and we are constantly being exposed to low levels of radiation from the air, the soil and the sun, as well as some human activity; this is not dangerous – the danger comes from exposure to unusually high levels of radiation, over a long or short period

- The relative dangers of alpha, beta and gamma radiation are directly linked to their ionizing power, their penetrating power and how the exposure takes place:
    - alpha and beta particles are highly ionising but cannot penetrate skin; external alpha and beta radiation is therefore not considered dangerous unless it is present in large quantities and very close, in which case it will kill skin cells (burn the skin)
    - if radioactive atoms are ingested, injected or inhaled, however, they can be very dangerous as they release ionising radiation inside the body; this can kill healthy cells or turn them into cancerous cells
    - gamma radiation is less ionising but can pass through the body; small quantities of gamma radiation are not considered dangerous; gamma radiation can come from space and is emitted by rocks, soil and as a result of human activity (this is known as background radiation); large quantities of gamma radiation can be dangerous, even if the source is a long way away

Lesson 3 – What are the main properties and uses of radioactive isotopes?

4) Rate of Radioactive Decay and Half-Life

- The rate of chemical reactions depends on various factors including temperature, pressure or concentration, surface area the presence of a catalyst

- The rate at which a nucleus emits α-particles and β-particles does not depend on temperature, surface area or any catalyst; it depends only on the identity of the atom itself and how many radioactive atoms are present in the sample; **the rate of radioactive decay of a particular isotope is directly proportional to the number of atoms of that isotope in the sample and does not depend on any other factors**

- Given this fact, it is possible to prove that the time taken for half of a sample radioactive isotope to decay is fixed for every radioactive isotope; it does not even depend on the number of atoms of that isotope present; the time taken for half of the atoms to decay is called the **half-life** of that isotope; the half-life of radioactive isotopes can vary from fractions of a second to millions of years

    Eg ^{90}Kr has a half-life of 33 s
    Eg ^{108}Ag has a half-life of 2.4 min
    Eg ^{131}I has a half-life of 8 days
    Eg ^{238}U has a half-life of 160,000 years

- The amount of a sample remaining can be deduced from the following table:

Number of half-lives completed	% of sample decayed	% of sample remaining
0	0	100
1	50	50
2	75	25
3	87.5	12.5
4	93.75	6.25

- This relationship can be presented more mathematically as follows:

<table>
<tr><td>Equation 1: $N = N_i(0.5)^n$ or $\frac{N}{N_i} = (0.5)^n$
N = number of atoms remaining
N_i = initial number of atoms present
n = number of half-lives</td><td>Equation 2: $t = n \times t_{1/2}$
t = time elapsed
n = number of half-lives
$t_{1/2}$ = half-life</td></tr>
<tr><td colspan="2">If the number of half-lives is not a whole number, you will need a third, logarithmic equation:
Combining the above two equations gives (by eliminating n)
Equation 3: $\frac{N}{N_i} = (0.5)^{\frac{t}{t_{1/2}}}$ which can be rearranged to $\log(\frac{N_i}{N}) = \frac{t\log 2}{t_{1/2}}$</td></tr>
</table>

Example: cobalt-60 has a half-life of 5.3 years; starting with 1000 atoms of cobalt-60, how many atoms will remain after 10.6 years?

Answer: either 10.6 years = 10.6/5.3 = 2 half-lives so 25% remain; 25% of 1000 = 250

or: $\log(\frac{N_i}{N}) = \frac{t\log 2}{t_{\frac{1}{2}}}$ so $\log(\frac{1000}{N}) = \frac{10.6 \log 2}{5.3} = 0.602$

so $(\frac{1000}{N}) = 10^{0.602} = 4$, so 1000 = 4N, so N = 1000/4 = 250

Example: A sample contains 400 atoms of carbon-14; 17,190 years later, only 50 atoms of carbon-14 remain; what is the half-life of carbon-14?

Answer: either: 50/400 = 1/8 of 12.5%; this is three half-lives
so one half-life = 17190/3 = 5730 years

or: $\log(\frac{N_i}{N}) = \frac{t\log 2}{t_{1/2}}$ so $t_{1/2} = \frac{t\log 2}{\log(\frac{N_i}{N})} = \frac{17190 \log 2}{\log\left(\frac{500}{40}\right)} = \frac{17190 \log 2}{\log 8}$ = 5730 years

Example: Radon-220 has a half-life of 55.3 seconds. What percentage of a sample of radon-220 will have decayed after 20 s?
(Note - this question does not involve a whole number of half-lives, so you have to use the logarithmic equation)

Answer: $\log(\frac{N_i}{N}) = \frac{t\log 2}{t_{\frac{1}{2}}} = \frac{20 \log 2}{55.3} = 0.109$

So $\frac{N_i}{N} = 10^{0.109} = 1.28$ so $\frac{N}{N_i} = 1/1.28 = 0.78$ (78%)

- The more stable a nucleus, the longer its half-life; the less stable a nucleus, the shorter its half-life; nuclei which are completely stable (ie non-radioactive) do not have a half-life (they have an infinite lifetime)

- Radioactive isotopes with a long half-life are considered more of an environmental hazard than those with a short half-life, as they remain active in the environment for a much longer time

5) Uses of Radiation

- Although the radiation emitted by radioactive atoms can be dangerous, it also has a number of useful applications; the specific application of a radioactive isotope depends on the ionizing and penetrating power of the radiation it emits, and its half-life

(i) carbon-dating

- Most carbon atoms are either carbon-12 or carbon-13, neither isotope is radioactive; a small proportion of carbon atoms, however, are carbon-14, which is radioactive with a half-life of 5730 years; carbon atoms in living organisms are constantly being replaced due to the carbon cycle and so the proportion of carbon existing as carbon-14 in living organisms is fairly constant; but when cells die, the carbon atoms in those cells are no longer replaced and so the amount of carbon-14 in those cells gradually decreases over time as the carbon-14 decays; it is therefore possible to estimate how many years ago a sample of tissue died, and this can be used to estimate the age of fossils, skeletons and some fabrics; the technique is known as **carbon-dating**

(ii) tracers

- Because gamma radiation can travel through walls and earth, it is possible to track the location of gamma-emitting radioactive material by detecting the gamma rays; this is known as **tracing**

- Tracers are used in industry to locate blockages in underground or underwater pipes; a sample of radioactive material is inserted into the pipe and its progress is followed by tracking the radiation it emits; radiation will accumulate at a blockage and disperse at a leak; this can be used by engineers to find leaks and blockages without opening up the entire pipe

- Tracers are used in agriculture to monitor how and how fast plants are able to absorb certain nutrients from the soil

- Tracers are used in medicine to monitor the digestive system, respiratory system or circulatory system; radioactive material can be inhaled, ingested or injected and its progress through the body can be monitored

- Cancer cells also absorb certain atoms (for example thyroid cancer absorbs iodine) so radioactive iodine will concentrate in the cancerous area, allowing the cancer to be located

- Tracers should generally have a short half-life, so the affected area does not have high radiation levels for a long time

(iii) treating cancer

- Exposure to large quantities of radiation is known to kill cells or cause them to mutate and become cancerous; radiation can also be used to kill cancerous cells; cancerous cells are more easily killed by radiation than healthy cells and so a targeted dose of radiation can kill cancerous cells without harming healthy cells

- Gamma radiation can be applied externally; the gamma rays can be pointed directly at the cancerous cells from a range of different angles to stop the same healthy cells from receiving too much radiation

- If the cancerous region absorbs certain atoms, then alpha or beta-emitting radioactive isotopes of those atoms can be ingested or injected; they will accumulate in the cancerous area and emit radiation, hopefully killing the cancerous cells (eg iodine-131 is used to locate and treat thyroid cancer); these isotopes should have a short-half life so radioactive material does not remain in the body for long

(iv) industry and machinery

- Many machines and industrial processes make use of radiation, including smoke detectors; the radioactive material used in such machinery should have a long half-life so it does not need to be constantly replaced

Lesson 4 – What is the source of nuclear energy?

6) Binding Energy and Mass Defect

- Protons and neutrons (nucleons) in the nucleus are held together by a force called a "strong nuclear force"; when protons and neutrons combine to form a nucleus, the nucleus is more stable than its separate individual nucleons; hence energy is released when new nuclei form and energy is needed to separate a nucleus into its individual nucleons; this energy is called the **binding energy**

- When protons and neutrons combine to form a nucleus, it is found that the total mass of the new nucleus is slightly less than the mass of the separate nucleons:
  - Eg the mass of a single proton (p) is 1.0073 amu and the mass of a single neutron is 1.0087 amu
  - so the mass of a ${}^{4}_{2}\mathrm{He}$ nucleus should be 2(1.0073) + 2(1.0087) = 4.0320 amu
  - but the mass of ${}^{4}_{2}\mathrm{He}$ nucleus is, in fact, 4.0026 amu, 0.0294 amu less than the combined mass of the separate protons and neutrons
  - this reduction in mass when protons and neutrons combine is called the **mass defect;** it is the reason why different atoms have different masses per nucleon and why relative isotopic masses are not integers

- Einstein was able to prove that the reduction in mass was directly proportional to the reduction in potential energy and followed the relationship:

  $\mathbf{\Delta E = \Delta mc^2}$ (more commonly known as $E = mc^2$)
  - ΔE is the change in potential energy (ie the binding energy)
  - Δm is the change in mass (ie the mass defect)
  - c is the speed of light (3×10^8 m/s)

- So the decrease in potential energy when 2 protons and 2 neutrons combine to form one atom of $^{4}_{2}\mathrm{He}$ is (given that 1 amu = 1.66 x 10^{-27} kg):
  $\Delta E = \Delta mc^2 = (0.0294 \times 1.66 \times 10^{-27}) \times (3 \times 10^8)^2 = 4.39 \times 10^{-12}$ J
  This means that the decrease in potential energy when one mole of He atoms (L = 6.02 x 10^{23} mol^{-1}) is formed is (given that L = 6.02 x 10^{23} mol^{-1}):
  4.39×10^{-12} J x 6.02 x 20^{23} = 2.63 x 10^{12} J/mol or 2.63 x 10^{9} kJ/mol (2,630,000,000 kJ/mol)
  This is approximately 10 billion times more energy than is released by burning 4 g of carbon

7) Nuclear energy: fission and fusion

- The emission of an α-particle or a β-particle from a nucleus (known as radioactive decay) is just one example of a **nuclear reaction**; there are two other important types of nuclear reaction:

(i) nuclear fission

- Nuclear fission is the break-up of a large nucleus to form two or more smaller nuclei; it does not occur spontaneously and only happens when a nucleus is bombarded with a neutron:
  Eg $^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{236}_{92}\mathrm{U}$ (very unstable)
  $^{236}_{92}\mathrm{U} \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3^{1}_{0}\mathrm{n}$
  Overall: $^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3^{1}_{0}\mathrm{n}$
  - the two smaller nuclei are usually more stable than the original large nucleus, so a lot of heat energy and gamma rays are released during nuclear fission
  - most nuclear fission reactions release neutrons (more than the one neutron needed to initiate the reaction); the neutrons produced can collide with more ^{235}U atoms and cause further fission, starting a **nuclear chain reaction**

- Most nuclear fission reactions are man-made and the products are often radioactive isotopes; radiation emitted from isotopes produced by man-made nuclear reactions is called "artificial radiation"

- Nuclear fission is carried out in **nuclear reactors** to produce **nuclear energy**:
  - most nuclear reactors use ^{235}U; this is present in small quantities in naturally occurring uranium; uranium needs to be "enriched", which means increasing the amount of ^{235}U, before it is used in nuclear reactors
  - the ^{235}U atoms are bombarded with neutrons and break up (ie they undergo nuclear fission); the process produces a large amount of heat as well as extra neutrons
  - the heat is used to boil water, which is used to drive a turbine which powers a generator and produces electricity
  - the reaction must be carefully controlled to prevent a chain reaction taking place which will cause the reactor to overheat and explode
  - boron rods are inserted into the reactor to absorb neutrons and control the speed of the reaction

- An **atom bomb** is a device which releases a large amount of energy very quickly as a result of a nuclear fission reaction, causing an explosion; usually plutonium-239 or uranium-235 is used and the reaction is started by firing neutrons at the sample; because nuclear fission produces radioactive isotopes as products, atom bombs can leave behind radioactive material long after they have exploded

(ii) nuclear fusion

- Nuclear fusion is the joining together of two smaller nuclei to form a single, larger nucleus:
  Eg $^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \rightarrow ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n}$

- The larger nucleus is usually more stable than the two smaller nuclei, and so a lot of heat energy and gamma rays are released during nuclear fusion

- Nuclear fusion takes place naturally in the sun – especially the fusion of hydrogen into helium; nuclear fusion reactions are the source of the sun's energy; it is not currently possible to produce energy commercially using nuclear fusion reactions because very high temperatures are needed

- Nuclear fusion does not generally produce radioactive products; as a result it is considered much safer than nuclear fission

- A **hydrogen bomb** is a device which releases a large amount of energy very quickly as a result of the nuclear fusion of hydrogen atoms; due to the large amount of energy required to start nuclear fusion, a nuclear fission reaction is used to create the heat necessary for the nuclear fusion reaction to start; no hydrogen bomb has ever been deployed in war

END OF UNIT 6

END OF CHEMISTRY

GOODBYE AND GOOD LUCK!