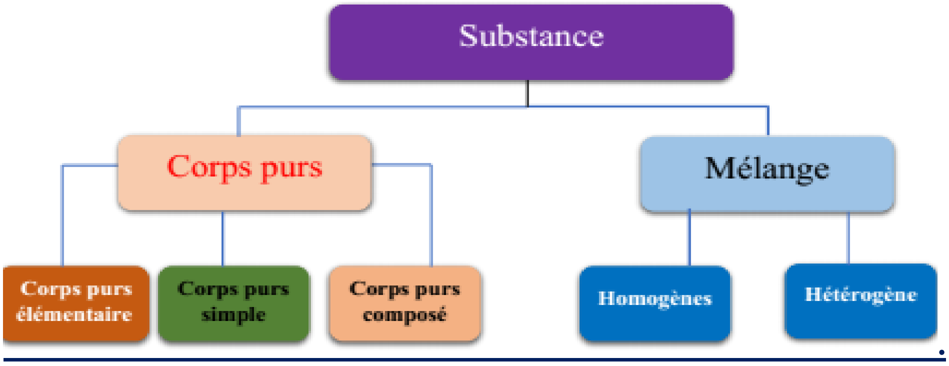
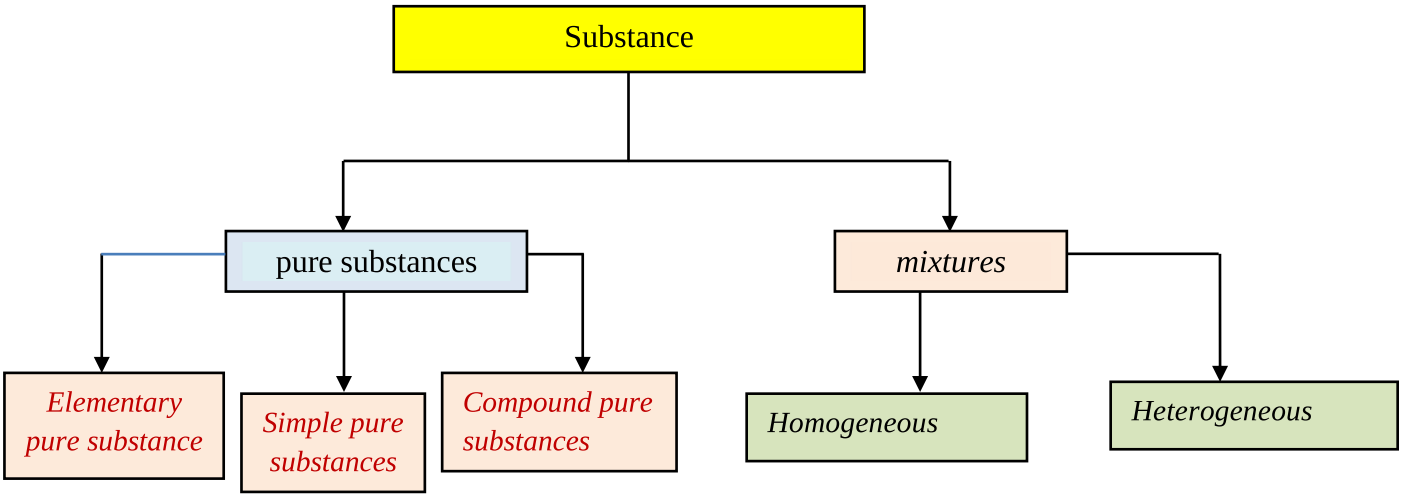
Chemistry 1 Course - Structure of matter

2nd lesson:

1- Qualitative aspects of matter :

Matter is a mixture of particles, atoms and/or molecules.





We can classify substances into two main categories: ***pure substances*** and ***mixtures***.

1.1 Pure substances:

Among pure substances, we can further distinguish three categories:

1. ***An elementary pure substance***: it is a pure substance whose atoms, all identical, are not bonded in a molecule. It consists of a number of identical atoms. For example, Ne is an elementary pure substance. Elementary pure substances are those present in the periodic table of elements and can be further classified as metals and non-metals.

Examples include Fe, Cu, Ar...

2. ***Simple pure substances***: These are molecules composed of several identical atoms.

Examples include O_2, H_2, O_3.

3. ***Compound pure substances***: It is a pure substance in which each molecule is made up of different atoms. Examples include HCl, H_2SO_4, NaCl, H_2S... The smallest part of a pure substance (matter composed of the same type of elements or the same sets of elements) that has the same characteristics as that pure substance is an atom or a group of "associated" atoms called a molecule.

1.2 Mixtures:

A mixture is made up of the juxtaposition of two or more different substances. Most substances found in nature are mixtures.

Examples:

- ✓ tap water
- ✓ glass
- ✓ gold less than 24 carats,
- ✓ The air we breathe,
- ✓ the wood that makes up the table,
- ✓ And you (!)...

There are 2 types of mixtures:

a) ***Homogeneous mixtures*** **:** it is a mixture that appears in the form of a single phase. (The constituents cannot be distinguished by the naked eye).
Example: water + sugar
b) ***Heterogeneous mixtures*** : it is a mixture made up of 2 or more phases.
Example: Water + oil

1.2 The solutions: solute, solvent, aqueous solution, dilution, and saturation:

- In chemistry, a solution is a homogeneous mixture (consisting of a single phase) resulting from the dissolution of one or more solutes (dissolved chemical species) in a solvent. The solute molecules (or ions) are then solvated and dispersed in the solvent.
- What is a solution?
  The dissolution of a chemical species (called solute) in a large volume of liquid (called solvent) produces a mixture called a solution.
- Note:
  - ✓ The solute can be solid, liquid, or gaseous, but it will always be present in small quantity compared to the solvent.
  - ✓ A solution can contain molecules, ions, or both.
  - ✓ When the solvent is water, it is called an aqueous solution.
- What is a saturated solution?
  - ✓ Experiment: Dissolving salt in water, stirring to make the solution homogeneous.
  - ✓ Observations: This is only possible if the amount of salt is small.
  - ✓ Beyond a certain quantity, the salt can no longer dissolve.
  - ✓ Conclusion: At this point, we say that the solution is saturated.

1.4 Dilution of a solution Definition:

- Diluting a solution means increasing the volume of the solvent in the solution without changing the amount of solute.
- The solution to be diluted is called the mother solution. Its volume is denoted as Vm, and its concentration is denoted as Cm.
- The solution(s) obtained from the mother solution are called daughter solutions. Their volume is denoted as Vf, and their concentration is denoted as cf. (cm > cf)
- When the solvent is water, the solution is called an aqueous solution.
- Diluting an aqueous solution involves decreasing the concentration by adding solvent (water).
- During dilution, the amount of solute is conserved, so we can write:
- ni = nf => Ci .Vi = Cf .Vf (dilution law)
-

✓ **Application exercise:**

Calculate the volume of a 6M aqueous solution of H_2SO_4 that needs to be taken to obtain 500 mL of H_2SO_4 with a concentration of 0.3 M.

✓ *Calculation of the volume to be taken:*

$$\mathbf{C_m \cdot V_m = C_f \cdot V_f \Rightarrow V_m = \frac{C_f \cdot V_f}{C_m} = \frac{0{,}3 \times 500}{6}} = 25\text{ mL} \Rightarrow \mathbf{V_m = 25\text{ mL}}$$

❖ The volumetric flask allows for measuring a volume with good precision. Thus, it is used for:

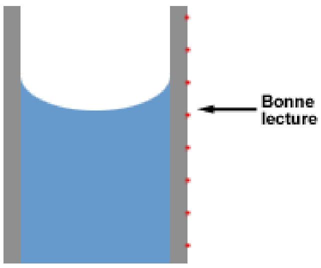
- the preparation of a solution of a given concentration
- the dilution of a solution.

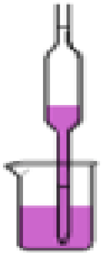
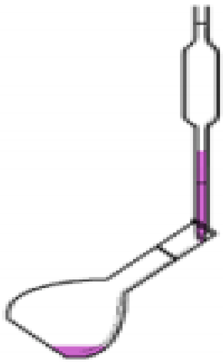
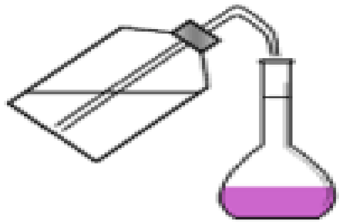
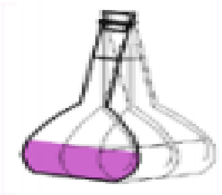
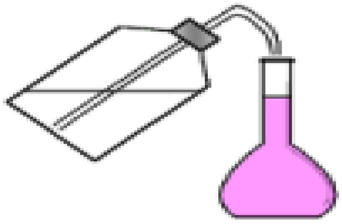
The reading is done at the level of the calibration mark.

✓ Good reading with meniscus

• Reading is done at the bottom of the meniscus.

• The eye should be at the same height as the bottom of the meniscus.



 Prélever, à l'aide d'une pipette jaugée, la quantité de matière de solution mère nécessaire.	 Transvaser ce prélèvement dans une fiole jaugée de volume approprié. Voir : pipette jaugée	 Ajouter de l'eau distilléejusqu'au 3/4 de la fiole jaugée.
 Boucher et agiter pour favoriser la dilution.	 Compléter la fiole avec de l'eau distillée jusqu'au trait de jauge.	 Boucher et homogénéiser la solution.

<u>Examples of solutions.</u>

Soluté	Solvant	Solution	Exemples [soluté(s) avant le solvant]
Gaz	Gaz	Gaz	Air (O_2, Ar, CO_2... dans N_2) Gaz naturel (C_2H_6, C_3H_8... dans CH_4)
Gaz	Liquide	Liquide	Boisson gazeuse (soda) (CO_2 dans H_2O) Substitut du sang (O_2 dans la perfluorodécaline)
Liquide	Liquide	Liquide	Vodka (CH_3CH_2OH dans H_2O) Vinaigre (CH_3COOH dans H_2O)
Solide	Liquide	Liquide	Solution saline (NaCl dans H_2O) Carburant de course (naphtalène dans l'essence)
Gaz	Solide	Solide	Hydrogène (H_2) dans du palladium (Pd)
Solide	Solide	Solide	Or 14 carats (Ag dans Au) Laiton (Zn dans Cu)

2- Quantitative aspect of matter

2-1 Amount of matter: the number of moles:

n: number of moles.

N_A: Avogadro's number = 6.022 x 10^{23} atoms, molecules, or ions.

Let's calculate the amount of matter n from a number of entities N:

$$N_i = n_i \cdot N_A \quad \Rightarrow \quad n_i = \frac{N_i}{N_A} = \frac{m_i}{M}$$

2-2 Calculation of amount of matter:

- **If the matter is solid,**

For a mass of iron = 400 mg, M(Fe) = 55.8 g/mol

$$n_i = \frac{m_i}{M} \quad \Rightarrow n = \frac{400 \text{ x } 10\text{-}3}{55{,}8} \quad \Rightarrow \boldsymbol{n_{Fe} = 7.17 \,.10^{-3}\, mol}$$

- **If the matter is a pure liquid,**

$n = \frac{m}{M}$; m: mass of the liquid

Example: pure water v = 2 L

We know that : $\rho = m/v \Rightarrow m = \rho.\ v \Rightarrow n = \frac{\rho . v}{M}$

$$n = \frac{1 \, x \;\, 2.10^3}{18} \approx 111\, mol$$

2-3 Molar concentration or Molarity:

Number of moles of solute in one liter of solution.

The molar concentration (also called concentration) of a species **A** dissolved in a volume **V** of solution is denoted as **[A]**. It is equal to the ratio of the amount of substance of **A** dissolved to the volume **V** of solution.

$$\mathbf{C_A = [A] = \frac{n_{soluté}}{V_{solution}} \quad mol/L}$$

2-4 Molality:

Number of moles of solute in one kilogram of solvent.

$$\mathbf{C_{mol} = \frac{n_{soluté}}{m_{solvant}} \qquad mol/kg}$$

2-5 Weight concentration: mass concentration, Weight fraction

- The mass concentration **C** of a solute is equal to the ratio of the mass **m** (in g) of solute dissolved in the volume **V** (in L) of solution:

$\mathbf{C} = \frac{\mathbf{m}}{\mathbf{V}}$ $\boldsymbol{(en\ g/L\ ) = T_m}$: weight fraction

- The relationship between mass concentration **C** ($g.L^{-1}$) and molar concentration **[A]** ($mol.L^{-1}$) of a solute **A** with molar mass MA (in $g.mol^{-1}$) is

$$C_{massique} = T_m = \frac{m}{V} = \frac{n,\ M}{V} = C_M \,.\, M_i \quad \Rightarrow \quad C_{massique} = T_m = C_M \,.\, M_i$$

Application Exercise

The molar mass of sodium hydroxide (NaOH) is M(NaOH) = 40.0 g.mol^{-1}.

Let's calculate the weight fraction of the previous sodium hydroxide solution with a molar concentration of 0.20 mol/mol.

Solution

A volume V = 1.00 L contains a quantity of sodium hydroxide

n(NaOH) = 0.20 mol.

It has a mass m(NaOH) = n(NaOH) . M(NaOH) = 0.20 . 40.0 = 8.0 g

The weight fraction of the sodium hydroxide solution is:

$$T(\mathrm{NaOH}) = \frac{\mathrm{m}}{\mathrm{V}} = 0.8 \text{ g/L}$$

2-6 Normal concentration or normality

- The normality of a solution is the number of gram-equivalents of solute contained in one liter of solution.
- The unit of normality is ***the gram-equivalent per liter***, represented by the symbol N:
- **1 N = 1 eq-g/L**. Given the definition of equivalent mass, the normality of a solution will always be an integer multiple (1, 2, 3, ...) of its molarity, that is:
- **N = p. M** P: number of equivalents; M: molarity

This concentration unit, which has been widely used, has the disadvantage of depending on the reaction in which this solution will be used...

- The normality N_a of an acidic solution is the number of moles of H_3O^+ ions that can be released per liter of this solution.
- The normality N_b of a basic solution is the number of moles of OH^- ions that can be released per liter of this solution.
- The normality N_o of an oxidizing solution is the number of moles of electrons that can be captured per liter of this solution.
- The normality N_r of a reducing solution is the number of moles of electrons that can be released per liter of this solution.

Examples: N = p. M

Composé	HCl	H_2SO_4	H_3PO_4	NaOH
nombre d'équivalent P	P=1	P=2	P=3	P=1

3- The Isotopes

3-1 Definition:

Isotopes are elements with the same atomic number "Z" but different mass numbers (their nuclei contain a different number of neutrons, N).

${}^{A}_{Z}X$ and ${}^{A'}_{Z}X'$ are isotopes, where A = Z + N and A' = Z + N'.

In nature, the element exists in the form of a mixture of isotopes but with different percentages.

Generally, we use the abundant elements, which are the ones found in the periodic table.

Examples:

${}^{1}_{1}H$: Hydrogen (N = A - Z = 0)

${}^{2}_{1}H$: Deuterium (N = A - Z = 1)

${}^{3}_{1}H$: Tritium (N = A - Z = 2)

The 3 isotopes of carbon are ${}^{12}_{6}C$; ${}^{13}_{6}C$; ${}^{14}_{6}C$

Natural magnesium consists of 3 isotopes.

$${}^{24}_{12}Mg;\ {}^{25}_{12}Mg;\ {}^{26}_{12}Mg$$

Note: Isotopes of the same element occupy the same position in the periodic table.

Mass spectroscopy has shown that most natural elements are composed of a mixture of isotopes.

$$\begin{cases} {}^{54}Fe : 5{,}845\ \% \\ {}^{56}Fe : 91{,}754\ \% \\ {}^{57}Fe : 2{,}119\ \% \\ {}^{58}Fe : 0{,}282\ \% \end{cases}$$

3-2 The calculation of the atomic mass

The calculation of the atomic mass of a chemical element depends on the abundance of each isotope. Abundance is the percentage of the isotope's presence in the chemical element. The average molar mass is calculated using the following relationship: $\mathbf{M = \frac{\sum Xi\,.\,Mi}{100}}$

i: is the isotope ; **Mi**: atomic mass of the isotope ; **Xi**: percentage of the isotope in the mixture

Example:

Calculate the average atomic mass of natural chlorine. It is a mixture of 2 isotopes:

$^{35}_{17}Cl$; $^{37}_{17}Cl$

Atomic Number	**Isotopic Mass**	**Abundance (%)**
$^{35}_{17}Cl$	34.97	75.8
$^{37}_{17}Cl$	36.97	24.2

Solution

$$M = \sum \frac{Xi\,.\,Mi}{100} = \frac{X1\,.\,M1+X2.\,M2}{100} = \frac{75{,}8\;x\;34{,}97+24{,}2\;x\;36{,}97}{100}$$

M = 35,454 uma

- **note**

Two atoms with:

The same **Z** but different A are **isotopes.**

The same **A** but different Z are **isobars.**

The same **N** but different Z are **isotones.**

Examples:

$^{12}_{6}C$; $^{13}_{6}C$; $^{14}_{6}C$	**isotopes.**
$^{40}_{18}Ar$; $^{40}_{19}K$; $^{40}_{20}Ca$	**isobars.**
$^{52}_{6}V$; $^{52}_{24}Cr$; $^{54}_{26}Fe$	**isotones**

4- Binding energy of nuclei (Cohesion energy)

This is the energy required for the formation of any nucleus from its nucleons (protons and neutrons) according to the reaction below:

$$P + N \rightarrow \; ^{A}_{Z}X$$

"with : E < 0. The formation of a nucleus requires negative energy."

This energy results from a loss of mass (**mass defect**) "Δm"

Δm = mtheo - mreal ; **mtheo = Z mp + (A-Z) mn**

Einstein's relation relates mass and energy,

$E_l = \Delta m\, C^2$ with C: speed of light.

Example:

Consider the formation of a helium nucleus from these nucleons:

$$2\,{}_{1}^{1}p + 2\,{}_{0}^{1}n \longrightarrow {}_{2}^{4}He^{2+}$$; With m_{real} = 4.001503 amu ; 1eV = $1{,}602.10^{-19}$ J

Calculation of mass loss Δm

mtheo = Z mp + (A-Z) mn = 2 x 1.007278 + 2 x 1.008665

mtheo = 4.0031886 amu, therefore

Δm = mtheo - mreal = 4.0031886 - 4.001503 = 0.030383 amu ⇒ Δm = 0.030383 amu

1 amu = 1.66 x 10^{-27} kg

1 eV = $1{,}602.10^{-19}$ J; 1 MeV = 10^6 eV

The formation of a helium nucleus releases:

$\Delta E = E_l = \Delta m\, C^2 = \mathbf{0{,}030383 \times 1{,}66 \cdot 10^{-27}} \times (3 \cdot 10^8)^2$

$E_l = 4{,}54 \cdot 10^{12}$ joule $= 28{,}35 \cdot 10^6$ eV = **28,35 MeV**

This is the binding energy (or cohesion energy) of a helium nucleus. **El = 28.35 MeV**

This is the energy released to form the He^{2+} nucleus. It is equivalent to the energy required to break the nucleus.

A specific species of nucleus is called a nuclide.

Example 2: Calculation of binding energy per nucleon

The iron nuclide ${}_{26}^{56}Fe$ lies near the top of the binding energy curve and is one of the most stable nuclides. What is the binding energy per nucleon (in MeV) for the nuclide ${}_{26}^{56}Fe$ (atomic mass of 55.9349 amu)?

Solution

As in Example 1, we first determine the mass defect of the nuclide, which is the difference between the mass of 26 protons, 30 neutrons, and 26 electrons, and the observed mass of an ${}_{26}^{56}Fe$ atom:

Mass defect = [(26×1.0073 amu)+(30×1.0087 amu)+(26×0.00055 amu)]−55.9349 amu

Mass defect =56.4651 amu − 55.9349 amu = **0.5302 amu**

We next calculate the binding energy for one nucleus from the mass defect using the mass-energy equivalence equation:

$E = mc^2 = 0.5302 \times 1.6605\times10^{-27}\,\text{kg} \times (2.998\times10^8\,\text{m/s})^2$

$E = = 7.913\times10^{-11}$ kg·m/s^2 = 7.913×10^{-11} J

We then convert the binding energy in joules per nucleus into units of MeV per nuclide:

$E = 7.913\times10^{-11}\,\text{J} \times \frac{1\ \text{MeV}}{1.602\times10^{-13}\ J}$ **E = 493.9 MeV**

Finally, we determine the binding energy per nucleon by dividing the total nuclear binding energy by the number of nucleons in the atom:

Binding energy per nucleon = $\frac{493.9\ \text{MeV}}{56}$ = **8.820 MeV/nucleon**

Note that this is almost 25% larger than the binding energy per nucleon for $^{4}_{2}\boldsymbol{He}$.

(Note also that this is the same process as in Example 1, but with the additional step of dividing the total nuclear binding energy by the number of nucleons.)

What is the binding energy per nucleon in $^{19}_{9}\boldsymbol{F}$ (atomic mass, 18.9984 amu)?

Solution

Binding energy per nucleon ($^{19}_{9}\boldsymbol{F}$) = **7.810 MeV/nucleon**

- **Calculation of the energy equivalent for 1 a.m.u.**

1 **a.m.u** = $1{,}6605 . 10^{-24}$ g ; c = $2{,}998 . 10^{+8}$ m/s

$\Delta E = E_l = \Delta m\ C^2 = 1 \times 1{,}6605 . 10^{-27} \times (2{,}998 . 10^{8})^2$

$\Delta E = E_l = 1{,}4924 . 10^{-10}$ J

1eV = $1{,}6022.10^{-19}$ J ;   1 MeV = 10^{6} eV = $1{,}6022.10^{-13}$ J

$\Delta E = E_l = \frac{1{,}4924 . 10^{-10}}{1{,}6022 . 10^{-13}}$ = **931,5 MeV,**

$\Delta E = E_l$ (1 a.m.u) = 931,5 MeV

5- Stability and Cohesion Energy

- There exists a force between nucleons, which is attractive and has a short range. This is the strong nuclear interaction (~1000 times more intense than the electromagnetic interaction).
- The strong nuclear interaction ensures the cohesion of the nucleus. It binds protons and neutrons together. It is attractive. Its range is finite and on the scale of nuclear matter. Electrons do not experience this interaction.

5-1 Stability of nuclei: Binding energy per nucleon EL / A. Aston curve (- EL / A = f (A))

- *General case: The binding energy per nucleon of the nucleus*

The binding energy of a nucleus (Z protons, A nucleons) is $\mathbf{E_L}$.

The average binding energy per nucleon of a nucleus is **"E_L" / A.**

Nuclear stability: A nucleus is more stable when its average energy per nucleon is high.

Example: The binding energy per nucleon of the lithium nucleus

The binding energy of the 7 nucleons of the lithium nucleus is:

$$E_L\ (^{7}Li) = 6{,}287 \cdot 10^{-12}\ J = 39{,}3\ MeV$$

The average binding energy per nucleon of a lithium nucleus is:

$$\frac{E_L}{A} = 39{,}3 / 7 = 5{,}61\ \text{MeV/ nucléon}$$

- **Application:**

The binding energy of an oxygen-16 nucleus is 126 MeV, and that of a uranium-238 nucleus is 1802 MeV.

To compare their stability, we need to calculate the average binding energy per nucleon.

We find:

$$\frac{E_L}{A}\ (^{16}O) = 126 / 16 = 7{,}88 \text{ MeV par nucleon.}$$

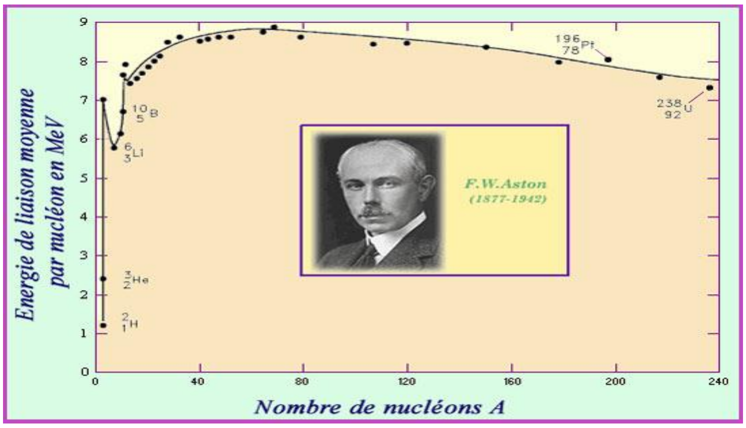
$$\frac{E_L}{A}\ (^{238}U) = 1802 / 238 = 7{,}57 \text{ MeV par nucléon.}$$

$$\frac{E_L}{A}\ (^{16}O) > \frac{E_L}{A}\ (^{238}U) \Rightarrow$$

Therefore, ***the oxygen-16*** nucleus is **more stable** than ***the uranium-238*** nucleus.

5-2 Aston's Curve

- The binding energy per nucleon represents the average energy required to remove a nucleon from a nucleus.
- It is a measure of the stability of a nucleus. This curve of binding energy as a function of the number of nucleons A is named after the English physicist F.W. Aston, who was one of the pioneers in measuring nuclear masses.



- He received a Nobel Prize in 1922. A classic in nuclear physics.
- Aston's curve shows that for natural nuclei, it takes approximately 8 MeV to remove a nucleon and that the binding energy reaches a maximum of 8.8 million electronvolts (MeV) for nickel-62, and then slowly decreases to 7.6 million electronvolts for uranium.
- It should be noted that nuclei with:
  - ✓ A < 20 are unstable (light nuclei).
  - ✓ 20 < A < 200 are stable.
  - ✓ A > 200 are unstable (heavy nuclei).
- This curve shows that nuclei with relatively low binding energies per nucleon (small or large A) can transform into more stable nuclei (medium A) by releasing energy.
- This can occur through the fusion of light nuclei, such as deuterium, tritium, etc., or through the fission of heavy nuclei, such as uranium.

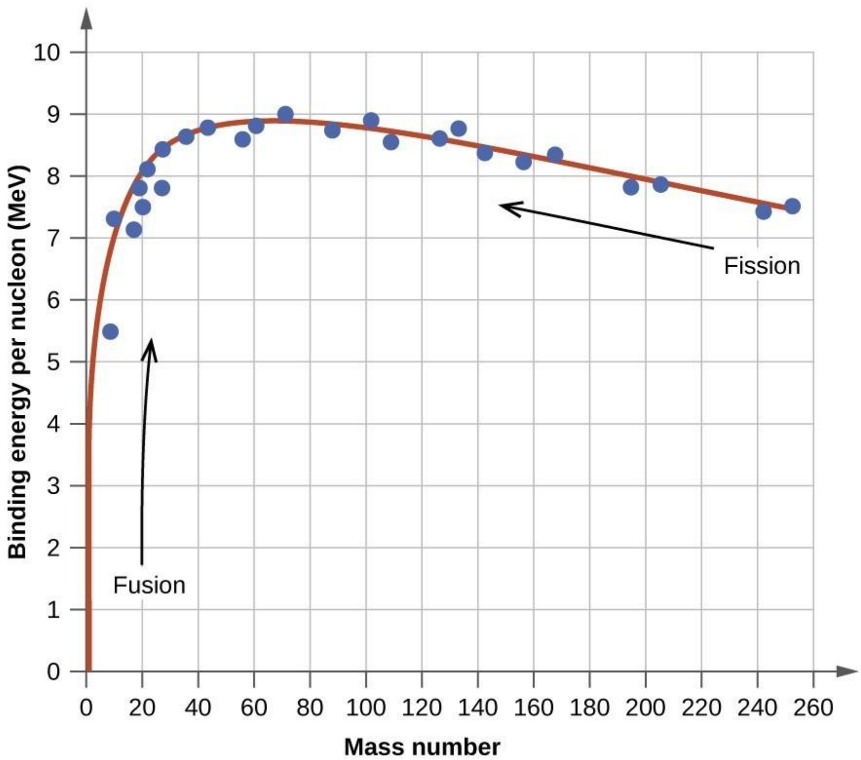
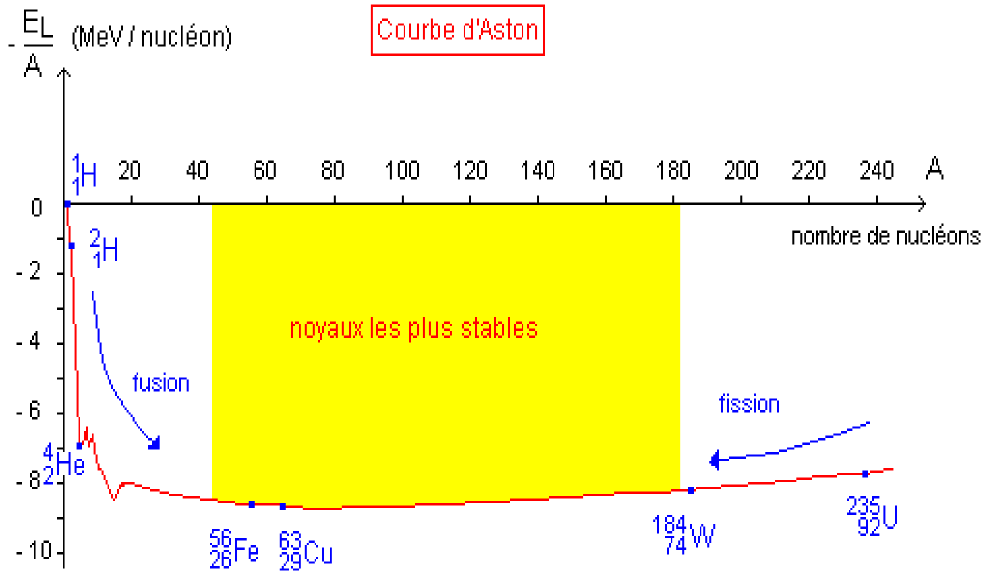
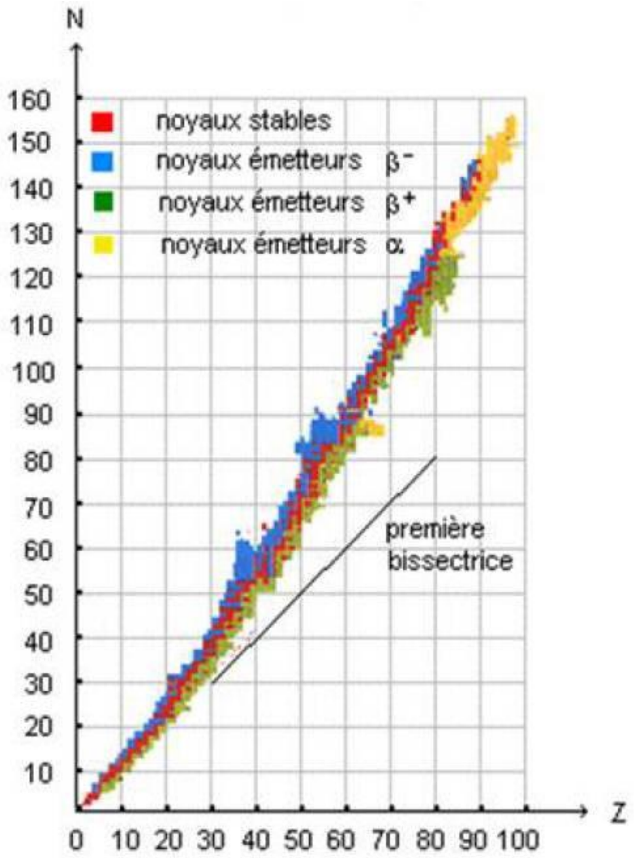


Figure . The binding energy per nucleon is largest for nuclides with mass number of approximately 56.



5-3 Stability and number of nucleons: N = f(Z) Segre diagram

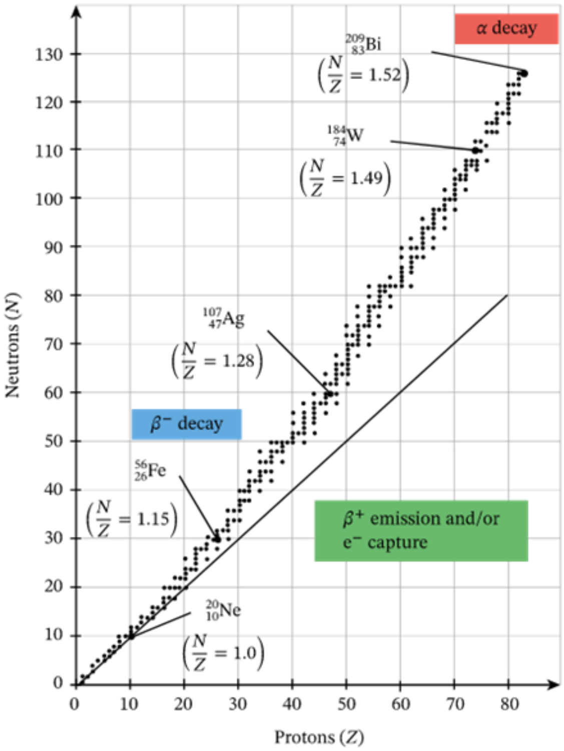
Some isotopes are stable while others are not and are therefore radioactive.
The Segre diagram indicates the stable or radioactive isotopes and provides the type of radioactive emission.
The axes are:
on the x-axis: the number of neutrons N = A - Z
on the y-axis: the number of protons: Z
This diagram is also known as the (N,Z) diagram.



- **For Z < 20:** stable isotopes roughly follow the line Z = N. The number of neutrons is roughly equal to that of protons.
- Beyond that, stability is achieved when N is greater than Z.
- Nuclei with a large number of protons are of the beta plus *(β+) emitter type.*
- Nuclei with a low Z value are of the beta minus *(β-) emitter type*.
- Finally, **heavy nuclei** with an excess of protons are *alpha (α) emitters*.

Forces at play

- ***Complement:*** Within the nucleus, three forces come into play:
  - ✓ Strong interaction: repulsive, acts at very short distances.
  - ✓ Weak interaction: neither attractive nor repulsive. It is responsible for the transformation of a neutron into a proton (beta decay).
  - ✓ Electromagnetic interaction: repulsive between protons.
  - ✓



✓

✓ The graph shows that small atomic nuclei are stable if they contain either exactly or approximately the same number of protons and neutrons. All of the smallest atomic nuclei are stable if their neutron-to-proton ratio is exactly equal to one ($\frac{N}{Z}$=1.0) or approximately equal to one ($\frac{N}{Z}$≈1.0).All of the larger atomic nuclei have higher neutron-to-proton number ratios. The stable medium-sized iron (Iron-56) and silver isotope nuclei (silver-107) are shown as having NZ values of 1.15 and 1.28. The largest stable nuclei are shown as having $\frac{N}{Z}$ values that are approximately equal to 1.50.

✓ The graph also shows how unstable atomic nuclei can undergo different forms of radioactive decay. The type of radioactive decay depends on neutron-to-proton ratios. Small and medium-sized unstable atomic nuclei tend to undergo β+ decay processes if they have too many protons to be stable. Small and medium-sized unstable atomic nuclei tend to undergo β- decay if they could gain a more stable $\frac{N}{Z}$ ratio by having one of their neutrons transform into a proton. The green box shows the area of β+ decay. It shows how small-to-medium sized nuclei tend to undergo β+ decay if they have too many protons to be stable. The blue box shows the area of β- decay. It shows how small-to-medium sized nuclei tend to undergo β- decay if they could gain a more stable $\frac{N}{Z}$ ratio by having one of their neutrons transform into a proton.

✓ The heaviest unstable atomic nuclei tend to emit an α particle ($^4_2He^{2+}$) that is made up of two protons and two neutrons. The area of alpha decay processes is represented with a red-colored box. It shows that large atomic nuclei tend to emit alpha particles. The figure has shown that unstable atomic nuclei can attain a more stable $\frac{\mathbf{N}}{\mathbf{Z}}$ number ratio through different forms of radioactive decay. Unstable nuclei tend to undergo the type of radioactive decay that moves them toward the band of stability.

- ✓ This rationale is confirmed in graphs that show the relationship between nuclear stability and the neutron-to-proton $\frac{\mathbf{N}}{\mathbf{Z}}$ number ratio. The following graph uses black dots to represent stable atomic nuclei that do not undergo radioactive decay. This band of stable nuclei is sometimes called the band of stability, but it can also be called the belt, zone, or valley of stability.