Atomic Mass and Molecular Mass-Part 1

Basic Concepts in Chemistry(BCC)
Lecture- 4

Atomic Mass

Carbon Standard(1961)

$$\text{Atomic Mass} = \frac{\text{Mass of one atom of an element}}{\frac{1}{12} \text{ of the mass of one } C^{12} \text{atom}}$$

Unit : Carbon Unit(cu) or
Unified Atomic mass Unit (u)
or Dalton(Da)

C = 12.00 u; Others are not whole numbers

H = 1.0078 u ≃ 1.0 u
O = 15.96 u ≃ 16.0
N = 14.007 u ≃ 14.0
F = 18.996 u ≃ 19.0
Na = 22.990 u ≃ 23.0

- Mass Number(A) : Total number protons and neutrons in the nucleus. It is a whole number always.
- Atomic Mass : It is relative mass with respect to 1/12 part of a C-12 atom taken as one unit(u) for comparison. It is not a whole number, except that of C-12.
- Rounding off the atomic mass(in fact isotopic atomic mass) to the nearest whole number gives the Mass number of the isotope.

Isotopes and Isotopic Masses

- Excepting 21 elements, which are monoisotopic(19 stable and 2 radioactive), all other natural elements exist in more than one isotopes.
- These 21 elements are monoisotopic and their isotopic masses are their atomic masses. For other elements, the average atomic masses of all the isotopes of the element is used for chemical calculations.
- Isotopes are same elements but have different isotopic atomic masses and hence different Mass Numbers. They differ in the number of neutrons present in nucleus.
- In fact, atomic masses of each isotope is called Isotopic atomic masses or Isotopic Mass.

21 Monoisotopic Elements

$^{9}_{4}Be$ $^{19}_{9}F$ $^{23}_{11}Na$ $^{27}_{13}Al$ $^{31}_{15}P$ $^{55}_{25}Mn$ $^{59}_{27}Co$

$^{75}_{33}As$ $^{127}_{53}I$ $^{133}_{55}Cs$ $^{197}_{79}Au$ $^{45}_{21}Sc$ $^{89}_{39}Y$

$^{93}_{41}Nb$ $^{103}_{45}Rh$ $^{141}_{59}Pr$ $^{159}_{65}Tb$ $^{165}_{67}Ho$ $^{169}_{69}Tm$

} 19 stable

$^{209}_{83}Bi$ $^{231}_{91}Pa$ → 2 radioactive

$^{A}_{Z}X$

A = Isotopic Atomic Mass
≃ Mass Number
Z= Atomic Number

7 Elements having one stable isotopes alongwith one radioactive isotope

- $^{85}_{37}Rb$ (present along with radioactive Rb-87)
- $^{51}_{23}V$ (present along with radioactive V-50)
- $^{113}_{49}In$ (present along with radioactive In-115 which is highly abundant and very high half life period) 4.4×10^{14} yrs.
- $^{139}_{57}La$ (present along with radioactive Ln-138)
- $^{153}_{63}Eu$ (present along with radioactive Eu-151)
- $^{175}_{71}Lu$ (present along with radioactive Lu-176)
- $^{185}_{75}Re$ (present along with radioactive Re-187 which is more abundant))

Some common Polyisotopic Elements with their Relative Abundance

$$^{35}_{17}Cl : ^{37}_{17}Cl = 3:1$$

Isotopic Masses : Cl(35) = 34.96885 u;
Cl(37) = 36.96590 u

$$^{79}_{35}Br : ^{81}_{35}Br = 1:1$$

Isotopic Masses : Br(79) = 78.9183371 u;
Br(81) = 80.9162906 u

Average Atomic Mass for Polyisotopic Elements

- For monoisotopic elements: Isotopic Atomic Mass = Atomic Mass (eg : F = 19, Al = 27 etc.)
- For polyisotopic elements:

  Average Isotopic Atomic Mass = Atomic Mass
- This average is Weighted Average of all isotopes taking their relative natural abundance into account.

$$\text{Average atomic mass} = \frac{(\%)_1 \text{ X } (\text{I.M})_1 + (\%)_2 \text{ X } (\text{I.M})_2 + \text{and so on}}{100}$$

$$\text{Av. Atomic mass of Cl} = \frac{3 \text{ X } 35 + 1 \text{ X } 37}{3+1} \simeq 35.5 \text{ u}$$

$$\text{Av. Atomic mass of Cl} = \frac{75 \text{ X } 35 + 25 \text{ X } 37}{100} \simeq 35.5 \text{ u}$$

$$\text{Av. Atomic mass of Br} = \frac{79 \times 50 + 81 \times 50}{100} = 80$$

- There is no Cl (35.5 u) and no Br (80 u) in the respective elements.
- We use average Atomic mass of chemical calculations.

$$^{16}_{8}O : ^{17}_{8}O : ^{18}_{8}O = 99.78 : 0.02 : 0.2$$

(O-16)=15.99491 u, (O-17)=16.99913u and (O-18)= 17.99916u

Av. Atomic mass (O) ≃ 16

$$^{12}_{6}C : ^{13}_{6}C : ^{14}_{6}C = 98.9 : 1.1 : trace \ (radioactive)$$

(C-12) = 12.000(exact); (C-13) = 13.00335483521u;
(C-14) =14.003241988

Av. Atomic mass (C) ≃ 12

$$^{1}_{1}H : ^{2}_{1}H\,(^{2}_{1}D) : ^{3}_{1}H\,(^{3}_{1}T) = 99.9885 : 0.0115 : trace \ (radioactive)$$

(H-1) =1.00782503207u; (D-2) = 2.0141017778u; (T-3)=3.0160492777u

Av. atomic mass (H) ≃ 1

$$^{32}_{16}S : ^{34}_{16}S = 95.6 : 4.4$$

(S-32)= 31.9720711744u; (S-34) = 33.9678670u,
Sulphur has two more stable isotopes i.e S-33 and S-36 having negligible abundance.

$$\text{Av. Atomic mass (S)} = \frac{32 \times 95.6 + 34 \times 4.4}{100} = 32.088 \simeq 32$$

Maximum Number of stable Isotopes = 10 (Sn)

Element	Atomic No	No. of Stable isotopes	Number of radioactive natural isotopes	Average Atomic Mass
Al	13	1		26.98
Ar	18	3		39.948
As	33	1		74.92
Ag	47	2		107.87
Au	79	1		196.97
Ba	56	7		137.34
Be	4	1		9.012
Bi	83	1		208.98
B	5	2		10.81
Br	35	2		79.909
Ca	20	6		40.08
Cd	48	8		112.4
C	6	2	1	12.011
Cs	55	1		132.905
Cl	17	2		35.453
Cr	24	4		52
Co	27	1		58.93
Cu	29	2		63.54
F	9	1		19
Ga	31	2		69.72
Ge	32	5		72.59
He	2	2		4.003
Ho	67	1		164.93
H	1	2	1	1.00797

$^{153}_{63}Eu$ stable 1, radioactive 1

Hg	80	7		200.59
In	49	1	1	114.82
I	53	1		126.9
Ir	77	2		192.2
Fe	26	4		55.85
K	19	2	1	39.102
Kr	36	6		83.8
Li	3	2		6.939
Mg	12	3		24.31
Mn	25	1		54.94
Mo	42	7		95.94
Na	11	1		22.99
Ne	10	3		20.183
Ni	28	5		58.71
Nb	41	1		92.91
N	7	2		14.007
Os	76	7		190.2
O	8	3		15.9994
Pd	46	6		106.4
P	15	1		30 974

$^{139}_{57}La$ 1 1

$^{175}_{71}Lu$ 1 1

Po	84	-		209
Pt	78	4		195.09
Pb	82	4		207.19
Re	75	1	1	186.2
Rh	45	1		102.905
Rb	37	1	1	85.47
Ru	44	7		101.1
Sc	21	1		44.96
Se	34	6		78.96
Si	14	3		28.09
Sb	51	2		121.75
Sr	38	4		87.62
S	16	4		32.064
Sn	50	10		118.69
Ta	73	2		180.95
Te	52	8		127.6
Tb	65	1		158.92
Tl	81	2		204.37
Ti	22	5		47.9
V	23	1	1	50.94
W	74	5		183.85
Xe	54	9		131.3
Zn	30	5		65.37
Zr	40	5		91.22

$^{185}_{75}Re$ 1 1

$^{51}_{23}V$ 1 1

- SAQ 1: Copper has two stable isotopes as follows. Cu-63 : Cu-65 = 69.17 : 30.83. Calculate the average atomic mass of Cu.

$(AM)_{Cu} = \frac{63 \times 69.17 + 65 \times 30.83}{100} = 63.616$

- SAQ 2: For every 10, 000 oxygen atoms that you will count how many O^{16}, O^{17} and O^{18} isotopes you will find?

$^{16}O : {}^{17}O : {}^{18}O = 99.78 : 0.02 : 0.2 \quad : (100)$

$= 9978 , 2 , 20 \quad (10,000)$

Determination of Atomic Mass

- Primitive Methods

  (For polyisotopic elements, these methods measured average atomic mass)

  – Dulong and Petit's Law (for solid metallic elements)

  – Law of Isomorphism

Dulong and Petit's Law

- **Specific Heat Capacity of a solid(metallic) element X Atomic mass ≃ 6 cals.K^{-1}.mol^{-1}** (25 J.K^{-1}.mol^{-1})
- Molar heat capacity of solid(metallic) element is approximately equals to 3R.
- Approx. Atomic Mass is known from this law.
- From equivalent mass of the element(exact), the exact valency is determined. Then the exact atomic mass is determined.
- (Equivalent Mass concept will be discussed later) : Equivalent Mass = (Atomic Mass)/valency

- SAQ 3: A metallic element has specific heat 0.11 cal/g/K. Its equivalent mass was determined to be exactly 27.92. Calculate the exact atomic mass of the element.

Solution

sp. heat × A. M ≃ 6 cals

$\Rightarrow$ Approx. A. M $= \frac{6}{0.11} = 54.54$.

$\because$ Equivalent Mass $= \frac{A.M}{valency}$

$\Rightarrow$ Approx. valency $= \frac{54.54}{27.92} = 1.9536$

$\therefore$ Exact valency = 2

$\therefore$ Exact Atomic Mass $= 2 \times 27.92 = 55.84$

Law of Isomorphism(Mitscherlich)

- Isomorphous substances possess similar chemical constitution(formula) i.e their molecules contain same number of atoms which are similarly arranged.
- $FeSO_4.7H_2O$(Green Vitriol) is isomorphous with $ZnSO_4.7H_2O$(White Vitriol)
- KCl is isomorphous with RbCl etc.
- From known data about two isomorphous solids, the atomic mass of an unknown element can be determined.

- SAQ 4: Potassium sulphate is isomorphous with potassium chromate which contains 26.79% by mass of Cr. Calculate the atomic mass of Cr. (K = 39, O = 16)

Atomic Mass and Molecular Mass-Part 2

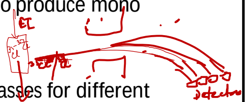
Basic Concepts in Chemistry(BCC)
Lecture-5

Modern Technique to find Isotopic Masses

- **Mass Spectrometer** with high resolving power is now used to find the exact isotopic masses of all isotopes of an element.
- Aston first discovered Mass spectrometer in 1919.
- Modern Mass spectrometers makes use of highly superconducting magnets to separate the isotopes and determine their exact isotopic masses and relative abundances.

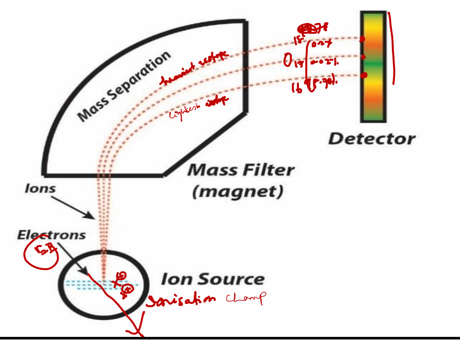
Principles of Mass Spectrometer

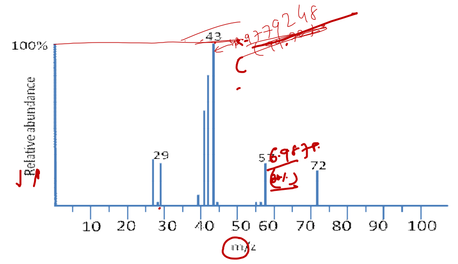
- The element in the vapour form is subjected to powerful Electron Impact(EI) by cathode rays to produce mono positive ions.



- $X(g) + Energy \rightarrow X^{+}(g) + e$
- These positive ions carry different masses for different isotopes of same element(neglect the mass of one electron).
- Then, they are allowed to pass through electric and magnetic field to take different curvatures(Fleming's Left hand Rule) according to their masses. Heavier ions take lesser curvature than lighter ions.

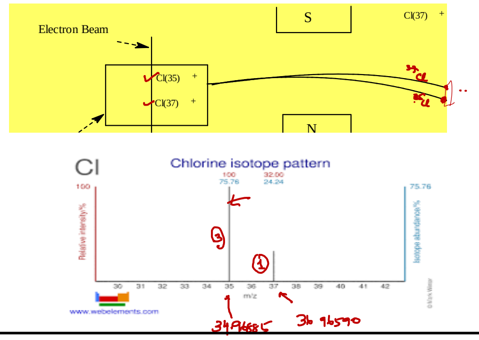
- As many number of isotopes are there, same number of ionic streams with different radii of curvatures are formed and are converted to micro current at the Detector which is interfaced with a computer.
- The magnitude of current gives their relative abundances(y-coordinate)
- Their positions in x-axis relative to the standard(C-12.0) gives their isotopic masses.
- Mass spectrograph gives a graph of isotopic masses(m/e) of the isotopes against their relative abundances. The height(y-coordinate) gives relative abundance and x-coordinate gives their isotopic masses.





A Mass Spectrograph or Mass Spectrum

(Note that the term spectrum is a misnomer here. Used only as convention.)



Gram Atomic Mass

- 1 g. atomic mass of an element contains one mole of atoms (N_A = 6.022 X 10^{23})
- 23 g of Na; 108 g of Ag, 1 g of H, 16 g of O, 14 g of N; 35.5 g of Cl, 80 g of Br etc. contain 1 mole of atoms each i.e Avogadro Constant number fo atoms.
- SAQ 5: How many moles and how many atoms of each element be present in the amounts given against each.
  (a) 2.3 g of Na (b) 0.355 g of Cl
  (c) 1.08 Kg of Ag (d) 480 g of O

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Solution (a) 23 g Na = 1 mol of atoms = 6.022×10^{23} atoms
⇒ 2.3 g Na = $\frac{2.3}{23}$ = $\frac{6.022 \times 10^{23} \times 2.3}{23}$
= 0.1 mol = 6.022×10^{22} atoms

(b) 35.5 g Cl = 1 mol of atoms = 6.022×10^{23} atoms
0.355 g Cl = $\frac{0.355}{35.5}$ = $\frac{6.022 \times 10^{23} \times 0.355}{35.5}$
= 0.01 mol = 6.022×10^{21} atoms

(c) 108 g Ag = 1 mol of atoms = 6.022×10^{23} atoms
(1.08 kg) 1080 g = $\frac{1080}{108}$ = $\frac{6.022 \times 10^{23} \times 1080}{108}$
= 10 mol = 6.022×10^{24} atoms

(d) 16 g O = 1 mol of atoms = 6.022×10^{23} atoms
480 g O = $\frac{480}{16}$ = $\frac{6.022 \times 10^{23} \times 480}{16}$
= 30 mol = 1.8066×10^{25} atoms

Molecular Mass

$$\text{Molecular Mass} = \frac{\text{Mass of one molecule}}{1/12 \text{ part of one atom of C(12)}}$$

(u)

Molecular mass = sum of atomic masses of all elements

1 gm molecular mass (1 g. molar mass) is the mass of one mole or $N_A(6.022X10^{23})$ number of molecules.

CO_2 = 44g = 1 mole ≃ 6.022×10^{23} molecules

Determination of Molecular Mass

- 1. Vapour Density Method(Victor Meyer's Method) : For volatile liquids
  (DISCUSSED BEFORE)
- 2. Gram Molar Volume Method : For gaseous substances.
- 3.Ideal Gas Equation : For gaseous substances
  (DISCUSSED BEFORE
- 4. Mass spectroscopy : For all

Gram Molar Volume(GMV) method

- 22.4 L of any gas at STP weighs one g. molecular mass.
- So from the mass of a given volume of the gas at a certain temperature and pressure, its MM can be found out.
- For that, first the volume at STP is calculated from that given in other conditions by using Combined Gas Equation.
- Then the mass of the substance having 22.4 L volume at STP gives the g. MM.

- SAQ: *80 mg of liquid on vaporization occupied 24.9 ml at 27^0C and 740mm pressure. Calculate the molecular mass of the subtance.*

m = 0.08 g

$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \Rightarrow \frac{740 \times 24.9}{300} = \frac{760 \times V_2}{273} \Rightarrow V_2 = 22.062$ mL

22.062 mL (STP) weighs 0.08 g

22400 mL " " $\frac{0.08}{22.06} \times 22400$ = 81.23 g

MM = 81.23

Alt: PV = nRT

$\frac{740}{760} \times \frac{24.9}{1000} = \left(\frac{0.08}{M}\right) \times 0.082 \times 300$

$\Rightarrow$ M = 81.17

Assignments

- 1. When 3.2 gm of sulphur is vapourized at 450^0C and 723 mm pressure, the vapour occupies a volume of 780ml. What is the molecular mass and molecular formula of sulphur vapour under these conditions? (A : S_8)
- 2. 250ml of ozonised oxygen(ozone + oxygen)at NTP weighed 0.393gm. On passing the sample through turpentine oil there was contraction in volume by 50ml. Find the molecular mass of ozone. (Hint: Turpentine oil absorbs only ozone) (A: 48.6)
- 3. If a gas has a density of 0.5 gm per litre at NTP, then find the mass of one mole of the gas.(A: 11.2 g)

- 4. The molecular mass of a volatile liquid substance is 46. What will be the volume of air displaced by 0.1665 g of the substance at 15^0C and 773.3 mm pressure in Victor Meyer's apparatus? (Aqueous Tension at 15^0C =13.3 mm) *(Hint: First find the volume at NTP and then convert it to given conditions by using combined gas equation)* (A: 85.52 mL)
- 5. What is the mass of one mole of a gas, one gram of which occupies 0.9822 L at 100^0C and 740 mm pressure? (A : 32 g)
- 6. Calculate the number of molecules of CO_2 gas present in 0.44 g of it. (A: $6.022X10^{21}$)

- 7. At STP, 5 litres of a gas weighs 14.4gm. What is its molecular Mass? If the gas is made up of S and O, could you guess what is the gas? (A:64.5; SO_2)
- 8. 380ml of an unknown gas at 27^0C and 800mm of Hg pressure weighed 0.455gm. Calculate the molecular mass of the gas. If the gas is made up of a single element, could you guess what is the gas ? Supposing the gas consists of two elements C and O, could you guess what it is? (A: 27.982; N_2, CO)
- 9. Br has an atomic mass of 80 u. What does it mean ? What is the mass number of Br atoms. (A: It is average at. mass. There are two mass numbers i.e Br-79 and Br-81)

- 10. If the Molecular Mass of HBr is determined in mass spectrometer, how many molecular masses will be obtained and what are those. What will be their abundance ratio ? But in chemical calculation, what molecular mass of HBr you shall take. (A: 80 and 82 in the ratio 1:1; 81 will be used for calculation)
- 11. Indicate which one among these elements have only one stable isotopes ?

  K, Na, Be, Co, Fe, Bi, Cl, I, Br, F, P, S, H, O, C

  (A: Na, Be, Co, I, F, P)
- 12. In-113 and In-115 isotopes exist in the abundance 4.3% and 95.7% respectively. What is the average atomic mass of In. (Note that In-115 is radioactive) (A : 114.914)

- 13. An element was found to have specific heat capacity 0.0276 cal/g^{0}C. If the equivalent mass of the element is 79.3, calculate the exact atomic mass of the element. (A: 237.68)
- 14. The sulphate of a metal contains 20.9% of the metal and is isomorphous with $ZnSO_4.7H_2O$. Find the probable atomic mass of the metal. (A: 58.65)