Chapter 4
Atoms and Elements

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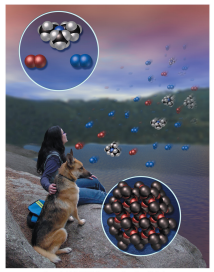
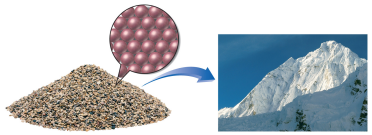
Chem 118
Introductory Chemistry



Map: Introductory Chemistry (Tro) https://chem.libretexts.org/@go/page/45050 (accessed Mar 25, 2022).

Experiencing Atoms

- Atoms are incredibly small, yet they compose everything.
- Atoms are the pieces of elements.
- Properties of the atoms determine the properties of the elements.



Experiencing Atoms

- There are about 91 elements found in nature.
  - ✓Over 20 have been made in laboratories.
- Each has its own, unique kind of atom.
  - ✓They have different structures.
  - ✓Therefore they have different properties.

The Divisibility of Matter

- Infinitely divisible
  - ✓For any two points, there is always a point between.
- Ultimate particle
  - ✓Upon division, eventually a particle is reached which can no longer be divided.

"Nothing exists except atoms and empty space; everything else is opinion." - Democritus 460–370 B.C.

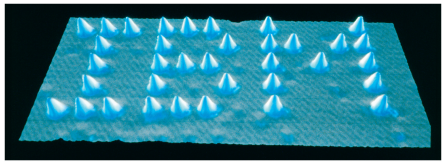
Dalton's Atomic Theory

1. Each Element is composed of tiny, indestructible particles called atoms.
   - ✓ Tiny, hard, indivisible, spheres.
2. All atoms of an element are identical.
   - ✓ They have the same mass, volume, and other physical and chemical properties.
   - ✓ So, atoms of different elements are different.
   - ✓ Every carbon atom is identical to every other carbon atom.
     - ➢ They have the same chemical and physical properties.
   - ✓ However, carbon atoms are different from sulfur atoms.
     - ➢ They have different chemical and physical properties.

Dalton's Atomic Theory

3. Atoms combine in simple, whole-number ratios to form molecules of compounds.
   - ✓ Because atoms are unbreakable, they must combine as whole atoms.
   - ✓ The nature of the atom determines the ratios in which it combines.
   - ✓ Each molecule of a compound contains the exact same types and numbers of atoms.
     - ➢ Law of Constant Composition
     - ➢ Chemical formulas

Modern Evidence for Atoms



Sizes of Atoms

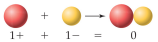
- Using compositions of compounds and assumed formulas, Dalton was able to determine the **relative** masses of the atoms.
  - ✓Dalton based his scale on H = 1 amu.
    - ➢We now base it on C-12 = 12 amu exactly.
  - ✓Unit = **atomic mass unit**.
    - ➢Amu or dalton.
- Absolute sizes of atoms:
  - ✓Mass of H atom= 1.67×10^{-24} g.
  - ✓Volume of H atom = 2.1×10^{-25} cm^3.

Some Notes on Charges

- There are two kinds of charges, called positive and negative.
- Opposite charges attract.
  - ✓+ attracted to –.
- Like charges repel.
  - ✓+ repels +.
  - ✓– repels –.
- To be neutral, something must have no charge or equal amounts of opposite charges.

Positive (red) and negative (yellow) charges attract.

Positive–positive and negative–negative charges repel.



Positive and negative charges cancel.

The Atom Is Divisible

- Work done by J. J. Thomson and others proved that the atom had pieces called **electrons**.
- Thomson found that electrons are much smaller than atoms and carry a negative charge.
  - ✓The mass of the electron is 1/1836th the mass of a hydrogen atom.
  - ✓The charge on the electron is the fundamental unit of charge that we call –1 charge unit.

Thomson's Interpretation— The Plum Pudding Model

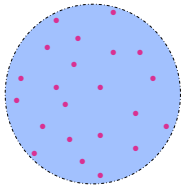
Takes the place of Dalton's first statement.

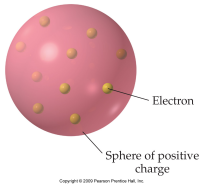
1. The atom is breakable.
2. The atom's structure has electrons suspended in a positively charged electric field.
   - ✓ It must have a positive charge to balance a negative charge of electrons.
   - ✓ Because there was no experimental evidence of positive matter, Thomson assumed there must be positive energy.

Predictions of the Plum Pudding Model

1. The mass of the atom is due to the mass of the electrons.
2. There must be a lot of empty space in the atom.
   - ✓ Since the electrons are negative, it is assumed you must keep them apart so they will not repel each other.

Plum Pudding Atom

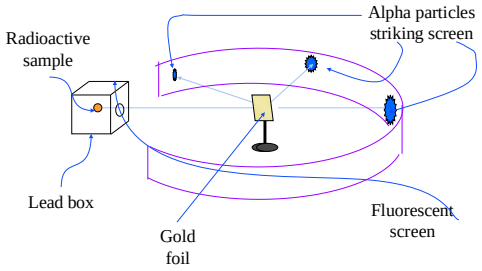




Rutherford's Experiment

- How can you prove something is empty?
- Put something through it.
  - ✓Use large target atoms.
    - ➢Use very thin sheets of target so they do not absorb "bullet".
  - ✓Use very small particles as "bullet" with very high energy.
    - ➢But not so small that electrons will effect it.
- Bullet = alpha particles; target atoms = gold foil
  - ✓ α particles have a mass of 4 amu & charge of +2 c.u.
  - ✓ Gold has a mass of 197 amu and is very malleable.

Rutherford's Experiment

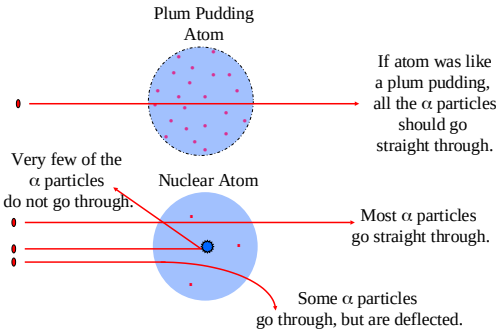


Rutherford's Results

- Over 98% of the α particles went straight through.
- About 2% of the α particles went through, but were deflected by large angles.
- About 0.01% of the α particles bounced off the gold foil.
  - ✓"...As if you fired a 15"-canon shell at a piece of tissue paper and it came back and hit you."

Rutherford's Conclusions

- Atoms are mostly empty space.
  - ✓Because almost all the particles went straight through.
- Atom contains a dense particle that was small in volume, compared to the atom, but large in mass.
  - ✓Because of the few particles that bounced back.
- This dense particle was positively charged.
  - ✓Because of the large deflections of some of the particles.



Rutherford's Interpretation—The Nuclear Model

1. The atom contains a tiny dense center called the **nucleus**.
   - ✓ The amount of space taken by the nucleus is only about 1/10 trillionth the volume of the atom.
2. The nucleus has essentially the entire mass of the atom.
   - ✓ The electrons weigh so little they contribute practically no mass to the atom.
3. The nucleus is positively charged.
   - ✓ The amount of positive charge balances the negative charge of the electrons.
4. The electrons are dispersed in the empty space of the atom surrounding the nucleus.
   - ✓ Like water droplets in a cloud.

Structure of the Nucleus

- Rutherford proposed that the nucleus had a particle that had the **same amount of charge as an electron** but opposite sign.
  - ✓Based on measurements of the nuclear charge of the elements.
- These particles are called **protons**.
  - ✓Protons have a charge of +1 c.u. and a mass of 1 amu.
- Since protons and electrons have the same amount of charge, for the ***atom to be neutral, there must be equal numbers of protons and electrons.***

Some Problems

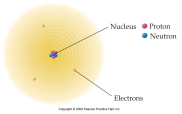
- How could beryllium have 4 protons stuck together in the nucleus?
  - ✓Shouldn't they repel each other?
- If a beryllium atom has 4 protons, then it should weigh 4 amu, but it actually weighs 9.01 amu! Where is the extra mass coming from?
  - ✓Each proton weighs 1 amu.
  - ✓Remember: The electron's mass is only about 0.00055 amu and Be has only 4 electrons—it can't account for the extra 5 amu of mass.

There Must Be Something Else There

- To answer these questions, Rutherford proposed that there was another particle in the nucleus—it is called a **neutron**.
- Neutrons have no charge and a mass of 1 amu.
  - ✓The masses of the proton and neutron are both approximately 1 amu.

The Modern Atom

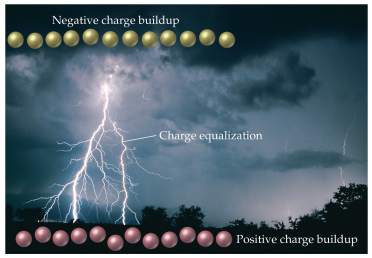
- We know atoms are composed of three main pieces—protons, neutrons, and electrons.
- The nucleus contains protons and neutrons.
- The nucleus is only about 10^{-13} cm in diameter.
- The electrons move outside the nucleus with an average distance of about 10^{-8} cm.
  - ✓Therefore, the radius of the atom is about 10^5 times larger than the radius of the nucleus.



The Nature of Electrical Charge

- Electrical charge is a fundamental property of protons and electrons.
- Positively and negatively charged objects attract each other.
- Like charged objects repel each other.
  - ✓+ to +, or - to -.
- When a proton and electron are paired, the result is a neutral charge.
  - ✓Because they have equal amounts of charge.

Maintaining and Restoring Charge Balance



Subatomic particle	Mass (g)	Mass (amu)	Location in atom	Charge (c.u.)	Symbol
Proton	1.67262×10^{-24}	1.0073	nucleus	1+	p, p^+, H^+
Electron	9.1×10^{-28}	0.00055	empty space	1-	e, e^-
Neutron	1.67493×10^{-24}	1.0087	nucleus	0	n, n^0

Practice—An Atom Has 20 Protons. Determine if Each of the Following Statements Is True or False?

- If it is a neutral atom, it will have 20 electrons. — True
- If it also has 20 neutrons, its mass will be approximately 40 amu. — True
- If it has 18 electrons, it will have a net 2- charge. — False

The Periodic Table

Mendeleev

- Ordered elements by atomic mass.
- Saw a repeating pattern of properties.
- **Periodic law**—When the elements are arranged in order of increasing relative mass, certain sets of properties recur periodically?
- Used pattern to predict properties of undiscovered elements.
- Where atomic mass order did not fit other properties, he reordered by other properties.
  - ✓Te & I

Periodic Pattern

nm H_2O a/b H 1 H_2						
m Li_2O Li b 7 LiH	m/nm BeO Be a/b 9 BeH_2	nm B_2O_3 B a 11 $(BH_2)_n$	nm CO_2 C a 12 CH_4	nm N_2O_5 N a 14 NH_3	nm O_2 O 16 H_2O	nm F 19 HF
m Na_2O Na b 23 NaH	m MgO Mg b 24 MgH_2	m Al_2O_3 Al a/b 27 $(AlH_3)_n$	nm/m SiO_2 Si a 28 SiH_4	nm P_4O_{10} P a 31 PH_3	nm SO_3 S a 32 H_2S	nm Cl_2O_7 Cl a 35.5 HCl

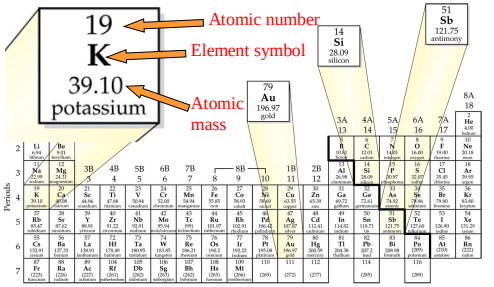
m = metal, nm = nonmetal, m/nm = metalloid

a = acidic oxide, b = basic oxide, a/b = amphoteric oxide

Elements

- Each element has a unique number of protons in its nucleus.
  - ✓All carbon atoms have 6 protons in their nuclei.
- The number of protons in the nucleus of an atom is called the **atomic number**.
  - ✓**Z** is the short-hand designation for the atomic number.
  - ✓Because each element's atoms have a unique number of protons, **each element can be identified by its atomic number**.
  - ✓The elements are arranged on the Periodic Table in order of their atomic numbers.
- Each element has a unique name and symbol.
  - ✓The symbol is either one or two letters
    - One capital letter or one capital letter + one lower case letter.

The Periodic Table of Elements



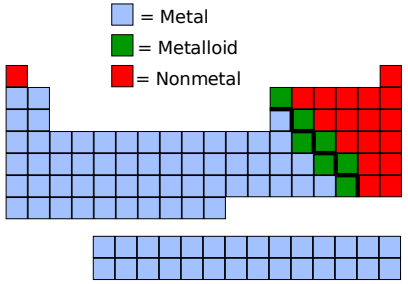
Review

- What is the atomic number of boron, B?
- What is the atomic mass of silicon, Si?
- How many protons does a chlorine atom have?
- How many electrons does a neutral neon atom have?
- Will an atom with 6 protons, 6 neutrons, and 6 electrons be electrically neutral?
- Will an atom with 27 protons, 32 neutrons, and 27 electrons be electrically neutral?
- Will an Na atom with 10 electrons be electrically neutral?

Review

- What is the atomic number of boron, B? 5
- What is the atomic mass of silicon, Si? 28.09 amu
- How many protons does a chlorine atom have? 17
- How many electrons does a neutral neon atom have? 10
- Will an atom with 6 protons, 6 neutrons and 6 electrons be electrically neutral? Yes
- Will an atom with 27 protons, 32 neutrons, and 27 electrons be electrically neutral? Yes
- Will an Na atom with 10 electrons be electrically neutral? No

Periodicity

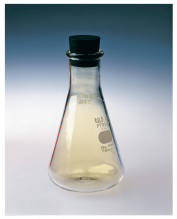


Metals

- Solids at room temperature, except Hg.
- Reflective surface.
  - ✓Shiny
- Conduct heat.
- Conduct electricity.
- Malleable.
  - ✓Can be shaped.
- Ductile.
  - ✓Drawn or pulled into wires.
- Lose electrons and form cations in reactions
- About 75% of the elements are metals.
- Lower left on the table.

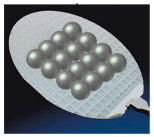
Nonmetals

- Found in all 3 states.
- Poor conductors of heat.
- Poor conductors of electricity.
- Solids are brittle.
- Gain electrons in reactions to become anions.
- Upper right on the table.
  - ✓Except H.



Metalloids

- Show some properties of metals and some of nonmetals.
- Also known as semiconductors.



Properties of Silicon:
- ✓Shiny
- ✓Conducts electricity
- ✓Does not conduct heat well
- ✓Brittle

Practice—Classify Each Element as Metal, Nonmetal, or Metalloid.

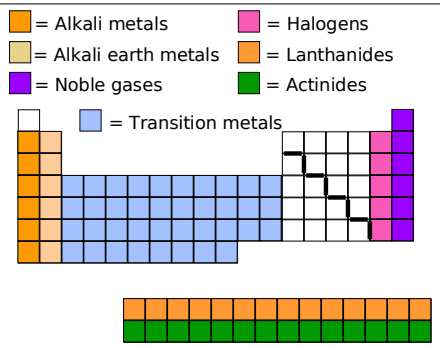
- Xenon, Xe — Nonmetal
- Tungsten, W — Metal
- Bromine, Br — Nonmetal
- Arsenic, As — Metalloid
- Cerium, Ce — Metal

The Modern Periodic Table

- Elements with similar chemical and physical properties are in the same column.
- Columns are called **Groups** or **Families**.
  - ✓Designated by a number
- Rows are called **Periods**.
- Each period shows the pattern of properties repeated in the next period.

The Modern Periodic Table, Continued

- Main group = representative elements
- Transition elements
  - ✓All metals.
- Bottom rows = inner transition elements = rare earth elements.
  - ✓Metals
  - ✓Really belong in periods 6 and 7.

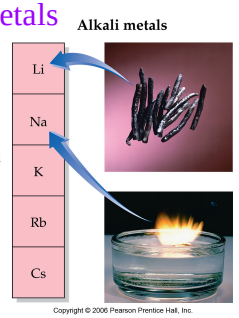


Important Groups—Hydrogen

- Nonmetal.
- Colorless, diatomic gas.
  - ✓Very low melting point and density.
- Reacts with nonmetals to form molecular compounds.
  - ✓HCl is an acidic gas.
  - ✓H_2O is a liquid.
- Reacts with metals to form hydrides.
  - ✓Metal hydrides react with water to form H_2.
- hydrogen halides dissolve in water to form acids.

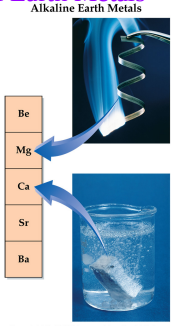
Important Groups—Alkali Metals

- Group 1 = Alkali metals.
- Hydrogen is usually placed here, though it doesn't belong.
- Soft, low melting points, low density.
- Flame tests: Li = red, Na = yellow, and K = violet.
- Very reactive, never found uncombined in nature.
- Tend to form water soluble compounds that are crystallized from seawater then molten salt electrolyzed.
  - ➢Colorless solutions.
- React with water to form basic (alkaline) solutions and H_2:
  - $2\ Na + 2\ H_2O \rightarrow 2\ NaOH + H_2$
  - ➢Releases a lot of heat.



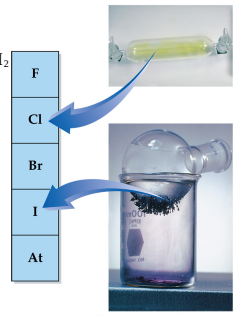
Important Groups—Alkali Earth Metals

- Group 2 = Alkali earth metals.
- Harder, higher melting, and denser than alkali metals.
  - ✓Mg alloys used as structural materials.
- Flame tests: Ca = red, Sr = red, and Ba = yellow-green.
- Reactive, but less than corresponding alkali metal.
- Form stable, insoluble oxides from which they are normally extracted.
- Oxides are basic = alkaline earth.
- Reactivity with water to form H_2:
  Be = none, Mg = steam, Ca, Sr, Ba = cold water.



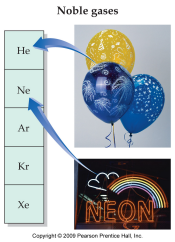
Important Groups—Halogens

- Group 17 = Halogens.
- Nonmetals.
- F_2 and Cl_2 gases, Br_2 liquid, and I_2 solid.
- All diatomic.
- Very reactive.
- Cl_2 and Br_2 react slowly with water:
  $Br_2 + H_2O \rightarrow HBr + HOBr$
- React with metals to form ionic compounds.
- hydrogen halides all acids:
  - ✓HF weak < HCl < HBr < HI.



Important Groups—Noble Gases

- Group 18 = Noble gases.
- All gases at room temperature.
  - ✓Very low melting and boiling points.
- Very unreactive, practically inert.
- Very hard to remove electron from or give an electron to.



Charge and Ions

Charged Atoms

- The number of protons determines the element.
  - ✓All sodium atoms have 11 protons in the nucleus.
- In a chemical change, the number of protons in the nucleus of the atom doesn't change.
  - ✓No transmutation during a chemical change!!
  - ✓During radioactive and nuclear changes, atoms do transmute.
- Atoms in a compound are often electrically charged, these are called **ions.**

Ions

- Atoms acquire a charge by gaining or losing electrons.
  - ✓Not protons!
- Ion charge = # protons – # electrons.
- Ions with a positive charge are called **cations**.
  - ✓More protons than electrons.
  - ✓Form by losing electrons.
- Ions with a negative charge are called **anions**.
  - ✓More electrons than protons.
  - ✓Form by gaining electrons.
- Chemically, ions are much different than the neutral atoms.
  - ✓Because they have a different structure.

Atomic Structures of Ions

- **Nonmetals form anions.**
- For each negative charge, the ion has 1 more electron than the neutral atom.
  - ✓F = 9 p^+ and 9 e^-; F^- = 9 p^+ and 10 e^-.
  - ✓P = 15 p^+ and 15 e^-; P^{3-} = 15 p^+ and 18 e^-.
- Anions are named by changing the ending of the name to ***–ide***.

fluorine	$F + 1e^- \rightarrow F^-$	fluoride ion
oxygen	$O + 2e^- \rightarrow O^{2-}$	oxide ion

- The charge on an anion can often be determined from the group number on the periodic table.
  - ✓Group 17 ⇒ 1-, Group 16 ⇒ 2-.

Atomic Structures of Ions, Continued

- **Metals form cations**.
- For each positive charge the ion has 1 less electron than the neutral atom.
  - ✓Na atom = 11 p^+ and 11 e^-; Na^+ ion = 11 p^+ and 10 e^-.
  - ✓Ca atom = 20 p^+ and 20 e^-; Ca^{2+} ion = 20 p^+ and 18 e^-.
- Cations are named the same as the metal.

sodium	$Na \rightarrow Na^+ + 1e^-$	sodium ion
calcium	$Ca \rightarrow Ca^{2+} + 2e^-$	calcium ion

- The charge on a cation can often be determined from the group number on the periodic table.
  - ✓Group 1 ⇒ 1+, Group 2 ⇒ 2+, (Al, Ga, In) ⇒ 3+.

Example 4.5—Find the Number of Protons and Electrons in Ca^{2+}.

Given:	Ca^{2+}
Find:	# p^+, # e^-
Solution Map:	symbol ⇒ atomic number ⇒ # p^+ ⇒ # e^-
Relationships:	ion charge = #p^+ − #e^-
Solution:	Z = 20 = #p^+ ion charge = #p^+ − #e^- +2 = 20 − #e^- −18 = − #e^- 18 = #e^-
Check:	For cations, $p^+ > e^-$, so the answer is reasonable.

Practice—Fill in the Table, Continued.

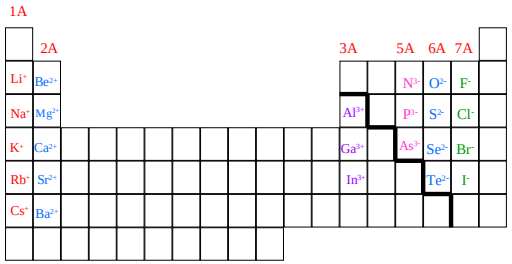
Ion	p^+	e^-
Cl^{-1}	17	18
K^{+1}	19	18
S^{-2}	16	18
Sr^{+2}	38	36

Valence Electrons and Ion Charge

- The highest energy electrons in an atom are called the **valence electrons**.
- Metals form cations by losing their valence electrons to get the same number of electrons as the previous noble gas.
  - ✓Main group metals.
  - ✓Li^+ = 2 e^- = He; Al^{3+} = 10 e^- = Ne.
- Nonmetals form anions by gaining electrons to have the same number of electrons as the next noble gas.
  - ✓Cl^- = 18 e^- = Ar; Se^{2-} = 36 e^- = Kr.

Ion Charge and the Periodic Table

- The charge on an ion can often be determined from an elements position on the periodic table.
- Metals are always positive ions, nonmetals are negative ions.
- For many main group metals, the cation charge = the group number.
- For nonmetals, the anion charge = the group number – 8.



Isotopes

Structure of the Nucleus

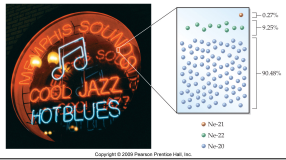
- Soddy discovered that the same element could have atoms with different masses, which he called **isotopes**.
  - ✓There are two isotopes of chlorine found in nature, one that has a mass of about 35 amu and another that weighs about 37 amu.
- The observed mass is a weighted average of the weights of all the naturally occurring atoms.
  - ✓The atomic mass of chlorine is 35.45 amu.

Isotopes

- All isotopes of an element are chemically identical.
  - ✓Undergo the exact same chemical reactions.
- All isotopes of an element have the same number of protons.
- Isotopes of an element have different masses.
- Isotopes of an element have different numbers of neutrons.
- Isotopes are identified by their **mass numbers**.
  - ✓Protons + neutrons.

Isotopes, Continued

- Atomic Number.
  - ✓Number of protons.
  - ✓Z
- Mass Number
  - ✓ = Protons + Neutrons.
  - ✓Whole number.
  - ✓A
- ✓Percent natural abundance = Relative amount found in a sample.



Neon

Symbol	Number of protons	Number of neutrons	A, mass number	Percent natural abundance
Ne-20 or $^{20}_{10}Ne$	10	10	20	90.48%
Ne-21 or $^{21}_{10}Ne$	10	11	21	0.27%
Ne-22 or $^{22}_{10}Ne$	10	12	22	9.25%

Isotopes

- Cl-35 makes up about 75% of chlorine atoms in nature, and Cl-37 makes up the remaining 25%.
- The average atomic mass of Cl is 35.45 amu.
- Cl-35 has a mass number = 35, 17 protons and 18 neutrons (35 - 17).

$^{35}_{17}Cl$

Atomic symbol
A = Mass number
Z = Atomic number

$^{A}_{Z}X = X\text{-}A$

Example 4.8—How Many Protons and Neutrons Are in an Atom of $^{52}_{24}Cr$?

Given:	$^{52}_{24}Cr$
Find:	therefore A = 52, Z = 24 # p^+ and # n^0
Solution Map:	symbol ⇒ atomic & mass numbers ⇒ # n^0
Relationships:	mass number = # p^+ + # n^0
Solution:	Z = 24 = # p^+ A = Z + # n^0 52 = 24 + # n^0 28 = # n^0
Check:	For most stable isotopes, $n^0 > p^+$.

Practice—Complete the Following Table, Continued.

	Atomic Number	Mass Number	Number of protons	Number of electrons	Number of neutrons
Calcium-40	**20**	**40**	**20**	**20**	**20**
Carbon-13	**6**	**13**	**6**	**6**	**7**
Aluminum-27^{+3}	**13**	**27**	**13**	**10**	**14**

Mass Number Is Not the Same as Atomic Mass

- The mass number refers to the number of protons + neutrons in one isotope.
- The atomic mass is an experimental number determined from ***all*** naturally occurring isotopes.
  - ✓The atomic mass on the periodic table is a weighted average of the atomic masses of an isotope taking into account their natural abundance

Example 4.9—Ga-69 with Mass 68.9256 Amu and Abundance of 60.11% and Ga-71 with Mass 70.9247 Amu and Abundance of 39.89%. Calculate the Atomic Mass of Gallium.

Given:	Ga-69 = 60.11%, 68.9256 amu Ga-71 = 39.89%, 70.9247 amu
Find:	atomic mass, amu
Solution Map: Relationships:	isotope masses, isotope fractions ⇒ avg. atomic mass $\text{Atomic Mass} = \sum \left(\text{fractional abundance of isotope}\right)_n \times \left(\text{mass of isotope}\right)_n$
Solution:	$\text{Atomic Mass} = (0.6011)(68.9256\ \text{amu})$ $+(0.3989)(70.9247\ \text{amu})$ $\text{Atomic Mass} = 63.72\underline{3}041 = 69.72\ \text{amu}$
Check:	The average is between the two masses, closer to the major isotope.

Practice—If Copper Is 69.17% Cu-63 with a Mass of 62.9396 Amu and the Rest Cu-65 with a Mass of 64.9278 Amu, Find Copper's Atomic Mass.

Practice—If Copper Is 69.17% Cu-63 with a Mass of 62.9396 Amu and the Rest Cu-65 with a Mass of 64.9278 Amu, Find Copper's Atomic Mass, Continued.

Given:	Cu-63 = 69.17%, 62.9396 amu Cu-65 = 100-69.17%, 64.9278 amu
Find:	atomic mass, amu
Solution Map: Relationships:	isotope masses, isotope fractions ⇒ avg. atomic mass $\text{Atomic Mass} = \sum \left(\text{fractional abundance of isotope}\right)_n \times \left(\text{mass of isotope}\right)_n$
Solution:	$\text{Atomic Mass} = (0.6917)(62.9396\ \text{amu})$ $+(0.3083)(64.9278\ \text{amu})$ $\text{Atomic Mass} = 63.5525 = 63.55\ \text{amu}$
Check:	The average is between the two masses, closer to the major isotope.