

# 1

## The periodic table

**M**ATTER is everywhere around you, from the water you drink to the air you inhale. The matter is made of elements and elements are made of atoms. Even the atoms of an element can be different, having a distinct number of protons and neutrons. This chapter covers the principles of atomic structure. You will learn what makes an atom and will be able to quantify the particles that make atoms. Perhaps more importantly, you will also learn about the periodic table of the elements and the different types of chemical formulas.

### 1.1 The periodic table

The periodic table is a chart containing all known elements arranged in increasing number of electrons per atom in a way that elements with similar chemical and physical properties are located together. The periodic table contains all existing elements—some of them are synthetic others are natural—that form the matter arranged in columns and rows. Every element has a different name accompanied by a symbol that represents their name. The tabular arrangement of elements in the form of rows and columns allow further classification of the elements according to their properties. This section will cover the different features of the periodic table.

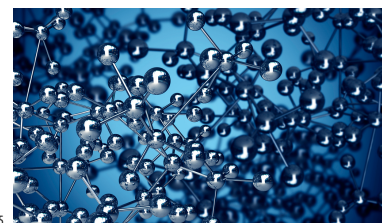
*Elements and Symbols* Elements cannot be broken down into simpler substances. For example aluminum is an element only made of aluminum atoms and if you analyze the composition of a piece of this metals you would only find aluminium atoms. Chemical symbols are one- or two-letter abbreviations that represent the names of the elements. Only the first letter is capitalized and if a second letter exist in the element's name, the second letter should be lowercase. For example, the chemical symbol for aluminum is Al with capital A and lowercase l. The periodic table in next page contains the symbols of all elements.

#### Sample Problem 1

Give the symbol or name the following elements: C, Oxygen, N, Phosphorus, Au, Iron, Na and Iodine.

#### **SOLUTION**

The name of the element with symbol C is carbon, whereas the chemical symbol of oxygen is O. Similarly, N stands for nitrogen, whereas the chemical symbol of Phosphorus is P. The chemical symbol of Au is Gold. The chemical symbol of Iron is Fe and the chemical symbol of Iodine is I.



#### GOALS

- 1 Navigate the periodic table
- 2 Calculate average atomic masses, number of electrons, protons and neutrons in an atom
- 3 Calculate simple molecular weights
- 4 Calculate molecular formulas from empirical formulas

**Discussion:** Why having a periodic table? What is the basic information all periodic tables provide? Do you know any other periodic table design?

“Nothing exists except atoms and empty space; everything else is opinion.”

*Democritus*

### STUDY CHECK

Give the symbol or name the following elements: Ni.

*Periods and groups* The periodic table contains all elements arranged in rows and columns. The horizontal rows are called *periods* and the vertical columns are called *groups or families*. For example, the first period contains hydrogen (H) and helium (He), whereas the second group contains Beryllium (Be), Magnesium (Mg), Calcium (Ca), Strontium (Sr), Barium (Ba) and Radium (Ra). There are seven periods (periods 1-7) and 18 groups. Some of the groups are labeled with an A (e.g. group 8A) whereas others are labeled with a B (e.g. group 8B). The groups numbers can be found written with roman numbers and a letters (A or B) or with a more modern group numbering of 1-18 going across the periodic table. For example, the group 2 (Mg-Ra) can also be called IIA, and the group 13 (B-Ti) is also known as IIIA.

*Properties in the periodic table* The physical and chemical properties of some elements of the table are similar, and these similarities led to the organization of the periodic table. Elements in the same group share properties and for example, oxygen and sulfur have similar properties: both are reactive elements. Differently, the properties across periods change going from metals to nonmetals. For example, the properties of Li and Ne are very different and lithium is a reactive metal whereas neon is a nonreactive gas.

*Metals, Nonmetals, and Metalloids* Overall, the elements of the periodic table can be classify as metals, nonmetals, and metalloids. Metals are those elements on the left of the table and nonmetals are the elements on the right of the table. The elements between metals and nonmetals are called metalloids and include only B, Si, Ge, As, Sb, Te, Po, and At. Metals are shiny solids and usually melt at higher temperatures. Some examples of metals are Gold (Au) or Iron (Fe). Nonmetals are often poor conductors of heat and electricity with low melting points. They also tend to be matt (non-shinny), malleable, or ductile. Some examples of nonmetals are Carbon (C) or Nitrogen (N). Metalloids are elements that share some properties with metals and others with the nonmetals. For example, they are better conductors of heat and electricity than the nonmetals, but not as good conductors as the metals. Metalloids are semiconductors because they can act as both conductors and insulators under certain conditions. An example of metalloids is Silicon (Si) that should not be confused from silicone, a chemical employed in prosthetics.

#### Sample Problem 2

Answer the following questions: (a) Give the group and period of the following elements, and give the name: Ca, Ir, and C. (b) Classify as alkali metal, alkali earth metal, transition metal, halogen or noble gas, and give the name: Mg, Li, Co, He, F. (c) Classify as metal, nonmetal or metalloid, and give the name: Ba, N, Si.

#### SOLUTION

(a) The period and group of Ca (Calcium) is 2 (2A) and 4, respectively. The period and group of Ir (Iridium) is 9 (8B) and 6, respectively. The period and group of C (Carbon) is 14 (IVA) and 2, respectively. (b) Mg (Magnesium) is an alkali earth metal, whereas Li (Lithium) is a alkali metal. Co (Cobalt) is a transition metal. He (Helium) is a noble gas. F (Fluorine) is an halogen. (c) Ba

(Barium) is a metal. N (Nitrogen) is a nonmetal. Si (Silicon) is a metalloid.

### STUDY CHECK

Answer the following questions: (a) Give the group and period of the following elements, and give the name: Cl. (b) Classify as alkali metal, alkali earth metal, transition metal, halogen or noble gas, and give the name: Ne. (c) Classify as metal, nonmetal or metalloid, and give the name: W.

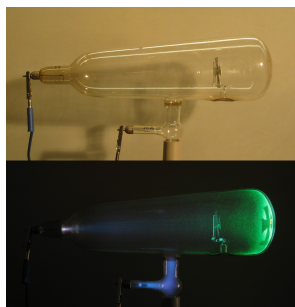
*Classification of elements in terms of groups* Some of the groups in the periodic table have specific names such as alkali metals, alkaline earth metals, transition metals, chalcogens, halogens or noble gases. Alkali metals are the group 1A elements: lithium (Li), sodium (Na), potassium (K), rubidium (Rb), cesium (Cs), and francium (Fr). Alkali elements are soft and shiny metals, and they are also good conductors of heat and electricity, with low melting points. Alkali earth metals are the group 2A (2) elements: beryllium (Be), magnesium (Mg), calcium (Ca), strontium (Sr), barium (Ba), and radium (Ra). Transition metals are the elements from group 3 to 12 and they are located in the middle of the table. Chalcogens are the group 6A (16) elements: oxygen (O), sulfur (S), selenium (Se), tellurium (Te), and polonium (Po). Halogens are the group 7A (17) elements: fluorine (F), chlorine (Cl), bromine (Br), iodine (I), and astatine (At). Halogens are very reactive elements. Finally, noble gases are the group 8A (18) elements: helium (He), neon (Ne), argon (Ar), krypton (Kr), xenon (Xe), and radon (Rn). They are inert and rarely combine with other elements in the periodic table, like a noble family: have you ever meet a royal?

*How to classify Hydrogen* At first sight, hydrogen (H) may seem to be put in the wrong spot at the periodic table. Although it is located at the top of Group 1A (1), it is not an alkali metal, as it has very different properties. Thus hydrogen does not belong to the alkali metals, being a nonmetal.

1 IA																		2 VIIIA																	
1																		2																	
H Hydrogen																		He Helium																	
2																		10																	
Li Lithium																		Ne Neon																	
3																		9																	
Na Sodium																		Ar Argon																	
4																		8																	
K Potassium																		Kr Krypton																	
5																		7																	
Ca Calcium																		Br Bromine																	
6																		6																	
Sc Scandium																		Se Selenium																	
7																		5																	
Ti Titanium																		I Iodine																	
8																		4																	
V Vanadium																		Te Tellurium																	
9																		3																	
Cr Chromium																		Sb Antimony																	
10																		2																	
Mn Manganese																		Sn Tin																	
11																		1																	
Fe Iron																		Pb Lead																	
12																		0																	
Co Cobalt																		Bi Bismuth																	
13																		17																	
Ni Nickel																		At Astatine																	
14																		16																	
Cu Copper																		Po Polonium																	
15																		15																	
Zn Zinc																		Uu Ununseptium																	
16																		14																	
Ga Gallium																		Uuq Ununquadium																	
17																		13																	
Ge Germanium																		Uub Ununbium																	
18																		12																	
As Arsenic																		Uut Ununtrium																	
19																		11																	
Se Selenium																		Uuq Ununquadium																	
20																		10																	
Br Bromine																		Uuq Ununquadium																	
21																		9																	
Kr Krypton																		Uuq Ununquadium																	
22																		8																	
Rb Rubidium																		Uuq Ununquadium																	
23																		7																	
Sr Strontium																		Uuq Ununquadium																	
24																		6																	
Y Yttrium																		Uuq Ununquadium																	
25																		5																	
Zr Zirconium																		Uuq Ununquadium																	
26																		4																	
Nb Niobium																		Uuq Ununquadium																	
27																		3																	
Mo Molybdenum																		Uuq Ununquadium																	
28																		2																	
Tc Technetium																		Uuq Ununquadium																	
29																		1																	
Ru Ruthenium																		Uuq Ununquadium																	
30																		0																	
Rh Rhodium																		Uuq Ununquadium																	
31																		17																	
Pd Palladium																		Uuq Ununquadium																	
32																		16																	
Ag Silver																		Uuq Ununquadium																	
33																		15																	
Cd Cadmium																		Uuq Ununquadium																	
34																		14																	
In Indium																		Uuq Ununquadium																	
35																		13																	
Sn Tin																		Uuq Ununquadium																	
36																		12																	
Sb Antimony																		Uuq Ununquadium																	
37																		11																	
Te Tellurium																		Uuq Ununquadium																	
38																		10																	
I Iodine																		Uuq Ununquadium																	
39																		9																	
Xe Xenon																		Uuq Ununquadium																	
40																		8																	
Cs Cesium																		Uuq Ununquadium																	
41																		7																	
Ba Barium																		Uuq Ununquadium																	
42																		6																	
La-Lu Lanthanide/Actinide																		Uuq Ununquadium																	
43																		5																	
Hf Hafnium																		Uuq Ununquadium																	
44																		4																	
Ta Tantalum																		Uuq Ununquadium																	
45																		3																	
W Tungsten																		Uuq Ununquadium																	
46																		2																	
Re Rhenium																		Uuq Ununquadium																	
47																		1																	
Os Osmium																		Uuq Ununquadium																	
48																		0																	
Ir Iridium																		Uuq Ununquadium																	
49																		17																	
Pt Platinum																		Uuq Ununquadium																	
50																		16																	
Au Gold																		Uuq Ununquadium																	
51																		15																	
Hg Mercury																		Uuq Ununquadium																	
52																		14																	
Tl Thallium																		Uuq Ununquadium																	
53																		13																	
Pb Lead																		Uuq Ununquadium																	
54																		12																	
Bi Bismuth																		Uuq Ununquadium																	
55																		11																	
Po Polonium																		Uuq Ununquadium																	
56																		10																	
At Astatine																		Uuq Ununquadium																	
57																		9																	
Rn Radon																		Uuq Ununquadium																	
58																		8																	
Fr Francium																		Uuq Ununquadium																	
59																		7																	
Ra Radium																		Uuq Ununquadium																	
60																		6																	
Ac-Lr Actinide																		Uuq Ununquadium																	
61																		5																	
Rf Rutherfordium																		Uuq Ununquadium																	
62																		4																	
Db Dubnium																		Uuq Ununquadium																	
63																		3																	
Sg Seaborgium																		Uuq Ununquadium																	
64																		2																	
Bh Bohrium																		Uuq Ununquadium																	
65																		1																	
Hs Hassium																		Uuq Ununquadium																	
66																		0																	
Mt Meitnerium																		Uuq Ununquadium																	
67																		17																	
Ds Darmstadtium																		Uuq Ununquadium																	
68																		16																	
Rg Roentgenium																		Uuq Ununquadium																	
69																		15																	
Uub Ununbium																		Uuq Ununquadium																	
70																		14																	
Uut Ununtrium																		Uuq Ununquadium																	
71																		13																	
Uuq Ununquadium																		Uuq Ununquadium																	
72																		12																	
Uuq Ununquadium																		Uuq Ununquadium																	
73																		11																	
Uuq Ununquadium																		Uuq Ununquadium																	
74																		10																	
Uuq Ununquadium																		Uuq Ununquadium																	
75																		9																	
Uuq Ununquadium																		Uuq Ununquadium																	
76																		8																	
Uuq Ununquadium																		Uuq Ununquadium																	
77																		7																	
Uuq Ununquadium																		Uuq Ununquadium																	
78																		6																	
Uuq Ununquadium																		Uuq Ununquadium																	
79																		5																	
Uuq Ununquadium																		Uuq Ununquadium																	
80																		4																	
Uuq Ununquadium																		Uuq Ununquadium																	
81																		3																	
Uuq Ununquadium																		Uuq Ununquadium																	
82																		2																	
Uuq Ununquadium																		Uuq Ununquadium																	
83																		1																	
Uuq Ununquadium																		Uuq Ununquadium																	
84																		0																	
Uuq Ununquadium																		Uuq Ununquadium																	
85																		17																	
Uuq Ununquadium																		Uuq Ununquadium																	
86																		16																	
Uuq Ununquadium																		Uuq Ununquadium																	
87																		15																	
Uuq Ununquadium																		Uuq Ununquadium																	
88																		14																	
Uuq Ununquadium																		Uuq Ununquadium																	
89																		13																	
Uuq Ununquadium																		Uuq Ununquadium																	
90																		12																	
Uuq Ununquadium																		Uuq Ununquadium																	
91																		11																	
Uuq Ununquadium																		Uuq Ununquadium																	
92																		10																	
Uuq Ununquadium																		Uuq Ununquadium																	
93																		9																	
Uuq Ununquadium																		Uuq Ununquadium																	
94																		8																	
Uuq Ununquadium																		Uuq Ununquadium																	
95																		7																	
Uuq Ununquadium																		Uuq Ununquadium																	
96																		6																	
Uuq Ununquadium																		Uuq Ununquadium																	
97																		5																	
Uuq Ununquadium																		Uuq Ununquadium																	
98																		4																	
Uuq Ununquadium																		Uuq Ununquadium																	
99																		3																	
Uuq Ununquadium																		Uuq Ununquadium																	
100																		2																	
Uuq Ununquadium																		Uuq Ununquadium																	
101																		1																	
Uuq Ununquadium																		Uuq Ununquadium																	
102																		0																	
Uuq Ununquadium																		Uuq Ununquadium																	
103																		17																	
Uuq Ununquadium																		Uuq Ununquadium																	
104																		16																	
Uuq Ununquadium																		Uuq Ununquadium																	
105																		15																	
Uuq Ununquadium																		Uuq Ununquadium																	
106																		14																	
Uuq Ununquadium																		Uuq Ununquadium																	
107																		13																	
Uuq Ununquadium																		Uuq Ununquadium																	
108																		12																	
Uuq Ununquadium																		Uuq Ununquadium																	
109																		11																	
Uuq Ununquadium																		Uuq Ununquadium																	
110																		10																	
Uuq Ununquadium																		Uuq Ununquadium																	
111																		9																	
Uuq Ununquadium																		Uuq Ununquadium																	
112																		8																	
Uuq Ununquadium																		Uuq Ununquadium																	
113																		7																	
Uuq Ununquadium																		Uuq Ununquadium																	
114																		6																	
Uuq Ununquadium																		Uuq Ununquadium																	
115																		5																	
Uuq Ununquadium																		Uuq Ununquadium																	
116																		4																	
Uuq Ununquadium																		Uuq Ununquadium																	
117																		3																	
Uuq Ununquadium																		Uuq Ununquadium																	
118																		2																	
Uuq Ununquadium																		Uuq Ununquadium																	
119																		1																	
Uuq Ununquadium																		Uuq Ununquadium																	
120																		0																	
Uuq Ununquadium																		Uuq Ununquadium																	
121																		17																	
Uuq Ununquadium																		Uuq Ununquadium																	
122																		16																	
Uuq Ununquadium																		Uuq Ununquadium																	
123																		15																	
Uuq Ununquadium																		Uuq Ununquadium																	
124																		14																	
Uuq Ununquadium																		Uuq Ununquadium																	
125																		13																	
Uuq Ununquadium																		Uuq Ununquadium																	
126																		12																	
Uuq Ununquadium																		Uuq Ununquadium																	
127																		11																	
Uuq Ununquadium																		Uuq Ununquadium																	
128																		10																	
Uuq Ununquadium																		Uuq Ununquadium																	
129																		9																	
Uuq Ununquadium																		Uuq Ununquadium																	
130																		8																	
Uuq Ununquadium																		Uuq Ununquadium																	
131																		7																	
Uuq Ununquadium																		Uuq Ununquadium																	
132																		6																	
Uuq Ununquadium																		Uuq Ununquadium																	
133																		5																	
Uuq Ununquadium																		Uuq Ununquadium																	
134																		4																	
Uuq Ununquadium																		Uuq Ununquadium																	
135																		3																	
Uuq Ununquadium																		Uuq Ununquadium																	
136																		2																	
Uuq Ununquadium																		Uuq Ununquadium																	
137																		1																	
Uuq Ununquadium																		Uuq Ununquadium																	
138																		0																	
Uuq Ununquadium																		Uuq Ununquadium																	
139																		17																	
Uuq Ununquadium																		Uuq Ununquadium																	
140																		16																	
Uuq Ununquadium																		Uuq Ununquadium																	
141																		15																	
Uuq Ununquadium																		Uuq Ununquadium																	
142																		14																	
Uuq Ununquadium																		Uuq Ununquadium																	
143																		13																	
Uuq Ununquadium																		Uuq Ununquadium																	
144																		12																	
Uuq Ununquadium																		Uuq Ununquadium																	
145																		11																	
Uuq Ununquadium																		Uuq Ununquadium																	
146																		10																	
Uuq Ununquadium																		Uuq Ununquadium																	
147																		9																	
Uuq Ununquadium																		Uuq Ununquadium																	
148																		8																	
Uuq Ununquadium																		Uuq Ununquadium																	
149																		7																	
Uuq Ununquadium																		Uuq Ununquadium																	
150																		6																	
Uuq Ununquadium																		Uuq Ununquadium																	
151																		5																	
Uuq Ununquadium																		Uuq Ununquadium																	
152																		4																	
Uuq Ununquadium																		Uuq Ununquadium																	
153																		3																	
Uuq Ununquadium																		Uuq Ununquadium																	
154																		2																	
Uuq Ununquadium																		Uuq Ununquadium																	
155																		1																	
Uuq Ununquadium																		Uuq Ununquadium																	
156																		0																	
Uuq Ununquadium																		Uuq Ununquadium																	
157																		17																	
Uuq Ununquadium																		Uuq Ununquadium																	
158																		16																	
Uuq Ununquadium																		Uuq Ununquadium																	
159																		15																	
Uuq Ununquadium																		Uuq Ununquadium																	
160																		14																	
Uuq Ununquadium																		Uuq Ununquadium																	
161																		13																	
Uuq Ununquadium																		Uuq Ununquadium																	
162																		12																	
Uuq Ununquadium																		Uuq Ununquadium																	
163																		11																	
Uuq Ununquadium																		Uuq Ununquadium																	
164																		10																	
Uuq Ununquadium																		Uuq Ununquadium																	
165																		9																	
Uuq Ununquadium																		Uuq Ununquadium																	
166																		8																	
Uuq Ununquadium																		Uuq Ununquadium																	
167																		7																	
Uuq Ununquadium																		Uuq Ununquadium																	
168																		6																	
Uuq Ununquadium																		Uuq Ununquadium																	
169																		5																	
Uuq Ununquadium																		Uuq Ununquadium																	
170																		4																	
Uuq Ununquadium																		Uuq Ununquadium																	
171																		3																	
Uuq Ununquadium																		Uuq Ununquadium																	
172																		2																	
Uuq Ununquadium																		Uuq Ununquadium																	
173																		1																	
Uuq Ununquadium																		Uuq Ununquadium																	
174																		0																	
Uuq Ununquadium																		Uuq Ununquadium																	
175																		17																	
Uuq Ununquadium																		Uuq Ununquadium																	
176																		16																	
Uuq Ununquadium																		Uuq Ununquadium																	
177																		15																	
Uuq Ununquadium																		Uuq Ununquadium																	
178																		14																	
Uuq Ununquadium																		Uuq Ununquadium																	
179																		13																	
Uuq Ununquadium																		Uuq Ununquadium																	
180																		12																	
Uuq Ununquadium																		Uuq Ununquadium																	
181																		11																	
Uuq Ununquadium																		Uuq Ununquadium																	
182																		10																	
Uuq Ununquadium																		Uuq Ununquadium																	
183																		9																	
Uuq Ununquadium																		Uuq Ununquadium																	
184																		8																	
Uuq Ununquadium																		Uuq Ununquadium																	
185																		7																	
Uuq Ununquadium																		Uuq Ununquadium																	
186																		6																	
Uuq Ununquadium																		Uuq Ununquadium																	
187																		5																	
Uuq Ununquadium																		Uuq Ununquadium																	
188																		4																	
Uuq Ununquadium																		Uuq Ununquadium																	
189																		3																	
Uuq Ununquadium																		Uuq Ununquadium																	
190																		2																	
Uuq Ununquadium																		Uuq Ununquadium																	
191																		1																	
Uuq Ununquadium																		Uuq Ununquadium																	
192																		0																	
Uuq Ununqu																																			

Figure 1.1 The periodic table of the elements

▼ A cathode tube



© www.wallpaperflare.com

▼ Millikan apparatus



© www.wallpaperflare.com

▼ A plum pudding, with the electrons represented by the raisins



© wikipedia

## 1.2 Early experiments of the atom

85 Scientists wondered about the nature of the atom and its structure. In a series of experiments in the late nineteenth century, scientists such as J.J. Thomson and Henri Becquerel, or Ernest Rutherford gained insight into the nature and structure of the atom. These experiments helped shape the view of the atom that we have nowadays.

90 *Charge to mass ratio of an electron* The English researcher J.J. Thomson investigated electric discharges in partially evacuated tubes—tubes in which the air has been partially removed. these tubes are also called cathode-ray tubes and are the base of old-fashion, bulky televisions. Thomson found that by applying high-voltage to these tubes rays—called cathode rays—emanated from the cathode of the tube, the negative electrode of the tube. These types of rays were repelled from the negative pole of an electric field. These rays were postulated to be a stream of negatively charged particles, now known as electrons. By studying the deflection of these rays by an electric field, Thomson was able to calculate the charge-to-mass ratio of an electron:

$$\frac{e}{m_e} = -1.76 \times 10^8 \text{ C/g} \quad (1.1)$$

where:

$e$  is the charge of an electron

$m_e$  is the mass of an electron

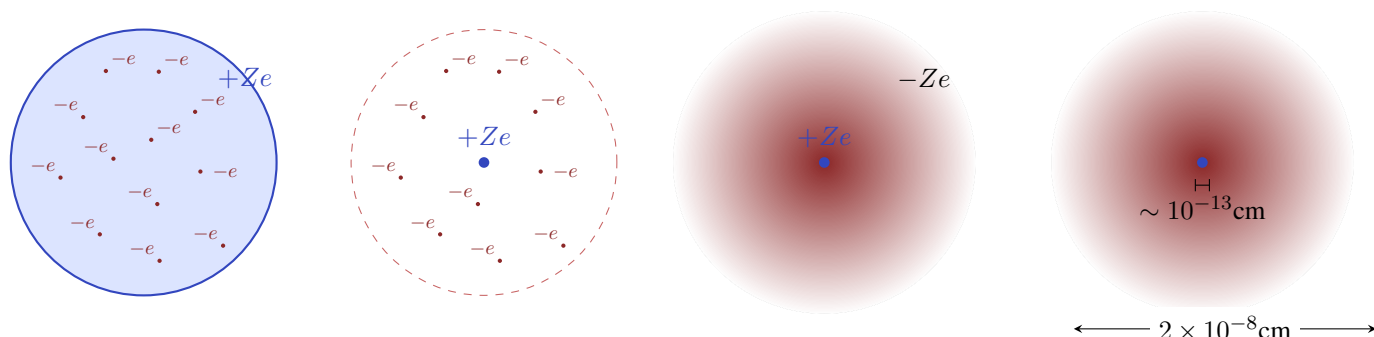
100 The main discovery Thomson made was that all atoms are made of negatively charged particles. As atoms are charge-neutral, they are also made of positively charged particles. These observations led to the *plum pudding model* that envisioned atoms as a diffuse cloud of positive charges with negative electrons embedded in it. The name plum pudding comes from an English dessert that contains a raising spread on it. Further experiments from Robert Millikan revealed the magnitude of the electric charge of the electron. Millikan used an apparatus that dispersed charged oil droplets that fell under the influence of an electric field. By knowing the applied voltage and the droplet mass one can calculate the droplet charge. Millikan found that the oil drop charge was always a whole-number time the electron charge,  $e=1.60 \times 10^{-19} \text{ C}$ , where a Coulomb is a unit of charge. With the value of the charge-to-mass ratio of an electron and the electron charge, Millikan was also able to calculate the mass of an electron,  $m_e=9.11 \times 10^{-31} \text{ kg}$ .

115 *Radiation* In the last part of the nineteenth century, scientists came to the discovery that some materials were able to produce high-energy radiation. Among the scientist working in this field, Henri Becquerel discovered that pitchblende, a mineral containing uranium, was able an image on a photographic plate in the absence of light. In the early twentieth century, three different types of radiation were discovered: alpha radiation, beta radiation, and gamma radiation. Further studies revealed that gamma radiation was made of gamma particles, high-energy radiation, whereas beta radiation was made of high-energy electrons. Alpha particles were found to be positively charged, with a charge twice the charge of an electron and a mass 7300 times that of the electron.

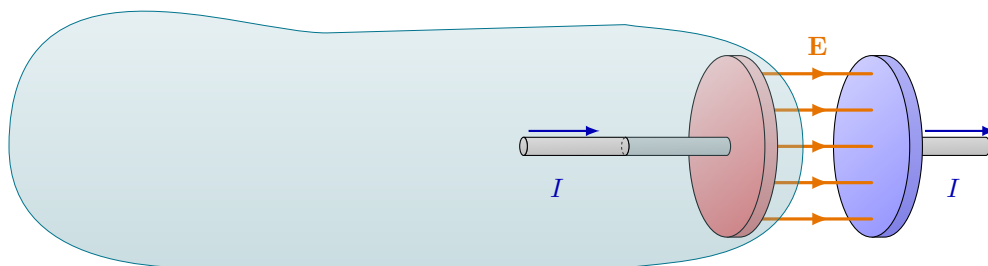
120 *The atom nucleus* Ernest Rutherford carried further experiments to understand the atomic structure hence validating the plum pudding model of the atom. He exposed a thin sheet of metal foil to  $\alpha$  particles known to be massive and positively charged particles. Following the plum pudding model, the bulky  $\alpha$  particles should crash through the thin foil and traverse through without being deflected. However, the results did

125

not corroborate his expectations. Indeed, some particles traversed the film, whereas other were slightly deflected and some were strongly deflected at large angles. These observations did not corroborate the plum pudding model. They contributed to a different vision of the structure of the atom in which a large number of positive charges were concentrated at a point—called the nucleus— instead of being spread whereas the electrons move around the nucleus at large distances from it. 130



**Figure 1.1** Three models of the atom. From left to right: the plum pudding model, the plum pudding model including Rutherford observations, the modern atomic model.  $Z$  is the atomic number of the atom.



### 1.3 The atom

Atoms are the smallest piece of an element that retains its characteristics. They are the building blocks of matter. This section covers the structure of the atom. You will learn how to calculate the number of subatomic particles that made an atom and how to differentiate atoms of an element—all atoms of an elements are not equal.

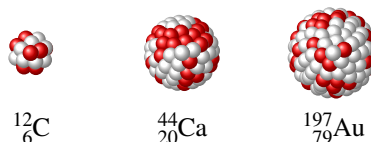
*Atomic Structure* Atoms contain three atomic particles: the proton, neutron, and electron. Protons have positive charge (+), whereas electrons carry negative charge (-). Neutrons on the other hand are neutral, and they have no electrical charge. Protons and neutrons are located in the core of the atom, which is called the nucleus, and account for the mass of the atom. Electrons are delocalized in the exterior part of the atoms. They are not necessarily located in a specific spot and their existence spreads in the area next to the nucleus. When an atoms is neutral it has no charge and the number of electrons and protons are the same. Some atoms have positive charge, resulting of removing electrons, and we call these cations. Others—called anions—can have negative charge as a result of accepting a negatively charged electron. 140 145

*Atomic and mass number* Elements are made of atoms, and each atom of an element is characterized by a atomic number ( $Z$ ) and a mass number ( $A$ ). The atomic 150

number ( $Z$ ) of an element indicates the number of electrons of an atom. This number can be easily located in the periodic table. The mass number ( $A$ ) of an element indicates the combined number of protons and neutrons. Mass numbers are nowhere located in the periodic table as different atoms of the same element can have different mass numbers. Both  $A$  and  $Z$  for an atom  $X$  are indicated in the following form called isotope notation:



As an example, the notation  ${}^{24}_{12}\text{Mg}$  means that the atomic number of Mg is  $Z=12$  and the mass number is  $A=24$ . Remember that the atomic number can be found in the periodic table whereas the mass number  $A$  is not on the table. By means of the isotope notation, one can quickly identify the number of protons, neutrons and electrons in an atom. As the atomic number is always indicated on the bottom part (e.g. Mg has 12 electrons). At the same time, the number of electrons and protons in a neutral atom is the same—neutral means an atom without a charge. The number of neutrons of an isotope can be computed by subtracting the atomic number from the mass number.



### Sample Problem 3

Calculate the number of protons, neutrons and electrons of the following atoms:

- (a)  ${}^{27}_{12}\text{Mg}$                       (b)  ${}^{22}_{10}\text{Ne}$                       (c)  ${}^{20}_{10}\text{Ne}$

#### **SOLUTION**

- (a)  ${}^{27}_{12}\text{Mg}$  has 12 electrons ( $Z=12$ ) and 12 protons as well (the number of electrons and protons are the same if the atom is neutral), and 15 neutrons, as  $27-12=15$ .  
 (b)  ${}^{22}_{10}\text{Ne}$  has 10 electrons and 10 protons, and 12 neutrons. (c)  ${}^{20}_{10}\text{Ne}$  has 10 electrons and 10 protons, and 10 neutrons as well.

#### **STUDY CHECK**

Calculate the number of protons, neutrons and electrons of the following atoms:

- (a)  ${}^{32}_{16}\text{S}$  (b)  ${}^{34}_{16}\text{S}$  (c)  ${}^{36}_{16}\text{S}$

**Isotopes** All atoms of the same element are not the same. Some are heavier than others. Isotopes are atoms of the same element with different numbers of neutrons and therefore with different mass number but with the same atomic number. For example:  ${}^{24}_{12}\text{Mg}$ ,  ${}^{25}_{12}\text{Mg}$  and  ${}^{26}_{12}\text{Mg}$  are three isotopes of Mg.  ${}^{27}_{12}\text{Mg}$  is heavier than  ${}^{24}_{12}\text{Mg}$  as it contains more neutrons and protons in the nucleus. Each of the isotopes has a specific abundance, as some isotopes are more abundant than others. For example, the abundance of  ${}^{24}_{12}\text{Mg}$  is 79%, and the abundance of  ${}^{25}_{12}\text{Mg}$  and  ${}^{26}_{12}\text{Mg}$  is 10% and 11%, respectively. This means,  ${}^{24}_{12}\text{Mg}$  is more abundant than for example  ${}^{26}_{12}\text{Mg}$ .

**Average atomic mass** The average atomic mass represents the mass of the atoms of an element and results from all existing isotopes taking into account their abundance. The units of atomic mass are called *amu*, which stands for atomic mass units. This value can be simply found at any periodic table. Using the periodic table provided in this manual Figure 1.1, you can find the atomic mass of each element on top of the symbol at the right side. For example, the atomic mass of oxygen (O) is 15.999 amu

and the atomic mass of nitrogen (N) is 14.007 amu. As atoms are made of numerous isotopes—this means different atoms of the same element but with different number of neutrons and hence different weight—the atomic mass found in the periodic table is an average that result from including the mass of the different isotopes and their abundance. That is you need to do an average of the mass of each isotope using values of abundance. In another words: the *average atomic mass* of an element—herein called simply atomic mass—, expressed in *amu* (atomic mass units), is the weighted average of the masses of the individual isotopes of the element. For an element with  $n$  isotopes with different masses ( $A_1, A_2, \dots, A_n$ ) and different fractional abundances for each isotope ( $f_1, f_2, \dots, f_n$ ), the atomic mass is given by

$$\text{Atomic mass} = \sum_{i=1}^n A_i \cdot f_i = A_1 \cdot f_1 + A_2 \cdot f_2 + \dots + A_n \cdot f_n$$

Also, note that when adding the fractional abundances of all isotopes, one should obtain a value of one:

$$\sum_{i=1}^n f_i = f_1 + f_2 + \dots + f_n = 1$$

#### Sample Problem 4

Naturally occurring copper (Cu) consists of 69.17%  $^{63}\text{Cu}$  and 30.83%  $^{65}\text{Cu}$ . The mass of  $^{63}\text{Cu}$  is 62.939598 amu, and the mass of  $^{65}\text{Cu}$  is 64.927793 amu. What is the atomic mass of copper?

#### **SOLUTION**

The weighted average is the sum of the mass of each isotope times its fractional abundance. We have that the isotope  $^{63}\text{Cu}$  has a mass of 62.939598 amu and an abundance of 69.17%, that is the same as 0.6917. At the same time, the isotope  $^{65}\text{Cu}$  has a mass of 64.927793 amu and an abundance of 0.3083. After adding both contributions, we have:

$$62.939598 \text{ amu} \times \frac{69.17}{100} + 64.927793 \text{ amu} \times \frac{30.83}{100} = 63.55 \text{ amu}$$

#### **STUDY CHECK**

Lithium is made up of two isotopes, Li-7 (7.016003 amu) and Li-6 (6.015121 amu). Calculate the percent abundance of each isotope knowing that lithium's atomic weight is 6.94 amu.



Table ?? Isotope abundance of some elements

Element	Isotope	% Abundance	Element	Isotope	% Abundance
Hydrogen	$^1\text{H}$	99.9885%	Silicon	$^{28}\text{Si}$	92.2297%
	$^2\text{H}$	0.0115%		$^{29}\text{Si}$	4.6832%
Helium	$^3\text{He}$	0.000137%	Sulfur	$^{30}\text{Si}$	3.0872%
	$^4\text{He}$	99.999863%		$^{32}\text{S}$	94.93%
Lithium	$^6\text{Li}$	7.59%		$^{33}\text{S}$	0.76%
	$^7\text{Li}$	92.41%		$^{34}\text{S}$	4.29%
Boron	$^{10}\text{B}$	19.9%		$^{36}\text{S}$	0.02%
	$^{11}\text{B}$	80.1%	Chlorine	$^{35}\text{Cl}$	75.78%
Carbon	$^{12}\text{C}$	98.93%		$^{37}\text{Cl}$	24.22%
	$^{13}\text{C}$	1.07%	Argon	$^{36}\text{Ar}$	0.3365%
Nitrogen	$^{14}\text{N}$	99.632%		$^{38}\text{Ar}$	0.0632%
	$^{15}\text{N}$	0.368%		$^{40}\text{Ar}$	99.6003%
Oxygen	$^{16}\text{O}$	99.757%	Potassium	$^{39}\text{K}$	93.2581%
	$^{17}\text{O}$	0.038%		$^{40}\text{K}$	0.0117%
	$^{18}\text{O}$	0.205%		$^{41}\text{K}$	6.7302%

## 1.4 An introduction to molecules

The periodic table contains all elements in nature. At the same time, elements combine to form molecules. For example, in the air there are traces of Argon—this is an element—and also water, a molecule ( $\text{H}_2\text{O}$ ) that results from the combination of two elements, hydrogen (H) and oxygen (O). This section will first introduce some of the properties of molecules, without paying attention to their chemical names that will be covered in the following chapters.

**Molecular weight** Here are two examples of molecules: molecular oxygen  $\text{O}_2$  and molecular nitrogen  $\text{N}_2$ . How do we interpret these formulas? The subscript "2" indicates that each molecule contains two atoms. For example, a  $\text{O}_2$  molecule is made of two oxygen atoms O. At the same time, the weight of a set of molecules is called the molecular weight (MW). However, you will find different terms to refer to the same property such as: molecular mass, molar mass, or formula unit mass. All these terms indeed mean the weight of a large set of molecules. We can calculate the MW by adding the weight of each atom that forms the molecule taking into account the number of atoms of each element present in the molecule. The units of molecular weight are the same as the units of atomic weight: amu, atomic mass units.

### Sample Problem 5

Calculate: (a) The atomic weight of O; (b) the molecular mass of molecular oxygen,  $\text{O}_2$

#### **SOLUTION**

- (a) According to the periodic table the atomic weight (AW) of O is 15.999 amu.  
 (b) The molar mass of  $\text{O}_2$  is the result of adding the atomic masses of 2 O atoms, that is 31.998 amu, close to 32 amu.

#### **STUDY CHECK**

Calculate the molar mass of water  $\text{H}_2\text{O}$  and ammonia,  $\text{NH}_3$



*Mass percent composition of a compound* Look at these two molecules:  $C_2H_2$  and  $C_2H_6$ . They contain different amounts of hydrogen. We quantify the amount of an element in a compound by means of the mass % composition. The mass % of an element in a compound is the mass of the element with respect to the molecular weight of the molecule in percent form. Mind that you have to take into account the molecular indexes in the compound as  $C_2H_2$  is made of 2H and  $C_2H_6$  is made of 6H. For example, given that the molar mass of  $C_2H_2$  is 26 amu, the mass % of hydrogen in  $C_2H_2$  would be:

$$\%_H \text{ in } C_2H_2 = \frac{2 \cdot AW(H)}{MW(C_2H_2)} \times 100 = \frac{2 \cdot 1}{26} \times 100 = 7.7\%$$

Similarly, the mass % of C would be:

$$\%_C \text{ in } C_2H_2 = \frac{2 \cdot AW(C)}{MW(C_2H_2)} \times 100 = \frac{2 \cdot 12}{26} \times 100 = 92.3\%$$

By adding the mass % of all elements in a molecule we should obtain 100.

$$\%_H \text{ in } C_2H_2 + \%_C \text{ in } C_2H_2 = 100$$

#### Sample Problem 6

Calculate the mass % composition for each element of glucose,  $C_6H_{12}O_6$ .

#### **SOLUTION**

We first need the molecular weight of glucose,  $C_6H_{12}O_6$ , that is:  $6 \cdot 12 + 12 \cdot 1 + 6 \cdot 16 = 180$  amu. Now we can calculate the mass percent of carbon, hydrogen and oxygen:

$$\%_C \text{ in } C_6H_{12}O_6 = \frac{6 \cdot 12}{180} \times 100 = 40\%$$

$$\%_H \text{ in } C_6H_{12}O_6 = \frac{12 \cdot 1}{180} \times 100 = 6.6\%$$

By subtraction, we have that  $\%_O \text{ in } C_6H_{12}O_6 = 53.4$ .

#### **STUDY CHECK**

Urea  $CO(NH_2)_2$  is a colorless crystalline compound excreted in urine, product of protein metabolism in mammals. Calculate the mass % composition for each element of urea.

## 1.5 Empirical and molecular formula of a chemical

There are two different types of formulas: molecular formulas and empirical formulas. Empirical formula (EFs) are simplified formulas resulting from an experiment, whereas molecular formulas (MFs) are exact formulas of molecules. For example: the molecular formula of hydrogen peroxide, a mild antiseptic used on the skin to prevent infection of minor cuts, is  $H_2O_2$  as the hydrogen peroxide molecule is made of two oxygen and two hydrogen atoms. Differently, the empirical formula of the same chemical is HO, being this the result of the simplification of  $H_2O_2$ . One can obtain empirical formulas simply by dividing the molecular formula by the smallest integer number, of course, given you know the molecular formula. The word empirical means "from an experiment", and the use of empirical formulas comes from the fact that the formulas of all chemicals actually come

from experiments, and from experiments one normally can only obtain ratios of atomic composition.

#### Sample Problem 7

From the following formulas identify the empirical and molecular formulas:  $\text{P}_4\text{O}_{10}$ ,  $\text{C}_3\text{H}_6\text{O}$ ,  $\text{N}_2\text{O}_4$  and  $\text{C}_5\text{H}_{11}$ .

#### SOLUTION

Empirical formulas are simplified versions of molecular formulas. For example,  $\text{C}_3\text{H}_6\text{O}$  and  $\text{C}_5\text{H}_{11}$  are empirical formulas. Differently,  $\text{P}_4\text{O}_{10}$  and  $\text{N}_2\text{O}_4$  are molecular formulas.

#### STUDY CHECK

Given the following molecular formulas, obtain the corresponding empirical formula:  $\text{P}_4\text{O}_{10}$ ,  $\text{N}_2\text{O}_4$  and  $\text{C}_6\text{H}_{18}\text{O}_3$ .

240

#### Molecular weight of empirical formulas and molecular formulas

The molecular weight of an empirical formula and its corresponding molecular formula are related by the following formula:

$$n = \frac{MW_{MF}}{MW_{EF}}$$

where:

$MW_{EF}$  is the molecular weight of the empirical formula

$MW_{MF}$  is the molecular weight of the molecular formula

$n$  is a integer number such as 1, 2, 3...

Understanding the formula above is simple. On one hand, the MW of a molecular formula  $\text{H}_2\text{O}_2$  that is 34 amu. On the other hand, the molecular weight of the empirical formula of the same chemical  $\text{HO}$  is 17 amu. If we do  $34/17$  we would obtain 2, as we need to multiply  $\text{HO}$  by two in order to obtain  $\text{H}_2\text{O}_2$ . As a final note, mind that empirical formulas are just simplified formulas. So when we think about the molecular weight of a chemical we normally have molecular formula in mind. Let us work on an example:

245

250

#### Sample Problem 8

Given that the empirical formula of dichloromethane is  $\text{ClCH}_2$  and the molecular weight of the chemical is 98 amu, calculate the molecular formula of dichloromethane.

#### SOLUTION

Given the empirical formula of dichloromethane one can think of many different molecular formulas, for example:  $\text{Cl}_3\text{C}_3\text{H}_6$  or  $\text{Cl}_2\text{C}_2\text{H}_4$ . From these, and many other, there is only one real molecular formula. How do we calculate the real molecular formula? By comparing the MW of the molecular and empirical formula we can figure out the number of times we need to multiply the MF to obtain the EF. We know the MW is 98 amu. Using the EF we can also calculate a MW:  $35 + 12 + 2 \cdot 1 = 49$  amu. If we compare both numbers using the formula:

$$n = \frac{MW_{MF}}{MW_{EF}}$$

we have:  $n = 98/49$  and solving we have  $n = 2$ . Therefore the MF is:  $\text{Cl}_2\text{C}_2\text{H}_4$ .

### STUDY CHECK

The empirical formula of dinitrogen tetroxide, a red-brown liquid with an unpleasant chemical odor, is  $\text{NO}_2$  and the molecular weight of the chemical is 92 amu. Calculate the molecular formula of dinitrogen tetroxide.

## 1.6 Determining empirical formulas

We said that the formula of a chemical that takes into account the correct number of atoms in a molecule is the molecular formula and therefore the real molecular weight of a chemical comes from these formulas. Empirical formulas are obtained from experiments in which a chemical is fragmented and analyzed so that the elements in the molecule and the mass percentage of each element is determined. Molecular formulas are obtained by using the molecular weight of the chemical and the empirical formula. Mind that the formula of a chemical that takes into account the correct number of atoms in a molecule is the molecular formula and therefore the real molecular weight of a chemical comes from these formulas. Let us work on an example in order to learn the procedure of obtaining molecular formulas.

*Calculating molecular formulas* By means of an experiment, we want to calculate the empirical formula of a chemical given that the chemical contains 2.8 g of nitrogen and 6.4 g of oxygen. In order to calculate the EF we will set up a table like the one presented below.

Empirical Formula Calculation		
	N	O
Grams	2.8g	6.4g
AW	14	16
Grams/AW	0.2	0.4
∇ • by smallest	1	2
Formula	$\text{N}_1\text{O}_2 = \text{NO}_2$	

In each column we will add each of the elements that form the molecule. In the first row we will include the grams of each element (sometimes this information is given in terms of mass %), in the second we will divide the grams of each element by its atomic weight ( $\text{AW}(\text{N})=14\text{amu}$ ,  $\text{AW}(\text{O})=16\text{amu}$ ). Among all numbers of the second row (in this example 0.2 and 0.4), we will select the smallest number (0.2). Once we have the smallest, we will divide all numbers by the smallest and that will give us round numbers (1 and 2); these will be the numbers in an empirical formula:  $\text{NO}_2$ .

### Sample Problem 9

The mass percentage composition of a compound is: 18.59% O, 37.25% S, and 44.16% F. Calculate its empirical formula.

### SOLUTION

We will set up the the molecular formula table, knowing that the percentage are mass percentages, that is the mass of each element in the chemical, hence they should go in the grams row. Also the atomic weights of O, S and F are 16, 32 and 19 amu.

Empirical Formula Calculation			
	O	S	F
Grams	0.1859g	0.3725g	0.4416g
AW	16	32	19
Grams/AW	0.0116	0.0116	0.0232
$\nabla \cdot$ by smallest	1	1	2
Formula	OSF <sub>2</sub>		

### **STUDY CHECK**

What is the empirical formula of a compound if a sample contains 10.28 g of C, 1.71 H and 12.71 g of oxygen?