Why?

The atomic theory of matter is the great organizing principle of chemistry. Atoms are the fundamental building blocks of all matter. The mass relationships between elements and compounds in chemical reactions ultimately relate back to the characteristics of the atoms of which they are composed. To understand how atoms combine to form compounds, you need to understand their basic composition and structure.

Learning Objective
- Understand the basis for atomic theory
- Understand the structure of atoms, isotopes, and ions
- Understand the relationship between the masses of isotopes and the atomic weight of an element
- Become familiar with the periodic table

Success Criteria
- Be able to write the standard nuclide notation for an isotope
- Be able to determine the numbers of fundamental particles in atoms and ions
- Be able to calculate atomic mass of a mixture of isotopes and percent isotopic composition
- Be able to categorize elements by position in the periodic table

Prerequisite
- Have read Chapter 2 in the text
- Understand percentage, scientific units, and unit analysis

Information

Dalton's Atomic Theory was based in part on the work of the French scientist Joseph Louis Proust in 1799. Proust discovered what is now called the **Law of Definite Proportions** (also called the Law of Constant Composition): A compound is always composed of the same elements in a fixed ratio by weight.

Example: When 200.59 g of mercury reacts completely with 32.066 g sulfur, 232.66 g of red mercury sulfide is produced. What is the **percent composition by weight** of red mercury sulfide?

$$\% \text{Hg} = \frac{200.59\,\text{g}}{232.66\,\text{g}} \times 100\% = 86.216\,\%\text{Hg}$$

$$\% \text{S} = \frac{32.066\,\text{g}}{232.66\,\text{g}} \times 100\% = 13.782\,\%\text{S}$$

For every sample of red mercury sulfide the same percent composition by weight is found. (The mineral cinnabarite is this compound.) It follows from this that a compound of mercury and sulfur with any other percent composition by weight must be a different substance.

Proust's discovery suggested to Dalton that the elements from which compounds are formed must be composed of indivisible units, which combine in specific ways. From this idea, he proposed an atomic theory, which in modern terminology consists of the following points:

① All matter is composed of atoms.

❷ All atoms of an element have the same mass (*atomic weight*).

❸ All atoms of different elements have different masses (i.e., different atomic weights).

❹ Atoms are indestructible and indivisible.

⑤ Compounds are formed when atoms of two or more elements combine.

⑥ In a compound the relative numbers and kinds of atoms are constant.

Points ❷, ❸, and ❹ are now known to be incorrect, in light of the following later discovered facts:

② Many elements are composed of a mixture of **isotopes**, atoms of the same element with different masses.

③ Some atoms of two different elements may have virtually the same mass; these are called **isobars**.

④ Atoms can be split (**fission**) or merged (**fusion**) in **nuclear reactions**. Some of the mass of atoms is converted to energy in nuclear reactions.

Key Questions
1. What is the Law of Definite Proportions?

2. Why Does the Law of Definite Proportions suggest the postulates of Dalton's atomic theory?

Information
Dalton knew that some pairs of elements could make more than one kind of compound and that the percentages of each element were different in each case. On the basis of his atomic theory he predicted and experimentally verified the **Law of Multiple Proportions**: If two elements can form more than one compound, then the ratios of the weights of one element in the compounds to a fixed weight of the other element are small whole numbers.

Key Questions
3. Explain how Dalton's atomic theory predicts the Law of Multiple Proportions.

4. Suppose elements X and Y can form two compounds. One compound has as many X atoms as Y atoms (formula XY), and the other compound has twice as many X atoms as Y atoms (formula X_2Y). What mass ratios would you compare between these compounds to

demonstrate the Law of Multiple Proportions? What whole number ratio would be expected between these ratios?

Exercise
5. A chemist prepared three different compounds that contain only iodine and fluorine and determined the mass of each element in each compound, as shown below. Calculate the mass of fluorine per gram of iodine in each compound, and explain how your results support atomic theory.

Comp.	m_I (g)	m_F (g)	m_F/m_I
1	4.75	3.56	
2	7.64	3.43	
3	9.41	9.86	

Information
Today we know that atoms may be composed of three fundamental particles: protons, neutrons, electrons.

| Particle	Unit Charge	Mass
Proton (p)	1+	1.6726×10^{-24} g
Neutron (n)	0	1.6749×10^{-24} g
Electron (e)	1–	9.1095×10^{-28} g

Unit electrical charge is is $\pm 1.6022 \times 10^{-19}$ coulomb (C). The **nucleus** at the center of the atom contains one or more positively charged **protons**. All atoms of a given element have the same number of protons, which defines the element's atomic number, given the symbol Z. In addition, the nucleus may contain one or more **neutrons**, which have approximately the same mass as protons but have no charge. Together, protons and neutrons are known as **nucleons**. Any atom with a certain number of nucleons is called a **nuclide**. The number of nucleons defines the nuclide's **mass number**, given the symbol A:

$$A = \text{number of protons} + \text{number of neutrons}$$

Note that the mass number is an integer count of the number of nucleons, and not a statement of an atom's mass. **Isotopes** of an element have the same atomic number (Z) but have different mass numbers (A), because they have different numbers of neutrons. **Isobars** are nuclides of different elements (different Z) with the same mass number (A). Isobars have nearly the same mass.

The standard notation for a nuclide has the form $_Z^A X$, where X is the element's symbol; Z is its atomic number, equal to the number of protons; and A is the mass number, equal to the total number of nucleons (protons and neutrons). An electrically neutral atom has the same number of

protons as **electrons**, negatively charged particles that reside outside the nucleus. Atoms may acquire electrical charge by either gaining or losing one or more electrons, thus becoming **monatomic ions**. Positive ions are **cations**; negative ions are **anions**.

$$\text{Atom} \rightarrow [\text{Cation}]^{n+} + ne^-$$
$$\text{Atom} + ne^- \rightarrow [\text{Anion}]^{n-}$$
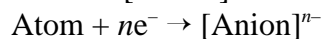
Key Questions

6. What is the basis for defining the atomic number (Z) of an element?

7. What is the basis for defining the mass number (A) of a nuclide?

8. Are Z and A exact or inexact numbers?

9. How does an atom become a cation or anion?

10. Does Z or A change in forming an ion? Why or why not?

11. In some nuclear reactions an atom's number of protons can change. Is it the same element after such a change?

Exercises

12. On the periodic table attached, each block shows the atomic number of the element at the top, above the element's symbol. With the aid of the periodic table, give the standard nuclide notation for the following isotopes used in medicine: phosphorous-32, chromium-51, cobalt-60, iodine-131.

13. With the aid of the periodic table, fill in the blanks in the following table:

Charge	0	0	0	3+	2–
Symbol	^{56}Fe				
Protons		35			34
Neutrons		45		38	
Electrons			79	28	
Mass no.			197		79

Information

Because the masses of atoms are so small, it is more convenient to give nuclide masses in **atomic mass units**, abbreviated **amu** or **u** (the latter is the official SI abbreviation), rather grams. The atomic mass unit is defined as follows:

One atomic mass unit is defined as 1/12 of the mass of a $^{12}_{6}$C atom.

In atomic mass units the fundamental particles have the following masses

$$\text{proton} \quad 1.007277 \text{ u}$$

$$\text{neutron} \quad 1.008665 \text{ u}$$

$$\text{electron} \quad 0.0005486 \text{ u}$$

We cannot use these data to calculate the mass of a given atom, because the mass of a nuclide is not simply the sum of the masses of its fundamental particles. When atoms are formed from protons, neutrons, and electron, some mass is converted into energy, called the **binding energy**. The mass equivalent of this energy can be calculated from the difference between the measured mass of the nuclide and the sum of the masses of its subatomic particles, using $E = mc^2$, where m is the mass converted into energy, and c is the speed of light in a vacuum.

Because of the existence of isotopes, the masses of individual atoms in a sample of an element may not all be the same. Indeed, with a few exceptions, most naturally occurring samples of an element are mixtures of two or more isotopes in unequal portions. We generally deal with samples containing large numbers of atoms with the usual mix of isotopes for the element, so it is more useful to use an **average atomic mass**, weighted according to isotopic abundance. By long standing tradition, this average has been called the **atomic weight**, even though the quantity is actually mass. In general, tabulated values of atomic weights for elements do not represent the mass of a single nuclide, unless the element occurs naturally as only one isotope.

Key Questions
14. For all elements except fluorine, the atomic weight listed on the periodic table *does not* correspond to the mass of any nuclide? What does the atomic mass of most elements represent?

15. The atomic weight listed for fluorine on the periodic table (18.998403 u) *does* correspond to the mass of a particular nuclide. What does that imply about the isotopic composition of naturally occurring fluorine?

Exercises
16. Boron consists of 19.78% ^{10}B with atomic mass 10.0129 u and 80.22% ^{11}B with atomic mass 11.00931 u. Calculate the atomic weight of naturally occurring boron.

17. By definition, the mass of a $^{12}_{6}$C atom is exactly 12 u. What is the sum of the masses of the particles comprising a $^{12}_{6}$C atom? Why is the sum not 12 u?

Information
In 1869 Dmitri Mendeleev (Russian) and Julius Lothar Meyer (German) independently discovered that when elements are arranged in order of their atomic weights, characteristic properties of certain elements are repeated in other heavier elements at regular intervals in the sequence. From this emerged the first statement of **periodic law**:

The properties of elements are a periodic function of their *atomic weights*.

This ordering, however, seemed to place some elements out of sequence. A better arrangement, based on atomic number, became possible in 1913, when **Henry G. J. Moseley** found that the atomic numbers of elements could be determined experimentally from their characteristic x-ray frequencies. Today the periodic law is based on atomic numbers, rather than atomic weights:

The properties of elements are a periodic function of their *atomic numbers* (*Z*).

In most modern periodic tables, each block for an element shows its atomic number in the first line, the element's symbol underneath that, and the atomic weight of a naturally occurring sample of the element below its symbol. The following definitions are used in conjunction with the periodic table:

group - a column in the periodic table, listing elements that tend to show similar chemical behavior. In North America, groups have been numbered 1 through 8 (or 0) with appended letter designations A or B (e.g., 1A, 3B). The newer I.U.P.A.C. system uses numbers 1 through 18. Although hydrogen, H, is sometimes shown in group 1 (and even group 17), it really belongs to no group, because its chemistry is unique.

period - a row in the periodic table. Periods are numbered 1 through 7.

main group elements (or **representative elements**) - members of the A group elements (old North American system); i.e., groups 1A (1) and 2A (2), and 3A (13) through 8A (18) (newer I.U.P.A.C. system designations in parentheses).

transition elements - members of the B group elements (old North American system), corresponding to the groups 3 through 12 in the I.U.P.A.C. system. The first, second, and third transition series span these groups in periods 4, 5, and 6, respectively. [Element number 89 (actinium, Ac) in period 7 begins a fourth transition series that would be continued with elements 104 through 112, but these are all unstable, synthetic elements.]

lanthanides - elements 58 through 71 in the first row at the bottom of the periodic table (a continuation of period 6). Lanthanum (La) is actually the first element of the third transition series, not a lanthanide.

actinides - elements 90 through 103 in the second row at the bottom of the periodic table (a continuation of period 7). Actinium (Ac) is actually the first element of an incomplete fourth transition series, not an actinide.

There are three categories of elements: metals, nonmetals, and metalloids, defined as follows:

metals - elements in groups 1A (1) and 2A (2), the transition elements, the lanthanides and actinides, and the heavier elements in groups 3A (13) through 5A (15) that lie below the stair step shown on some periodic tables. At room temperature metals are shiny solids (except mercury and gallium above 29.78°C, which are liquids) that are malleable, ductile, and conductive of heat and electricity. Metals characteristically are cations in their ionic compounds.

nonmetals - the elements in groups 4A (14) through 7A (17) that lie above the stair step on some periodic tables. Individual nonmetals may be either solids, liquids, or gases at room temperature. They are poor conductors of heat and electricity. Nonmetals characteristically are anions, when existing as monatomic ions in ionic compounds. When combined with other nonmetals, they typically form molecular compounds or complex ions.

metalloids - the elements B, Si, Ge, As, Sb, Te, Po, At, which lie along the stair step shown on some periodic tables. All are solids with semi-metallic properties. They show poorer conductivity relative to metals and may be semiconductors (e.g., Si and Ge).

Key Questions

18. What information about an element is provided in the box for that element in the periodic table?

19. What determines the sequence of elements from the first to the last?

20. What is the difference between a group and a period?

21. Where are the metals, nonmetals, and metalloids located?

22. Are the majority of elements metals, nonmetals, or metalloids?

23. Does hydrogen belong to group 1? Why or why not?

Exercises

24. Write the name, symbol, atomic number and average mass for each of the following, and indicate whether the element is metal, nonmetal, or metalloid:
    a. The group 2 element in period 3
    b. The group 16 element in period 2
    c. The group 15 element in period 4

25. Write the name and symbol of the element that has 48 electrons.

26. Name the elements with properties similar to chlorine, Cl.

27. Give the symbols and names of elements 57 and 72 in the period 6. Why are they adjacent to each other in the periodic table?

Problem

28. Chlorine consists of ^{35}Cl with a mass of 34.96885 u and ^{37}Cl with a mass of 36.96590 u. The atomic weight of chlorine is 35.453 u. What is the percent abundance of each isotope?

Periodic Table of the Elements

1A 1																	8A 18
1 H 1.008	2A 2											3A 13	4A 14	5A 15	6A 16	7A 17	2 He 4.003
3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.31	3B 3	4B 4	5B 5	6B 6	7B 7	8	8B 9	10	1B 11	2B 12	13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc [98]	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
55 Cs 132.9	56 Ba 137.3	57 La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po [209]	85 At [210]	86 Rn [222]
87 Fr [223]	88 Ra [226]	89 Ac [227]	104 Rf [261]	105 Db [262]	106 Sg [263]	107 Bh [264]	108 Hs [265]	109 Mt [268]	110 Uun [269]	111 Uuu [272]	112 Uub [277]						

58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm [145]	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np [237]	94 Pu [244]	95 Am [243]	96 Cm [247]	97 Bk [247]	98 Cf [251]	99 Es [252]	100 Fm [257]	101 Md [258]	102 No [259]	103 Lr [262]